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VEREINSMITTEILUNGEN

Einladung zur Jahreshauptversammlung:
Die nächste Jahreshauptversammlung findet am 23. 01. 2006 um 17:45 Uhr im Geozentrum der Universität Wien, Althanstraße 14, Hörsaal 2 (Raum 2A122) mit folgender Tagesordnung statt:

1. Feststellung der Beschlussfähigkeit
2. Rechenschaftsbericht des Vorstandes
3. Bericht der Rechnungsprüfer
4. Genehmigung des Rechenschaftsberichtes und Entlastung des Vorstandes
5. Bestimmung der Anzahl und Wahl der Vorstandsmitglieder 2006
6. Wahl der Rechnungsprüfer für das Vereinsjahr 2006
7. Festsetzung des Mitgliedsbeitrages für das Vereinsjahr 2006
8. Ehrungen, Verleihungen
9. Allfälliges

Sollte die für 17:45 Uhr einberufene Jahreshauptversammlung nicht beschlussfähig sein, so findet satzungsgemäß eine neue Jahreshauptversammlung ohne Rücksicht auf die Zahl der anwesenden Mitglieder um 18:00 Uhr statt.

Vereinsvorstand für 2005 (gewählt am 17 01. 2005)

Präsident:	Prof.Dr. Peter Mirwald, Innsbruck
Vize-Präsident:	Prof.Dr. Friedrich Koller, Wien
Kassier:	Prof.Mag.Dr. Gerald Giester, Wien
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	Prof.Dr. Franz Pertlik, Wien
	Prof.Dr. Franz Walter, Graz

Mitgliedsbeiträge: Die Jahreshauptversammlung beschloss, die Höhe der Mitgliedsbeiträge für 2005 mit € 30 für ordentliche Mitglieder und € 10 für studentische Mitglieder unverändert zu belassen.

Mitteilungen der Österreichischen Mineralogischen Gesellschaft: Ab Band 142 sind Originalarbeiten über http://earthsciences.uibk.ac.at/oemg/index.html als PDF-Dateien zu finden.
Artikel für Band 151 der „Mitteilungen der Österreichischen Mineralogischen Gesellschaft" werden bis Ende April 2006 angenommen. Autorenhinweise entnehmen Sie bitte dem letzten Band oder unserer Homepage. Einreichen: per E-mail: friedrich.koller@univie.ac.at; per Post: Prof. Dr. F Koller, Institut für Geologische Wissenschaften, Universität Wien-Geozentrum, Althanstraße 14, 1090 Wien.

Mineralbestimmungen: Vereinsmitglieder können sich zur Mineralbestimmung nach telefonischer Terminvereinbarung an folgende Personen wenden:
Institut f. Mineralogie & Kristallographie der Universität Wien: Prof. Dr. A. Beran (Tel.: 4277-532 53), Prof. Dr. M. Götzinger (Tel.: 4277-532 52), Prof. Mag. Dr. E. Libowitzky (Tel.: 4277-532 50).
Naturhistorisches Museum, Mineralogisch-Petrographische Abteilung: Dr. F. Brandstätter (Tel.: 52177-270); Dr. V. M. F. Hammer (Tel.: 52177-272), Dr. G. Niedermayr (Tel.: 52177-274).

Erinnerung: Wir ersuchen, Adressen- und Titeländerungen bzw. die Beendigung des Studiums dem Sekretariat der Gesellschaft schriftlich bekannt zu geben.

gez. P Mirwald (Präsident) V.M.F Hammer (Schriftführung)

Mitteilungen der Österreichischen Mineralogischen Gesellschaft

Band 150 **2005**

7th International Eclogite Conference

Editors: A. Proyer and K. Ettinger
Institute of Earth Sciences, Department of Mineralogy and Petrology, Karl Franzens University of Graz

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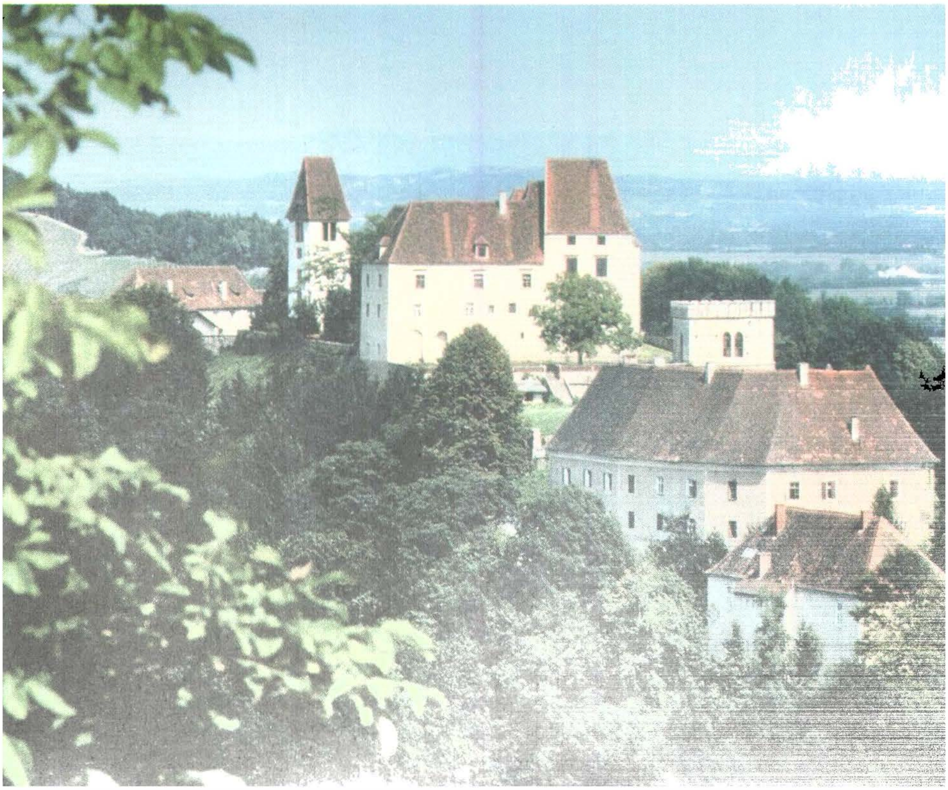
7th International Eclogite Conference 2005
Juli 3rd - July 9th, Seggau, Austria – Excursions

7th International Eclogite Conference

July 3rd - July 9th, 2005

Seggau, Austria

Abstracts



TRACE ELEMENT ABUNDANCES IN RUTILE AND ZR-IN-RUTILE GEOTHERMOMETER APPLIED TO THE SUDETIC ECLOGITES

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The Sudetic eclogites outcrop in the eastern termination of the West Sudetes in the Orlica-Snieznik Dome (OSD) and in the Fore-Sudetic Block (FSB) within the Kamieniec Zabkowicki metamorphic complex. Most of the OSD eclogites can either display the MORB provenance and belong to the Mg-Al-Cr eclogite sub-type (OSD1) or show calc-alkaline affinity (OSD2). The OSD eclogites from eclogite-granulite series (OSD3) originated at the expense of bimodal volcanics. The FSB eclogites belong to Fe-Ti sub-type (BAKUN-CZUBAROW, 1998). The OSD eclogites underwent UHPM during continental collisional event (BAKUN-CZUBAROW & KUSY, 2001), whereas the FSB eclogites are subduction related ophiolitic rocks. In rutiles from OSD & FSB eclogites, abundances of high field strength (Zr, Nb), 3d type transition (Cr, Fe) and other trace elements (Al, Si, Ca) were determined by means of CAMECA SX 100 electron microprobe, with the use of the TR-type software. Rutile grains from different eclogites show large variations (1 2 orders of magnitude) for compatible – Cr (60 - 6400 ppm), Nb (100 - 4700 ppm), Zr (70 - 1750 ppm), Fe (500 - 6000 ppm), and for incompatible elements Ca (< 25 - 14000 ppm), Si (< 12 - 6500 ppm), Al (< 12 - 600 ppm). Most analysed rutile grains are homogenous on single grain scale, and less so between the grains in the same rock sample. The element order of decreasing preference for rutile Nb > Ti >> Cr > Zr, established by ZACK et al. (2002) for Trescolmen eclogites, has been confirmed for the Sudetic eclogites. From among the analyzed grains, rutiles from the OSD1 eclogites are the Cr-richest, from the OSD3 eclogites are the Zr-richest, while rutiles from FSB eclogites are richest in Nb. Thus the analyzed trace compatible elements (HFS and transition) are significant for the rutile provenance study. A new Cr-Zr-Nb discrimination diagram for rutile, with distinguished fields for rutile from OSD1, OSD3 and FSB eclogites, has been constructed and tentatively verified. For the estimation of the rutile-quartz-zircon equilibration temperature in the Sudetic eclogites, the newly formulated Zr-in-rutile geothermometer: $T(in\ ^{o}C) = 127.8 \times ln(Zr\ in\ ppm) \quad 10$ (ZACK et al., 2004), was applied. The obtained results plot close to the upper limits of the previous geothermobarometric estimates: 740 °C for OSD1, 780 °C for OSD2 and 930 °C for OSD3, but are ca 50 °C higher than earlier results for the FSB eclogites (660 °C).

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LATE MIOCENE–PLIOCENE ECLOGITES OF EASTERN PAPUA NEW GUINEA: THE YOUNGEST KNOWN HP/UHP TERRANE ON EARTH

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Eastern Papua New Guinea (PNG) evolved within the rapid (10 - 11 cm / a) obliquely convergent Australian-Pacific (AUS–PAC) plate boundary zone. Presently the Woodlark Basin of eastern PNG forms the plate boundary between AUS and the Woodlark microplate, and at its western end is undergoing the transition from distributed rifting to seafloor spreading as part of the most rapidly extending (~ 2 - 4 cm / a at 151.5 °E) rift system on Earth. The Cenozoic evolution of this complex plate boundary zone involved northwards subduction of the northern Australian continental margin beneath oceanic lithosphere, a collision that led to HP metamorphism of Jurassic – Cretaceous sediments and basalts, and southward obduction of PAC oceanic crust and mantle. Relics of this subduction event occur as variably retrogressed eclogites subsequently exhumed within the lower plates of the D'Entrecasteaux Islands metamorphic core complexes, located west of the active seafloor spreading rift tip. Results of P-T-t studies demonstrate that this is the youngest exhumed HP/UHP terrane presently known on Earth. Eclogites occur as cross-cutting dikes and layers/lenses within gneisses, and as xenoliths in granodiorites and preserve peak assemblages of Omp + Grt + Rt + Ky + Phn + Qtz. *In situ* ion probe analysis of zircons that occur primarily as inclusions in garnet yielded $^{238}U/^{206}Pb$ ages for six samples ranging from 7.9 - 2.0 Ma. *In situ* ion probe garnet and zircon trace and REE patterns and Grt/Zrc distribution coefficients are similar to those reported for Alpine eclogites and indicate coeval growth of these phases under eclogite facies conditions. We report the first documented occurrence of coesite in eastern PNG, recognized petrographically and confirmed by *in situ* Raman spectroscopy, from a 7.9 Ma eclogite xenolith. The 150 μm diameter SiO_2 inclusion exhibits partial transformation to palisade quartz which led to radial fracturing of its omphacite host grain. Six Raman spectra for this bimineralic inclusion yielded diagnostic Raman bands for coesite at 520, 354 - 356, 270 and 176 cm^{-1} and diagnostic Raman bands for quartz at 463 - 465 cm^{-1}. Results extend the depths of metamorphism for these eclogites and indicate that some were metamorphosed under UHP conditions. Eclogite exhumation from HP/UHP conditions occurred at plate tectonic rates (cm / a) and was facilitated by removal of upper plate rocks during microplate rotation, movement from beneath kilometer scale mylonitic shear zones, and partial transport within magmatic rocks. In this active plate boundary zone it is likely that HP/UHP rocks are still in the process of being exhumed from depth, and structures that facilitate exhumation are still in their geodynamic configuration. Thus, eastern PNG represents the best opportunity globally for finding HP/UHP rocks at depth and unraveling their *in situ* exhumation.

ZIRCON STUDY FROM THE RHODOPE METAMORPHIC PROVINCE, GREECE

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The Kimi complex of the northern Rhodope Metamorphic Province, Greece, is considered to be a proven ultrahigh-pressure unit since the presence of tiny (3 – 9 µm) microdiamond inclusions in metapelitic garnets was proven by Micro Raman Spectroscopy (PERRAKI et al., 2004). Zircons, known as containers of UHP minerals, were investigated from this area with Micro Raman Spectroscopy and Scanning Electron Microscopy to obtain information about the growth history and the petrogenesis of their host rocks. More than 1500 grains were separated from orthogneisses and kyanite-bearing garnet micaschists.

The first part of the work was an inclusion study using Micro Raman Spectroscopy. The grains were separated, handpicked and put on glass plates as loose grain mounts. This method allows the non-destructive investigation of the rare inclusions in the whole volume of the grains. Furthermore, fluorescence effects caused by the embedding material are prevented.

The zircons separated from the orthogneisses show characteristics of magmatic formation, which are idiomorphic shape and typical magmatic inclusions like quartz, feldspar, apatite or xenotime. The roundish, metamorphic zircons from kyanite-bearing garnet micaschists bear fewer inclusions than the magmatic grains. They enclose carbon phases (carbonates, CO_2, graphite and disordered graphite) as well as rutile, quartz, feldspar or apatite.

A second step was a SEM study using BSE- and CL – imaging. The grains were embedded maintaining their position to enable the correlation of the different information gained from Raman and SEM investigations. The zircons from orthogneisses are about 100 to 200 µm in size. They show oscillatory zoning, a metamorphic rim of variable thickness and zones of recrystallization. Numerous inclusions of biotite or ilmenite were detected, which could not be proven by Raman because of strong fluorescence. The zircons from metapelites are about 40 to 70 µm in size. They show metamorphic characteristics like xenomorphic, chubby shape and simple growth zoning, while magmatic cores are rare.

Despite the expectation that zircons from UHP rocks contain characteristic indicators of these extreme conditions, it was not possible to find typical (U)HP mineral inclusions, like in other UHP regions, where indicative mineral inclusions are hosted by zircons (e.g. KORSAKOV et al., 2002). Inclusion mineralogy suggests that growth of metamorphic zircon in the investigated samples occurred after the UHP event.

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BLUESCHIST-FACIES METAMORPHISM & GEOCHEMISTRY OF METABASITES FROM UPPER TECTONIC UNIT IN LAVRION AREA (SE ATTICA, GREECE)

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The broad area of Lavreotiki peninsula is a part of the Attic-Cycladic crystalline complex. It consists of two tectonic units that underwent a HP/LT metamorphism of Tertiary age. The lower tectonic unit comprises a thick marble sequence intercalated with schists. The upper tectonic unit is mainly composed of phyllites, calc-schsits and quartzites. Metabasic bodies are tectonically mixed with the surrounding sediments. Primary volcanic features are observed in the metabasic rocks; i.e. porphyritic textures with clinopyroxene phenocrysts.
The mineral assemblage of the metabasites is: Ca-Amp + Na-Amp + Ab + Ep + Chl + Pmp ± Phg ± Bt ± Cpx ± Law ± Stp. Based on the dominant amphibole phase in the rock, the metabasites are divided into blueschists and greenschists. Blue amphibole has the composition of glaucophane to ferroglaucophane. Zoned blue amphiboles show an increase in Al^{IV} and Al^{VI} from the core to the rim and decrease in Al^{VI} at the outermost rim. Actinolitic inclusions in glaucophane, glaucophane inclusions in actinolite and zoned blue amphiboles record the prograde and retrograde path of metamorphism. Magmatic clinopyroxene is augite. Metamorphic clinopyroxene is omphacite to aegirine-augite with a jadeite component ranging from 23 to 35 mol%. Iron-rich pumpellyite (FeO = 9.19 - 12.58 wt%) coexist with iron-poor ones (FeO = 1.12 - 5.08 wt%). Lawsonite inclusions in epidote and albite show that the rocks passed from the lawsonite-blueschists to the epidote-blueschists field (EVANS, 1990). The composition of glaucophane, omphacite and phengite (Si = 3.65 a.p.f.u.) constrain minimum pressure of ~8 - 9 kbar for assumed temperature 300 - 350 °C.
The greenschists and blueschists have basaltic composition with subalkaline affinities and tholeitic character. Trace elements and REE contents indicate MORB environment for the protoliths. The greenschists have higher contents in MgO compared to the blueschists. TiO_2, Zr, Y, LREE and HREE show a positive, Al_2O_3, Ni and Cr a negative and V a positive and then a negative correlation trend with decreasing #Mg. Such correlations are expected during magmatic fractionation processes. Also, the #Mg shows that the more evolved compositions are enriched in REE compared to the less evolved ones, indicating fractionation of basaltic magmas rather than variable degrees of partial melting in the mantle source region or post-magmatic processes such as alteration or metamorphism.

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OXYGEN AND HYDROGEN ISOTOPE INHOMOGENEITIES, AN IN SITU STUDY ON ECLOGITES FROM DABIE SHAN, CHINA

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Dabie Shan eclogites are well known for their low oxygen ($\delta^{18}O$ = -11 ‰ wr) and hydrogen isotopic signatures (δD= -60 to -100 ‰ for mica and amphibole, e.g. RUMBLE & YUI 1998, ZHENG et al. 2003), the lowest ever observed in an UHP terrane. These low values are explained by the interaction with meteoric waters prior to the ultra high pressure event. The preservation of these early signatures suggests a fast subduction followed by a rapid uplift. The heterogeneity of the isotopic signatures at the outcrop scale gives evidence of later fluid events. In this study, O and H isotopic signatures have been investigated at the microscale to trace the behaviour of these fluids during subduction and exhumation in more detail. Thus O-isotopes on garnets and H- isotopes on micas and amphiboles were analysed by ion microprobe on samples from Bixilling and Shuanghe after reconstruction of their PT paths.

Bixilling garnets are unzoned in main elements, whereas Shuanghe ones may be unzoned or zoned, with zonations associated with their retrograde path. O isotopes show constant values within each sample for Bixilling garnets, with a $\delta^{18}O$ variation from 0 to 6 ‰ on the whole sample set. Values 1 2 ‰ higher in rim than in core are occasionally observed. For the Shuanghe samples suite, $\delta^{18}O$ ranges from –10 ‰ to +10 ‰ with variations up to 7 ‰ within a sample. Typical variations are observed 1) along veins with values decreasing of 2 - 3 ‰ away from the vein, 2) in single minerals with rims 3 to 6 ‰ higher than cores and 3) on mm and cm scale within samples without any clear association with a fluid pathway. The constant values for Bixilling support that the garnets preserved an initial mantle signature, without meteoric water interaction prior to subduction. In contrast, the Shuanghe garnets negative $\delta^{18}O$ values indicate an early hydrothermal meteoric waters overprint. During subduction, these primary values are preserved for both localities. Exhumation had only a minor effect on Bixilling garnets, whereas Shuanghe garnets show overprint from mantle or crustal waters.

For hydrogen isotope the lowest δD values are observed in the UHP white micas for both localities (δD from -230 to -120 ‰ for Bixilling and -190 to -150 ‰ for Shuanghe). Amphibole shows higher δD values (-110 to -50 for all samples except one Shuanghe sample -10 to -40 ‰). Therefore, for Bixilling, in contrast to oxygen isotopic data from garnet, hydrogen data in white mica shows an overprint from the meteoric water prior to subduction, which is preserved due to the low H diffusion in white mica (GRAHAM, 1981; ZHENG et al., 2003). The retrograde phases such as biotite and amphibole seem to present a "mix-signature" in between the initial negative values and later more positive retrograde fluids.

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THE IMPORTANCE OF PRE-350 MA AGES IN ECLOGITES FROM THE ORLICA- ŚNIEŻNIK COMPLEX, BOHEMIAN MASSIF, POLAND

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In the Orlica-Śnieżnik complex (OSC), eclogites and HP granulites occur as isolated lenses within partially migmatized orthogneisses. There seems to be a general consensus that most orthogneisses have Cambrian-Ordovician protolith ages and that all rock types underwent at least one episode of high-temperature metamorphism during Variscan times (~340 Ma). Although geochronological results are practically indistinguishable, textural relationships suggest that an eclogite-facies stage preceded amphibolite-facies metamorphism. A key aspect for a better understanding of the OSC history and a challenge for geochronological studies is the necessity to look through the metamorphic overprint at ~340 Ma. A previous study of eclogites and associated gneisses from the location Nowa Wieś has indicated that geochronological information related to earlier events was possibly not completely erased by the last metamorphism. BAKUN-CZUBAROW (1968) reported K-Ar phengite and biotite dates of ~380 Ma for both an eclogite and a country rock gneiss from this location. These results are similar to recently reported Lu-Hf garnet ages of HP granulites (SZCZEPANSKI et al., 2004) and ionprobe U-Pb monazite ages of orthogneisses (GORDON et al., 2003) from the study area. However, caution is warranted in assigning geological significance to the K-Ar data, because the presence of excess ^{40}Ar leading to geologically meaningless dates was documented for many HP and UHP occurrences. By means of ^{40}Ar - ^{39}Ar, Rb-Sr, Sm-Nd and U-Pb dating, we have investigated the geological significance of the Nowa Wieś dates. ^{40}Ar - ^{39}Ar dating of phengite from the eclogite yielded an age of 390.3 ± 1.4 Ma. For the same sample, both the Rb-Sr (phengite, omphacite) and the Sm-Nd (garnet, omphacite) methods provided considerably younger ages (346.3 ± 2.7 Ma and 352.2 ± 3.4 Ma, respectively), which are in good agreement with results for similar occurrences throughout the Bohemian Massif. Two different country rock gneisses yielded Rb-Sr (biotite, whole rock) ages of 321.6 ± 3.2 Ma and 278.8 ± 2.8 Ma, indicating late orogenic processes and/or retrograde disturbance. Our results suggest that contamination by excess Ar has caused ~380 - 390 Ma dates without geological significance. This conclusion is further corroborated by an exotic ^{40}Ar - ^{39}Ar date (455.4 ± 1.8 Ma) for another eclogite occurrence from the OSC.

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PROTOLITH AGES AND TIME OF HIGH-PRESSURE METAMORPHISM IN THE CYCLADIC BLUESCHIST BELT, GREECE

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The Cycladic blueschist belt belongs to the Alpine-type Hellenic orogen in the Aegean region. A lower group of tectonic units comprises a pre-Alpidic crystalline basement, which is overlain by thrust sheets of a metamorphosed volcano-sedimentary sequence. Protolith ages of the cover rocks are broadly constrained by sporadic findings of Mesozoic fossils, but details are unknown. White mica geochronology (Rb-Sr, K-Ar, ^{40}Ar - ^{39}Ar) has established time constraints for at least two metamorphic events, which affected both basement and cover rocks: eclogite- to epidote-blueschist facies rocks yielded Eocene ages (~50 - 40 Ma); samples representing a greenschist-facies overprint provided Oligocene-Miocene dates (~25 - 20 Ma). Unresolved issues concern the protolith ages of the major rock types in the thrust sheets and the duration of HP metamorphism. These aspects are addressed in a SHRIMP U-Pb zircon study, focussing on the islands of Andros, Sifnos and Syros. The results obtained so far indicate a regional consistent pattern of Triassic ages (~233 - 245 Ma) for the magmatic precursors of acid metavolcanites. Such ages were not only observed for samples collected from structurally coherent sequences (e.g. Sifnos), but also for a tectonic slab from the mélange on Syros. The geological significance of Cretaceous U-Pb zircon ages (~80 Ma) previously reported for other blocks from this mélange is controversial and was either related to metamorphic or magmatic processes (e.g. BRÖCKER & ENDERS, 1999; TOMASCHEK et al., 2003). We have studied zircons from a metasomatic alteration profile, which developed around a jadeitite block enclosed in a serpentinite matrix. From the outside in, distinct blackwall alteration zones (~5 30 cm in thickness) can be distinguished, which predominantly consist either of actinolite- chlorite, glaucophane or omphacite. Zircon from the unaltered jadeitite and all reaction zones yielded $^{206}Pb/^{238}U$ ages of ~80 Ma. Across this profile, systematic changes are observed in zircon morphology and CL patterns. U- and Th-concentrations in zircon decrease towards the peripheral rinds. These observations are difficult to reconcile with a magmatic origin of the zircons and instead we suggest a relationship of zircon formation/recrystallization to block-matrix interaction during subduction zone processes at ~80 Ma. A superimposed characteristic is the recrystallization of U- and Th-rich zircons in the jadeitite and the omphacitite rind, indicated by complex cauliflower-like CL patterns. This process is associated with incomplete age resetting, leading to variable < 80 Ma dates. Most likely this recrystallization occurred in the Eocene.

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CALDERITE–SPESSARTINE GARNETS IN ECLOGITIC METACHERTS

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The nature of the compositional gap(s) between aluminous and ferric garnets is a pending problem, which was repeatedly addressed for the Ca-rich members grossular and andradite (e.g. POLLOCK et al., 2001). The finding of coexisting spessartine, ideally $Mn_3Al_2(SiO_4)_3$, and calderite, ideally $Mn_3Fe^{3+}{}_2(SiO_4)_3$, raises the question for the Mn-rich members as well.
We found them in eclogite-facies manganese concentrations hosted in metaradiolarite and siliceous strata interlayered in the 'Schistes lustrés' Mesozoic sequence associated to the ophiolites of the Western Alps. The localities studied, the Praborna mine near Saint-Marcel, Val d'Aoste, Italy (MARTIN & KIENAST, 1987), and the upper end of the Maurienne Valley, France (CHOPIN, 1978), belong to the eclogite-facies ophiolitic Zermatt Unit, which locally reaches coesite-eclogite conditions (REINECKE, 1991). The presence of eclogitic metabasite (with paragonite and glaucophane stable) and of the talc–chloritoid–garnet (± phengite) assemblage in metapelite (CHOPIN, 1981) is characteristic in both places.
The coexistence of the two garnets was observed both in the oxidised quartzite with hematite and braunite (+ minor Mn-pyroxenoid and tirodite; with ardennite or piemontite in distinct layers), and in reduced, carbonate-rich boudins included in it. The co-occurrence takes a variety of textural aspects, from coexisting euhedral garnets (10 to 100 µm in size for the calderite to mm-size for spessartine) to sharp overgrowths of yellow calderitic garnet on colourless spessartine, to cauliflower-like masses (a few hundreds of µm in size) overgrowing spessartine and showing evidence of oscillatory zoning, resorption stages and resumed growth. Sector zoning and anisotropy are common, although not consistent features.
Compositions can be expressed to 95% in the quadrilateral system Ca–Mn^{2+}–Al–Fe^{3+} and coexisting pairs define two gaps, bounded by values of the $Fe^{3+}/(Al + Fe^{3+})$ ratio of 10 and 15 % for the first one, of 40 and 65 % for the other. Interestingly, the optically obvious discontinuity (colour change and Becke's line) corresponds to the narrower gap, whereas the broad compositional gap occurs within yellow garnet, only revealed by SEM. Only the latter can be candidate for a miscibility gap, if any. This point will be discussed on the basis of textural, paragenetic and experimental (LATTARD & SCHREYER, 1983) evidence.

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DIFFUSION MODELLING AS A TOOL FOR TRACKING TIMESCALES: POTENTIAL AND PROBLEMS

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Modelling frozen concentration gradients (or lack thereof) produced by diffusion is a powerful tool for understanding the rates and timescales of a wide range of geological processes. The method has a number of features that make it particularly attractive:
(i) it relies on a kinetic process that is governed by a well defined quantitative relation - the diffusion equation, (ii) it directly yields duration of processes rather than dates that must be combined to yield durations or rates, (iii) it relates timescales directly to the chemical reactions that are used to determine pressure, temperature and other intensive parameters (e.g. fO_2), (iv) it accesses a wide range of timescales from hours to millions of years, (v) the temporal resolution of the method is independent of the age of the rocks, (vi) it depends on a process that is widespread, (vii) the tool can be applied on different minerals and elements on the same thin section, so that an internal consistency check is possible, and (viii) the tool can be applied to different specimens from the same sample or suit of rocks, so that it is possible to test the statistical significance of results with relatively modest investments of time and money
The last two features make the tool particularly versatile because it is possible to use the results of modelling some concentration gradients to predict the concentration distribution of other elements. The results can be used to falsify or vindicate the hypothesized model. A mismatch with observations immediately points to a flaw in some aspect of the model - in identifying the process (e.g. diffusion vs. dissolution precipitation), in setting up the initial and / or boundary conditions, or in the choice of parameters (e.g. diffusion coefficients). Modelling concentration distributions of elements that diffuse at very different rates can allow different segments of the thermal history of a rock to be characterized so that a combination yields a picture of the complete thermal evolution. Finally, accounting for diffusive coupling in multicomponent systems such as garnets provides additional constraints on the nature of the thermal history Nowadays easily available software tools provide convenient access to both - analytical models to study the general behavior of systems as well as numerical models to reproduce faithfully the details of individual systems.
In spite of the many positive aspects, there are obstacles that have prevented widespread application of the tool. The most significant among these is the unavailability of diffusion coefficients and uncertainties associated with their determination. Recent advances in experimental technology and theoretical developments in the area of ab initio calculations have alleviated some of the problems and hold great promise for the near future. The current status of some relevant diffusion data will be reviewed. Other difficulties arise from the very nature of the diffusion process for example, it is more challenging to retrieve thermal histories of rocks metamorphosed at 500 °C than of granulites. This aspect calls for care in the choice of rocks and problems to which diffusion modelling is applied.

PETROCHEMICAL AND GEOCHEMICAL FEATURES OF DIAMONDIFEROUS ECLOGITES FROM THE UDACHNAYA KIMBERLITE PIPE, YAKUTIA (RUSSIA)

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There are known several types of eclogites from kimberlite pipes, origin of which is connected with different genetic processes (JERDE et al., 1993, JACOB, 2004).
This work is devoted to study of processes of eclogite formation on example of 60 xenoliths of diamondiferous eclogites from the Udachnaya kimberlite pipe (Yakutia, Russia). The crystallization of these rocks took place at T = 900 - 1400 °C, P = 35 - 55 kbar. These parameters show the formation of the xenolith majority under mantle conditions.
The chemical composition of rock-forming minerals of the eclogites and the presence of accessory minerals (ilmenite, rutile, corundum, kyanite and sulfides) allow to divide the eclogites into three groups: magnesian, magnesian-ferrous and high-alumina varieties.
The bulk composition of the eclogites was determined by X-ray fluorescent analysis. The received data were compared with the some get from oceanic basalts of different types. Several simular and differ features were determined. Both for eclogites and oceanic basalts the same correlations between f = Fe/(Fe+Mg) and (Mg+Fe)/Si was established. This points to the magmatic nature of the Udachnaya eclogites. These eclogites and oceanic basalts differ by TiO_2 and SiO_2 contents and have absolutely different correlations between (Mg+Fe)/Si and Al/Ca. Another essential evidence of magmatic origin of the Udachnaya eclogites is positive correlation between Ni-content and f = Fe/(Fe+Mg), and negative correlation Co with f = Fe/(Fe+Mg). The contents of Na_2O, K_2O and FeO were determined by atomic-absorption method. The diamondiferous rocks are characteristically enriched in Na_2O and K_2O.
The study of garnet REE patterns from eclogites the Udachnaya pipe was carried out by neutron-activation analysis and secondary ion mass-spectrometry methods. There are three types of REE distribution in the garnets were established: "typical" garnet patterns, unusual garnet REE patterns with negatively-sloped HREE and garnets with positive Eu anomalies. These data are confirmed the earlier information (JERDE et al., 1993). The correlation between the type of REE patterns and CaO content in the garnets was determined. The "typical" garnet patterns are specific only for this mineral (with contents $\leq$ 6 wt.% CaO) from the magnesian and magnesian-ferrous eclogites. The garnets with unusual REE patterns are characterized by higher concentrations FeO (19.31 wt.%) and CaO (9.59 wt.%) and occur in the magnesian-ferrous type of eclogites. The garnets (9 15 - 11.27 wt.% CaO) from the high-alumina eclogites are characterized by REE patterns with positive Eu anomalies.
We conclude that magnesian- and magnesian-ferrous eclogites from the Udachnaya kimberlite pipe were probably formed in processes of crystallization differentiation in upper mantle. Some high-alumina eclogite xenoliths may be of crustal origin.

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PARGASITE AND ILMENITE EXSOLUTION TEXTURE IN CLINOPYROXENE FROM THE HUJIALING GARNET-PYROXENITE, SU-LU UHP TERRANE, CENTRAL CHINA: A GEODYNAMIC IMPLICATION

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Deep subduction of crustal material significantly affects the mantle convection and Earth dynamics, during this process a great amount of water and potassium are transported into the deep mantle, and affect the rheology of the upper mantle rocks (PEACOCK, 1990; ERNST, 2001, ZHANG & LIOU, 2001, ZHU & OGASAWARA, 2002). Some exsolution textures, formed during the exhumation stage of the subducted slab, are good indicators for ultrahigh pressure (UHP) metamorphism (e.g., LIOU et al., 1998). For example, the exsolution lamellae of quartz (e.g. SMITH, 1984) and garnet (e.g., SMYTH et al., 1989) in clinopyroxenes have been well documented in UHP eclogites.

We report here the discovery of amphibole exsolution texture from the Hujialing garnet-pyroxenites, which were exhumed from mantle together with coesite eclogites in the Su-Lu UHP metamorphic belt. The garnet-pyroxenite consists mainly of garnet and diopside with minor amounts of pargasitic amphibole, ilmenite, Mg-Al spinel, magnetite, tremolite, pyroxene, and olivine. Diopside contains abundant garnet inclusions as well as pargasite and ilmenite lamellae. The present mineral assemblages observed in the Hujialing garnet-pyroxenite indicate that the parental mineral of the reported exsolution texture should have a composition of the mixture of pargasite, ilmenite and diopside. The prevailing exsolution of pargasite (stage I) and ilmenite (stage II) suggests at least two-stages of exsolution processes, which implies a complex exhumation history for the Hujialing garnet-pyroxenites. The primary clinopyroxene in the Hujialing garnet-pyroxenite contains ~2000 ppm H_2O, indicating a peak metamorphic pressure of probably 80 kbar. The pargasite lamellae apparently formed earlier than the ilmenite lamellae in diopside, which indicated that the exhumation of such UHP metamorphic rocks happened in two steps, one at depths of ~100 km, another occurs at much shallower levels.

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PETROGENESIS OF THE YUGU SPINEL HARZBURGITE IN WESTERN GYEONGGI MASSIF, SOUTH KOREA

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The extension of a Triassic suture along the Dabie-Sulu belt towards the Korean peninsula has been recently supported by the presence of Neoproterozoic zircons and omphacitic clinopyroxenes, in the western Gyeonggi Massif (CHO et al., 2004; OH et al., 2005). We report here petrologic features of the Yugu spinel harzburgite, which may represent tectonic slivers obducted during Triassic continental convergence. The 3 × 1 km Yugu peridotite occurs as an orogenic massif and is one of the largest ultramafic bodies emplaced into the upper-amphibolite facies basement gneisses of the western Gyeonggi Massif. This ultramafic body consists predominantly of spinel harzburgite together with very minor dunite and clinopyroxenite. The majority of peridotites is significantly serpentinized, and highly deformed yielding mylonitic textures characterized by deformed porphyroclasts of orthopyroxene and spinel. Recrystallized olivine grains form clusters of fine grains in the matrix, and show a restricted compositional range (Fo_{89-93}). Porphyroclastic orthopyroxenes are characterized by bent cleavages and lamellae, and are commonly mantled by equigranular, exsolution-free neoblasts of orthopyroxene. The Al_2O_3 and Cr_2O_3 contents of these porphyroclasts decrease toward the rim (8.2 → 1.5 wt.% and 1.1 → 0.1 wt.%, respectively), while MgO increases (31.9 → 34.8 wt.%). Compositions of orthopyroxene neoblasts are similar to the porphyroclastic rims. Spinel porphyroclasts are commonly mantled by chromite-magnetite and pentlandite, and zoned in the Fe, Mg and Al contents: FeO decreases toward the rim, while MgO and Al_2O_3 slightly increase. The Mg# [= $100Mg/(Mg+Fe^{2+})$] of spinel increases from 67 to 76 towards the rim, while Cr# [= 100Cr/(Cr+Al)] remains constant (24 – 25). However, the Mg# and Cr# of interstitial spinel (62 – 76 and 14 – 29, respectively) significantly varies depending on the mineral assemblage. Cr-free aluminous spinel (Mg# = 81 – 82) is present in olivine clinopyroxenite layers. The Mg and Cr numbers of olivine and spinel suggest that the Yugu peridotite belongs to an abyssal to passive margin peridotites. Further geochemical studies are necessary for delineating the tectonic setting and emplacement mechanism of ultramafic bodies in the western Gyeonggi Massif.

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METABASITES WITH ECLOGITE FACIES RELICS IN THE VARISCAN BELT OF NORTHERN SARDINIA, ITALY: REVIEW AND DISCUSSION

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Metabasites with eclogite facies relics occur as decametric to hectometric boudins or lenses in the Variscan belt of northern Sardinia. They are enclosed as allochthonous bodies in the Variscan migmatites (NE Sardinia) or embedded in the medium-grade metapelitic complex of Anglona and Asinara regions (NW Sardinia). Based on mineral assemblage and microstructure four main stages of recrystallization have been distinguished:
Stage I the eclogite stage is documented by the occurrence of omphacite relics, garnet porphyroblasts, quartz, zoisite, rutile and barroisite. The eclogite assemblages of Golfo Aranci metabasites also include kyanite, high-Mg garnet and pargasite. Stage II - The granulite stage is documented by the destabilisation of omphacite and by the growth of clinopyroxene + plagioclase symplectite, sometimes with orthopyroxene. In the retrogressed eclogites from Golfo Aranci the symplectitic rims consist of sapphirine + anorthite + corundum + spinel or spinel + anorthite + corundum in contact with relict kyanite. Stage III - The amphibolitisation of the granulite assemblage led to the formation of amphibole + plagioclase kelyphite between garnet porphyroblasts and pyroxene-plagioclase symplectites and to the growth of orthoamphibole on orthopyroxene. Tschermakite to Mg-hornblende, plagioclase, cummingtonite, ilmenite, titanite and biotite are coexisting phases. Stage IV - The later greenschist to subgreenschist stage is characterised by actinolite, chlorite, epidote s.s., titanite, sericite and prehnite. All these stages are not always recognizable in the various outcrops, owing to re-equilibration at lower temperatures and/or pressures. Mineral relics of a pre-eclogitic prograde amphibolite stage have also been documented in the metabasite from Golfo Aranci. The granulite stage has not been recognized in the metabasite from the medium-grade complex of Anglona. Here, the eclogite stage was directly overprinted by the amphibolite one. The following P-T ranges have been estimated for the different stages. Eclogite stage: 460 – 760 °C; minimum pressure: 1.3 GPa at 700 °C. Granulite stage: 650 - 899 °C; 0.8 - 1.2 GPa. Amphibolite stage: 550 – 740 °C; 0.3 - 0.7 GPa. Greenschist stage: 300 – 400 °C; 0.2 - 0.3 GPa. Radiometric data on zircons (SHRIMP, PALMERI et al., 2004 – a; LA-ICPMS – b; Conventional – c) from eclogites from different sites indicate: protolith ages of 453 ± 14 Ma (a), 460 ± 5 Ma (b) and 457 ± 2 Ma (c); presumed age of eclogite facies metamorphism or the result of a Pb-loss during the Variscan metamorphism around 400 ± 10 Ma (a) and 403 ± 4 Ma (c); ages of 352 ± 3 Ma and 327 ± 7 Ma has been attributed to the main Variscan retrograde events.

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A NEW TOOL FOR OLD ROCKS - CHARGE CONTRAST IMAGING OF MICROSTRUCTURES AND COMPOSITIONAL VARIATION IN GARNET AND OTHER HP/UHP MINERALS

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The environmental scanning electron microscope (ESEM) allows imaging of insulating materials without a conductive coating. Instead, the sample chamber is charged with a gas that is ionised by the electron beam or backscattered electrons (BSE), and attracted to the sample surface (the "ion flood"), thus neutralising charge accumulation. Secondary electrons (SE) generated during these interactions cascade to a positively-biased Gaseous Secondary Electron Detector (GSED), creating a GSE image dominated by the influence of specimen BSE. Under normal operating conditions, specimen SE emission is suppressed by the ion flood. However, under appropriate conditions of beam dosage, gas pressure and detector bias, SE originating within the specimen may escape and be collected at the GSED. Emission appears to be a function of the charge-trapping characteristics of the material. Within the same phase, charge-trapping and image brightness is thought to vary with the concentration of lattice defects. Exploiting this capability of the ESEM gives us a novel and rapid method – Charge Contrast Imaging (CCI) - for resolving compositional and microstructural features in insulating and semi-conducting materials (GRIFFIN, 1997; WATT et al., 2000; CUTHBERT & BUCKMAN, 2005). Image acquisition is reproducible, stable and rapid.

CCI patterns are very similar to cathodoluminscence (CL) suggesting a common cause. However, in luminescent materials such as zircon, CCI may also reveal features not visible in CL. Importantly, CCI shows patterns in non-luminescent materials, e.g. minerals rich in "quencher" ions like Fe. For example, CL images of UHP pyropes from Dora Maira quartzite show oscillatory zoning, but emission is suppressed by small increases in Fe. CCI gives identical image patterns. However, almandine-rich garnets in an eclogite from Norway give no detectable CL emission, but CCI images are rich in detail. In the latter example conventional BSE images are featureless, even though CCI patterns match major element variation, but abundances of P, Ti, Y, Zr and REE follow CCI grey-scale variation, suggesting a possible role for substitutions generating vacancy defects. Other candidates for generation of CCI are incorporation of "defect hydroxyl", growth faults, and dislocations due to crystal-plastic deformation. CCI patterns may be obscured by surface shear effects due to polishing. This may be overcome by more sophisticated polishing techniques, but these artefacts suggest that lattice strain may be resolvable by the CCI method. Thus, CCI offers a rapid, cost-effective method for reconnaissance exploration of mineral microstructure and compositional variation, offering similar insights to CL petrography, but is more effective than CL in Fe-rich phases such as garnet commonly found in HP/UHP rocks.

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CHARGE CONTRAST IMAGE PETROGRAPHY OF ECLOGITE FACIES ROCKS USING THE ENVIRONMENTAL SCANNING ELECTRON MICROSCOPE

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Charge contrast imaging (CCI) exploits the capability of the low vacuum, or "environmental" scanning electron microscope (ESEM) to generate a controlled build-up of charge on the uncoated surface of a polished thin section. Under appropriate operating conditions image contrast patterns appear that are thought to result from variations in the charge-trapping characteristics of the material. Grey-scale variation correlates with major and trace element composition. In phases exhibiting cathodoluminescence (CL), CCI patterns mimic CL, indicating a common physical cause related to the presence of lattice defects. However, CCI patterns are resolvable in some non-luminescent phases, such as those in which CL is suppressed by "quencher" elements like Fe. Charge contrast images are stable and reproducible, and may be acquired in a few seconds.

Pyrope-rich garnets ($Py_{97.6-98.1}Alm_{2.1-1.6}And_{0.3}$) from a coesite-bearing quartzite in the Dora Maira massif have been shown to exhibit oscillatory zoning in CL images, with CL intensity and colour correlating with Fe content (SCHERTL et al., 2004). Minor increases in Fe are sufficient to suppress CL emission. CL patterns are exactly reproduced by the CCI method, suggesting a common fundamental control on both CL and CCI in these garnets.

Almandine-rich garnets ($Py_{15.1-23.7}Alm_{67.7-59.0}Gr_{12.7-16.4}Sp_{4.6-0.8}$) from an eclogite at Kroken, Norway (CUTHBERT & BUCKMAN, 2005) fail to give detectable CL emission, presumably due to the quenching effect of Fe. However, under optimal imaging conditions the garnets give clear CCI patterns with an outer, dark rim zone and an internal network of fine, dark lines. CCI-dark features correspond to areas richer in Ca and Mg and poorer in Fe and Mn, and are interpreted as UHP overgrowths and fracture-fill. CCI-dark garnet is depleted in HREE, Zr, P and Y relative to the older core garnet, and enriched in LREE and Ti, indicating that trace-element substitutions involving the creation of vacancy defects may be the cause of the image contrast pattern.

Charge contrast imaging of garnet using the ESEM has the potential to provide rapid, high-resolution image patterns rich in microstructural and compositional information, even in grains too rich in Fe to give CL emission, and offers a time-efficient reconnaissance method for exploration of garnet microstructure as a basis for application of more time-consuming and costly techniques such as EPMA mapping and SIMS or laser ablation.

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PETROLOGY OF ECLOGITES FROM NORTH OF SHAHREKORD, SANANDAJ – SIRJAN ZONE, IRAN

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Metabasic rocks from north of Shahrekord which is a part of structural zone of Sanandaj-Sirjan are found in a ductile shear zone. They are including eclogites, garnet-amphibolites and amphibolites. Eclogites are either as bands or lens with assemblage of amphibolite and paragneiss.

The shear zone is an oblique reverse shear zone with northwest–southeast trend parallel to Main thrust Zagros and it is responsible for juxtaposition of eclogites.

Metamorphic P-T conditions of eclogites were evaluated based on the application garnet – clinopyroxene geothermometer and garnet – clinopyroxene – phengite geobarometer e.g. programs PET (DACHS, 1998). Peak P-T values in eclogites are around 600 °C at 17 kbar.

Main phases at high pressure metamorphism are omphacite + garnet + sodic-calcic amphiboles (barroisite, magnesiokatophorite and magnesiotaramite) + phengite + rutile + zoisite + quartz ± dolomite. Calcic amphiboles (hornblende, tschermakite and pargasite) + plagioclase are secondary phases on retrograde path with amphibolite – facies metamorphism.

Garnets display mainly an almandine-pyrope composition, which fits with the C type eclogites (COLEMAN et al., 1965) classification. Distinct compositional zoning is preserved in fresh garnets which are formed during eclogite facies. The composional or growth zoning in eclogite rocks shows clockwise P-T-t path as at first P and T metamorphism increases to reach to peak of high pressure metamorphism and then P decreases while T increases, so that after decompression and uplift T has increased.

Geochemical studies based on major and trace elements show that eclogites originated from oceanic floor basalt protolith.

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ECLOGITE AND PERIDOTITE XENOLITHS FROM KAALVALLEI, KAAPVAAL CRATON: IMPLICATIONS FOR THE FORMATION OF SUBCONTINENTAL LITHOSPHERE

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The Kaalvallei kimberlite (Kaapvaal Craton) contains abundant eclogitic and lherzolitic mantle xenoliths. Garnet-lherzolites equilibrated at 35 - 75 kbar and follow a 40 mW/m^2 geotherm. They can be divided into three discrete groups: a high-temperature relatively fertile group (FP), an intermediate temperature depleted group (DP), and a low-temperature ultra-depleted group (UDP) that also contains spinel. A similar division can be made for the eclogites, in which fertile (FE) and depleted eclogites (DE) correspond to Group I and Group II eclogites, respectively. As both eclogites and peridotites show similar depletion trends with depth, the mantle sampled by the Kaalvallei kimberlite appears to be layered. The mantle down to 140 km is ultradepleted, depleted between 140 and 170 km, and fertile at deeper levels.

Depletion patterns are illustrated by trace-element patterns of clinopyroxenes, which show remarkable similarities between depleted peridotites and Group II eclogites, and between fertile peridotites and Group I eclogites.

Low abundances of Ti and Y in the DP and UDP suites (<0.1 and <0.01 relative to primitive mantle) suggest that these rocks are the residues of large amounts of near-fractional melting in the garnet stability field - possibly in a plume setting - resulting in a harzburgitic rock. The presence of clinopyroxene and garnet is therefore surprising and suggests that these minerals were formed by modal metasomatism or exsolved from orthopyroxene during depressurization. Sinusoidal REE patterns in garnets point to an important role for metasomatism, with an LREE-rich metasomatic agent and incomplete equilibration between rock and melt or fluid.

Depleted eclogites show similar Ti and Y depletions, and comparable LREE, U, Th enrichments, as the DP suite. The low Y content indicates that DE cannot be melt residues, hence their signature is of different origin from the DP suite. Most likely they represent crystallized siliceous melts that were significantly modified by interaction with the peridotites.

The FP suite shows signs of moderate melt extraction, as the more incompatible elements are increasingly depleted, whereas Ti and Y are close to primitive mantle values. Major elements point to melt extraction at much lower pressures than the pressure of subsolidus equilibration. The FE suite is thought to be derived from basaltic ocean floor with some admixed sediments, which is consistent with its trace-element signature. This suggests that both FP and FE are derived from subduction - the FP suite representing former oceanic lithospheric mantle - and were stacked at the bottom of the cratonic root.

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INCLUSIONS IN DIAMONDS FROM UHPM TERRANES: A NEW CONSTRAINT FOR DEPTH OF SUBDUCTION AND EXHUMATION

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Diamond is the strongest mineral and is essentially inert in rocks, hence it resists chemical reaction with its host or included minerals. Therefore, it is the most reliable sampling container for transporting fluid and solid crystalline materials from depth within the Earth to its surface. Determination of depth from which subducted ultra-high pressure metasedimentary rocks may return back to the surface is crucial for understanding tectonic aspects of exhumation and mountain building due to continental collisions, global recycling or/and sequestration of H, C and K in deep Earth's mantle. Several years ago we applied an innovative focused ion beam (FIB) technique that allows cutting of small diamonds crystals *in situ* and preparation of high quality 400 Å thick foils to be studied by transmission electron microscopy (TEM). These studies revealed that diamonds from felsic gneisses of the Kokchetav massif, Kazakhstan contain a rich inclusion suite of Si-, Fe-, Ti- and Cr-oxides. However, no good electron diffraction patterns were obtained to verify their structure due to technical difficulties Because unit cell parameters of SiO_2 included in microdiamonds have not been known, such diamonds used to serve only as an indicator of a minimum pressure, ca. 4 GPa. Other methods applied to Kokchetav diamond-bearing rocks yielded: T= 700 °C, or 920 to 1250 °C, and P = 4 to ~9 GPa. Our recent research on diamonds from dolomitic marbles of Kokchetav massif established that these diamonds contain nanometric fluid pockets enveloping well-shaped $CaCO_3$ crystals. Fluid consists of O, C, H, Cl, S, Ca, Fe and K. Electron diffraction patterns obtained from $CaCO_3$ inclusions confirmed their aragonite structure. Both inclusions of $MgCO_3$ with a few content of Ca, and $CaCO_3$ inclusions were also found in diamonds from Kokchetav site. In frame of this research, we determine the lower boundary of aragonite stability field by reaction: $CaMg(CO_3)_2 = CaCO_3$(aragonite) + $MgCO_3$. This allows us to use available experimental data on studies of dolomite break down reaction with production of aragonite and magnesite to evaluate pressure at which diamond was crystallized. Taking into consideration all uncertainties existing between experimental data produced in different laboratories, we propose the most accurate evaluation of minimum pressure for Kokchetav diamond crystallization to be between ~7 to 9 GPa. This evaluation is based on assumption that temperature was determined correctly as 980 °C (minimum) and as 1250 °C (maximum) for diamond-grade dolomitic marbles. Our data provide more convincing evaluation that metasedimentary rocks of Kokchetav massif containing diamonds were subducted to the minimum depth ~210 - 220 km.

GRANULITIZATION OF ECLOGITIZED DYKES IN THE GRIDINO AREA, BELOMORIAN BELT, RUSSIA

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Archaean eclogites were recently found in the Gridino zone of tectonic mélange (northern Karelia), (VOLODICHEV et al., 2004). Eclogite bodies are cut by dykes, assigned to a complex of "drusites" of an early Proterozoic age. The geological and petrological research has shown that the dykes, having preserved signs of magmatic stage of the evolution (Fig. 1), were subsequently subjected to metamorphic trans-formations under conditions of eclogite (Fig. 2a) and granulite (Fig. 2b) facies. P-T parameters of granulite stage 770 ± 30 °C, 13.6 ± 0.9 kbar (GCPQ and GOPQ geothermo-barometers, paragenesis presented on Fig. 2b). The P-T evolution of metamorphism of the dykes coincide with the evolution trend of the Archaean eclogites.

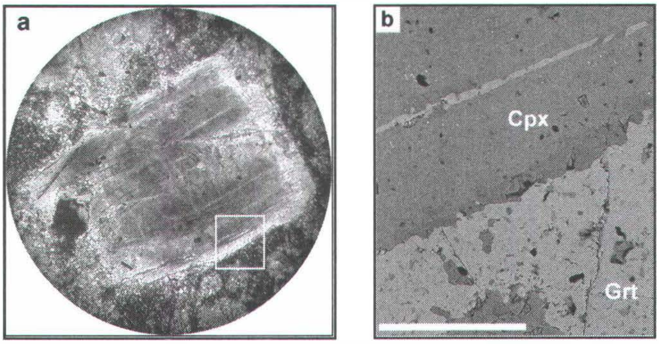

Fig. 1. Sample t1111-8.
Relics of magmatic clinopyroxene surrounded by fine-grained garnet.
(a) Microphotograph
White box marks the area of image in (b). Crossed polars;
(b) BSE image
Note the platy garnet and white dots of ilmenite exsolutions inside clinopyroxene.
Length of the bar is 200 µm.

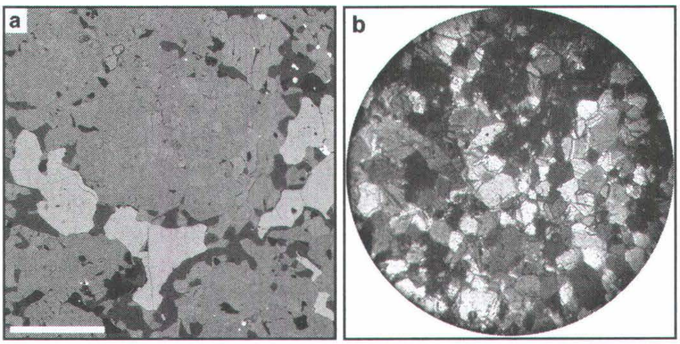

Fig. 2.
(a) Sample 996-10. BSE image. Lamellae and inclusions of orthopyroxenes in metamorphic (eclogitic) clinopyroxene (center of the picture), white grains are garnet. Length of the bar is 200 µm.
(b) Sample t1111-4. Photomicrograph of garnet-two pyroxene granulite. Crossed polars, field of the picture is 1 mm.

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EVIDENCE OF ULTRA HIGH PRESSURE CONDITIONS IN ECLOGITES FROM THE MOLDANUBIAN ZONE, BOHEMIAN MASSIF

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Results of thermobarometric calculations done on eclogites and garnet peridotites from two units (the Gföhl and the Monotonous) of the Moldanubian zone are presented. The Kutná Hora crystalline complex is assumed to be a part of the Gföhl unit that consists of gneisses, migmatites and granulites with lenses of eclogites and garnet peridotites (SYNEK & OLIVEROVÁ, 1992). MEDARIS et al. (1995) estimated pressures of 3.8 GPa / 1100 °C for garnet peridotite, but lower pressures of 1.5-2.0 GPa / 850-1000 °C were established for eclogites containing garnet and omphacite + rutile. Thermobarometric calculations done on two kyanite-bearing eclogites, one occurring in granulite and the other in serpentinized garnet peridotite indicate very high-pressure conditions. Eclogite from peridotite forms ca. 20 cm thick and 2 m long sills/dykes having composition of plagioclase-rich gabbro close to anorthosite. It contains Mg-rich garnet ($Py_{42}Grs_{34}Alm_{22}$) and omphacite with Jd_{30}. Garnet is replaced by Al-rich clinopyroxene (CPx) and anorthite ± amphibole and kyanite by anorthite and spinel. The content of majorite in garnet ranges between 0.6-1.3 mol%. The surrounding garnet peridotite has relics of olivine, orthopyroxene (OPx), CPx, spinel and rare amphibole. Chromium-rich spinel forms inclusions in garnet and in CPx. Compositional maps indicate transformation of spinel into Mg-rich garnet ($Py_{69}Grs_{11}Alm_{18}$). CPx is diopside with X_{Mg} = 0.9, and OPx with X_{Mg} = 0.8 contains about 1 7 wt. % of Al_2O_3 Eclogite enclosed in granulite contains two textural and compositional varieties of garnet and CPx. The eclogite facies garnet –Gr I ($Py_{36}Grs_{34}Alm_{28}$) associates with omphacite Cpx- I (Jd_{29}). Garnet I is partly replaced by Al-rich CPx II and anorthite. The new Ca-rich garnet Gr-II ($Py_{10}Grs_{65}$ Alm_{23}), forming either individual grains or rimming the coarse-grained eclogite facies garnet, indicates textural equilibrium with Al-rich CPx and plagioclase. There is a sharp compositional jump between these two garnet varieties. Small amount of tschermakitic amphibole replacing Ca-rich garnet is also present. Maximum PT conditions of ~4 GPa at 750 °C were calculated for eclogite. The garnet peridotite reveals pressure conditions similar to eclogite but at relatively high temperature of about 1000 °C. Textural relations and chemical composition, mainly the presence of Ca-rich garnet in eclogite, suggest that the decompression was followed by rapid cooling.

Eclogite from the Monotonous unit near Svetlík, studied by O'BRIEN & VRÁNA (1995) have only relics of eclogite facies assemblages. Maximum pressure estimated for the garnet-omphacite-kyanite assemblage is 2 GPa at 750 °C. Some samples, however, contain omphacite with parallel rods of quartz and garnet with inclusions of disordered graphite that may suggest UHP metamorphism.

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DURATION OF EO-ALPINE METAMORPHIC EVENTS OBTAINED FROM MULTI-COMPONENT DIFFUSION MODELING OF GARNET: A CASE STUDY FROM THE EASTERN ALPS

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Metamorphosed pelitic rocks from the Mica schist-Marble Complex of the Wölz Tauern, which are part of the middle Austroalpine unit, contain large (up to 2 cm) garnet crystals that show clear evidence of two stage growth. Isotopic dating indicates that a Variscan (~270 Ma) garnet core was overgrown by new garnet formed during Eo-Alpine metamorphism at Cretaceous times. The Pre-Alpine garnet in core has lower Ca and Mg (Alm_{71-83}, Grs_{3-16}, Sps_{0-15}, Prp_{5-9}) compared to the Eo-Alpine rim (Alm_{71-82}, Grs_{4-24}, Sps_{0-2}, Prp_{10-21}) and higher Mn. P-T conditions obtained using the method of pseudosections (POWELL & HOLLAND, 1998) for the Eo-Alpine metamorphism indicate a clockwise P-T path from 540 °C / 7.5 kbar to 600 °C / 10 kbar followed by cooling and exhumation to 540 °C / 4 kbar. These P-T conditions are consistent with earlier results from independent thermobarometry applied to metapelites and adjacent amphibolites (FARYAD & HOINKES, 2003). Due to the large size of the garnets, growth zoning was preserved during amphibolite facies metamorphism at both Variscan and Alpine times. The multicomponent diffusion profiles measured in the microprobe in the Alpine and Pre-Alpine garnets have been modeled using the approach, proposed by CHAKRABORTY & GANGULY (1991). Diffusion coefficient was calculated for Mn, Mg and Fe, where Ca was treated as dependent component. The advantage of such simultaneous calculation is that it allows subtle details of variations in compositional profiles to be interpreted and considerably reduces the uncertainty in retrieved time scales that may be obtained from using only one profile. The modeling suggests that a minimum subduction / exhumation rate of ~ 4 cm / a and heating / cooling rates on the order of 100 – 260 °C / Ma for a 60 ° subduction angle are required to preserve the observed compositional zoning overall while modifying the zoning at the interface between two garnets to the extent observed. Such rapid rates of burial / exhumation are consistent with results of direct GPS measurements of convergence rates at several orogenic belts as well as with inferred rates from modeling several generations of tectonic processes in the Alps and other areas. In combination, this indicates that such rapid rates during some stage of evolution of an collisional orogen where high pressure metamorphism occurs are the rule rather than the exception and places important constraints on the rheological behavior of crustal blocks in such orogens

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A CONTINUOUS SUBDUCTION-EXHUMATION CYCLE IN THE LIGURIAN ALPS: NEW CONSTRAINTS FROM ^{39}Ar / ^{40}Ar DATING OF ALPINE HIGH-PRESSURE ROCKS

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The Voltri massif (Ligurian Western Alps) underwent alpine high-pressure metamorphism (550 °C, 18 - 19 kbar) and is overlain by late to post-orogenic Tertiary conglomerates. We present ^{39}Ar - ^{40}Ar dating of phengite, muscovite and paragonite of samples from the Voltri eclogite to blueschist-facies metabasites and metasediments and from eclogite clasts of the Tertiary conglomerates. We have performed a careful electron microprobe study of mineral assemblages and of mica compositional zonations to be able to link the age to the metamorphic stage. As a consequence, we interpret the resulting ^{39}Ar - ^{40}Ar Eocene ages as the time of different metamorphic equilibrations. In particular, high-Si phengites from eclogite clasts record a ~49 Ma age for the eclogite peak and ~43 Ma for the blueschist retrogression; phengites from a blueschist basement sample record ~40 Ma for the metamorphic peak; low-Si muscovite from a metasediment dates the formation of the greenschist paragenesis at ~33 Ma. The internal discordance of age spectra is proportional to the chemical complexity of the micas.

Our data document that the rock samples analyzed reached peak HP conditions at different times over a time - span of ~10 Ma. The subduction to peak blueschist conditions is in fact still going on during the exhumation of higher-pressure, eclogite-facies rocks. We therefore suggest a tectonic model with different ophiolitic slices subducted at different moments, over a time span ranging from Lower Eocene until the Eocene-Oligocene boundary. This implies that the subduction and exhumation processes occurred simultaneously, allowing the uprising HP-rocks to escape thermal re-equilibration.

Our data require a decoupling of exhumation from erosion: exhumation was largely accomplished before significant erosion of the wedge. Fast exhumation was not accompanied by a high uplift of the mountain chain, whose erosion and input into the sedimentary basin occurred more than 10 Ma later.

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THE DIFFERENT P-T HISTORIES RECORDED BY HP BLOCKS IN A TECTONIC MELANGE (LIGURIAN ALPS - NW ITALY): IMPLICATIONS FOR SUBDUCTION AND EXHUMATION PROCESSES

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The Voltri meta-ophiolitic massif is located at the southern end of the Western Alps: it records subduction-related high-pressure metamorphism followed by exhumation to crustal environments with greenschist-facies retrogression.

We present a structural and petrologic analysis of a tectonic mélange in the north-western sector of the Voltri massif. In the mélange, a foliated chlorite-actinolite greenschist matrix encloses decametre-scale lenses of metabasites and metasediments. The mélange zone is hosted by country serpentinites which do not enclose such a variety of HP rocks. All lenses well preserve the dynamic structures and the mineral assemblages formed during stages of HP metamorphism. Moreover, they are characterized by internal high-pressure foliations discordant respect to the greenschist foliation of the surrounding matrix. The lenses display foliated chlorite-actinolite rinds, the orientation of which parallels the main matrix foliation. The mafic lenses in the mélange zone equilibrated over a wide range of peak metamorphic conditions: peak assemblages range from eclogite- to blueschist-facies. Some blocks record the prograde transition from lawsonite-bearing assemblages to epidote + omphacite + garnet eclogites. Omphacite-garnet foliations in the eclogites are overprinted by the multiple growth of syn-tectonic garnet- and epidote-blueschist assemblages. The blueschist lenses display peak syn-tectonic garnet-blueschist assemblage overgrown by epidote-blueschist ones. A late stage greenschist-facies re-equilibration heterogeneously affects the HP lenses and is particularly widespread at their rims. On the other hand, the surrounding chlorite-actinolite matrix does not contain relics of HP assemblages.

The HP lenses sampled by this mélange zone thus record different segments of subduction-related P-T paths. This suggests that the HP blocks were sampled by deformation horizons in a dynamic regime active during the entire peak and exhumation history. Even if development of the present-day mélange zone clearly post-dates the HP events recorded inside the lenses, the mélange shear zone likely reactivated older structures incorporating blocks from different tectonic levels. Tectonic mechanisms responsible for the mélange formation are therefore discussed in the framework of the subduction and exhumation processes.

MULTI-STAGE CARBONIFEROUS-ALPINE HIGH-P METAMORPHISM IN NORTHERN SAMOS (GREECE): EVIDENCE FROM GARNET ZONING AND INCLUSIONS

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The island of Samos occupies a transitional position between the Attic-Cycladic-Metamorphic-Complex (ACMC) in the Aegean Sea and the Menderes-Complex in SW-Turkey. Like the ACMC rocks, the Samos rocks have experienced an early Alpine high-P, low-T metamorphism (M1) followed by a late Alpine, medium-P, greenschist-grade event (M2). The latter is related to the emplacement of the blueschist facies rocks into higher crustal levels.
Porphyroblastic garnet schists from northern Samos, however, show also evidence of an older higher temperature metamorphism. Large Fe-rich garnets, ranging up to 1.5 cm in diameter and displaying an internal foliation discordant with that in the matrix, have developed thin (0.1 - 0.8 mm) discontinuous rims strongly enriched in Ca (20 - 26 mole% grossular component). Most garnet cores show a growth-zoning with Mn, Ca and Y highest in the core, whereas Mg, Fe and Mg # increase towards the rims; some garnet cores are fairly homogeneous. The thin Ca-rich rims, which are locally resorbed (most probably during the M2 event) compare in composition to a second generation of small (< 1 - 2 mm) garnets in the matrix. Textures and element partitioning indicate that the second garnet generation and the Ca-rich rims of the large garnets are in equilibrium with typical M1-minerals such as chloritoid and phengite (Si = 6.6 - 6.85 and (Fe + Mg) = 0.8 - 1.0 atoms / 22 O). Typical inclusions in garnet cores are: white K-mica compositionally matching high-T muscovite (Si = 6.02 - 6.15 and (Fe + Mg) = 0.25 - 0.36 atoms / 22 O; Ti = 0.8 - 1.2 wt%; Ba = 0.20 - 0.45 wt%); F-rich apatite; monazite; irregular intergrowths of white K-Na micas + albite + quartz, probably a replacement product of K-Na feldspar. Monazite inclusions appear to be confined to the marginal parts of the garnet cores which are also characterized by elevated Y contents. Electron microprobe U-Th-Pb dating of monazite inclusions yielded ages in the range 220 - 320 Ma. Alpine monazite occurring in the matrix or in late veinlets crosscutting garnet could not be dated by the EMP method owing to its low Pb contents.
The various types of relict minerals included and the rather „flat“ chemical zoning of the large garnets suggests that they formed at middle amphibolite-facies conditions. Detailed EMP work failed to detect significant element diffusion between the pre-Alpine cores and the Ca-rich Alpine overgrowths, which is in accord with the comparitively low temperatures prevailing during Alpine metamorphism. Amphibolite facies conditions have been documented in the "Variscan" basement rocks exposed as lowest unit of the ACMC on some Cycladic islands. It is tempting, therefore, to correlate the garnet rocks described from N-Samos with these occurrences. In general, the present study demonstrates that high-T muscovite, apatite and monazite trapped in garnet may survive a subsequent low-T, high-P metamorphism (≈500 °C, ≈20 kbar). Thus such inclusions may provide important petrogenetic information on the early metamorphic history of rocks.

TECTONIC UNROOFING OF ALPINE ULTRAHIGH-PRESSURE TERRANES

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The return of ultrahigh-pressure metamorphic terranes to Earth's surface is mostly discussed in the framework of gravity-driven extrusion from a subduction channel. This implies the simultaneous activity of a thrust fault with foreland-directed shear sense at the base of the UHP terrane and a normal fault with hinterland-directed shear sense at the top. However, the shear zones at the top of UHP terranes in the Alps are generally not normal faults but foreland-directed thrust faults. They were partly reactivated as or cut by hinterland-directed normal faults, but this generally occurred after the main exhumation stage. Therefore, the extrusion model and its variants (e.g., slab break-off, serpentinisation) do not adequately describe the exhumation of UHP terranes in the Alps.

During UHP metamorphism, part of the overburden of any UHP terrane is invariably formed by mantle rocks because the required overburden exceeds the maximum thickness of crust. We show that in the cases of Tertiary UHP rocks in the Adula - Cima Lunga nappe, Central Alps, and of probably Cretaceous UHP rocks in the Pohorje unit, Eastern Alps (JANÁK et al., 2004), these mantle rocks belonged to transient microplates (Briançonnais microplate in the case of Adula, Upper Central Austroalpine microplate in the case of Pohorje) bounded by parallel-dipping subduction zones on two sides, the UHP rocks being buried in the lower and more external subduction zone. This subduction zone was oceanic in the case of Adula but intracontinental in the case of Pohorje. The lower crustal and mantle parts of the microplates are not present any more in the Alps, neither at the surface nor in deep seismic profiles and therefore must have been subducted. In both cases, a dense oceanic slab was attached to the microplates (South Penninic slab in the case of Adula, Meliata slab in the case of Pohorje). We assume that these slabs exerted a pull which caused the downward removal or extraction of the microplates during ongoing plate convergence, leading to the partial unroofing of the UHP rocks (slab extraction model, FROITZHEIM et al., 2003). In this model, the ultimate driving force of exhumation is not the buoyancy of the UHP terrane but the negative buoyancy of the oceanic slab.

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MINERAL NEEDLES AND MELT INCLUSIONS IN GARNET FROM THE CHEPELARE AREA, CENTRAL RHODOPE, BULGARIA

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The garnet-kyanite schists from the Chepelare area, Central Rhodope, Bulgaria, were recently reported as ultrahigh-pressure metamorphism locality In virtue of high-silica content in garnet and exsolution lamellae of rutile and thick quartz prisms, maximum pressure of 6.8 GPa and temperature up to 1000 °C at 4 GPa were suggested (KOSTOPOULOS et al., 2003). A detailed petrographic work on the same rocks revealed the presence of significant amount of tiny needles and rods of quartz, biotite, white mica, apatite and rutile (1 to 5 µm in width and up to 20 µm in length) (Fig. 1a). Quartz and apatite grains have usually euhedral shape, similar to those reported by MPOSKOS & KOSTOPOULOS (2001) in garnets from UHP localities in Greek Rhodope and they were supposed to exsolve from a garnet precursor richer in Si, K and P

In same garnets small polyphase melt inclusions (5 15 µm in diameter) of quartz, biotite, white mica, potassic feldspar, apatite, rutile and zircon were detected. In some inclusions, just one single crystal of each mineral is exposed at the surface (Fig. 1b), whereas in others, intergrowths of different phases are documented. The inclusions shape is euhedral and many of them have faceted boundaries with the host garnet. Similar shape of polyphase melt inclusions from Erzgebirge were interpreted by STÖCKHERT et al. (2001) to be a result of brittle failure of the host garnet due to the overpressure in the inclusion and subsequent crack healing. In Erzgebirge garnet gneiss the polyphase inclusions are systematically associated with microdiamonds. However in our case no diamonds have been yet detected although graphite is found in the matrix assemblages and rarely in the porphyroblasts. The reason could be that microdiamonds (if present) are not so abundant or that the kyanite-bearing schists from the Chepelare area did not reach pressures high enough for diamond formation. Retrograde graphite in association with the melt inclusions was not detected either.

Our preliminary data supports the idea that the rocks from the deepest structural level of the Central Rhodope, Bulgaria, experienced higher pressure and temperature, than estimated by conventional thermobarometry.

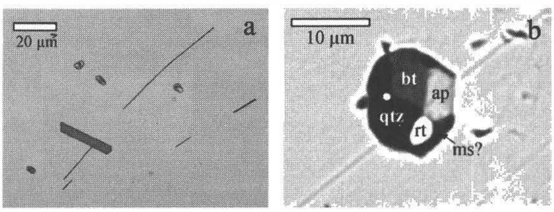

Fig. 1. BSE images of:
a) biotite needles in garnet
b) biotite - quartz- apatite-rutile - white mica? melt inclusion in garnet

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HOT TECTONIC CHANNEL: A KEY FOR THE ORIGIN OF ULTRAHIGH-PRESSURE ROCKS

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On the basis of well known P-T-t paths and using two-dimensional numerical modeling of incipient continental collision associated with subduction of the lithospheric mantle, the formation and exhumation of coesite- and diamond-bearing rocks metamorphosed at T > 700 °C in presence of the dense supercritical silicate fluid and / or melts is explained by a "hot channel effect" This process involves the transient formation of a hot tectonic channel in crustal and mantle rocks at the beginning of collision. The channel formed along the plate interface and could penetrate toward the bottom of the lithosphere of the overriding plate (150 - 200 km) within the range of 700 °C and 1000 °C. Anomalously high temperature is caused by intense viscous and radiogenic heating produced in the channel by deeply subducted radiogenic upper-crustal rocks (e.g., sediments of passive margin origin). Heating is also associated with intense aqueous fluid flow released in the course of rapid dehydration (deserpentinization) of the mantle lithosphere of the overriding plate that has been hydrated during previous subduction stages. Lower effective viscosity of rocks subjected to increased temperature, partial melting, and fluid infiltration promotes the mélange of hydrated mantle and crustal rocks within the hot channel. This channel may exist only at the earliest stages of collision and producing rapidly large amounts of UHP-HT rocks. Further collision closes the channel through squeezing rheologically weak (partially molten) buoyant rocks between the rigid lithospheric mantle and two colliding plates. An assemblage of complicated P-T paths with repetitive loops characterizes the exhumation of UHP rocks in the hot channel. Combined effects of tectonic overpressure and shear heating are investigated numerically for the P-T paths of UHP rocks.

A FEASIBLE TECTONIC MODEL FOR UHP METAMORPHISM AT THE END OF THE CALEDONIAN COLLISION

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New U-Pb SHRIMP dating and trace element analysis of coesite-bearing zircon (McCLELLAND et al., this volume) confirms that UHP metamorphism along the Laurentian margin of the North-East Greenland Caledonides occurred at 360 Ma, and likely persisted through 350 Ma. The hot (> 900 °C) UHP rocks were exhumed through the Sm - Nd closure temperature at 342 ± 6 Ma. These results push the duration of Caledonian collision between Laurentia and Baltica well into the Carboniferous, and beg the question: What tectonic scenario can produce UHP metamorphism near the end of the Caledonian orogeny?

The eclogite-bearing Laurentian continental basement exposed in Greenland generally lacks mantle peridotites, and therefore, is taken to be the upper, over-riding plate in a collision with Baltica as the down-going slab. Continental subduction of the Baltic margin at ca. 400 Ma, inferred from UHP metamorphism of the peridotite-rich Western Gneiss Region in Norway, marks the closure of the Iapetus ocean. Rapid exhumation of the Western Gneiss Region at 395 Ma is most likely caused by slab break - off. This event may trigger synorogenic extension at the surface and formation of the Old Red Sandstone Devonian basins in Greenland and Norway. HP granulites and eclogites were also forming in the overriding plate around 400 Ma due to crustal thickening by imbricate thrusting and / or vertical stretching processes. Once slab break-off occurs, continental subduction is likely to stop, and continued convergence will lead to the formation of an overthickened orogenic welt. Plate convergence, perhaps in a transpressional setting, must have continued into the Carboniferous in order to form UHP assemblages in the hinterland of the orogen in North - East Greenland. A "drip" model, whereby parts of the over-thickened Laurentian crust are pulled down to mantle depths of 100 - 120 km, may explain the high temperatures as well as the young age of UHP metamorphism in North-East Greenland. The difficulty then comes in trying to exhume UHP rocks from the bottom of the pile. We suggest that a change in plate motion resulting in decreased convergence is needed to exhume the Greenland UHP rocks. This occurred between 350 340 Ma, perhaps in a transpressional or transtensional setting. Gneisses in the UHP terrane are cut by undeformed pegmatites dated by U-Pb zircon at ca. 330 Ma, demonstrating that amphibolite facies exhumation and deformation were waning. Pennsylvanian (i.e. Late Carboniferous) terrestrial conglomerates, sandstones and siltstones were deposited directly on eclogite - bearing basement in Germania Land, approximately 50 km south of the UHP locality and mark the final exhumation of the Laurentian margin.

IS UHPM DIAMOND ABNORMAL?

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With respect to normal diamond, the Raman band of diamond at Kokchetav, Kazakhstan (SMITH et al., 2004) and at Straumen, Norway (GODARD et al., 2003) is weaker, wider and downshifted from 1332 cm^{-1} to values between 1329 and 1323 cm^{-1} Several non-exclusive hypotheses (cf. SMITH et al., 2004) are re-discussed with reference to new data from a lonsdaleite standard and from Kokchetav: (a) transformation into another polymorph of carbon, notably lonsdaleite which shows a weak, wide band at ~1328 cm^{-1}; defects caused by (b) plastic deformation, (c) temperature effects, (d) radiation damage, (e) abundant nanometric oxide inclusions, (f) impurities such as B, N & P, or (g) other growth features. These abnormal diamonds are usually intimately associated with retrograde graphite (Fig. 1).

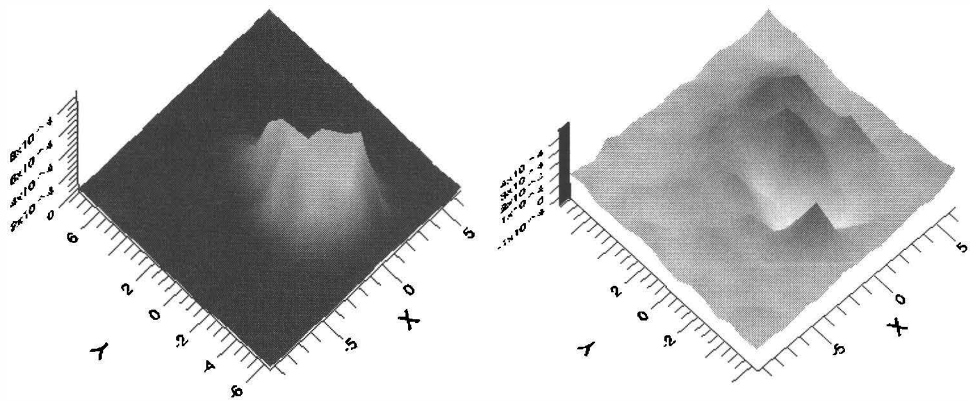

Fig. 1. Raman peak intensity maps of a micron-sized carbon inclusion in metamictised zircon (Kokchetav, sample K210-LD): [left]: diamond, only in the core (lighter); [right]: graphite surrounding the diamond (darker).

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ECLOGITE AND ECLOGITE - LIKE ROCKS OF THE OPHIOLITE BELT OF ARMENIA

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The ophiolite belt association in the territory of Armenia is a part of the Alpine-Himalayan folded mountain belt. Intrusive rocks of mafic and ultramafic composition are associated with the ophiolites. Simultaneously with the ophiolites, the intrusive rocks were formed in a zone being the Tethys oceanic basin of a riftogene trough type in the Jurassic time, accompanying by formation of rift with new ophiolite (oceanic) crust and exhumation of mantle material upward to the Earth's surface. High-P / T laboratory experiments in combination with petrography and mineral analysis of mafic / ultramafic intrusive rocks, their serpentinised variety and major accessory minerals in glaucophane - almandine facies show a broadband grade of metamorphism (TATEVOSYAN, 1951, ABOVIAN, 1982; GRIGORIAN et al., 2003, 2004; GRIGORIAN & ABOVIAN, 2004). Some results of studies on various types of eclogite - like rocks: eclogites, eclogite facies, amphibole garnet schist, as well as some allied country rocks of different structural and tectonic settings within the ophiolite belt of Armenia are discussed in present paper. Field works, petrological / SEM / TEM / microstructural analysis and standard chemical and spectral analysis were curried out to study considered materials. Most of units of pale-pinkish to dark-red garnets with almandine prevalence represent the variety of greenschist-to-eclogite, glaucophane-almandine foliated metamorphic facies and gabbro-amphibolite facies, up to one-centimetre size, with visible weathering effects. The studies show a range of low-to-high grade metamorphism for gabbroid rocks, amphibolites, greenschist facies, accompanied by metasomatism and retrograde metamorphism in some cases, and correlate with Sr / Ba, K / Ar, U / Pb, Sm / Nd aging measurements as well as with the report on microdiamonds found in some rocks of ophiolite melange in Armenia (GEVORKYAN et al., 1976). Present results demonstrate complexity in geological situation and geodynamics of the Earth's crust in Armenia.

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NEW PETROLOGICAL CONSTRAINTS ON THE P-T DECOMPRESSION PATH OF THE UHP BROSSASCO-ISASCA UNIT (DORA-MAIRA MASSIF, WESTERN ALPS) FROM THE P-T PSEUDOSECTION STUDY OF A GARNET-KYANITE METAPELITE

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A Grt-Ky–bearing metapelite from the UHP Brossasco-Isasca Unit (BIU), Dora-Maira Massif, Western Alps, has been analysed in order to better define the decompression path. The meta-pelite consists of pre-Alpine porphyroblastic garnet (Grt1) up to 2 cm in diameter, idioblastic Alpine garnet (Grt2), phengite, kyanite, quartz pseudomorphous after coesite and small-grained paragonite aggregates after former jadeite. Late chloritoid and staurolite idioblasts, first reported from a BIU metapelite, are randomly oriented across the main UHP foliation defined by phengite.

Grt2 is characterized by high almandine (Alm_{72-77}) and very low grossular (Grs_{1-9}) contents, suggesting a growth from a Ca-poor pelitic composition. Large, high-Si phengites (Si up to 3.55 a.p.f.u.) are partially replaced by low-Si phengites (Si = 3.15 - 3.05 a.p.f.u). Staurolite is strongly zoned, with Mg-richer cores ($X_{Mg} = 0.20$) and Fe-richer rims ($X_{Mg} = 0.12$). Chloritoid is homogeneous and relatively Fe-rich ($X_{Mg} = 0.20 - 0.22$).

A P-T pseudosection in the MnNKFMASH model system was calculated in the range T = 500 - 700 °C and P = 6 - 18 kbar, using the "effective bulk rock composition" obtained by SEM-EDS analyses of a representative number of metamorphic domains with only Alpine mineral assemblages. The P-T pseudosection was calculated following the approach of CONNOLLY (1990), and using the internally consistent thermodynamic data set and H_2O equation of state of HOLLAND & POWELL (1998, upgrade 2002).

Microstructural and mineral chemistry data, together with the calculated P-T pseudosection, strongly constrain a portion of the BIU decompression P-T path from T = 550 °C, P = 9 kbar to T = 650 °C and P = 15 kbar. This trajectory is in good agreement with the P-T paths previously estimated by COMPAGNONI et al. (1995), NOWLAN et al. (2000), CHOPIN & SCHERTL (2000), RUBATTO & HERMANN (2001) and HERMANN (2003).

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DECOMPRESSIONAL P-T PATH IN THE ALBITE-STABILITY FIELD OF ORTHOGNEISS FROM THE UHP UNIT OF THE DORA-MAIRA MASSIF

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In order to constrain the low-P portion of the decompressional P-T path of the UHP Brossasco-Isasca Unit (BIU) (Dora-Maira Massif), a Grt-bearing phengite orthogneiss has been examined. The orthogneiss, derived from the Alpine deformation and recrystallization of a Variscan granite, consists of Qtz, Ab, Ep, Phe, Grt and Bt. Phengite flakes with Si = 3.52 - 3.45 a.p.f.u. are partially replaced by smaller, less celadonitic phengite (Si from 3.38 to 3.20 a.p.f.u.). Garnet occurs as small idioblasts, with average composition $Grs_{59}Alm_{37}Sps_4$. These mineral compositions are representative of those formed in Ab-bearing BIU orthogneisses (CHOPIN et al., 1991).
A P-T pseudosection in the MnNCKFMASH model system was calculated at $a(H_2O)$ = 1.0, 0.75 and 0.5, using the software PERPLEX and the approach of CONNOLLY (1990) with the internally consistent thermodynamic data set of HOLLAND & POWELL (1998, upgrade 2002).
Comparing measured compositions of the Grt-Phe-Bt assemblage with those modeled in the P-T pseudosection, an equilibration T of 610 °C at P = 12 kbar has been obtained for $a(H_2O)$ = 0.5. This estimate fits along the P-T paths previously proposed for the BIU (*e.g.* COMPAGNONI et al., 1995; CHOPIN & SCHERTL, 2000; HERMANN, 2003; GROPPO et al., 2005). Specifically: i) the Si-richer phengite cores (Si = 3.52 - 3.50) formed in the Ab stability field, at ~14 kbar; ii) a decompression from ~14 kbar to 5 kbar, with a T decrease to ~500 °C, is suggested by variation of Si contents in Phe and topology of the pseudosection; iii) the low $a(H_2O)$ obtained along this portion of the decompressional P-T path is in agreement with dehydration during exhumation as shown by PROYER (2003) in N(C)KFMASH metagranites.
These petrological data suggest that the BIU granite gneisses were thoroughly equilibrated under high-P amphibolite facies conditions along the decompressional P-T path.

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230 Ma ECLOGITE FROM BIBONG, HONGSEONG AREA, GYEONGGI MASSIF, SOUTH KOREA: HP METAMORPHISM, ZIRCON SHRIMP U-Pb AGES AND TECTONIC IMPLICATION

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We report here an eclogite occurrence in Bibong, Hongseong area, southwestern part of the Gyeonggi Massif in South Korea. It outcrops as a lens in Precambrian quarzofeldspathic gneisses together with lenses of ultramafic rocks and HP granulite (or retrograde eclogite) with omphacite inclusions in garnet (OH et al., 2003; 2005). The eclogite preserves traces of four metamorphic stages: eclogite (M1), HP granulite (M2), MP granulite (M3) and amphibolite (M4) facies.

The eclogite facies (M1) mineral assemblage grt + omp + qtz + ab (An < 10) + kf + rut + ap is well preserved both within and outside garnet porphyroblasts. The jadeite contents in omphacites are usually in the range of 0.28 - 0.22, and the jadeite contents of omphacites in the matrix can be as high as within garnet, although some omphacites have broken down into fine grained intergrowth of omphacitic cpx + sodic pl. The HP granulite facies (M2) mineral assemblage is grt + diopsidic cpx + pl + qtz ± ilm ± amp, it is indicated by a coronitic texture of diopsidic cpx + pl arround and within garnet. The MP granulite facies (M3) mineral assemblage is grt + opx + pl ± diopsidic cpx + qtz ± ilm ± amp. It is indicated by a coronitic texture of opx + pl ± diopsidic cpx around and within garnet. The amphibolite facies (M4) mineral assemblage is grt + amp + pl + ilm + qtz ± sp ± ep. The feature of this metamorphic stage is the symplectitic texture of amp + pl ± ilm around garnet. Biotite and chlorite occur in some parts. They represent later alteration. The metamorphic P-T conditions of the eclogite and granulite facies were estimated by the TWQ method. They are (M1): 19.5 - 18.5 kbar and 750 – 800 °C, (M2): 16.5 - 14.0 kbar and 750 – 800 °C, (M3): 11.5-9.0 kbar and 750-820 °C. The amphibolite facies conditions are 5.5 - 7.5 kbar and 600-720 °C calculated by conventional thermobarometers.

These metamorphic P-T calculation results confirmed the HP metamorphism and depicted a clockwise P-T path with significant isothermal-decompressional section (CW-ITD). From eclogite facies (M1) to granulite facies (M2, M3), the metamorphic pressures decreased sharply from 19 kbar to about 9 kbar, with a slight increase in temperature. After the MP granulite facies (M3), the eclogite experienced cooling and uplift. A metamorphic age of 231.2 ± 3.3 Ma has been determined by zircon SHRIMP U-Pb technique. The inferred P-T path and metamorphic age of the eclogite are similar to those of the retrograded eclogite from Weihai area, Sulu UHP collisional belt in eastern China. These results indicate that the western part of the Gyeonggi massif in South Korea may be a possible extension of the Sulu collision belt in China.

THE POLYMETAMORPHIC EVOLUTION OF CRETACEOUS HP ROCKS FROM THE TEXEL COMPLEX (AUSTROALPINE UNITS, EASTERN ALPS): PETROLOGICAL AND GEOCHRONOLOGICAL CONSTRAINTS

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New mineral chemical and (micro)structural investigations combined with geochronological data of HP metamorphic rocks from the Texel Complex (TC, SÖLVA et al., 2005) evidence a polymetamorphic evolution and constrain the age and PT conditions of HP-metamorphism.
All major mineral phases except for Grt-cores in metasediments and Bt-bearing orthogneisses and Kfs-clasts had (re)equilibrated during or after the P-peak. Conventional thermobarometry using Grt – Omp ± Ab assemblages gave peak PT results of 560 - 610 °C / 1.2 - 1.4 GPa, which correspond to data by HOINKES et al. (1991). Intergrowths of Ab and Omp justify using Jd-Ab-Qtz barometry Mineral zoning trends indicate a clockwise PT path close to Pmax.
All lithologies show two Grt growth stages separated by a stage of Grt-resorption. Within eclogite both the Grt core and rim were in equilibrium with Omp, and Grt-consumption was related with Omp-producing mineral reactions and deformation. The entire Grt-growth in eclogite is thus assigned to the HP event. Consistently, Sm-Nd data of 6 Grt-fractions (hand-picked fractions, HCl-leachates and residues) of eclogite sample HK11200 gave 82 ± 9 Ma (MSWD = 1.6, εNd(t) = +5.4) reflecting Upper Cretaceous isotopic equilibration of Grt and its inclusions. In contrast, data from Grt-two-mica-gneiss and Amp-Bt-Pl orthogneiss indicate the presence of significantly older mineral relics (Grt cores or inclusions) which were not isotopically equilibrated during the Cretaceous event. In line with compositional evidences of two-stage Grt growth in metasediments and tonalitic orthogneisses, these data may reflect pre-Cretaceous magmatic and / or metamorphic processes in the TC.
Apart from deformational inclusion fabrics in Grt core domains, the dominating foliation and a new compositional layering formed at eclogite facies conditions (D1). The orientation of related stretching lineations, which are reflected by HP phases, and fold axes of intrafolial folds, scatter SW to NW due to subsequent (re)folding with N-S (D2) and E-W trending (D3) axes at amphibolite facies conditions. All major deformational structures are related with Cretaceous SE-directed extrusion of the HP rocks (SÖLVA et al., 2005). Rb-Sr Bt-WR ages of Grt-two-mica-gneiss and Amp-Bt-Pl orthogneiss are at 73.1 ± 0.7 Ma respectively 78.1 ± 0.8 Ma. Along with mica-ages from the wider study area they are interpreted as to reflect the time of cooling below ~300 °C. Despite of the evidences of pre-Cretaceous mineral relics the predominating deformational and metamorphic imprint of the TC is confined to the Upper Cretaceous.

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NEAR-ULTRAHIGH PRESSURE PROCESSING OF CONTINENTAL CRUST: MIOCENE CRUSTAL XENOLITHS FROM THE PAMIR

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Xenoliths of subducted crustal origin hosted by Miocene ultrapotassic igneous rocks in the Southern Pamir provide important new insight into the fate of subducted continental slabs at high temperature and pressure. Four types have been studied: sanidine eclogites (omphacite, garnet, sanidine, quartz, biotite, kyanite), felsic granulites (garnet, quartz, sanidine and kyanite), basaltic eclogites (omphacite and garnet), and a glimmerite (biotite, clinopyroxene and sanidine). Apatite, rutile and carbonate are the most abundant minor phases. Hydrous phases (biotite and phengite in felsic granulites and basaltic eclogites, amphiboles in mafic and sanidine eclogites) and plagioclase form minor inclusions in garnet or kyanite. Solid-phase thermobarometry reveals recrystallization at mainly ultrahigh temperatures of 1000 - 1100 °C and near-ultrahigh pressures of 2.5 2.8 GPa. Textures, parageneses and mineral compositions suggest derivation of the xenoliths from subducted basaltic, tonalitic and pelitic crust that experienced high-pressure dehydration melting, K-rich metasomatism, and solid-state re-equilibration. The timing of these processes is constrained by zircon ages from the xenoliths and ^{40}Ar / ^{39}Ar ages of the host volcanic rocks to 57 - 11 Ma. These xenoliths reveal that deeply subducted crust may undergo extensive dehydration-driven partial melting, density-driven differentiation and disaggregation, and sequestration within the mantle. These processes may also contribute to the alkaline volcanism observed in continent-collision zones.

REDISCOVERY OF THE LIVERPOOL LAND ECLOGITES (CENTRAL EAST GREENLAND): A POST AND SUPRA-SUBDUCTION UHP PROVINCE

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The eclogites of the Western Gneiss Region in Norway, that became famous by the work of Eskola, suggested that the high pressures were a record of large stresses, seeing no mechanism to bring rocks from large depths to the surface. At the same time Eskola confirmed that hand samples from Liverpool Land (East Greenland) were eclogites. Since then the latter eclogite province has been mapped out, but little modern petrological studies or dating exist from the province. Moreover, a large late Caledonian UHP eclogite province has been documented in Northeast Greenland. Collectively these eclogite provinces cover far greater areas than the Western Gneiss Region in Norway, but nevertheless the Norwegian eclogites are explained by subduction of Baltic continental crust deep into the mantle below Laurentia.
A 'rediscovery' and modern study of the Liverpool Land eclogites is reported here, in hopes of bringing these rocks back into tectonic models for the Caledonides. Fieldwork in the area generally confirmed the classic studies: The region consists of granitic gneiss densely packed with eclogite lenses varying in size of dm to 1 km across. Petrologic analysis confirm that the rocks are eclogites *s. s.* and record peak metamorphic conditions of > 25 Kbar, and 800 °C. Peak metamorphism is dated by U-Pb TIMS to extend from ca. 397 to 393 Ma. Widespread migmatites appear to have generated in the high strain zones between the eclogites and their host rocks, and typically collect in the boudin necks of the lenses. Locally the melts collect into sheeted dikes cutting both eclogites and their hostrocks. A suite of U-Pb TIMS ages on these late to post-strain granites group from ca. 388 to 385 Ma. U-Pb TIMS dating of titanite and rutile from both eclogites, host rocks and granites confirm that these cooled nearly instantly to below 450 °C, within 1 million years after melting (384 Ma). Petrological analysis suggests a cold cooling path, through prehnite-pumpellyite facies.
A very important feature in understanding the setting of the Liverpool Land eclogites, is that they occur in basement gneisses cut by large (> 1000 km^2) stocks of ca. 425 Ma granitoids. The eclogites and their strained hostrocks, has hereto been regarded as predating these virtually unstrained plutons. However, the new data show that deformation, melting and UHP metamorphism all are local phenomena.
Collectively the Greenland data calls for revisions of models of Caledonian Tectonics. The asymmetric distribution of subduction products (arcs, ophiolites, etc.) probably confirms a westerly pre-collision subduction. However the Greenland UHP eclogite provinces are in direct contrast with models of these areas riding above a continental subduction zone, as the same anchor of oceanic lithosphere could not have pulled down both continental plates synchronously Invariably the expanding documentation of dual sided Caledonian UHP metamorphism, and the link between high strain and high pressures questions a simple pressure to depth correlation.

UHP P-T-TIME LOOPS: A RECORD OF ULTRADEEP SUBDUCTION OR TECTONIC OVERPRESSURE?

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Ultra high pressures are reported from more and more places, and with increasingly high pressures around the world. Assuming lithostatic pressure, these extreme pressures are generally presented as evidence for subduction of continental crust deep into the mantle. However, as the recorded pressures in continental roots grow, they become an increasing challenge to the basic assumption of a simple correlation between pressure and depth. For example: 1) why was the pressure highly heterogeneous within UHP terrains; 2) why are UHP minerals (e.g. coesite) typically found inside hard minerals or bodies potentially acting as pressure vessels during compression and decompression; 3) why is there no evidence for huge erosional products resulting from exhumation of UHP rocks; 4) how can both sides of an orogen like the Caledonides subduct to extreme depths; and 5) what are the driving forces behind such super-deep subduction and near instant exhumation?

Models of tectonic overpressure (TO) basically suggest that P(total) locally is higher (e.g. 2x) as the lithostatic P(load), depending on several variables, including strength of rocks, pressure deviations around lenses of variable viscosity (i.e. mafic bodies, garnets with coesite inclusions, diamonds in a peridotite) or in the hinges of or between flexed strong layers.

Arguments against tectonic overpressure usually are based on the assumption that rocks are too weak to sustain substantial differential pressures. Such arguments can be disproved by the fact that big mountain chains need an integrated lithospheric strength on the order of 10^{13} Pa•m, in order to sustain its surface and moho-topography. Secondly the strength argument can be met on its own turf. Tectonic overpressure in its simplest form is proportional to differential stress (strength) that for creep is a function of rheological parameters, temperature and strainrate. When strength is calculated it is typically the temperature that is varied through the crust, while strainrate is kept constant. There is no doubt that the temperature has a major influence on strength, but heat diffuses, and thus does not vary that much within region over long periods of time. Strain, in contrast, tend to localize, and therefore can vary > 10 orders of magnitude within a handsample. In the models presented here we 'free' the strainrate parameter, in order to investigate its effect on P-T loops in 'dynamic P-T-time diagrams, which takes shear heating, overpressure and strainrate into account. Clearly low strain lenses in UHP regions like the Flatraket granulites in Norway, the Hurry Inlet granite in Greenland, or the Dora Maira Massif in the Alps, will not record large overpressure, whereas the highly strained surrounding rocks will. It is of course interesting to speculate why some rocks are strained and others not, but it remains a first order observation that strain and thus strainrate was low in these 'low' P lenses.

Implementing this type of structural information in the 'strength Christmas three' (Brace-Goetze Lithosphere), it can be illustrated how different and complex P-T-time loops can form in neighboring rocks as a result of tectonic overpressure and shear-heating. Implementing the strain record into P-T-time data, thus suggest that high pressures are 'tectonometers' rather than altimeters.

NATURAL AND EXPERIMENTAL CONSTRAINTS ON HIGH-PRESSURE FLUIDS

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Recent experiments have shown that in felsic compositions the complete miscibility of aqueous fluids and hydrous melts leads to a termination of the wet solidus in a second critical end point at about 25 - 30 kbar. This caused considerable confusion surrounding the nature of fluids at conditions encountered by high pressure (HP) and ultra-high pressure (UHP) rocks. We argue that mineral-saturated fluids at pressures above the upper critical point are in most cases compositionally well defined. For example, the diamond-facies quartzo-feldspatic rocks of the Kokchetav massif and Erzgebirge equilibrated at temperatures much higher than the wet solidus close to the critical end point. Hence the fluid phase in these rocks has properties of a hydrous silicate melt. In contrast, eclogite facies metamorphism often found in subducted slices of oceanic crust reaches conditions of 20 kbar and 600 - 650 °C. The peak temperature in such rocks is lower than the wet solidus and consequently a silica-rich, aqueous fluid is stable. A special case is encountered in the Dora Maira Massif, where peak metamorphic conditions of ~730 °C and ~40 kbar are situated directly above the second critical endpoint. It is expected that the fluid phase at peak conditions was transitional between a hydrous melt and an aqueous fluid. The examples show that first order estimates on the composition of the fluid phase can be made if the wet solidus and the second critical endpoint are known. Further-more, this permits to estimate the activities of H_2O in such systems, which is essential for all thermodynamic modeling. As the position of the wet solidus, the critical point and the solubility isopleths are all bulk rock dependent, the activity of H_2O in HP rocks will be a function of P, T and bulk.

While we can obtain a general picture about total solubility of major elements in fluids from phase relations, this is not possible for trace elements. We present a case study from eclogite facies rocks of New Caledonia (P ~19 kbar, T ~600 °C) showing that only minor amounts of trace elements were mobile during peak metamorphic conditions. On the other hand, the rocks lost most of their water indicating that there is a decoupling of dehydration and loss of trace elements during prograde subduction zone metamorphism. To further test this hypothesis we performed piston cylinder experiments in which we were able to trap such fluids in synthetic fluid inclusions or in a diamond trap layer. Both methods confirm that during eclogite facies dehydration the liberated fluids are surprisingly dilute. A low concentration (< 5 ppm) of trace elements in eclogite facies aqueous fluids in equilibrium with metapelites is also in agreement with published mineral / fluid partitioning. The combined study of phase relations, natural samples and experiments puts new constraints on the nature and composition of fluids in HP and UHP rocks which provide an important window on subduction zone processes.

SUPERZONED GARNET IN YANGKOU PERIDOTITE, SU-LU UHP BELT, EASTERN CHINA.

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Two types of millimeter size garnet porphyroclasts (PC) are found in Yangkou peridotite in the Su-Lu UHP belt, eastern China. They are accompanied with fine-grained (0.1 - 0.2 mm) garnet neoblasts at the margin, but the Fe-Mg zoning trend shows an opposite sense in each type PC; Type A: Reddish garnet (ca. 4 - 6 mm in diameter) occurs in garnet-clinopyroxenite layer up to a few cm thickness and boudinaged in the host peridotite. Some grains have a relatively homogeneous core with $Prp_{32-42}Alm_{41-45}Grs_{15-22}$. MgO gradually increases towards the rim and FeO vice verse and the rim composition reaches ca. $Prp_{58-62}Alm_{25}Grs_{13-15}$. The garnet neoblast ($Prp_{67}Alm_{22-23}Grs_{5-7}Uvr_{3}$) is similar composition to the PC rim, but slightly magnesian and Cr_2O_3-rich. Randomly oriented clinopyroxene inclusions (0.5 1.5 mm length) are found in the core of the PC. Type B: A few porphyroclasts are observed in the fine-grained (0.1 0.2 mm) granoblastic matrix of the host garnet peridotite. The largest porphyroclast (ca. 3 mm in diameter) shows a slight chemical zoning: the core is richer in MgO ($Prp_{69}Alm_{17}Grs_{14}$) than the rim ($Prp_{65}Alm_{22}Grs_{11}Sps_{2}$). The garnet neoblast ($Prp_{66}Alm_{22-24}Grs_{5-6}Uvr_{5-7}$) has a composition similar to the PC rim. Although the both types of PC are almost free from Cr_2O_3 (ca. 0.1 wt.%), the neoblasts developed at the margin of the both types of PC contain a significant amount of Cr_2O_3 (ca. 1.0 - 2.5 wt.%).

The detail petrography of the host peridotite (YOSHIDA et al., 2004) suggests that Type B PC was formed pre-UHP stage at moderate P-T conditions (ca. 800 - 830 °C and 1.2 - 2.9 GPa) and the subsequent subduction caused UHP metamorphism at P-T conditions of 730 – 760 °C and 3.6 - 4.1 GPa accompanied with pervasive granulation of precursor phases and then finally exhumed almost isothermal conditions along with surrounding UHP meta-supracrustals (e.g, eclogite and UHP meta-granite). The compositions of Type B PC and the rim of Type A PC are identical to the composition range of garnet ($prp_{60-75}grs_{5-12}$) in the garnet peridotite in Caledonides, but the core of Type A PC has a similar composition to those of fine–grained eclogite in the Yangkou UHP unit.

These data envisage following growth history of porphyroclasts: Type B PC and Type A PC formed synchronously at the moderate depth in the host peridotite and in basaltic intrusion or trapped melt in the peridotite, respectively. Syn-UHPM granulation enhanced the element migration between the basaltic layer and the host peridotite, and then Type A PC modified its composition from the margin mainly by the volume diffusion.

The core composition of Type A PC is almost identical to "the reconstructed majoritic Grt" by YE et al. (2000), who envisaged the more deeper origin of the protolith, at the same outcrop. Our data, however, cannot support their idea.

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PETROGRAPHY AND GEOCHEMISTRY OF ECLOGITE PEBBLES FROM PLEISTOCENE CONGLOMERATES AT DUNAVARSÁNY, HUNGARY

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Eclogite pebbles have been found in the Upper Pleistocene gravel load of the Palaeo Danube at Délegyháza, 15 km south of Budapest (Hungary). The gravel load contains a wide variety of pebbles of igneous, sedimentary, and metamorphic origin. Provenance of most rock types is unclear (i.e. limestones, tourmaline- and garnet-bearing granitoids, amphibolites, granulites and eclogites). The gravel is very polymict; the roundness of the pebbles ranges from well-rounded to angular types, and their size is between 20 mm to 200 mm.
Eclogite gravels are usually elongated and well rounded. Reddish brown garnets (1 - 4 mm in size) with dark rims give 20 - 30 volume % of the whole rock. Groundmass is slightly schistose and consists of fine-grained acicular amphiboles and plagioclases with colour ranging from white to dark green. Subhedral, porphyroblastic garnets have cores full of inclusions such as quartz, rutile, zoisite and rare omphacite with a jadeite content of 44 – 48 %. Garnets have homogenous composition, but show variations between the analyzed samples. They exhibit multiple replacement textures: 1. (sometimes resorbed) kelyphytic rims made of hornblende; 2. Si-poor hornblende (SiO_2 less than 40 wt.%), plagioclase (An 46 – 47 %) and magnetite. This assemblage show radial textures growing from the rims into the interior of garnet grains. These zones contain spinel-anorthite inclusion assemblages possibly formed after kyanite. Similar assemblages were found in the matrix. Kyanites are also replaced by spinel-corundum-anorthite-zoisite assemblage. Where kyanite was found as a stable phase, margarite and zoisite formed concentric rims on them with margarite forming the inner rim. Plagioclase broke down to zoisite and paragonite-margarite, while plagioclase and kyanite - when found together broke down to margarite and zoisite. The matrix consists of hornblende-plagioclase symplectites, in rare occasions relic diopsidic clinopyroxenes were also found. Clinopyroxene coronas developed around matrix quartz grains. Large actinolites overgrow the matrix.
Garnet-omphacite pairs yield 660 - 750 °C near garnet rims and 560 - 590 °C for the inner parts of garnet, minimum pressure is estimated around 15 - 17 kbar. P-T pseudosection calculations were performed for elucidating the P-T peak conditions of the studied eclogites. The peak assemblage (Grt – Omp – Ky - Qtz ± Zo) formed at 660 - 800 °C and over 17 kbar; we obtained the same P-T conditions for the peak assemblage Grt – Omp Qtz in Ky-free samples.
Although eclogites and other metamorphics (i.e. granulites) found in the locality are known in the Bohemian Massif 300 - 400 km upstream, their low resistance to attrition excludes or questions the possibility that the pebbles originated from there. We suggest that they were reworked from Lower Miocene conglomerates, synchronous with the birth of the Pannonian Basin.

THERMOBAROMETRY OF KYANITE ECLOGITES FROM THE HOHE TAUERN WINDOW, AUSTRIA

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P-T data of five kyanite eclogites from the Mesozoic sedimentary – magmatic unit of the Hohe Tauern Eclogite Zone are based dominantly on the metamorphic peak assemblage garnet + omphacite + phengite + kyanite + quartz. According to recent calibrations (1 = THERMOCALC 3.21, data set Nov. 2002, POWELL & HOLLAND, 1998; 2 = GCPKS.xls Thermobarometry, KROGH RAVNA et al., 2004; 3 = PTGIBBS, BRANDELIK & MASSONNE, 2004) pressures about 25 kbar result from 1 whereas calibrations 2 and 3 result in generally higher values, in part in the stability field of coesite. This contrasts with generally lower pressures according to calibration 4 (WATERS & MARTIN, 1993, updated 1996) and with the absence of textural indications of a former presence of coesite. Temperatures according to calibrations 1 and 3 are in the range of 595 - 675 °C with calibration 2 ranging up to 715 °C. However a relatively large spread resulting from different calibrations and from different domains of each sample is noticeable.

Additional members of the peak assemblage in some samples are talc and magnesite and are calculated as stable in a very H_2O-rich fluid.

The presence of lawsonite along the prograde path is inferred from rectangular pseudomorphs consisting mainly of clinozoisite and paragonite. Other inclusions are omphacite, amphiboles (barroisite, pargasite), rutile and sometimes titanite, ilmenite and carbonates.

Retrograde paragonite in part rimming kyanite is calculated as product of a reaction at lower pressure and the stability of matrix zoisite is also restricted to such lower values. Matrix amphiboles are dominantly barroisite – pargasite, rare glaucophane is restricted to rock compositions with low Ca / Na ratio.

Prograde garnet zonation is characterized by strong increase of pyrope, decrease of almandine and generally moderate decrease of grossular and spessartine components. Minor retrograde rims with reversed zoning are partly observed. THERMOCALC modelling of pseudosections in the simplified NCFMASH system including stepwise garnet fractionation results in better agreement with the observed zoning pattern than former calculations using a more simplified fractionation.

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NANOMETER-SIZE SILICA-RICH GLASS INCLUSIONS IN MICRODIAMOND FROM GNEISSES OF KOKCHETAV AND ERZGEBIRGE MASSIFS: DIVERSIFIED CHARACTERISTICS OF THE FORMATION MEDIA OF METAMORPHIC MICRODIAMOND IN UHP ROCKS

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Nanometer-size silica-rich glass inclusions, as well as silica-poor/potassium-rich fluid inclusions were observed within metamorphic microdiamonds in garnet from the Kokchetav and Erzgebirge ultrahigh-pressure rocks. The chemical characteristics of these inclusions, and thus the diamond formation media, differ significantly depending on the respective host rock acting as a buffer. Whereas glass inclusions from garnet-biotite gneisses from the Kokchetav and Erzgebirge massifs generally are high in Si, K, P, Cl, fluid/melt pockets within diamonds from garnet-quartz-clinopyroxene rocks from Kokchetav are K-rich and Si-poor. Ultrapotassic fluid inclusions within diamonds of dolomite marble from Kokchetav typically are extremely poor in Si. Above all, fluid/melt inclusions within metamorphic diamonds also show chemical differences from those within the mantle-derived diamonds.

Depending on the different compositions of the fluid/melt media from which metamorphic diamonds were formed, the morphology of the microdiamonds also differs typically. Consequently, the fluid/melt medium responsible for the metamorphic microdiamond growth has been most probably generated within its own respective host rock. The nature and composition of this medium might play a decisive role in determining the different morphologies and growth rates/mechanisms of metamorphic diamonds in general.

FORWARD CALCULATION AND SOME PRELIMINARY ANALYSES ON THE GROWTH RATE AND CHEMICAL COMPOSITION OF GARNET

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Concentric chemical zoning retained in garnet is useful to reconstruct temperature and pressure history during garnet growth, assuming chemical equilibrium between garnet surface and other matrix minerals. Inverse and forward calculations have been applied to many garnet-bearing metamorphic rocks to derive the P-T trajectory. Forward calculation is mostly used just to support the results of inversions, that is, to show the possible mineral assemblage or define the P-T boundary. It is clear that detailed forward calculation provides much more quantitative information that can help unravelling the process of garnet growth: e. g., absolute P-T values, amount of garnet growth during certain P-T changes (INUI & TORIUMI, 2004). Change in the growth amount of garnet is especially of interest, since the formation of garnet is one of the dominant dehydration reactions in the subducting oceanic sediments and therefore may control the mass transfer in the subduction zone (e. g., TORIUMI & INUI, 2001). However, the modelled and the natural garnet behaviour still need to be calibrated with each other.

In order to provide the needed information, sensitivity analyses were firstly carried out on the forward model. Forward calculation by INUI & TORIUMI (2004) was performed to model the formation of zoned Mg-Fe-Mn-Ca garnet, applying published thermodynamic data set (e. g., HOLLAND & POWELL, 1998). The bell-shaped profile of Mn was reconstructed in response to heating and compression path of the Sambagawa metamorphic belt, SW Japan. Calculations were carried out varying the thermodynamic property data of minerals, P-T condition, and the initial chlorite composition. It was confirmed that variations concerning Mn influenced almost exclusively the core composition of garnet, whereas the uncertainty concerning Mg and Fe generally influenced the Mg/Fe ratio of garnet by a few mole%. In all calculated results, however, the amount of growth maximized when the Mg/Fe ratio in garnet started increasing rapidly. The volume of garnet crystal having certain compositional range (the amount of growth at a certain condition) was measured using the compositional mapping images of natural garnet from the Sambagawa metamorphic belt. The history of growth amount change was compared to that predicted by the forward calculation, using the P-T trajectory of the grains derived by the inverse analyses (INUI & TORIUMI, 2002) applied on the identical grain. It was shown that the volume of garnet maximized where Mg/Fe ratio started increasing rapidly, which was consistent with the behaviour predicted above. It suggests that garnet formation, and therefore the dehydration from metamorphic rocks, occurred within a narrow temperature range during subduction.

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RADIOMETRIC DATING OF ECLOGITE XENOLITHS FROM KIMBERLITES

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Unlike orogenic eclogites, those brought up from the Earth's mantle often consist only of clinopyroxene, garnet and rutile. Phases that would be especially interesting for dating purposes such as zircon (e.g. HEAMAN et al., 2002) are very rare in these rocks. Sm-Nd age determinations of eclogite xenoliths worldwide based on garnets and clinopyroxenes (internal ages) yield results that scatter over several orders of magnitude between 4 Ga and ages in the future and are not easy to interprete. The eclogite whole-rock system, however, often gives reliable age information (e.g. JAGOUTZ et al., 1984; PEARSON et al., 1995; JACOB & FOLEY, 1999). Re-Os isotopes can be applied to the bulk eclogites, but may give ages with high uncertainty, whereas Sm-Nd and Lu-Hf isotopic systems require a reconstruction of the whole rock eclogite based on mineral analyses to avoid erroneous results due to infiltration of the xenoliths by kimberlitic material. However, reconstruction of a "clean" bulk eclogites requires knowledge of the rock's exact modal composition which strongly depends on the sample size. In the case of Lu-Hf it could be shown that reconstructed whole rock eclogite ages can be too young if rutile occurs as an accessory with unknown exact modal amount (JACOB et al., 2005). Applying the U-Pb and Pb-Pb systems to eclogite silicates is probably the most promising method, because partitioning of Pb strongly favours cpx over gt (D (cpx / gt) = 16 for Udachnaya eclogites, JACOB & FOLEY, 1999) so that bulk rock reconstructions are not necessary. In the case of eclogite xenoliths from the Udachnaya pipe, it could be shown that the Pb-Pb isochron age on cpx was within error of the Os age on whole rock eclogites (JACOB & FOLEY, 1999; PEARSON et al., 1995). Pb contents in eclogitic minerals, however, are generally below 1 ppm and this method therefore requires low-blank chemistry procedures.

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TRACE ELEMENT BEHAVIOUR DURING ECLOGITISATION – A CASE STUDY FROM FLEMSØY, WESTERN GNEISS PROVINCE, NORWAY

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The Sandvikhaugane olivine-gabbro on the island of Flemsøy (Nordøyane Islands, Norway) shows well developed transitions from gabbro to eclogite recording metamorphic conditions of 1.5 - 2 GPa and 750 ± 60 °C (MØRK, 1985). MØRK divided the eclogitisation process into three stages based on petrographic evidence: an initial corona gabbro stage (I) is followed by a transitional coronitic eclogite stage (II) and an eclogite stage (III) in which the gabbro is completely transformed into eclogite. In this study, trace element concentrations of relict igneous as well as newly formed minerals were measured in situ by laser ablation ICP-MS (using an Agilent 7500ce equipped with New Wave UP213) to record the changes in trace element budgets and partitioning throughout the process of eclogitisation. Relict igneous minerals (cpx and fsp) preserved in stage I still show essentially unchanged REE element patterns despite petrographic signs of decomposition. Garnets newly formed at the expense of feldspar, on the other hand, have trace element concentrations and REE patterns far off their experimentally determined equilibrium trace element patterns (Fig. 1). Sc concentrations of newly formed garnets are close to those of the precursor feldspar (5 ppm), but increase throughout stage I and II towards concentrations that are closer to equilibrium partitioning values for garnets.

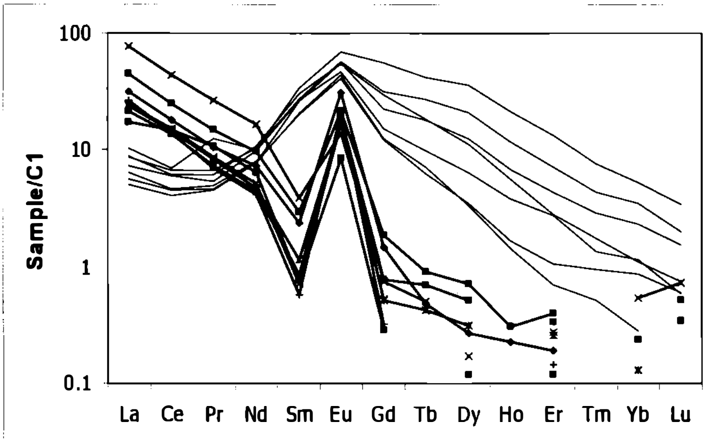

Fig. 1. REE element patterns of relict feldspar and newly formed garnet pairs in stage I and II gabbro-eclogite. Garnet inherits the typically depleted heavy rare earth (HREE) signature from its precursor and only gradually approaches more typically HREE enrichment with increasing degree of eclogitisation.

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ISOCHRON DATING OF LOW-TEMPERATURE HP/UHP ECLOGITES: ISOTOPE DISEQUILIBRIUM AND EFFECTS OF REE-RICH INCLUSIONS

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The Hong'an Block and Tongbaishan in central China underwent HP/UHP metamorphism at temperatures (700 to 500 °C) lower by 50 to 150 °C than that of the Dabie and Sulu terranes. We analyzed trace element and Sr - Nd - O isotopic compositions on minerals in order to gain better insight into the controversial geochronology in these regions.
The results: (1) Trace element distribution patterns suggest that garnet and omphacite in many cases are out of chemical equilibrium; and the presence of high-temperature LREE-rich mineral inclusions (e.g. epidote) in garnet and omphacite has contributed to isotope disequilibrium. (2) Sm - Nd isotope analyses yielded no isochron ages for the Hong'an and Tongbaishan eclogites. (3) Rb Sr isotope analyses gave mixed results; in some cases, coexisting minerals are completely out of isotope equilibrium, and in others, isochron relationship is established, yielding ages from 210 to 225 Ma for Hong'an and 183 to 253 Ma for Tongbaishan. The pattern of Rb - Sr isotope disequilibrium appears to be independent of the petrological and O-isotope temperatures. (4) In contrast to the unequilibrated Sm - Nd isotopic systems, oxygen isotopes of the Hong'an eclogite minerals seem to have attained isotope equilibrium or near-equilibrium. Oxygen isotope temperatures are comparable with petrological temperatures. However, this is an apparent feature due to mass balance constraints. (5) Whole-rock $\delta^{18}O$ values show a large variation from +10 ‰ to -8 ‰, suggesting that their protoliths have undergone very different processes of water-rock interaction. In view of the overall geochronological information, we conclude that the HP/UHP metamorphism in the Hong'an Block took place in the Triassic at about 220 - 230 Ma, as observed in the Dabie and Sulu terranes. The significance of published Paleozoic dates (450 to 300 Ma) for the Xiongdian eclogite is not clear. However, any hypotheses advocating two periods of UHP metamorphic events for the same tectonic unit or in the same locality are not constrained by the geochronological data.

ECLOGITE FACIES RELICS IN THE METABASITES OF THE WESTERN CARPATHIANS

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High-pressure, true eclogite facies rocks have previously been unknown in the Western Carpathians. However, microtextures indicating former eclogite facies stage (symplectites, kelyphites and coronas due to a breakdown of primary omphacite) have been observed in the amphibolite facies metabasites. The recent finding of omphacite (JANÁK et al., 2003) has definitely confirmed the existence of eclogite facies metamorphism in the Western Carpathians.

These rocks occur in the eastern part of the Nízke Tatry Mountains, in the Koleso valley, ca. 8 - 9 km northwards of Hel'pa. Relicts of eclogites form lenses and boudins in amphibolites and metagabbros. Other country rocks of eclogites are kyanite–bearing gneisses yielding an Ordovician (~ 470 Ma) age of the protolith, and Variscan (~ 340 Ma) age of recrystallization. All these rocks belong to the pre-Mesozoic basement complexes of the Veporic unit in the Central Western Carpathians.

High-pressure, eclogite facies assemblage in the metabasites is omphacite + garnet + phengite + rutile + quartz + zoisite ± amphibole. Omphacite occurs as inclusions in garnet, attaining the size of less than 10 µm. Omphacite composition depends on bulk rock chemistry. In Fe-rich samples omphacite contains up to 40 mole% of jadeite. Garnet is poikiloblastic with inclusions of quartz, zoisite, clinopyroxene, amphibole and rutile as primary assemblage of the eclogite facies. Phengite contains up to 3.4 Si p.f.u. Secondary phases occur in the coronas, symplectites and fractures. The most typical is clinopyroxene (diopside) with 10 - 20 % of jadeite content, forming the symplectites with plagioclase and amphibole after primary clinopyroxene (omphacite). Biotite, often as symplectite with plagioclase, occurs after primary phengite. These minerals formed at lower pressure, due to retrogression under amphibolite facies conditions. Results obtained from geothermometry and geobarometry on eclogite facies assemblage (garnet + omphacite + phengite) suggest a pressure of 2.3 - 2.7 GPa at temperatures ranging from 650 - 730 °C, well within the stability field of eclogite facies.

Eclogite facies metamorphism in the Western Carpathians is deduced to be Variscan, resulting from northwards migration and initial collision of continental blocks drifted from the northern margin of Gondwana with Laurussia. Eclogites in the Western Carpathians may therefore trace remnants of Variscan subduction zone in the lateral prolongation of the Intra-Alpine basement areas of the Alps (mainly Austroalpine units), further east of the Bohemian Massif and other Armorican terranes.

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ULTRAHIGH-PRESSURE METAMORPHISM OF GARNET PERIDOTITES FROM POHORJE MTS. (EASTERN ALPS, SLOVENIA)

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New evidence for ultrahigh-pressure metamorphism (UHPM) in the Eastern Alps is reported from garnet peridotites of Pohorje Mts. in Slovenia. In this area, an eo-Alpine UHPM has been recently documented in the eclogites (JANÁK et al., 2004). These eclogites are closely associated with meta-ultrabasites - predominantly serpentinised dunite and harzburgite with garnet peridotite remnants. The country rocks of eclogites and metaultrabasites are amphibolites, orthogneisses, paragneisses and micaschists. All these rocks belong to the Lower Central Austroalpine basement unit of the Eastern Alps, exposed in the proximity of the Periadriatic fault.

Ultramafic rocks have experienced a complex metamorphic history. At least four stages of recrystallization have been identified in the garnet peridotite based on an analysis of reaction textures and mineral compositions.

Stage I is a high-temperature protolith assemblage of olivine + orthopyroxene + clinopyroxene + Cr-spinel. Aluminous pyroxenes occur as inclusions in garnet, chromian spinel is preserved in the matrix.

Stage II – an ultrahigh-pressure stage is defined by matrix assemblage garnet + olivine + orthopyroxene + clino-pyroxene + Cr-spinel. Garnet contains up to 67 mole% of pyrope, olivine has 90 mole% of forsterite, orthopyroxene is low in Al_2O_3 (~0.8 wt%) and spinel has a Cr* ~50.

Stage III – a decompression stage is manifested by formation of kelyphitic rims of high-Al orthopyroxene, aluminous spinel and pargasitic hornblende replacing garnet. Due to retrogression, garnet shows a decrease in MgO.

Stage IV – is represented by formation of tremolitic amphibole, chlorite, serpentine and talc.

P-T estimates based on geothermobarometric calculations of a) Fe-Mg exchange between garnet, olivine and orthopyroxene thermometers, b) the Al-in-orthopyroxene barometer indicate that the peak of metamorphism (stage II) occurred at ~820 - 900 °C and 3 - 3.5 GPa. This is consistent with previous estimation of very high *P-T* conditions in meta-ultrabasites by HINTERLECHNER-RAVNIK et al. (1991) and the associated eclogites (JANÁK et al., 2004). These results suggest that the mantle fragment (garnet peridotite) and the crustal fragment (eclogite) in the Pohorje Mts. both experienced a common UHPM during the Cretaceous orogeny. We propose that UHPM resulted from deep subduction of a continental slab which incorporated peridotites from an overlying mantle wedge.

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THE METAMORPHIC EVOLUTION OF VARISCAN ECLOGITES FROM THE NORTHERN ÖTZTAL COMPLEX (TIROL, EASTERN ALPS)

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Within the polymetamorphic Austroalpine Ötztal Complex (ÖC), Variscan eclogites have been described mainly from the central part (MILLER & THÖNI, 1995) but also from the northern (EICHHORN, 1991) and western part (BERNHARD, 1994) of the ÖC. *P-T* data are very sparse and exist only from the eclogites from the central ÖC. The eclogites from the northern part of the ÖC occur as small lenses within amphibolites. The metamorphic peak assemblage is garnet + omphacite ± taramite ± katophorite ± hastingsite + clinozoisite + rutile + quartz. During the retrograde evolution of these rocks, the formation of abundant symplectites, composed of albite-rich plagioclase + tschermakite + diopside-rich clinopyroxene, occurred. The mineral assemblage in the adjacent amphibolites is hornblende + plagioclase + epidote + quartz ± barroisite.
Thermobarometry of the northern ÖC eclogites was performed by simultaneous calculation of all possible reactions within the peak metamorphic assemblage garnet + omphacite + clinozoisite + barroisite + quartz with the program THERMOCALC v. 3.1. (HOLLAND, 2001, written comm.) and the data set of HOLLAND & POWELL (1998). The approach we used is the average *P-T* calculation approach by POWELL & HOLLAND (1988, 1994). Calculations assuming $a(H_2O)$ = 1, yields *P-T* conditions of 620 – 650 °C and 1.7 - 2.3 GPa. It was not possible to obtain any additional information about $a(H_2O)$, since an independent *T*-estimate, to calculate P-$a(H_2O)$ diagrams, could not be obtained. Calculations of garnet-clinopyroxene temperatures with the calibration of KROGH-RAVNA (2000), yields a wide range of temperatures of 370 – 650 °C, depending on the calculation of Fe^{3+} and thus was not considered reliable.
The *P-T* conditions of symplectite formation were calculated to be ca. 650 °C and 1.0 - 1.3 GPa. This is in very good agreement with data from barroisite-bearing high-*P* amphibolites which yielded *P-T* conditions of 640 °C and 1.1 GPa. The adjacent amphibolites record information about the last stage of the Variscan *P-T* evolution, namely an amphibolite-facies overprint of 570 – 650 °C and 0.6 - 0.8 GPa. These data indicate that these eclogites underwent a nearly isothermal decompression at 600 – 650 °C from ca. 1.7 - 2.3 GPa to 1.1 and 0.7 GPa during the Variscan metamorphic event in the ÖC.

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LATE ARCHAEAN ECLOGITES OF THE KOLA PENINSULA (NE BALTIC SHIELD): U-Pb AND Sm-Nd DATA

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Eclogites, which supposed to be Archaean were documented in two places of the Belomorian Mobile Belt: the Gridino area (northern Karelia) (VOLODICHEV et al., 2004) and the Salma area (Kola Peninsula) (KONILOV et al., 2004). The NORDSIM U-Pb zircon dating of Gridino eclogites yielded an age of 2720 ± 8 Ma (VOLODICHEV et al., 2004). Salma eclogite rock assemblage (eclogite, eclogite residue and adakite) was dated by U-Pb and Sm-Nd methods. Petrologic description of the rocks is given in (KONILOV et al., 2005, this volume). U-Pb dating of metamorphic isometric zircons (common for high-pressure rocks) yielded an age of 2695 ± 26 Ma which coincides within error limits with the age of Gridino eclogites This age is interpreted to date zircon growth at slab dehydration during deep subduction. Zircons from eclogite-residue are of different type – short prismatic grains with inclusions and high Th / U ratio (1 1.5), which is typical for zircons from mafic rock. These zircons were probably formed during slab melting Their U-Pb age is 2684 ± 80 Ma. Large error is caused by tendency of points to scatter inside the triangular between 2.7 - 1.8 - 0 Ga. Such picture reflects two episodes of radiogenic lead loss: during Svecofennian and modern time; this interpretation implies that the obtained age corresponds to the minimal age of eclogites. Zircons from adakite vein contain cores and could not be dated by conventional U-Pb method. Age determinations for them were carried out using LA-ICPMS (Australia). U-Pb ages of 2875 ± 11 (cores) Ma and 2755 ± 11 Ma (rims) were interpreted as magmatic age of adakite vein and a metamorphic event, respectively (BELOUSOVA et al., 2004). The large difference in age of adakite and eclogite most likely suggest that zircon cores could be assimilated from already existed tonalite crust. Rutile ages of 1.79 - 1.80 Ga – the same as for rutiles throughout the Belomorian Belt (BIBIKOVA et al., 2001) – correspond to the time of rock cooling below T of 450 °C, the closure temperature for U-Pb rutile system. The preliminary Sm-Nd data for garnet and whole rock yielded ages of 1.86 - 1.96 Ga. The most meaningful ages were obtained for samples from eclogite residue and garnetite, where whole rock consists mainly of garnet. These ages reflect re-equilibration of Sm-Nd system during Svecofennian metamorphism. Planned U-Pb dating of garnet and SHRIMP dating of zoned zircons will provide more detailed information on timing of metamorphic and cooling history. Nevertheless, the obtained data obviously show the Archaean time of the eclogite formation, confirming manifestation of deep subduction in the Late Archaean.

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MATERIAL TRANSPORT PHENOMENA RELATED TO GARNET REACTION BANDS FORMED IN METAPELITES AT ECLOGITE FACIES CONDITIONS

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Metapelites from the Monte Rosa nappe (Western Alps) underwent a polymetamorphic history with a high-T / medium-P metamorphism during pre-Alpine stages. During the Alpine metamorphic cycle the rocks experienced a high-pressure overprint, which, among others, led to the formation of garnet reaction rims along former plagioclase-biotite grain contacts. The garnet forming reaction plagioclase (Pl) + biotite (Bt) = garnet (Grt) + phengite (Phe) + quartz (Qtz) took place at about 650 °C and 12.5 kbars.

The Grt rims (10-50 μm) show an asymmetric zoning pattern. Ca concentrations are relatively high towards Pl, but have their maximum within the Grt rim. Towards Bt Ca concentrations are generally low, but near the Grt / Bt interface a small increase in Ca concentrations is observed. Approaching the Gt / Bt interphase boundary Ca again decreases. Fe concentrations behave complementary to the Ca concentrations.

Pl is depleted in Ca towards Grt, indicating that Ca for Grt growth, was derived from incongruent dissolution of Pl, which preferentially extracted the anorthite component. Qtz is formed as a discontinuous rim (< 10 μm) of grains along the Grt / Pl reaction interface. Phe is predominantly formed within the preexisting Pl.

The formation of the reaction rims requires diffusive material transfer across the Grt rim or along interphase boundaries. The high Ca concentrations near the Grt / Bt interface give evidence of rapid transport along grain- or interphase- boundaries. Potential diffusion pathways through the Grt rim are detected by electron backscatter diffraction. Grt rims are composed of (sub)grains separated predominately by low angle boundaries (< 15 °). The grain boundaries within the garnet rim probably allowed for short circuit diffusion between the Gt / Pl and the Gt / Bt reaction interfaces. High-resolution transmission microscopy reveals the internal structure of Grt grain boundaries. These grain boundaries often contain islands of < 5 nm width, where the lattice of the neighboring grains fits badly. The islands contain an amorphous material, the phase nature of which at the presumed P-T conditions of Grt formation is not known, but which may have served as a medium for fast mass transport. Electron energy-loss spectroscopy shows that Ca and Fe segregate to the Grt grain boundaries and Ca is depleted near the grain boundary These observations in combination with the Grt zoning profile demonstrate that material transport indeed occurred via grain boundaries through the Grt rim.

Bright and dark field TEM images of the Ca depleted part of Pl reveal up to 100 nm wide channels filled with amorphous material forming potential diffusion pathways. Newly formed Phe is often spatially associated with such channels.

PROTOLITHS OF ECLOGITES FROM NORTHERN QAIDAM BASIN, CHINA: IMPLICATIONS ON TECTONIC EVOLUTIONS

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The occurrence of high-pressure eclogites in the northern border of Qaidam basin in central China indicates the existence of a 350 km orogenic belt. The protoliths of these eclogites provide constraints for reconstructing the tectonic evolution history in this region. In this study, we analyzed thirty-seven eclogites sampled from the eastern, central and western parts of this orogenic belt for their major and trace element abundances as well as Nd isotopic ratios to investigate the nature of their protoliths.

In the AFM plot, the variation trend of these eclogites resembles that of tholeiites. Based on the U-Pb dating on zircons, the metamorphic age of these eclogites is inferred to be ~ 450 Ma. After age corrections, the $\varepsilon Nd_{(450)}$ values of the studied eclogites can be divided into two groups; greater than 9 for Group I and 2.9 ~ 4.3 for Group II. Group I samples occur at all sampling localities but are most abundant at the eastern portion of the studied orogenic belt. They have high HREE/LREE ratios resembling that of normal mid-ocean ridge basalts (N-MORB). However, their ε $Nd_{(450)}$ values (9 ~ 15) are higher than that of N-MORB (7 ~ 9) possibly reflecting post-metamorphic metasomatism which decreased their Sm/Nd ratios. In contrast, Group II samples have HREE/LREE ratios lower than that of N-MORB, and can be further divided into two subgroups; IIa and IIb, characterized by the absence and presence of HFSE depletions, respectively. The geochemical characteristics of the former are similar to those of the enriched MORB (E-MORB) whereas those of the latter are of typical arc lavas. The IIa samples mainly collected from the central part while the IIb samples were only discovered at the eastern edge of northern Qaidam Basin.

The occurrence of arc-related protoliths only at the eastern edge of northern Qaidam eclogites possibly indicates two subduction events. These arc protoliths might result from the collision between the paleo-Qilian ocean on the north of Qaidam block and eastern Yangtz block. The subsequent subduction of the paleo-Qilian ocean and the associated eastern arcs completely consumed this ocean-arc system leading to the formation of north Qaidam eclogites. Alternatively, the relative proportions of oceanic and arc protoliths might reflect the size of the consumed ocean with high proportions of arc-related protoliths indicating subduction of a small size ocean. In such case, the opening of paleo-Qilian might propagate from west to east. Distinguishing these two models requires analyzing more eclogites and amphibolites from this region.

P-T-t-D EVOLUTION OF HIGH-PRESSURE BARROVIAN-TYPE METAPELITES IN THE IMJINGANG BELT, KOREA

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The east-trending Imjingang belt, a candidate for eastward extension of the Dabie-Sulu UHP belt, consists of Barrovian-type metapelites, ranging from garnet through staurolite to kyanite zones, and the structurally lower calc-silicate rocks. The Imjingang belt records three major episodes of deformation: (1) initial contractional deformation (D_{n-1}); (2) penetrative deformation (D_n) producing major foliation; and (3) extensional ductile shearing. Mineral parageneses and reactions producing porphyroblastic and accessory minerals in the metapelites were investigated for delineating quantitatively the collision process. Metapelites experienced a clockwise P-T evolution characterized by: (1) prograde garnet formation associated with crustal thickening; and (2) staurolite growth during decompression. Both biotite and garnet have grown at two different stages. Biotite poikiloblasts started to form between D_{n-1} and D_n, but inclusion-free margins grew during D_n. Initial growth of poikiloblastic garnet was post-D_{n-1}, and took place predominantly during D_n. The inclusion-poor garnet overgrowth at the expense of biotite was post-D_n. Progressive rimward change of inclusion minerals within garnet, from ilmenite to rutile, is attributed to the burial of pelites. Inclusion mineral assemblages and compositions of staurolite suggest that two different reactions were responsible for the staurolite growth during a decompressional stage; staurolite in the staurolite zone was produced by the well-known reaction, Grt + Chl + Ms = St + Bt + Qtz + H_2O, whereas large staurolite (up to 6 cm) in the kyanite zone was formed by the hydration reaction, Grt + Ky ± Ms + H_2O = St ± Bt + Qtz. Kyanite, one of the reactant phases of the hydration reaction, was produced at the expense of garnet and chlorite prior to the formation of staurolite. Absence of epidote-group minerals in the matrix together with their common presence within kyanite suggests that fluids necessary for the growth of staurolite were probably derived from the breakdown reactions of (clino)zoisite and / or mica. This fluid generation may also account for the presence of monazite and xenotime, occurring exclusively in the kyanite zone and replacing allanite-(clino)zoisite aggregates. The paragenetic reversal between staurolite and kyanite compared to typical Barrovian-type suggests that the prograde P-T segment reaches a maximum pressure of greater than 11 kbar on the basis of petrogenetic grids using the KFMASH model system. In contrast, occurrences of rare sillimanite and minor andalusite suggest that exhumation switched from an isothermal decompression to isobaric cooling path at ca. 6 kbar and 600 - 650 °C.

DEHYDRATION DURING HP-METAMORPHISM: IMPLICATIONS FOR OCEANIC SLAB - MANTLE WEDGE TRANSFER

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Aqueous fluids which were released by the dehydration of subducted lithospheric mantle and / or oceanic crust are supposed to act as element carriers from the slab to the overlying mantle wedge They are widely believed to be responsible for trace element signatures of island arc magmas. This theoretical consideration concerning the dehydration of the oceanic crust is supported by recent findings in the Tianshan HP-belt (NW-China). Large eclogite-facies vein-networks in the Tianshan blueschist were found to be the product of hydrofracturing induced by fluids released by the breakdown of glaucophane, paragonite and epidote during blue-schist-eclogite transition and, thus represent former fluid pathways within a Paleozoic sub-duction zone. The veins are predominantly composed of omphacite fibers with minor quartz and calcite. The transition from blueschist- to eclogite-facies parageneses occurs as "dehydration" halos around these veins. The fluids are interpreted to have been derived from the host blueschist as a result of dehydration reactions such as 13 Gln + 5 Czo = 9 Prp + 26 Jd + 12 Di + 19 Qtz + 15 H_2O and Gln + Pg = Prp + 3 Jd + 2 Otz + 2 H_2O at peak metamorphic conditions of 480 - 600 °C and 18 - 21 kbar. Both dehydration reactions have steep, negative P-T slopes, which corresponds with the release of large amounts of H_2O and a volume reduction. However, the vein-network consists of these dehydration veins and veins which cross the blueschist host foliation and display sharp interfaces towards the blueschist host. The latter ones show no evidence of dehydration reactions in the immediate blueschist host. These veins may represent high-pressure transport veins, which acted as channelways of fluid escape. The here presented geochemical results focus on such a transport-vein, its blueschist host and an eclogitised reaction zone (blueschist alteration zone), which is located in the central part of the vein. Textural evidence and the almost twice as high Li-concentration of the vein and the blueschist alteration zone in comparison to the blueschist host indicate the external origin of the vein forming fluid. This fluid triggered eclogitisation of the blueschist alteration zone. The low in trace element fluid caused a strong leaching of LILE, REE, and HFSE in those parts of the host rock with which the passing fluid reacted. The main difference between the blueschist host and the blueschist alteration zone is the replacement of glaucophane, dolomite and titanite by omphacite and rutile respectively. Therefore we regard the fluid-flow regime as the main control of the trace element mobility.

AMPHIBOLE ZONATION AS A FUNCTION OF *P-T-X*CO_2-*f*O_2 IN BLUESCHISTS FROM THE AUSTROALPINE RECKNER NAPPE (EASTERN ALPS, AUSTRIA)

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Within the Austroalpine Reckner Nappe, blueschists with the mineral assemblage aegirine-rich clinopyroxene + riebeckite + muscovite + chlorite + albite + hematite ± biotite ± stilpnomelane ± calcite ± dolomite occur. This assemblage formed in carbonates as well as cherts at the contact to serpentinites and is thought to have formed during a Tertiary high-*P*/low-*T* metamorphic event with *P-T* conditions of ca. 350 °C and 1.0 GPa (DINGELDEY et al., 1997).

The amphiboles and clinopyroxenes show complex chemical zoning. Amphiboles show a zonation from riebeckite in the core to winchite or actinolite in the rims. Clinopyroxenes show a very irregular chemical zoning, are mostly aegirine-rich, but also show diopside- or jadeite-rich areas and contain abundant hematite inclusions in the core. Amphibole zoning can be explained by a combination of the following chemical vectors:

Riebeckit + Glaukophan => Arfvedsonit + Eckermannit $\square^{A}_{-1}(Al,Fe^{3+})^{M2}_{-1}Na^{A}(Mg,Fe)^{M13}$ Riebeckit + Glaukophan => Winchite => Tremolit + Actinolith $Na^{M4}_{-1}(Al,Fe^{3+})^{M2}_{-1}Ca^{M4}(Mg,Fe)^{M13}$, Arfvedsonit + Eckermannit => Tremolit + Actinolith $Na^{A}_{-1}Na^{M4}_{-2}(Al,Fe^{3+})^{M2}_{-1}\square^{A}Ca_2^{M4}(Mg,Fe)^{M13}$ In order to put quantitative constraints on the formation of the amphibole zonation, we evaluated three mineral equilibria in the system NCFMASHOC among the mineral assemblage amphibole$_{ss}$ + clinopyroxene$_{ss}$ + chlorite + calcite + dolomite + hematite + albite + quartz in *P-T-X*CO_2-*f*O_2 space. Textural observations indicate that the riebeckite-rich cores formed by a reaction involving the breakdown of the assemblage aegirine + hematite according to the following model reaction (1): 8 Aegirine + 24 Diopside + 6 Hematite+ 16 Jadeite +24 CO_2 + 12 H_2O -> 24 Calcite + 8 Glaucophane + 4 Riebeckite + 3 O_2. The reactions which lead to the formation of the amphibole zonation towards Ca-rich amphibole compositions are thought to be: 30 Dolomite + 2 Chlorite + 70 Quartz + 2 Riebeckite -> 4 Albite + 2 Actinolite + 8 Tremolite + 10 Calcite + 50 CO_2 + 1 O_2 (2) and 20 Aegirine + 130 Dolomite + 10 Chlorite + 310 Quartz -> 20 Albite + 4 Actinolite + 36 Tremolite + 50 Calcite + 210 CO_2 + 5 O_2 (3). The initial formation of amphiboles by reaction (1) requires in a *P-T* diagram either decreasing *P* or increasing *T*, in *T-X*CO_2 either decreasing *T* or increasing *X*CO_2 and in *T-logf*O_2 increasing T and decreasing *f*O_2. Reactions (2) and (3) require in *P-T* either decreasing *P* or increasing *T*, in *T-X*CO_2 either decreasing *T* or decreasing *X*CO_2 and in *T-logf*O_2 increasing *T* and decreasing *f*O_2.

These reactions indicate that *X*CO_2 and *f*O_2 play an important role, since amphibole formation requires increasing *X*CO_2 and the formation of Ca-rich amphiboles requires a decrease in *X*CO_2. In addition, all reactions require a decrease in *f*O_2 during the evolution of these rocks.

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ARCHAEAN ECLOGITES FROM THE CENTRAL PART OF THE BELOMORIAN MOBILE BELT, KOLA PENINSULA, RUSSIA

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Until recently the most ancient crustal eclogites of 2 Ga old were reported from the Usagaran Belt, Tanzania (MÖLLER et al., 1995). However, last year VOLODICHEV et al. (2004) reported the first finding of Archaean eclogite with U-Pb zircon ages of 2.72 Ga, occurring along with the tectonic mélange zone in the western shore of White Sea. Here we present for the first time some preliminary data on the other kind of eclogites discovered in the central part of the Belomorian Belt. This type of eclogites is largely emplaced amongst the Belomorian grey gneisses of TTG affinity We refer to it here as the Salma eclogite, which macroscopically appears as a massive mafic rock containing visible pink garnet porphyroblasts with obvious plagioclase-rich reaction coronas and both light green clinopyroxene-plagioclase and black hornblende-plagioclase as matrix phases. In thin section, the most common mineral assemblage within the Salma eclogite is garnet + diopsidic clino-pyroxene + plagioclase + hornblende ± kyanite ± quartz. Clinopyroxene is characterized by a vermicular symplectite of albite-rich plagioclase, known from many eclogites. In a few cases amongst the symplectite colonies we have found relicts of omphacite containing 32 mole% jadeite (~4.0 wt% Na_2O). Corona textures around garnet and between garnet and quartz are retrograde, with secondary low-Na clinopyroxene and plagioclase supporting thus to the decompression origin of the Salma retrogressed eclogite. Peak metamorphic conditions found in the Salma eclogite reached about 700 °C and 14 - 15 kbar. The thermobarometric study on the retrograde P-T evolution yields lower pressures of only 10 to 11 kbar, but the same temperature (GCPQ geothermobarometer). This implies that the uplift of the Salma eclogite bodies was caused by near-isothermal conditions. Zircons from the retrogressed eclogite show discordant U-Pb ages of ~2.7 Ga obtained by conventional technique (KAULINA, this volume).

Of particular interest is the occurrence of frozen partial TTG melts within the Salma eclogite bodies. These are turned into the Grt – Ky ± Crd gneisses which were formed under 690 °C (Bt-Grt geothermometer) and 9.7 kbar (GPKQ geobarometer). Their subsequent metamorphic evolution is recorded by forming of cordierite collars around garnet grains that took place under 530 - 600 °C (Bt-Grt and Crd-Grt geothermometers) and 6.0 - 6.8 kbar (GPKQ geobarometer). Zircons from the frozen partial melt have been dated by LAS ICP-MS technique in the ARC GEMOC, Sidney, Australia and have yielded two age populations, 2875 ± 11 Ma and 2755 ± 10 Ma (BELOUSOVA et al., 2004). Thus, the Salma eclogites appear to be the oldest now known crustal eclogites worldwide.

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THE Ca-ESKOLA COMPONENT OF ECLOGITIC CPX AS A FUNCTION OF P-T AND BULK COMPOSITION: AN EXPERIMENTAL STUDY TO 12 GPa

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In recent years an increasing number of high-P metamorphic localities has been described where Cpx contains oriented needles/rods of quartz/coesite with or without Cam (ZHANG et al., 2005 and references therein). These inclusions are often taken as UHP-indicators and are ascribed to the presence in solid solution of a Cpx $Ca_{0.5}\square_{0.5}AlSi_2O_6$ (Ca-Eskola pyroxene CaEsk) under high P that decomposes through a reaction 2 $Ca_{0.5}\square_{0.5}AlSi_2O_6 \rightarrow CaAl_2SiO_6$ + 3 SiO_2 during exhumation. To study the conditions under which Cpx incorporates $CaEsk_{ss}$, we performed experiments in the P-T range 6 - 12 GPa and 950 – 1500 °C using bulk composition 95-1C of TSAI & LIOU (2000) that contains Cpx with oriented quartz-rods. Cpx analyses were normalized to 6 ox. and Fe_{tot} = FeO which yields a minimum amount of $CaEsk_{ss}$. From 6 12 GPa, Cpx in the assemblage Grt + SiO_2 ± Rt does not show any significant deviation from 4.00 cations / 6 oxygens. This is thought to be due to the absence of a suitable Al-buffer phase that allows the formation of $CaEsk_{ss}$ through a reaction such as $Ca_3Al_2Si_3O_{12}$ + 2 Al_2SiO_5 + 7 SiO_2 = 6 $Ca_{0.5}\square_{0.5}AlSi_2O_6$. To test this hypothesis, two additional bulks were used representing 95-1C + 10 and 25 wt% Ky added. At 6 GPa / 950 °C, Cpx in 95-1C + 25 % Ky coexists with Grt + Ky + Coe + Rt and shows a significant non-stoichiometry with 3.950 ± 0.007 (n = 10) cat / 6 ox, corresponding to 10 mol% $CaEsk_{ss}$. 95-1C + 10 % Ky does not form Ky at 6 GPa / 950 °C and produces Cpx + Grt + Coe + Rt that only shows a slight deviation from ideal stoichiometry with 3.987 ± 0.006 (n = 10) cat / 6 ox corresponding to 3 mol% $CaEsk_{ss}$. At 6 GPa / 1200 °C, $CaEsk_{ss}$ increases to 14 and 11 mol% and at 7 GPa / 950 °C, Cpx in 95-1C + 25 % Ky and 95-1C + 10 % Ky has 9 and 5 mol% $CaEsk_{ss}$ respect-tively. Providing that breakdown of $CaEsk_{ss}$ is responsible for oriented SiO_2-inclusions in Cpx, then this study indicates that (1) an Al-buffer phase such as Ky or Phe is required to generate significant $CaEsk_{ss}$ in Cpx of metabasic eclogites and, hence, (2) that eclogites with oriented SiO_2-inclusions in Cpx did contain Ky or Phe at least during a part of their prograde P-T history.

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CALEDONIAN KYANITE-ZOISITE ECLOGITES OF THE SERBO-MACEDONIAN UNIT: PHASE RELATIONS, REACTION TEXTURES OF EXHUMATION STAGE AND U-Pb ZIRCON AGE

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Eclogites were found in the eastern part of the Serbo-Macedonian unit as lenses of 50 x 30 m among Bt-Ms gneisses. The primary assemblage corresponding to the metamorphic peak was omphacite (50-64 % *Jd*) + progradely zoned garnet + zoisite + kyanite + hornblende + muscovite + quartz + rutile. These minerals are in equilibrium but are often surrounded by various rims that developed during later decompression. During the <u>initial stage</u> of decompression, ***Omp*** was overgrown by $Na\text{-}Aug^2$ - *Ab(Olg)* ± Hbl^2 symplectites, which are always surrounded by an outer monomineralic $Na\text{-}Aug^2$-rim at contacts with *Qtz* $(Omp^1 \rightarrow Na\text{-}Aug + Olg \rightarrow Na\text{-}Aug^2 \rightarrow Qtz)$. ***Grt*** grains acquire retrograde rims and are armored by either $Hbl^2{}_{Al\text{-}rich}$ or bi-mineral Hbl^2 - *Pl* rims at contacts with *Omp*. The <u>next</u> decompression <u>stage</u> was responsible for formation of *Chl*-bearing rims around Grt $(Grt \rightarrow Labr\text{-}Btw \rightarrow Chl \pm Hbl^3)$ or Hbl^3 - Ep^2 ± *Chl* kelyphite. Garnet grains are corroded by *Pl* (*An* 30-50) - Hbl^3 - *Chl* veinlets. *Ky* prisms are surrounded by concentric margarite-zoisite-oligoclase-hornblende kelyphite in the succession $Ky \rightarrow Mrg \rightarrow Zs^2 \rightarrow Pl \rightarrow Hbl^3 \rightarrow Omp^1$ These textures mean decomposition of omphacite in assemblages with Ky and Grt, and a diminish in stability of Grt: Omp1 + Qtz→ $Na\text{-}Aug^2 + Pl$, $Omp^1 + Ky + H_2O \rightarrow Mrg + Zs^2 \quad Pl + Hbl^3 + H_2O$, $Omp^1 + Grt + H_2O \rightarrow Hbl^2{}_{Al\text{-}rich} \quad Pl$ (20 - 50 % *An*) and $Omp^1 \quad Grt + H_2O \rightarrow Hbl^3 + Ep^2 + Chl + Pl$. Thus, the *Omp-Grt-Zs-Hbl-Ky-Ms-Qtz* eclogites recrystallized during exhumation and were replaced first by symplectitic eclogites (an early exhumation stage) and then by *Hbl-Grt-Chl-Ep-Mrg-Ms-Pl* (20 - 40 % *An*)-*Qtz* amphibolites (final decompression stage). The maximum eclogite temperatures (*Grt-Omp* thermometry) is 530 - 570 °C (KROGH RAVNA, 2000), the minimum pressure (*Jd* isopleths in *Cpx* - HOLLAND, 1980) 15 kbar. Temperature of the development of *Cpx-Hbl-Pl* symplectites after omphacite and *Hbl-Pl* kelyphite between *Grt* and *Omp* was determined using the Grt_{retrog} - Hbl_{nm} pair (PERCHUK, 1989) to be 580 - 620 °C at P = 7 10 kbar (*Grt-Hbl-Pl-Qtz* barometer, KOHN & SPEAR, 1990). Thus, initial prograde decompression changes into retrograde one (*Chl*-, *Ep*- and Hbl^3-bearing rims – 540 - 580 °C according to Grt_{retrog} - Hbl^3 thermometry). Zircons from eclogites have been studied by U-Pb method. They are concordant and the mean ^{206}Pb / ^{238}U age of 455 ± 6 Ma is interpreted as the time of eclogite metamorphism.

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GROWTH RATE OF ACCESSORY AND ROCK-FORMING MINERALS IN UHPM ROCKS FROM THE KOKCHETAV MASSIF (NORTHERN KAZAKHSTAN)

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A new approach for estimating the growth rate of coexisting minerals is developed with data from the UHPM Kokchetav massif, where garnet and zircon are amongst the most common coexisting minerals. Both minerals grew within a wide range of P-T conditions in UHPM rocks (SOBOLEV et al., 1994; SHATSKY et al., 1995; KORSAKOV et al., 1998). Garnet porphyroblasts from the zoisite gneisses are characterized by a homogeneous core and a sharply marked rim zone, with CaO abruptly decreasing from 16 wt% core to 12 wt% rim. In addition to diamond/graphite and coesite/quartz also garnet commonly occurs as inclusions in zircon. Frequently such garnet inclusions occur in different growth zones of one single zircon crystal. In some cases garnet inclusions display marked compositional differences: garnet inclusions, close to the zircon core, are as Ca-rich as the core zones of garnet porphyro-blasts and garnets included in the rim of the zircon have similar composition as rim zones of the garnet porphyroblasts.

Since zircon is known as the best refractory "container" (SOBOLEV et al., 1994), the composition of its inclusions remains undisturbed from the moment of their entrapment. The garnet inclusions in zircon can be considered as isolated fragments from succeeding growth zones (core and rim) of garnet porphyroblasts. The distance between both garnet inclusions within the single zircon grain is 30 μm, while in porphyroblast the distance between similar composition points varies from 60 to 100 μm. The relative growth rates for zircon (G_{Zrn}) and garnet (G_{Grt}) can be estimated as high as $G_{Zrn} / G_{Grt} = 0.3 - 0.5$. Absolute values of growth rates can be obtained by SHRIMP dating of zircons including these garnets. Unfortunately Precambrian rocks from the Kokchetav massif are not suitable for this purpose, because the age intervals for the different zircon growth domains are within the analytical error of SHRIMP analyses (HERMANN et al., 2001). However for "young" UHPM complexes this approach could be a powerful tool for the estimation of mineral growth rates.

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THE ROLE OF PARTIAL MELTING IN GENESIS OF DIAMONDIFEROUS KYANITE-BEARING ASSEMBLAGES FROM THE KOKCHETAV MASSIF (NORTHERN KAZAKHSTAN)

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Recently a new microdiamonds area was discovered within the Kokchetav massif (SHATSKY et al., this volume). Contrary to Kumdy-Kol and Barchi-Kol type localities this block has a lot of similarities with Erzgebirge diamond-bearing locality (MASSONNE, 2003). Kyanite-bearing rocks (diamondiferous and diamond-free) are predominant. Diamondiferous kyanite-bearing rocks consist of large porphyroblasts of garnet and kyanite (up to 2 cm in length) in the quartzofeldspatic matrix. Diamond inclusions occur in garnet, zircon and kyanite, but a zonal distribution of carbon polymorphs was only observed in kyanite. Sometimes the core zones of kyanite contain abundant graphite and quartz inclusions. No diamonds was identified within the core zone. This zone is surrounded by clean overgrowth with abundant microdiamond inclusions. Diamonds included in garnet porphyroblasts occur side by side with low pressure (LP) quartz, paragonite, albite and biotite. Similar graphite- and diamond-bearing silicate pockets were described by HWANG et al. (2001). Most likely the diamond crystals were captured with some H_2O bearing melt. The crystallization of this melt during the retrograde stage caused formation of LP minerals. The geochemical characteristics of kyanite-bearing diamondiferous rocks also support this conclusion. Diamond-free rocks look like Kulet micaschists where only coesite was found as indicator of UHPM conditions (SHATSKY et al., 1998). No evidence of partial melting have bee found so far in this lithology. The prograde zoning pattern is preserved in the garnets from these rocks (MnO decrease from core to rim). It is unlikely that diamondiferous and diamond-free rocks belong to one coherent unit as proposed by MARUYAMA & PARKINSON (2000). Probably these two blocks have tectonic boundary and partial melting plays an important role in diamond genesis and exhumation of the diamond-bearing UHPM rocks.

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METASTABLE UHPM GRAPHITE AND METAMORPHIC DIAMOND FROM THE KOKCHETAV ROCKS (NORTHERN KAZAKHSTAN)

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Coexistence of graphite and diamond in the crustal-derived metamorphic rocks from the Kokchetav massif (northern Kazakhstan) was first interpreted in favour of their metastable origin (DOBRZHINETSKAYA et al., 1994). The abundance of ultrahigh-pressure (UHP) metamorphic relics in the diamond-bearing rocks of the Kokchetav massif (SOBOLEV & SHATSKY, 1990; SHATSKY et al., 1995) supports the UHP metamorphic origin of the diamond. Despite the lack of evidence, the occurrence of graphite in UHPM rocks is commonly explained by graphite formation during retrograde stage in diamond-bearing rocks (MASSONNE et al., 1998; ZHU & OGASAWARA, 2002). Graphite inclusions in and graphite coatings around microdiamonds from the Kokchetav massif are investigated with confocal Raman spectroscopy using the in situ point-by-point mapping technique. The lack of disordered carbon in the core of graphite inclusions testifies that graphite represents the co-genetic inclusions in diamond rather than have been formed through the solid stage diamond-graphite transformation. Based on these data and the experiments in carbonate-carbon and COH systems showed that contemporary crystallization of both polymorphs of carbon may occur in the diamond stability field, the presence of the graphite either as inclusions in diamond or as a coatings around diamond crystals is not proving for their formation during retrograde stage of UHP metamorphism.

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THE RIO SAN JUAN COMPLEX (NORTHERN DOMINICAN REPUBLIC): GEOTHERMOBAROMETRY AND AGE DETERMINATIONS

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Serpentinite mélanges associated with Cretaceous subduction at the leading edge of the eastward-drifting Caribbean plate now decorate the trace of the Caribbean / North-American suture zone exposed in Cuba and northern Dominican Republic. Blocks of various types of metamorphic rocks (e.g., eclogites, blueschists, metagranitoids) in the mélanges exhibit a series of different but interrelated P-T-paths. Comparison with numerical models yields critical information on the dynamics of a young and maturing subduction-zone / island-arc complex. The P-T paths can be summarized into three categories:
1) *oldest, "nascent" stage*: Typically shallow ("hot") P / T gradients and peak conditions of 700 °C / 22 kbar. Unusual anticlockwise P-T paths with isobaric cooling and later isothermal exhumation are common in eclogites. U-Pb-zircon protolith ages of 139.9 ± 4.1 Ma constrain the beginning of subduction. Lu-Hf-data on Grt-Ep-Amp-Omp-WR yield an age of 103.9 ± 2.2 Ma for peak metamorphic conditions. Rb-Sr-ages of 74.7 ± 0.5 Ma (Phe-Grt-WR) and Ar-Ar (Phe) of 73.18 ± 0.99 Ma constrain the exhumation path.
2) *maturing stage*: Continuous cooling and steepening of the subduction-zone P-T gradient is recorded. Omphacite blueschists yield an age of 80.3 ± 1.1 Ma (Rb-Sr on Phe-Amp-WR) for peak metamorphic conditions (550 °C / 18 kbar) and an age of 72.97 ± 1.01 Ma for cooling below 400 °C (Ar-Ar on Phe) during exhumation.
3) *mature stage*: Typified by jadeite-lawsonite blueschists (380 °C / > 16 kbar) recording very steep, "cold" P / T-gradients. Rb-Sr-ages (Phe-Amp-WR) of 62.1 ± 1.4 Ma date peak metamorphic conditions. This distinctive array of P-T paths in space and time is in accord with subduction-zone models calling for progressive serpentinization, weakening and incorporation into channel-flow circulation of the hanging-wall lithospheric mantle, induced by fluids emanating from the downgoing slab.

STRUCTURES AND PETROLOGY OF UHP-METAMORPHIC KIMI COMPLEX OF THE RHODOPE METAMORPHIC PROVINCE (RMP), NE-GREECE

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The Kimi Complex represents the tectonostratigraphic highest unit of the Rhodope Metamorphic Province and contains indicators for UHP-metamorphism. Two key areas near the city of Xanthi and Kimi village, where metamorphic microdiamond was found in garnets of metapelites, were mapped in detail. The lithological sequences, that underwent a conti-nental subduction process, are composed of marbles, paragneisses, orthogneisses, metabasites and ultrabasites and show striking similarities in their structural and metamorphic evolution. The rock units were exhumed during SW-directed shear and deformed into a NE-SW striking fold belt during amphibolite facies metamorphism. Within metapelites (grt-ky-micaschists), the formation of a fold axial plane cleavage developed in the kyanite stability field. P-T conditions in grt-ky-schists range from 15 - 18 kbar and 820 - 900 °C at Xanthi and 13 - 15 kbar and 720 - 800 °C at Kimi village. The P-T conditions during development of ductile cleavage in metapelites from Xanthi range between 780 - 860 °C and 13 - 15kbar. Metabasites occur mainly as boudin structures in metagranitoid gneisses and are surrounded by ductile shear zones. The asymmetry of these boudins and shear indicators within the surrounding host rocks suggest a lateral (sinistral) component during compressional formation of the ductile fold belt. The boudins are penetratively overprinted during folding under amphibolite facies metamorphism and contain remnants of granulitic mineral assemblages within their cores. Eclogitic parageneses with omphacite (Jd_{40}) are very rarely preserved in the cores of the boudin structures. Metabasites at Xanthi give P-T conditions between 580 - 630 °C and 10 - 12 kbar. Two types of stretching lineation are distinguished. A steep oblique dipping stretching lineation is always associated with the boudin structures. A second subhorizontal NE-SW lineation, characterizes the penetrative tectonic overprinting during amphibolite facies metamorphism. The combination of contraction and lateral extrusion due to oblique convergence seems to be one of the main mechanisms for the exhumation of the different segments of the Kimi Complex. Late discordant aplitic to pegmatoid dyke swarms and the formation of brittle faults parallel and perpendicular to the strike direction of the lithologies deform the segments into phacoid bodies, which contain remnants of the ductile, deformed and folded lithologies. These remnants are surrounded by cataclasites and represent in combination with pegmatoids the typical appearance of the Kimi Complex.

HP-METAMORPHISM OF A RODINGITE FROM THE RHODOPE MASSIF, GREECE

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The Rhodope Metamorphic Province (RMP) in northeastern Greece is one of only five localities where UHP-metamorphism has led to the formation of diamonds in metapelitic lithologies, indicating exceptionally deep subduction of continental crust. The diamond-bearing felsic gneisses of the RMP are associated with tonalitic to granodioritic metaplutons and an ultramafic complex of ± serpentinized lherzolites with lenses of Grt-clinopyroxenites and eclogites. In the ultramafic complex we have found a rock containing Grt + Cpx + Ky + Mg-St + Zo + Cam + Tur + Pmp + Rt + Zrn + Ap. The bulk composition is Si-poor and Al-, Ca-, and Mg-rich with 42.1 wt% SiO_2, 19.9 wt% Al_2O_3, 16.4 wt% CaO and 10.9 wt% MgO similar to that of metarodingites (e.g. LI et al., 2004 and references therein). An extremely high bulk Zr-content of 434 ppm along with 51 ppm Th and 22 ppm U gives rise to numerous zircons in part with strong BSE- and CL zoning. Grt of this sample is Mg- and Ca-rich with Prp_{41-52} Alm_{25-30} Grs_{21-24} Sps_{0-1}; Cpx is a Di-Cats solid-solution with very low Jd_{ss} ($Di_{78-82}Cats_{8-11}Jd_{0-5}$) corresponding to the low bulk Na_2O content of 0.7 wt%. Zo shows evidence of metasomatic alteration in the form of irregular zones strongly enriched in Sr with 0.8-1.1 wt% SrO. Both Zo and Grt contain numerous Ky-inclusions. Mg-St has an X_{Mg} of 0.59 - 0.62 and is exclusively present as inclusions in Zo. Metamorphic temperatures based on the Fe/Mg-exchange between Cpx and Grt are between 700 – 740 °C. Metamorphic pressures are more difficult to constrain due to the low bulk Na-content but the presence of Mg-St indicates $P \geq 1.5$ GPa. Textures and phase compositions point to a complex history of hydrous fluid infiltration during uplift and exhumation of the metarodingite involving amphibolitization followed by Pmp-formation and a very late tourmalinization in part consuming Pmp. Whether or not Zr- and Sr-metasomatism occurred unter peak metamorphic conditions, however, cannot be deduced from the mineral textures.

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MULTIPLE SUBDUCTION AND EXHUMATION OF ULTRA-HIGH- AND HIGH-P ROCKS: ARCHITECTURE, RHEOLOGY AND HISTORY OF AN ALPINE PLATE BOUNDARY AREA (RHODOPE MOUNTAINS, NE-GREECE)

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The Rhodope thrust and nappe complex exposes alpine high-P and ultra high-P rocks, formed within the framework of Cretaceous material accretion onto and Tertiary collision of Europe with Apulia. Between 65 - 18 Ma, seemingly unconnected tectonic pulses successively exhumed several superimposed high-P units. The structural relationships among, and the P-T-d histories of these units give a unique insight into the mechanical properties of rocks, and the velocity and kinematics of material flow within the lithosphere and upper asthenosphere during collision.

(i) A tectonic pulse at 65 ± 2 Ma exhumed ultra high-P metamorphic crustal rocks and intimately associated mantle-derived associations mostly preserved at the uppermost Rhodope Complex ("Kimi Complex"). Crustal rocks record ~60 kbar and quite high peak temperatures of ~1150 °C (MPOSKOS et al., this volume).

(ii) At about 42 – 40 ± 1 Ma, after emplacement of the UHP-rocks, a migmatic assemblage ("Sidironero Complex") containing kyanite eclogites that indicate ≥ 19 kbar at 700 °C intruded into the already cooled upper crustal domain. High-P / medium-T assemblages mainly consisting of orthogneisses, Al-rich metapelites, albite gneisses, eclogite lenses and ultramafic bodies that were not exposed to temperatures higher than 550 °C underlie this migmatic assemblage ("Kechros Complex"; E-Rhodope). Emplacement of the hot viscous migmatic assemblage is associated with contraction structures at its base, radial extension structures at its top, and with isothermal decompression consistent with rapid exhumation.

(iii) Subsequent to intrusion of migmatites, at about 37 ± 2 Ma, weakening of this crustal section associated with thermal relaxation facilitated formation of low angle normal detachment systems. They extend over more than 100 km, cut across the earlier structures, and excise, in sum, several tens of km of material within the crustal profile. Lutetian (ca. 48 - 43 Ma) to Oligocene marine basins transgressed atop the upper plate of all detachment generations.

(iv) The Thasos/Pangeon metamorphic core complexes formed at 26 - 8 Ma, simultaneously to the Aegean metamorphic core complexes, clearly unrelated to exhumation of any HP and UHP rocks.

We show that the Rhodope high-P complex was assembled during a long-term tectonic evolution in a channel of extremely low viscosity.

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RAPID OLIGOCENE EXHUMATION OF THE ECLOGITE ZONE, TAUERN WINDOW, EASTERN ALPS

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The Eclogite Zone (EZ) is a ~20 km long and 2 - 3 km wide coherent unit of the Tauern Window, sandwiched between the Venediger- and Glockner nappes. Thrusting of the EZ onto the underlying Venediger Nappe is documented by top-N shear indicators. The boundary of the EZ to the overlying Glockner Nappe is characterized by amphibolite to greenschist facies carbonate bearing mylonites and schists showing a sinistral sense of shear.

Within the EZ, eclogites occur as lenses of varying sizes enclosed in a matrix of metasedimentary rocks. Thermobarometry combined with information derived from P-T pseudosections constrain peak metamorphic conditions in the EZ to ~24 kbar and ~650 °C. With help of P-T pseudosections, both the prograde (blueschist to eclogite facies) and retrograde evolution (amphibolite facies) of the EZ rocks is visualized.

Five multi-mineral Rb/Sr internal isochrons of pristine eclogites and eclogite-facies veins gave identical ages, with a weighted average of 31.5 ± 0.7 Ma. Initial Sr-isotopic equilibria among all phases indicate absence of any significant posteclogitic isotope redistribution. Therefore, the above ages date eclogite facies assemblage crystallization (GLODNY et al., in revision). A retrograde amphibole-bearing vein crosscutting an eclogite body yielded an age of 31.5 ± 0.5 Ma, dating amphibolite-facies retrogression at ~8 kbar and ~500 °C. These two ages bracket the time interval for exhumation from eclogite facies to amphibolite facies conditions to between 32.2 and 30.8 Ma and suggest extremely fast exhumation of the EZ from ~80 km to ~20 km within less than 1.4 Ma, at rates of > 40 - 50 mm / a. Similarly rapid exhumation rates have been suggested by DACHS & PROYER (2002) from intragranular diffusion pattern in garnet. They suggested that < 1 Ma elapsed between prograde eclogitisation and cooling below 450 °C implying exhumation rates of 46 to 74 mm / a.

A Rb/Sr mineral isochron age of 31.4 ± 0.5 Ma for a mafic schist from the base of the Glockner Nappe, directly above the EZ, dates blueschist facies metamorphism within the Glockner Nappe. Rb/Sr data from carbonate-dominated mylonites marking the lower and upper contacts of the EZ provide deformation ages between 31 and 30 Ma. The youngest ages are obtained from the most fine-grained muscovites in these rocks, which are further characterized by particularly high Sr concentrations. This may be due to a change of the Sr partition coefficient between carbonate and muscovite during progressive deformation and decompression, related to the aragonite-to-calcite phase transition.

With respect to emplacement and exhumation of the EZ, we suggest that thrusting and large-scale folding due to N-S shortening was coeval with sinistral strike-slip faulting. In summary, our data indicate that today's nappe architecture must have been established in less than 2 Ma after the eclogite facies event.

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IS ARCHIMEDES THE KEY TO ECLOGITE EXHUMATION? THE ECLOGITE ZONE IN THE TAUERN WINDOW, REVISITED

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Eclogites occur in internal parts of many mountain belts and processes responsible for their return to the Earth's surface are widely discussed. Despite obvious and pronounced density differences between eclogites and their enclosing matrix, buoyancy is often invoked as an important driving mechanism for eclogite exhumation from great depths (CHEMENDA et al., 1995, ERNST, 1999). Commonly eclogites occur as blocks and lenses within a matrix of either metasedimentary rocks or hydrated serpentinites that are thought to have experienced the same P-T evolution. In both cases eclogites are more rigid and possess much higher densities as their surroundings. As such, their movement relative to its enclosing, less dense medium is subject to Archimedes' principle, mathematically described by Stokes' Law. This invokes parameters like size and shape of the bodies, density differences and the rheology of the matrix. As a consequence only small eclogite blocks can be exhumed in a weak matrix of hydrated metasedimentary rocks (effective viscosity of $\sim 10^{17}$ Pas) within a reasonable time-frame. The more viscous the matrix is, the slower eclogite exhumation and the larger exhumed eclogite blocks can be.

To test the validity of these assumptions we re-examined the well-known Eclogite Zone (EZ) in the Tauern Window. Eclogites make up ~25 % of the EZ and occur as blocks or lenses of varying size (10 to some 100 of meters in diameter) within a matrix of metasedimentary rocks. The eclogites have densities of 3.4 - 3.5 g / cm^3, while the densities of the surrounding metasediments are ~2.8 g / cm^3 Peak eclogite facies P-T conditions were 650 °C and ~23 - 25 kbar, corresponding to burial depths of ~80 km. New geochronological data imply a very rapid exhumation rate for the EZ of > 40 mm / a (KÜHN et al., this volume) during the Oligocene. In the EZ the metasediments form a network of shear zones, each between 50 and 100 m thick, enclosing the eclogite blocks. Assuming a minimum shear velocity of 40 mm / a the resulting strain rates vary between $6 \cdot 10^{12}$ s^{-1} and $2 \cdot 10^{12}$ s^{-1} From this follows that the effective viscosities during deformation were rather low ranging between 10^{18} Pas and $2.5 \cdot 10^{18}$ Pas.

Our data support the buoyant exhumation model of the Tauern eclogites by ENGLAND & HOLLAND (1979) who showed that small eclogite blocks embedded in a low-viscosity matrix may be exhumed by buoyant forces if the exhumation rate is > 40 mm / a. However, our calculations applying Stokes' Law show that eclogite blocks are only buoyantly exhumed in a metasedimentary matrix when they are relatively small (< 100-200 m in diameter), otherwise viscous forces are too small to overcome the pronounced negative buoyancy of the eclogite bodies.

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OMPHACITE CRYSTALLOGRAPHIC PREFERRED ORIENTATIONS FROM ECLOGITES OF THE TYPE LOCALITY

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Crystallographic Preferred Orientations (CPOs, textures) of omphacite within eclogites from the Koralm-Saualm Complex were analysed in order to constrain the deformation conditions during and after high-pressure metamorphism. The omphacite CPO bear significant details for the reconstruction of the deformational evolution of this unit.

The omphacite crystallographic preferred orientations from the Koralm-Saualm Complex may generally be described by S-type fabrics. Within coarse-grained samples the {001} poles are distributed along a girdle parallel to the XY plane of the finite strain ellipsoide (foliation plane). These textures show {001} maxima near the Y- axis of the finite strain ellipsoide, *i.e.* perpendicular to the lineation, but parallel to the foliation plane. The {010} poles, oriented parallel to the b [010] axes, show very well developed clusters centered within the Z; the {100} poles are distributed along a girdle within the XY-plane (foliation), with maxima near X. This type of CPO fabric ({100} and {001} girdle within the XY-plane, {010} poles with a cluster centered in Z) is formed within a deformation geometry of axial compression. The omphacite CPOs within fine-grained eclogite mylonites may be characterized as S- to transitional S > L- types with a {001} girdle within the XY- plane (foliation); clusters of {010} poles are centered in Z. However, the {001} poles show a tendency to form weak maxima centered in X; accordingly, the {010} poles show a tendency to form a girdle within YZ (normal to the foliation plane). Despite the intensity, the type of texture is not influenced by the modal composition, in particular by the occurrence of garnet layers and lenses and minor amounts of quartz as well.

We assume that the deformation geometry from the pressure peak onwards is directly related to the mechanism of exhumation. Hence, S-type fabrics predominantely occur within eclogites exhumed by crustal extension. This is associated with a flattening strain geometry and subvertical axial compression.

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EVIDENCE FOR PARTIAL MELTING IN METAPELITIC ROCKS FROM THE UHP TERRANE, NORTH-EAST GREENLAND ECLOGITE PROVINCE

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Although pelitic rocks are rare in the North-East Greenland Eclogite Province, a few samples of pelitic paragneiss were collected near the location where Caledonian ultra-high pressure (UHP) metamorphic conditions have been documented in mafic eclogites (GILOTTI & RAVNA, 2002). The most interesting of these pelitic paragneisses contain large (up to 2 cm), inclusion-rich garnet porphyroblasts, minor kyanite and layers and lenses of leucocratic, anatectic melt. The garnets contain abundant quartz inclusions, some of which are polycrystalline and surrounded by radial fractures, suggesting that they were initially coesite. In addition, the garnets contain inclusions of Ti-rich, phengitic white mica, which is consistent with UHP metamorphic origin, and large complex inclusions with polycrystalline quartz, white mica, biotite and feldspar. The matrix surrounding the large garnets in the pelitic paragneiss contains variably recrystallized quartz ribbons, and layers and lenses of migmatitic leucosome. The leucosome contains abundant small garnets, minor kyanite, biotite, myrmekite, plagioclase and antiperthitic alkali feldspar, which is consistent with dehydration melting of phengitic white mica (INDARES & DUNNING, 2001). The fact that phengite pseudomorphs occur in the matrix in contact with leucosomes produced by partial melting indicates that melting began during or after UHP metamorphism that produced phengite.
Large, complex inclusions in some large garnets preserve evidence of partial melting entirely within garnet. In particular, one inclusion contains phengitic white mica, biotite, rutile, kyanite, quartz, Na-rich plagioclase and K-feldspar (antiperthite?). Textures suggest that two large phengitic white mica inclusions and adjacent quartz included in this garnet experienced dehydration melting by the reaction Phengite ± Plagioclase + Quartz = Kyanite + K-feldspar + Biotite + Liquid (INDARES & DUNNING, 2001) to produce the large complex inclusion. Many other quartz inclusions in the large garnets have Plagioclase + K-feldspar rims against garnet. Partial melt textures and peak metamorphic minerals of the metapelites are better preserved inside the large, inclusion-rich garnets than in the matrix. Mineral textures and compositions from the inclusions will be important in reconstructing the peak and post-peak metamorphic and reaction history of UHP metapelites in the North-East Greenland Eclogite Province.

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EXPERIMENTAL CORONA TEXTURES MODELLING: DIFFERENCES IN CORONA-FORMING REACTIONS IN OLIVINE-PLAGIOCLASE AND ORTHOPYROXENE-PLAGIOCLASE INTERFACES DURING ECLOGITISATION OF GABBROS

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Corona textures usually develop between primary magmatic Fe-Mg minerals and plagioclase during prograde metamorphism (eclogitisation) of gabbros. Different types of the corona textures in Belomorian belt (Baltic shield) and in Marun-Keu (Polar Urals) display major differences of olivine-bearing and olivine-free coronites (formed at the same P-T conditions): "clouding" of plagioclase with spinel grains was found only in olivine-bearing coronites; garnet layer upon primary orthopyroxene was **never** found in Ol-bearing coronites (unlike Ol-free ones, where garnet corona is common). New experiment was made to study the compositional differences in corona sequences in Ol-Pl and Opx-Pl interfaces. Like our previous experiments (LARIKOVA & ZARAISKY, 2002, 2004), in which seven zones *En + Gedr2 / Trem / Gedr1 + Fo / Chl / Parg / Cpx / **Grt** + An* were received between primary Opx and Pl, the new run has been carried out in hydrothermal exoclave of IEM RAS at T = 700 °C and P = 5 kbar during three weeks. In a gold capsule fine-grained powder of plagioclase was interleaved with enstatite and olivine layers; crystals of Pl and Ol were placed inside the Pl layer. Well-defined corona textures were formed at all contacts; each corona has two distinct layers with sharp boundaries (100 μm in width):

***Ol** – (En + Gedr) – (Phlg1 + Ca Hbl) – **Pl**; **En** – (Phlg2 + Al En) – Ca Hbl - **Pl**.*

An inner layer in the corona around olivine consists of orthopyroxene and amphibole (gedrite), an outer - Al–rich phlogopite1 with some hornblende grains. In the corona after enstatite an inner layer consists of phlogopite2 with some newly formed Al-rich orthopyroxene, and an outer amphibole layer. Primary plagioclase (An_{62}) became more sodic (An_{52}) at the contact with the corona around olivine; in contrast to one in the corona after orthopyroxene that has higher Ca content (up to An_{71}). The compositions of the experimental coronas show the opposing gradual diffusion of Ca and Al from plagioclase and Mg from enstatite and olivine; and more aluminium-rich corona minerals were formed around olivine, and after orthopyroxene – Ca-rich minerals. According to the model of simultaneous coronas growth by mechanism of diffusion metasomatism, differences in layer sequence of the coronas are supposed to depend on the diverse chemical potential gradients of the diffusing components in the Ol-Pl and Opx-Pl interfaces in the fluid phase. Thus the experiment corroborates natural observations on the major differences in both compositions and sets of minerals, and mainly in the trends of the plagioclase composition changes, in coronas around olivine and orthopyroxene at their contacts with plagioclase.

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EVIDENCE FOR MASS TRANSFER AT THE CONTACT OF GARNET GLAUCOPHANITE AND QUARTZ-GARNET-OMPHACITE ROCK IN THE MAKSYUTOV COMPLEX, SOUTH URALS

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The contact of garnet glaucophanite and quartz-garnet-omphacite rock from the Maksyutov Complex (South Urals) was studied in detail. The distribution profiles of SiO_2, MgO and FeO_{tot} contents in rocks and FeO, MgO and CaO contents in garnet rims depending on the distance from the contact suggest the diffusion migration of chemical components across the boundary. They are described by the equation of linear diffusion at the contacts of two semi-infinite media ($x < 0$, $x > 0$) with stepwise initial distribution of concentrations. The values of C_1, C_2, D_1t and D_2t were calculated by least-squares method for the two models, i.e. when (a) $D_1 = D_2$ and (b) $D_1 \neq D_2$. The points of inflection in the concentration sigmoidal profiles calculated for the first model are noted away from the contact. This suggests that the observed boundary was displaced by 3.2 cm from its initial position towards garnet glaucophanite. The mass transfer scales at the contact of garnet glaucophanite and quartz-garnet-omphacite rock were estimated to be 4.5 to 13.7 cm for different components for the first model and 6.9 to 14.3 cm for the second model. Based on the calculated values of the reaction zone thickness and effective diffusion coefficients, a series of differential mobility of components is outlined. It was shown that the most mobile components are CaO and MgO, and the least mobile components are SiO_2 and FeO_{tot}. The volumes of local equilibrium near the contact of garnet glaucophanite and quartz-garnet-omphacite rock are estimated to be less than 1 mm^3 The differences of FeO, MgO and CaO contents in rims of garnet grains located at the distance of 1 mm, reach 3-5 wt%. Based on the study of zoned garnets, the duration of the thermal event should be less than 1 - 5 Ma. The calculated values of effective diffusion coefficients in the investigated rocks are $10^{-14} - 10^{-15}$ cm^2 / s or even less.

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THERMODYNAMIC COMPUTATION OF ECLOGITE PHASE EQUILIBRIA: THE KEY ROLE OF REDOX STATE

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Thermodynamic calculations are vital for estimating the temperatures and pressures experienced by eclogites. Such calculations are especially important for locating the minimum temperatures and pressures required for eclogite stability; i.e., the blueschist-eclogite and amphibolite-eclogite transitions. These transitions are best constrained by constructing pseudosections with programs such as THERMOCALC or PERPLEX. The accuracy of pseudosections for quantifying eclogite phase equilibria hinges on well-tested and robust solid-solution models.
We calculated pseudosections for a series of metabasalts used in high-pressure experiments and compared them to experimental phase equilibria. We initially used a series of models that have been repeatedly applied to high-pressure metabasites in the literature and found dramatically lower pressures and temperatures for the eclogite transitions compared to the experiments. These models do not consider ferric iron; however, high pressure rocks commonly have high ferric iron contents, particularly in phases such as clinopyroxene, amphibole, and epidote. Adding ferric iron to our models and imposing oxygen fugacities of QFM and NNO markedly increases the pressures and temperatures of the amphibole-out boundary and increases the temperature of the lawsonite-out curve. Nevertheless, notable discrepancies still exist, particularly with epidote. Within this framework, we are able to evaluate the strengths and weaknesses of various solid-solution models and to demonstrate the need for improved solid-solution models for certain phases.

ZIRCONS OVERPRINTED BY RODINGITIZATION AND THEIR U-Pb AGES FROM A SERPENTINITE COMPLEX, WESTERN TIANSHAN

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Tianshan rodingite derives from eclogite enclosed in the ultramafic rocks of Changawuzi ophiolites in the Southwestern Tianshan ophiolitic mélange. Serpentinized ultramafic rocks occur together with interlayered south-dipping blueschists and greenschists in Changawuzi ophiolites suggesting a relict Silurian oceanic crust. Rodingites contain a mineral assemblage of prehnite, clinozoisite, hydrogrossular, diopside, vesuvianite and chlorite, while partial rodingitized rocks still preserve the relict omphacite and Fe-Mg-Al garnet. The rodingitization started at 370 - 410 °C / 6.5 8.5 kbar, while pervasive rodingitization took place under conditions of 200 - 350 °C / 2 - 6 kbar. Cathodoluminescence reveals that the most zircon grains from the intensely rodingitized rock consist of distinct rim and core. The jagged cracks cross zircon rim, showing clear fluid channels to the core. A well defined group ^{206}Pb / ^{238}U age of 422 ± 10 Ma (2 sigma) from rims of zircon shows an age of middle Silurian, suggesting the hydrothermal metamorphic age of Silurian oceanic crust. The ages from cores of zircons in rodingites vary from 422 Ma to 291 Ma, implying a continuous fluid alteration to the core of zircon during exhumation and giving mixed ages. REE patterns obtained by LA-ICP-MS analyses from zircons of the rodingite are also variable from recrystallized core to the zircon rim, which are clearly correlated to the extent of hydro-metamorphic overprint. The higher the total amount of REE present in the core of the zircon, the younger its apparent age. The lower boundary of the core age was constrained by single grain zircons in the rodingite, which have no zoning texture observed. These single grain zircons around 291 Ma are considered formed during pervasive rodingitization, and the age correspondingly represents the event of intensive rodingitization during the collision of the Tarim and Yili--Central Tianshan plate. Zircons newly formed during pervasive rodingitization reflect a Late Paleozoic event, in which the dehydration of a subducted slab lead to arc magmatism and low-P granulite-facies metamorphism with SHRIMP U-Pb zircon ages of 290 - 280 Ma in the northern belt (LI & ZHANG, 2004), and provided abundant fluid for rodingitization in the exhuming HP terrane.

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ECLOGITES AND COUNTRY ROCK ORTHOGNEISSES REPRESENTING UPPER PERMIAN GABBROS IN HERCYNIAN GRANITOIDS, RHODOPE, GREECE: GEOCHRONOLOGICAL CONSTRAINTS

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Granitoid rocks constitute a significant part of the Variscan orogen of Europe. Although ages of granitoids in W and C Europe have received significant attention, the time of formation of such rocks in its ESE part remains to a great extent unknown.

In the Rhodope (U)HP zone of N' Greece, orthogneisses are widespread in the different metamorphic thrust nappes involved in the Alpine collisional histories. Lenses and layers of amphibolitized eclogites occur in places within the orthogneisses. We analysed by SHRIMP II (ANU, Canberra) zircons from one eclogite lens and its country rock orthogneiss in E Rhodope (within the so-called lower tectonic unit), metamorphosed at ca. 14 - 16 kbar, 550 - 600 °C (MPOSKOS, 1989; LIATI & MPOSKOS, 1990). Cathodoluminescence (CL) imaging of the zircons reveals that, in both rock types, they consist mainly of a single oscillatory zoned (magmatic) part. Metamorphic rims are lacking, as zircon, generally, starts responding to recrystallization at (or above) T conditions of the upper amphibolite- or high-T (> 650 °C) eclogite-facies (e.g., LIATI & GEBAUER, 2003). A very thin, CL-bright rim was observed around the magmatic core of some orthogneiss zircon crystals, probably due to local fluid enrichment. Zircons of the eclogite yielded a ^{206}Pb / ^{238}U age at 255.8 ± 2.1 Ma, interpreted as the time of crystallization of the gabbroic protolith. Zircons of the orthogneiss yielded a protolith age of 313.9 ± 2.1 Ma. Similar ages were obtained for the upper tectonic unit of W Rhodope (294.3 ± 2.4 Ma for the orthogneiss protolith and 245.6 ± 3.9 Ma for the protolith of the adjacent eclogite (LIATI, submitted to CMP). Metamorphic ages were not possible to obtain, because of the very thin rims. One mixed analysis located on both rim and the neighbouring older core of an orthogneiss zircon indicates that metamorphism was Alpine.

The presence of Hercynian magmatism also in this area of Europe is confirmed by our data. The 255.8 ± 2.1 Ma age determined for the crystallization time of the gabbroic protolith of the enclosed eclogite suggests either rift-related underplating of mafic magmas at that time or the presence of a Late Permian ocean. The lack of other deep sea indicators favours rather the first view. Rift-related, Late Permian mafic rocks are known in the Alps (e.g. Ivrea zone) but they are not HP Presence of Late Permian mafic magmas within Hercynan granitoids, as found in the Rhodope is an uncommon situation for W and C Europe. If the Late Permian eclogite protoliths of Rhodope represent indeed rift-related underplated mafic magmas, they are amongst the youngest mafic intrusions in the Hercynian basement of Europe metamorphosed under Alpine eclogite-facies.

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PRE-ALPINE AND ALPINE METAMORPHISM IN THE ADULA NAPPE, CENTRAL ALPS: CONSTRAINTS BY SHRIMP-DATING AND REE OF ZIRCON

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The Adula nappe (AN), including the Cima Lunga unit to the W and the Gruf Complex to the E is the structurally deepest and largest basement nappe in the eastern part of the Central Alps. It consists mainly of pre-Mesozoic orthogneisses, pelitic schists and minor metabasic / ultrabasic rocks, as well as metamorphosed Mesozoic marls, limestones, dolomites and sandstones. It contains HP relics (blueschist- to eclogite-facies). The northern part of the AN shows lower metamorphic grade, compared to the middle and southern parts.
We dated by SHRIMP II (ANU, Canberra and GSC, Ottawa) zircons from two eclogites and two country rock paragneisses, as well as from a quartz vein concordant to the schistosity of one paragneiss from the middle AN, area of Trescolmen, situated in the so-called 'Lepontine area' Zircon cores from the paragneisses yielded dates older than ca. 500 Ma (most between 500 - 650 Ma). The metamorphic rims yielded both pre-Alpine ages (378 ± 11 Ma and 372 ± 4 Ma; error at 95% c.l.) and Alpine ages (32.8 ± 0.6 Ma and 32.7 ± 1.4 Ma), as well as various amounts of Alpine Pb-loss. The eclogite zircons are strongly recrystallized and consist almost entirely of a metamorphic domain with rare relics of magmatic cores. Metamorphic domains yielded ages of 371 ± 8 Ma and 33.2 ± 1.1 Ma and Alpine Pb-loss. Three magmatic cores yielded analytically concordant ages of 655 ± 12 Ma, 610 ± 10 Ma and 561 ± 22 Ma (1σ). REE analyses (SHRIMP II, ANU, Canberra) of a 371 ± 8 Ma old metamorphic zircon rim of the eclogite show no Eu anomaly in the chondrite-normalised REE pattern, thus indicating that it formed in the absence of plagioclase (which would cause a negative Eu anomaly) at HP conditions.
The Alpine ages obtained for the HP rocks of Trescolmen are identical with the ca. 33 Ma granulite-facies ages reported for the middle AN (Cima Lunga: Alpe Arami and Cima di Gagnone; GEBAUER, 1994, 1996 and Gruf Complex; LIATI & GEBAUER, 2003). The ca. 35 Ma HP age recorded at Alpe Arami and Cima di Gagnone (GEBAUER, 1994, 1996) was not identified in the HP rocks of Trescolmen. HP metamorphism in this part of the AN is probably connected with a pre-Alpine, ca. 375 Ma old event known also in other parts of Europe (e.g., Münchberg Gneiss Massif, NE Bavaria or Cabo Ortegal, NW Spain). An additional ca. 35 Ma old HP metamorphism completely reset due to the ca. 33 Ma Lepontine metamorphism, although unlikely, cannot be excluded. Given the Alpine HP age of metamorphism in its N' and S' part, it is evident that the AN consists of different tectonic slices with different evolution in time. Pre-Alpine HP rocks constitute part of the AN basement, as is the case for the basement of other areas of Europe.

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LINKING U-Pb SHRIMP ZIRCON AGES WITH METAMORPHIC CONDITIONS: CONSTRAINTS FROM THE REE COMPOSITION OF ZIRCON IN ALPINE (U)HP ROCKS OF THE RHODOPE, N' GREECE

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Zircon (re)crystallization during metamorphism cannot, generally, be directly linked to a certain stage during P-T-t evolution. However, long-lasting observations based on cathodo-luminescence-controlled SHRIMP-dating of zircon from (U)HP/HT rocks worldwide show that zircon starts recrystallizing at (or above) T of the upper amphibolite- or high-T (ca. > 650 °C) eclogite-facies (e.g., LIATI & GEBAUER, 2003). However, the link between time of metamorphism and metamorphic conditions of zircon formation can be substantiated also by using the REE composition of metamorphic zircon domains: The REE composition of zircon reflects the concurrent growth of index metamorphic minerals, such as feldspars (causing negative Eu anomaly) or garnet (causing depletion in HREE).

We analysed for REE by LA-ICPMS (ETH, Zurich) and by SHRIMP II (ANU, Canberra) metamorphic zircon domains (already dated by SHRIMP) from different (U)HP rocks in Central (CR), West (WR) and East Rhodope (ER): In CR (Thermes area), the ca. 42 Ma old metamorphic zircon domains of both eclogites and orthogneisses show no Eu anomaly, implying absence of plagioclase and thus HP conditions, while the HREE profile of the eclogite zircons is flat, which is compatible with concurrent garnet growth. The ca. 40 Ma old leucosome zircons of migmatized orthogneisses in the same area are characterised by lacking or weak Eu anomalies, thus indicating leucosome formation still at HP Metamorphic zircon rims of grt-ky paragneisses (N' of Xanthi) dated at 152.8 ± 2.4 Ma (LIATI, submitted to CMP) grew probably also under HP (or UHP) and in the presence of garnet, as indicated by the absence of Eu anomalies and flat HREE patterns. The same is true for similarly old amphibolitized eclogites from the same area. In WR (close to Sidironero), 51 ± 1 Ma old metamorphic zircon rims of eclogites show again no Eu anomalies and a flat HREE pattern, compatible with formation at HP and garnet presence. Finally, in ER (Kimi area) 117.4 ± 1.9 Ma old magmatic domains and 73.5 ± 3.4 Ma old metamorphic domains of zircon in UHP mafic rocks show weak and no Eu anomalies, respectively, as well as steep HREE patterns, which indicates the presence of a trace element supply rich in HREE, during metamorphism.

Our data on the REE composition of zircon from (U)HP/HT rocks of Rhodope confirm the empirical observation that metamorphic zircon rims form close to both P-peak and T-peak. This follows from the usually fast rates of exhumation in (U)HP terranes (> 1 - 2 cm / a), which imply a relatively short time difference between T and P peak. Identification of four Alpine (U)HP events in the Rhodope argues for the presence of different micro-continents rifted off from Gondwana and participating in distinct subduction and collision cycles during Alpine orogeny.

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EXOTIC NON-UHP TERRANE IN THE SULU UHP BELT, NE CHINA

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The small Haiyangsuo peninsula in the NE Sulu UHP terrane has discontinuous exposures of massive metagabbroic intrusives to foliated amphibolite and gneiss with minor granulite pods along the coast over an area of about 15 km^2 Petrologic and geochronological investigations indicate that these rocks show no evidence of eclogite-facies metamorphism and have Pre-Triassic zircon SHRIMP U-Pb ages for intrusion and metamorphism. Gneissic rocks are dominant and have protolith ages of about 2500 Ma; the Early Proterozoic (~ 1845 Ma) metamorphism formed layered amphibolite with minor granulite lenses in gneiss. Granulite displays first granulite-facies recrystallization of Grt ($Alm_{55-64}Grs_{18-19}Prp_{16-25}$) + Pl + Opx + Cpx + Qtz ± Prg ± Bt at about 1850 Ma and amphibolite-facies overprint for coronal Grt (Alm_{42-58} $Grs_{19-44}Prp_{14-25}$) around Pl together with Hbl + Pl at 415 ± 80 Ma. Gabbroic bodies are characterized by: (1) distinct intrusive contacts with foliated Grt-bearing gneissic rocks; and (2) the occurrence of pale reddish fine-grained coronal metagabbro in the cores of massive blocks, and gradational to garnet amphibolite near the margins. In coronal metagabbros, the primary assemblage of Opx (En_{49-54}) + Cpx ($Jd_{02-08}Aug_{92-98}$) + Pl + Ilm ± Qtz is well preserved. Most Opx and some Cpx grains are partially rimmed by aggregates of Amp (II) + Qz ± Ab, and fine-grained garnet coronas develop at interfaces between plagioclase and other phases; some smaller coronas consist of Cpx + Pl + Grt or Qtz + Cpx + Pl ± Grt. Garnet amphibolites display various extents of recrystallization: Opx was entirely replaced by Hbl but minor relict Cpx and primary textures are preserved. Plagioclase grains were pseudomorphosed by fine-grained Zo + Ky + Pl (II). With increasing amphibolite recrystallization, coarser idoblastic Grt (~ 0.4 mm), Hbl (0.2 - 0.5 mm), Zo (up to 0.3 mm), and Pl occur, and the corona texture is not apparent. Ilmenite is rimmed by titanite; no rutile was found. Zircon separates from metagabbro yield intrusive age of 1735 ± 21 Ma and amphibolite-facies recrystallization at 340 ± 40 Ma. These metamorphic and gabbroic rocks in Haiyangsho were finally intruded by thin granitic dikes; zircon separates from one granitic dike yields complex metamorphic cores of 780 - 580 Ma and igneous overgrowth at 158 ± 3 Ma. The Jurassic dike is coeval with granitic intrusions in Rushan (15 km west of this region; SHRIMP U-Pb zircon ages of 161 ± 3 Ma) of the Sulu terrane. No Triassic age of 220 - 240 Ma was obtained for gneissic, mafic and granitic rocks of the Haiyangsuo region. These petrological and geochronological characteristics conclude that this region is exotic from the Triassic Sulu HP-UHP terrane in east China and was juxtaposed with the Sulu in Jurassic time.

ULTRAHIGH-PRESSURE MINERAL ASSEMBLAGES HIDDEN IN ZIRCONS FROM CORES IN THE MAIN DRILL HOLE OF CHINESE CONTINENTAL SCIENTIFIC DRILLING PROJECT

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The main drill hole of Chinese Continental Scientific drilling Project (CCSD-MH) is located at 34° 25' N, 118° 40' E near the village of Maobei, about 17 km SW of Donghai County, southwestern Sulu terrane. Up to now, the CCSD-MH has reached a depth of 5118.2 m and has penetrated five major lithologic units, including eclogite, amphibolite, ultramafic rock, paragneiss and orthogneiss unit. Because the amphibolite, paragneiss and orthogneiss have been overprinted by later amphibolite facies metamorphism, it is very difficult to determine the UHP mineral assemblages in these country-rocks of eclogite. However, zircon, an accessory mineral, has been considered an excellent container for the preservation of UHP minerals. Mineral inclusions in zircon separated from paragneiss, such as garnet epidote bitotite two-feldspar gneiss and garnet biotite amphibole albite gneiss, were investigated in detail. Abundant coesite inclusions occur in zircons from 45 paragneiss samples. Most coesite-bearing zircons contain the following UHP mineral assemblages: coesite + phengite, coesite + garnet, coesite + jadeite + garnet + apatite and coesite + garnet + apatite. Zircons separated from 48 orthogneiss samples also contain coesite inclusions; the index UHP mineral assemblages are characterized by coesite + phengite, coesite + kyanite + apatite and coesite + kyanite + titanite. Zircons separated from 15 amphibolite samples contain abundant UHP mineral inclusions, including coesite + garnet + omphacite, coesite + garnet + phengite and coesite + omphacite + rutile. UHP mineral assemblages as inclusions hidden in zircons from 17 eclogite samples were also identified by laser Raman spectroscopy; these include coesite + garnet, coesite + garnet + omphacite + rutile and coesite + phengite + apatite. These characteristic UHP mineral inclusion assemblages preserved in zircons from eclogites are similar to those in zircons from amphibolites, and are also consistent with matrix assemblages of the same eclogites. These data indicate that the paragneiss, orthogneiss and amphibolites in CCSD-MH undoubtedly experienced UHP metamorphism, and their UHP peak-stage assemblages in the matrix were retrograded and completely replaced by amphibolite-facies assemblages related to the rapid exhumation of the Sulu terrane.

Our studies show that coesite-bearing UHP mineral assemblages occur in zircons of eclogite and its country-rocks in CCSD-MH. Similarly, zircons separated from outcrops distributed in southwestern Sulu terrane, including gneissic rocks, quartzite, marble, schist and amphibolite also contain abundant coesite-bearing UHP mineral inclusions. Such consistent observations suggest that eclogite together with its country-rocks experienced in situ UHP metamorphism.

EXHUMATION *P-T* PATH OF UHP ECLOGITES IN THE HONG'AN AREA, WESTERN DABIE MOUNTAINS, CHINA

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Four generations of mineral assemblages have been identified in ultrahigh-pressure (UHP) eclogites from the Hong'an area, recording four metamorphic stages of the exhumation trajectory, i.e. garnet + omphacite + kyanite + zoisite / epidote + rutile + coesite formed at the UHP stage, garnet + omphacite + paragonite + phengite + amphibole + epidote + quartz at the high-pressure (HP) eclogitic stage, amphibole + epidote + albite-oligoclase + paragonite + quartz at the epidote-amphibolite facies (EA) stage, and actinolite + albite and pumpellyite + albite + K-feldspar + muscovite + chlorite + margarite + epidote + quartz at the greenschist facies (GS) stage. The following *P-T* conditions were estimated for these mineral assemblages: 480 to 560 °C / 2.5 to 2.9 GPa with median values of 520 °C / 2.8 GPa at UHP stage, 575 to 685 °C / 1.6 to 1.9 GPa with the average results of 634 ± 27 °C / 1.8 ± 0.6 GPa at the HP stage, 500 to 640 °C / 0.4 to 1 GPa at the EA stage and 160 to 320 °C / 0.2 to 0.8 GPa at the GS stage. Garnet formed at the UHP stage was overgrown by atoll garnet at the HP stage. X-ray images, mineral compositions and compositional profiles indicate that the UHP garnet experienced re-equilibrium of Fe^{2+}- Mg exchange with the early omphacite prior to the overgrowth of atoll HP garnet. A diffusion zone was also observed between the UHP and HP garnets. The Hong'an UHP eclogites experienced a temperature increase of over 100 °C from the UHP to HP stages and continued to exhume from the HP to EA stages through a process of approximately isothermal depression, which was followed by a dramatic temperature decrease from the EA to GS stages. In the process of exhumation, UHP eclogites witnessed a series of events involving fluid influx, resulting in the formation of hydrous minerals at different stages. The nature of fluids changed from K-rich at the HP stage to K-poor at the EA stage and then K-rich again at the GS stage.

TRACING THE PROTOLITHS OF RUTILE ECLOGITES FROM THE SULU UHPM TERRANE, EASTERN CHINA: IMPLICATIONS ON RUTILE FORMATION

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The rutile eclogites in the Sulu ultrahigh pressure metamorphic (UHPM) terrane have negative εNd values consistent with continental origin. They are characterized by enrichment in Ti accompanied by depletions in Nb, Ta, Zr and Hf. Because these high field strength elements (HFSE) are immobile, fractionations between HFSE are uncommon and provide critical constraints on the protoliths of these economically valuable rutile eclogites.

Comparing trace element variations of rutile eclogites to those of common geochemical reservoirs shows that only the high-Ti gabbros are possible protoliths for rutile eclogites. However, most gabbros are of oceanic origin without significant fractionation between Ti and other HFSE. To constrain the trace element characteristics of continental gabbro, we used the MELTS algorithm to model major element compositions and mineral proportions of gabbros derived from Emeishan high-Ti tholeiitic basalts by fractional crystallization. Despite of the variations in the proportions of constituting minerals, all gabbros crystallized from such tholeiites at 10 - 20 kbar have major oxide contents comparable to those of rutile eclogites. However, only the cumulates containing 63 % clinopyroxene, 32 % plagioclase and 5 % ilmenite have trace element abundances comparable to rutile eclogites. The fractionation of Ti from other HFSE reflects the combined effects of plagioclase/melt and ilmenite/melt partitioning. Based on major and trace element compositions as well as Nd isotopic ratio, we suggest that the protolith of Sulu rutile eclogite is gabbro crystallized from continental high-Ti tholeiitic basalts at 10 ~ 12 kbar and 1140 ~ 1160 °C.

During UHP eclogitization, ilmenite and clinopyroxene are the sources of Ti for forming rutile. Ilmenite might break down releasing Fe to form large grain rutile. In contrast, clinopyroxene transfer to omphacite liberating excess Fe and Ti, which might enter garnet enriching the Fe and Ti contents in garnet up to 26 wt% and 0.34 wt%, respectively. Retrograde eclogites with higher FeO and TiO_2 and lower SiO_2 and CaO contents are mainly composed of garnet and ilmenite without omphacite. These characteristics reflect the effects of interacting with fluid after peak metamorphism. As indicated by experimental results, Ti could become mobile at pressures > 1 GPa. Interacting with high pressure high-Ti fluids, the eclogites might be enriched in Ti abundance. Meanwhile, these fluids might trigger omphacite breakdown and remove SiO_2 and CaO from eclogites. Consequently, Ti was concentrated in two stages; breakdown of ilmenite during prograde metamorphism and interacting with fluids during retrograde metamorphism.

COMPOSITION AND U-Th-Pb AGES OF MONAZITE INCLUSIONS IN PYROPE MEGACRYSTS FROM THE UHP UNIT OF THE DORA MAIRA MASSIF, W ALPS

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The well known pyrope megacrysts of the UHP Brossasco-Isasca Unit (BIU) have a complex and varied suite of mineral inclusions. Most important for geochronology are the zircon inclusions of the Case Ramello (Parigi) outcrop where CHOPIN (1984) first identified coesite inclusions in the pyrope megacrysts. Zircon inclusions from this locality gave U-Pb ages of ca. 38 Ma for the UHP metamorphism (TILTON et al., 1991), further refined to ca. 35 Ma with the SHRIMP technique (GEBAUER et al., 1997).

In this contribution first results of an investigation on the composition and U-Th-Pb age of monazite inclusions from the outcrop of pyrope megacrysts at Case Tapina, Vallone di Gilba (COMPAGNONI et al., 1994) are described.

Major-element composition of monazite was determined by WDS-EPMA, while trace elements and the U and Pb concentrations were measured by µ-PIXE. The Tapina monazite is Ce- and Th-rich, with ThO_2 ranging from 7 to 11 wt%. Variations in Th concentration are accompanied by changes in LREE contents (Ce_2O_3: 26 - 30 wt%; La_2O_3: 10.5 - 13.5 wt%; Nd_2O_3: 10.5 - 12 wt%). U and Pb concentrations range between 500 and 2000 ppm, and from 100 to 250 ppm, respective- ly. Y and Sr are also present, at the thousand ppm level.

Because monazite contains significant amounts of Th and U, with little or no common Pb, it can be used for U-Th-Pb dating from the measured concentrations of U, Th and Pb. Two groups of ages were calculated for a Tapina monazite crystal: Ages from a homogeneous, high Th rim cluster around 35 Ma, while ages from a heterogeneous, low Th core with patchy zoning cluster around 60 Ma but a couple of outliers yield ca. 75 Ma. U-Th-Pb data on a larger sample set will try to clarify the significance of the two older age groups.

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PETROLOGY OF TITANIAN CLINOHUMITE AND OLIVINE AT THE HIGH-PRESSURE BREAKDOWN OF ANTIGORITE SERPENTINITE TO CHLORITE HARZBURGITE (ALMIREZ ULTRAMAFIC MASSIF, S. SPAIN)

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High-pressure breakdown of antigorite serpentinite to chlorite harzburgite (olivine + orthopyroxene + chlorite) is a significant dehydration reaction in subduction settings. Serpentinite subduction may be a suitable source or sink of significant elements for arc volcanism such as F, Cl, B, Be, Sr, Li, and HFSE. Stabilization of clinohumite during serpentinite dehydration may account for some of these geochemical characteristics (GARRIDO et al., 2005).
Rocks of the Almirez ultramafic massif (Sierra Nevada, Betic Cordillera, S. Spain) record the high-pressure dehydration of antigorite-olivine serpentinite to form chlorite harzburgite. In the field these two rock types are separated by a well defined isograd. Titanian clinohumite (TiCl) and olivine show textural and compositional differences depending on rock type. OH-TiCl occurs in the serpentinite as disseminated grains and in veins. F-OH-TiCl is observed exclusively in the chlorite harzburgite, where it occurs as porphyroblastic grains and within prograde olivine as irregular and lamellar, planar intergrowths at microscopic and submicroscopic scales. Petrological evidence of partial to complete breakdown of TiCl to olivine + ilmenite is preserved in both rock types. Chlorite harzburgite is characterized by a brown pleochroic olivine with abundant oriented microscopic to submicroscopic oxide particles. The mean Ti-content of the brown olivine is 144 ppm. Brown olivine preserves TiCl lamellae that sometimes grade into ghost lamellae outlined by oxide trails. This observation suggests that some of the oxide inclusions in brown olivine are derived from the breakdown of TiCl intergrowths.
Thermodynamic modelling of selected Almirez bulk rock compositions indicates a temperature increase from 635 to 695 °C, at pressures ranging from 1.7 to 2.0 GPa, as the cause for the compositional adjustment of TiCl between the Almirez antigorite serpentinite and chlorite harzburgite. Accordingly, TiCl can be stable in the vicinity of the antigorite serpentinite / chlorite harzburgite phase boundary in some subduction settings. In these circumstances clinohumite-olivine intergrowths in chlorite harzburgite may act as a sink for HFSE, and probably other elements, that are present in mantle-wedge fluids.

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THE HYPOTHESIS OF VOLUME-CONSERVATIVE SYMPLECTITIZATION OF HIGH-PRESSURE PHASES DURING RETROGRESSION OF ECLOGITES: EXAMPLES AND IMPLICATIONS

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We found compelling microtextural evidence to hypothesize that, in a reference frame of inert markers, growth of symplectites at the expense of high-pressure phases of eclogites are volume-conservative reactions, as suggested by CARLSON & JOHNSON (1991). Since symplectites are less dense than the phases they replace, a first order prediction of the above-formulated hypothesis is that net export of substance should always accompany their growth. In order to estimate possible petrological implications, we calculated local mass balances of symplectitization of omphacite, kyanite and garnet from selected retrogressed eclogites from the South Carpathians of Romania and the Western Gneiss Region of Norway. In this contribution, we focus mainly on the breakdown of omphacite. Our case studies reveal that, unlike other models, isochoric breakdown of omphacite to jadeite-poor clinopyroxene–plagioclase symplectites does not require contribution of other reactants. During this process, variable amounts of excess Si, Na, Mg, Fe and Ca, and only trace amounts of Al may leave the reaction front, implying a release of substance equivalent of up to 10 - 11 wt% of the consumed omphacite. Our results explain why extensive breakdown of omphacite to clinopyroxene–plagioclase symplectites may occur even in the simplest bimineralic eclogites, in which garnet may remain largely unaltered. Isochoric breakdown of kyanite to spinel–plagioclase symplectites needs input of Ca, Mg, Fe and trace Na, and eliminates Si and Al. This process results a net loss of substance equivalent of up to 10 wt% of the replaced kyanite. The breakdown of garnet to amphibole–plagioclase symplectites requires input of Na and H, and releases Si, Fe, Mg, Al and trace amounts of Ca, implying a net weight loss of up to 20 – 23 %. The eclogites we studied do not show any evidence for complementary reactions able to consume the excess substance released during symplectitization. Therefore, we infer that in these cases excess substance had to be expelled either to local veins or to the host rocks of the eclogitic bodies. We estimate that the breakdown of omphacite exerts major control on the composition of substance released during isochoric retrogression of eclogites, and could be responsible for various reactions, like albitisation that affects some felsic rocks in contact with these eclogites. Emphasizing, that volume-conservative symplectitization is an allochemical non-equilibrium thermodynamic process (e.g. JOHNSON & CARLSON, 1990, ASHWORT & CHAMBERS, 2000), we warn against using implied phases in geothermobarometry.

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GARNET-PHLOGOPITE WEBSTERITE XENOLITHS FROM THE PAMIR: SHALLOW MAFIC CUMULATES METAMORPHOSED AT HIGH PRESSURES, POTENTIAL SOURCES FOR (ULTRA)POTASSIC MELTS

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Rare garnet-phlogopite websterite xenoliths (hereafter "websterites") were found in an 11 Ma ultrapotassic diatreme from the southeastern Pamir that hosts a suite of dominantly K-rich eclogite and granulite xenoliths (HACKER et al., 2005). Understanding the websterites may contribute to revealing the nature of the deeper lithosphere beneath the Pamir and the sources of collision-related central Asian Cenozoic (ultra)potassic magmatism. The websterites equilibrated at 2.7 – 4 GPa and 950 – 1100 °C. Major and trace element geochemistry along with Nd and O isotopic data suggest that their protolith might have been a shallow, anhydrous mafic cumulate. The websterites preserve original major and compatible trace-element contents almost identical to those of pyroxenite cumulates from the Hustad igneous complex of the Western Gneiss Region of Norway (AUSTRHEIM et al., 2003). Their enrichment in volatiles and incompatible trace elements, including the formation of phlogopite, may be ascribed to interaction with K-rich fluids derived from surrounding felsic rocks. These results suggest that the websterites are parts of a subducted crust of which less refractory components, tonalites and metapelites, underwent high-pressure dehydration partial melting, producing residual sanidine eclogites and granulites (HACKER et al., 2005). In order to predict the fate of websterites exposed to further thermal relaxation, we conducted a series of calculations using the Adiabath_1ph program (SMITH & ASIMOW, 2005) running the thermodynamic database of GHIORSO et al. (2002). Isobaric dehydration melting calculated at 3 – 4 GPa yielded mainly (ultra)potassic liquids with major- and trace-element patterns resembling those of Tibetan (ultra)potassic lavas. Our calculations show that at the onset of melting websterites have mantle-like densities, whereas their melting residua at >3.5 GPa become progressively denser and are prone to foundering. The source region of much of the post-collisional (ultra)potassic lavas related to the India-Asia collision might have been dominated by phlogopite-enriched mafic crustal rocks similar to the websterites discussed here, rather than by K-metasomatized lithospheric mantle as previously suggested.

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MULTISTAGE METASOMATISM IN ULTRAHIGH PRESSURE MAFIC ROCKS FROM THE NORTH DABIE COMPLEX (CHINA)

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We present a petrologic and geochemical study of ultra-high pressure (UHP) rocks from the Northern Dabie Complex (China). The investigated samples are eclogites s.l. included in meta-lherzolitic bodies, which are in turn enclosed by leucocratic gneisses. The textural relations among the various rock-forming minerals enabled us to identify several recrystallisation stages. The peak (UHP) association is a garnet-clinopyroxene-rutile paragenesis. UHP garnet and clinopyroxene display segregations of polycrystalline rods of rutile+ilmenite and of albite, K-Ba-feldspar and quartz, respectively. Post peak parageneses correspond to ilmenite + amphibole, stable at HP conditions, and granulite-facies coronas around garnet. The bulk-rock major and trace element compositions of this eclogites indicate basaltic rocks with MORB and E-MORB affinity as protolith. Compared with such basalts, the studied rocks show strong depletion in SiO_2 and alkalis and enrichment in MgO and FeO, likely indicating an element exchange with ultramafic rock systems. On the other hand, the trace element compositions of the bulk rocks show strong enrichment in Cs, Ba and Pb, associated with moderate enrichment in Rb, K and Th. The same characteristic enrichment and fractionation is recorded by peak metamorphic clinopyroxene. Therefore, the bulk rock and mineral trace element patterns indicate influx of crustal fluids during subduction. Because retrograde amphibole and clinopyroxene does not show such features, the metasomatism must have occurred prior to or during UHP metamorphism.

The observed features in the studied eclogites provide evidence for two stages of metasomatism. The first stage features the income of Si-undersaturated and Mg-rich fluids, a process that likely occurred under low-grade metamorphic conditions, and possibly related with the serpentinization of the associated lherzolitic rocks (SCAMBELLURI & RAMPONE, 1999; YANG, 2003). A second stage of metasomatism was accompanied by the influx of crustal fluids transporting LILE and light elements. This stage likely record the tectonic coupling at HP to UHP with the associated crustal rock units and provides insight into the trace element mobility in deeply subducted crustal rocks.

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TRACE ELEMENT TRANSFER IN THE MANTLE WEDGE: EVIDENCE FROM POLYPHASE INCLUSIONS IN GARNET-PYROXENITES (DABIE-SHAN, CHINA)

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Ultra-high pressure (UHP) rocks are unique natural observatories on fluid-related metasomatism at subduction zones. We investigated garnet-pyroxenites from the Maowu ultramafic complex (China) that experienced UHP metamorphism. The pyroxenites are characterised by a peak assemblage of millimeter-sized orthopyroxene (opx_2), inclusion-rich garnet, and minor clinopyroxene, associated with discontinuous layers of titanian-clinohumite. Rounded blebs of relic olivine and orthopyroxene (opx_1) are included in poikiloblastic opx_2. Orthopyroxene has high Mg# (93 - 94) and garnet is pyrope-rich (70 – 73 %), indicative of ultramafic rocks. Low CaO (0.03 - 0.09 wt%) and Al_2O_3 (< 0.1 wt%) in orthopyroxene coexisting with clinopyroxene and garnet are in agreement with previously determined peak conditions of 750 °C and 40 – 50 kbar (LIOU & ZHANG, 1998). Relic olivine included in opx_2 with high Ni content (1729 – 5658 ppm) suggests olivine dissolution and orthopyroxene precipitation during percolation of siliceous agents at UHP conditions. Laser Ablation ICP-MS analyses show that opx_2 is enriched in LREE with respect to opx_1. The garnet REE pattern also shows a relative enrichment in LREE. This indicates that garnet and opx_2 growth was induced by the influx of a SiO_2 and Al_2O_3 rich melt characterised by high LREE content. Polyphase primary inclusions occurring at the core of garnet display negative crystal shapes and constant volume proportions of infilling magnetite (10 - 20 vol%), chlorite, amphibole, spinel and apatite. Separated inclusion-rich garnets were run in a piston cylinder experiment at 900 °C and 35 kbar. After the run, the primary inclusions were all homogeneised and contained porous SiO_2-rich quench indicating that garnet originally trapped solute-rich aqueous fluids. The trace element patterns of the quench material are generally enriched in LILE and LREE with respect to the host garnet. They also show positive spikes of Cs, Ba, and Pb relative to Rb and K and high U/Th ratios. The observed features indicate that the studied samples were harzburgites that reacted with a hydrous silicate melt derived from a crustal source at UHP conditions, to form orthopyroxene + garnet + residual fluid. The signature of this fluid is very similar to what is regarded as the "subduction component" in arc lavas. This study provides for the first time direct insights on crust-to-mantle wedge transfer of trace element at sub-arc depths.

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TECTONIC PRESSURES: A REVIEW OF PRINCIPLES AND APPLICATIONS

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Rocks in the earth are not perfect fluids at rest. The question is therefore not if pressures are non-lithostatic, but rather if deviations from lithostatic pressure are geologically significant. For tectonic models requiring information on the burial and exhumation history, it is the conversion of pressure (usually estimated from petrological "geobarometry") to depth that is critical and therefore the magnitude of tectonic over- or under-pressure. However, for many other applications (e.g. fluid flow, pressure solution, accumulation of melt), the spatial gradient in pressure is actually more important. Tectonic effects can produce horizontal gradients on the local or regional scale and even reverse the normal vertical pressure gradient (CONNOLLY & PODLADCHIKOV, 2004). This has significant effects on fluid flow and on the driving forces for lateral and vertical extrusion. Discrete rheological boundaries, e.g. across bedding or a porphyroclast, produce correspondingly discrete jumps in pressure, with effectively infinite pressure gradients. The effects of deformation on pressure will be considered in terms of: (1) general effects due to deviatoric stress of a flowing material or a material at failure; (2) effects due to geometrical constraints, e.g. a confined subduction channel or extrusion between rigid indentors (MANCKTELOW, 1995); (3) effects due to rheological boundaries and layering, e.g. inclusions, folds, or boudins; and (4) feedback effects in the deformation of rocks with pressure-dependent rheology, such as Mohr-Coulomb fracture. Considering magnitudes, for brittle failure or frictional slip on an existing fault, the effective pressure during crustal shortening under incompressible plane strain conditions is twice the lithostatic pressure due to the vertical load (PETRINI & PODLADCHIKOV, 2000) and 2/3 of lithostatic pressure for crustal extension. This is the basic reason why brittle normal faults extend deeper into the crust than thrusts (SIBSON, 1974). For viscous behaviour, the increase or decrease in pressure is equal to half the differential flow stress (MANCKTELOW, 1993). For layered viscous materials the increase or decrease in pressure is on the order of the deviatoric flow stress in the competent layer but varies in time and space during heterogeneous deformation, e.g. during folding or boudinage of a layer. Significant tectonic over-pressure can also develop in the matrix between converging limbs as folds become tight to isoclinal.

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EVIDENCE OF MULTI-STAGE METASOMATISM OF CHLORITE-AMPHIBOLE PERIDOTITES FROM TRACE ELEMENT COMPOSITIONS OF HYDROUS PHASES (ULTEN ZONE, ALPS)

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Peridotites from the Ulten Zone (Upper Austroalpine Domain, Central-Eastern Alps, Italy) outcrop as small lens-shaped bodies within high grade Grt-Ky gneisses and migmatites basement rocks belonging to the Tonale Nappe. Several lenses record a complex metamorphic history and display progressive transformation of spinel peridotites to garnet-amphibole peridotites. Previous trace element studies have shown that the garnet-amphibole peridotites have a geochemical signature compatible with the influx of crustal-derived fluid. These features have been interpreted by entrapment of mantle wedge peridotites by subducted continental crust.

We have investigated in detail the evolution of chlorite-amphibole peridotite lenses. Chlorite is generally closely intergrown with Cr-spinel, indicating that it grew at the expense of former Al-spinel. No garnet relics or chlorite pseudomorphs after garnet have been found. This suggests that the investigated lenses never equilibrated in the garnet-peridotite stability field. On the basis of textures, major and trace elements, three generations of amphibole can be distinguished. The youngest amphibole is a tremolite in equilibrium with chlorite and displays LREE and incompatible element enrichment, with positive anomalies in Cs, Ba, Pb and U, and strong LREE-HREE fractionation. Relics of pargasitic hornblende display a less pronounced enrichment of incompatible elements and a flat HREE pattern indicating that it did not coexist with garnet. We suggest that this amphibole formed in equilibrium with Al-rich spinel, prior to the formation of chlorite. Some of the amphibole and orthopyroxene relics display a positive Eu-anomaly and LREE enrichment. This feature is also present in the bulk rock composition and suggests that the rocks experienced a previous metasomatic event in the plagioclase peridotite field. A probably even older type of relic pargasite is characterised by flat Th/U and Rb/Ba ratios and by negative Sr and Pb anomalies and might be related to this earliest metasomatic event.

The new results indicate that there have been three stages of metasomatism of the mantle rocks. We propose that the earliest stage represents melt impregnation of plagioclase peridotites and is unrelated to subduction. The metasomatism leading to spinel and chlorite-amphibole peridotites is related to the progressive influx of a fluid with crustal signature derived from neighbouring subducted continental crust as the mantle wedge peridotites approach the slab. The observation that garnet and chlorite peridotites, which never passed through the garnet stability field, are hosted within the same gneisses, suggests that slices of mantle wedge peridotite with different P-T trajectories can be sampled by subducted crust.

ECLOGITES FROM THE CHUACÚS COMPLEX IN CENTRAL GUATEMALA: EVIDENCE FOR SUBDUCTION OF CONTINENTAL CRUST AT THE CARIBBEAN – NORTH AMERICAN PLATE BOUNDARY

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Eclogites from the Cretaceous (?) Chuacús complex in the Baja Verapaz region of central Guatemala occur as pervasive concordant bands ~0.5 m thick within epidote-amphibolite-facies felsic gneisses. Regional association of the eclogites with Grt-Ky Qtz-micaschist, semi-pelitic gneisses, marble and quartzite positively indicate a continental origin for this high-pressure complex. Eclogites are fine-grained and granoblastic, and their peak-pressure assemblage consists of garnet + omphacite + amphibole + phengite + rutile + quartz. Abundant omphacite ($Jd_{22-32}Aeg_{3-7}Aug_{60-78}$) crystals are well preserved; few were retrograded to symplectites of amphibole + albite along grain boundaries. Garnet is mainly an almadine-grossular solid solution ($Alm_{50-55}Pyr_{11-14}Sps_{3-7}Grs_{26-30}$) and occurs as fine-grained crystals in the matrix. Abundant amphibole is mainly pargasite with 0.47 - 0.53 X_{Mg} and 0.44 - 0.51 $^{[B]}$Na pfu. Rutile occurs as matrix mineral generally mantled by titanite; rutile inclusions also occur within omphacite, garnet and amphibole. Phengite (3.3 - 3.4 Si pfu) occurs as anhedral crystals in equilibrium with garnet and amphibole. Retrogression minerals are albite + garnet (rims) + titanite (mostly mantling rutile cores) + biotite. Albite grew from omphacite and formed poikiloblastic grains containing relics of garnet and amphibole. Country rock gneisses and pelitic schists chiefly contain phases formed during the epidote-amphibolite-facies retrogression event. Nevertheless scarce rutile and omphacite relics demonstrate that these lithologies were also subjected to eclogite-facies metamorphism. Grt-Cpx-Phe geothermobarometry of eclogites suggests peak conditions at 700 – 750 °C and 2.2 - 2.5 GPa, which indicates that Chuacús continental rocks were subducted to depths of ca. 75 km. Deeper subduction consistent with UHP conditions has been suggested based on petrographic features (ORTEGA-GUTIÉRREZ et al., 2004), but index UHP phases have not been confirmed in the Chuacús complex. Our ongoing research on minerals included in zircon by micro-Raman spectroscopy will help to clarify this issue.

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GENESIS OF DIAMONDS AND DIAMONDIFEROUS ROCKS FROM THE SAXONIAN ERZGEBIRGE, CENTRAL EUROPE

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Since the discovery of microdiamond in the Gneiss-Eclogite Unit of the central Saxonian Erzgebirge, an exposed basement unit of the NE Variscan orogen, in 1997 (MASSONNE, 1999), this mineral and the hosting and surrounding quartzofeldspathic rocks have been investigated by several analytical methods involving EMP, SEM, XRF, ICP-MS, and other mass spectrometric methods. The results of the corresponding studies have led to the subsequent genesis model for the Saxonian diamonds and the Variscan crust in which the microdiamonds were found.
The protoliths of the diamondiferous rocks were pelitic rocks not older than 395 Ma. These rocks probably contained biogenic carbon which crystallized to diamonds during an ultrahigh pressure (UHP) event according to the $\delta\ ^{13}C$(PDB) values of diamond around -28 ‰. The earliest (close to 340 Ma) metamorphic stage of the diamondiferous rocks is recorded by inclusions in cores of garnet and zircon, among them is jadeitic pyroxene, pointing to P-T conditions of about 18 kbar and 600 °C. These conditions can be related to the base of a thickened continental crust. Crustal thickening resulted from the collision of Gondwana and Laurussia which might have started already in Devonian times. It is believed that after extended crustal thickening portions from the lower continental crust were involved in delamination of the underlying continental lithosphere (MASSONNE, 2005) sinking deep into the mantle. Thus, the diamondiferous rocks were buried possibly to depths of 200 km or more due to the find of a nanocrystal of TiO_2 with α-PbO_2 structure (HWANG et al., 2000). During burial, these rocks were partially molten by heating to $\geq$ 1100 °C. Afterwards, they quickly ascended and intruded the continental crust 336 Ma ago. During rise and cooling, garnet, kyanite, and zircon crystallized early enclosing microdiamonds which had formed from the partial melt as well (MASSONNE, 2003). In addition, melt was included in garnet to crystallize to microdiamond, quartz, feldspars and various micas (STÖCKHERT et al., 2001). Final crystallization of the diamondiferous rocks occurred at about 15 kbar and 750 °C leading to abundant muscovite and some K-feldspar as late magmatic phases. In the lower continental crust these massive igneous rocks formed little homogeneous bodies and remained undeformed even after subsequent exhumation. The surrounding rocks, garnet-bearing HP gneisses, are richer in SiO_2 and show different trace element signatures compared to the diamondiferous rocks. Thus, these gneisses cannot be derived from the diamond-bearing rocks due to tectonic processes. Relatively SiO_2-rich eclogite boudins in the vicinity of the diamondiferous rocks show, in fact, features similar to these rocks but it is not clear yet if they have experienced a similar P-T evolution.

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PEAK TEMPERATURE VARIATIONS OF THE ECLOGITE IN THE SOUTHERN ELCOGITIC MICASCHIST COMPLEX OF THE SESIA ZONE, ITALY

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This paper briefly introduces the relationship between the peak temperature variation of the eclogite and the geological structure in the Orco Valley area (3 x 5 km^2) in the southern part of the Eclogitic Micaschist Complex of the Sesia Zone. The study area covers the northern slope, up to Frassinetto (~ 1000 m altitude) and the southern slope, up to the road cut between Alpette and Cuorgnè (~ 450 and 1000 m altitude) of the Orco Valley between Pont Canavese and Cuorgnè (~ 400 and 500 m altitude). In the northern slope, the general strikes are EW-trending and dipping 40 – 70 ° N. Along the Orco Valley, the general strikes are still EW-trending but the dipping becomes almost vertical. In the southern slope, the NS-trending antiform and synform with ca. 1 km wavelength is developed. These data suggest following two structural models; A) Structural discontinuity exists along the Orco Valley, B) the NS-trending antiform and synform in the southern slope is overprinted by regional EW trending antiform and synform. In both cases, lower elevation area of the northern slope, around St. Maria area, (~ 450 - 550 m altitude) is situated lower most horizon in the study area.

In the southern slope, lawsonite-bearing rocks and eclogite intercalate each other. Our textural study suggests the lawsonite was formed during the prograde metamorphism. However, lawsonite is not found along the Orco Valley and in the northern slope, where eclogitic rocks are predominant, i.e. lawsonite-disappearance isograd can be defined in the study area.

Eclogite in the study area is mainly composed of garnet, omphacite, glaucophane, epidote, paragonite, phengite, quartz, titanite and rutile, except for St. Maria eclogite, which lacks epidote and titanite as matrix phases. Omphacite shows homogeneous composition in each eclogite. Garnet generally shows a prograde type zoning with an increase of Mg# (= Mg/(Mg + Fe)) and a decrease of Mn from the core to the rim, with almost constant Ca and homogeneous rim compositions in most of eclogite. Garnet rim and omphacite pairs give following temperatures, using POWELL (1985) geothermometer; Frassinetto, Pont Canavese and Alpette eclogites give almost identical temperatures, 482 ± 14, 494 ± 11 and 503 ± 22 °C at 15 kbar, respectively. St. Maria eclogite gives significantly higher temperature, 550 ± 18 °C at 15 kbar, than the other eclogite. In the northern slope of Orco Valley, peak metamorphic temperature increases from ca. 480 °C at Frassinetto to ca. 550 °C at St. Maria, suggesting the metamorphic grade gradually increases with descending structural level. However, the relationship between the metamorphic grade and geological structure is still ambiguous in the southern slope of the Orco Valley.

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ZIRCON GEOCHRONOLOGY AND REE GEOCHEMISTRY, NORTH QAIDAM UHP TERRANE, NORTHWEST CHINA

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Amphibolite-facies felsic gneisses near Dulan, at the southeast end of the North Qaidam Mountains, enclose minor (<10 vol%) eclogite, peridotite and pyroxenite (± garnet) which record ultra-high pressure (UHP) metamorphism. Field relations and the presence of coesite inclusions in zircons from paragneiss suggest felsic, mafic, and ultramafic rocks all experienced UHP metamorphism and a common amphibolite-facies retrogression. Cathodoluminescence (CL) and SHRIMP-RG U/Pb and REE analyses of zircons from two granitic orthogneisses indicate magmatic crystallization at 932 ± 9 and 919 ± 7 Ma (all ages are $^{238}U/^{206}Pb$, ^{207}Pb corrected for common Pb, except as noted). Zircon cores from two paragneisses yield discordant Early Proterozoic $^{207}Pb/^{206}Pb$ ages (up to 2.5 Ga), and are probably of detrital origin; zircon rims contain Grt, Rt, and Phe inclusions, very low Th/U, high U, low REE abundances, and Eu anomalies are small or absent, suggesting eclogite-facies growth at 418 ± 3 and 411 ± 3 Ma. Two fresh eclogites contain zircon with inclusion-rich CL dark cores, and rounded, inclusion-poor, medium CL rims. Analyses of cores (partial overlap on rims) yield moderate to high Th/U and U, and ages up to 475 Ma, which places a minimum age constraint on eclogite protolith crystallization; Ab and Th + REE-rich Ep inclusions suggest greenschist- or epidote-amphibolite-facies growth. The rims contain Grt, Omp, Rt, and Phe, yield low Th/U, moderate to high U, and weighted mean ages of 449 ± 3 and 440 ± 4 Ma, reflecting eclogite-facies growth. Two retrogressed eclogites contain inclusion-poor zircon with CL bright, mottled cores (± faint oscillatory zoning; Grt, Omp and Rt inclusions) surrounded by irregular, CL dark rims characterized by low Th/U, and very low U, which yield weighted mean ages of 421 ± 5 and 415 ± 12 Ma. Amp and Pl inclusions in the rims suggest the measured ages may reflect retrogression. Two garnet amphibolites contain zircon with medium CL, oscillatory zoned, moderate Th, U cores surrounded by bright CL, low Th, U rims. Discordant ages from both cores and rims define ~440 Ma lower intercepts, and 1.9 – 2.4 Ga upper intercepts. Variable REE patterns suggest decoupling of the Pb and REE systems, and indicate the importance of both zircon recrystallization and new growth in these samples. The spread in metamorphic ages (449 - 411 Ma) is probably too large to be explained by a single metamorphic event, and suggests that mafic enclaves record polymetamorphic / tectonic histories prior to their incorporation in the surrounding gneisses. The association near Dulan of metamorphosed Middle Proterozoic granites with paragneisses containing Early to Middle Proterozoic detrital zircon cores is very similar to rock associations in HP/UHP localities 400 km NE, near Da Qaidam, and on the NE side of the Altyn Tagh fault, in the south Altyn Mountains near Bashiwake, supporting the proposed correlation of these localities in a HP/UHP belt.

DATING OF UHP METAMORPHISM, NE GREENLAND CALEDONIDES

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Obtaining reliable estimates for the timing of eclogite facies metamorphism is critical to establishing models for the formation and exhumation of high pressure and ultra-high pressure (UHP) metamorphic terranes in collisional orogens. The presence of pressure dependant phases such as coesite in metamorphic zircon is generally regarded as evidence that the zircon growth occurred at UHP conditions and, if dated, should provide the necessary timing information. We report U-Pb SHRIMP ages and REE SHRIMP data from coesite-bearing zircon suites from two samples in the North East Greenland Caledonides. The samples were collected from kyanite eclogites and quartzofeldspathic gneisses that enclose them exposed on an island in Jokelbugt (78° 00' N, 18° 04' W), NE Greenland. Kyanite-eclogite yielded round zircons with well defined growth domains observed in cathode-luminesence (CL) images. Low U cores (U = 1 - 85 ppm; Th/U = 0.004 - 0.055) contain an inclusion suite of kyanite-clinopyroxene-garnet-rutile. $^{206}Pb/^{238}U$ ages corrected for common Pb by the ^{207}Pb method yield a weighted mean age of 359 ± 8 Ma (MSWD = 2). REE patterns from cores are uniform and display negative Eu and positive Ce anomalies. A second core domain has an inclusion suite of coesite-kyanite-clinopyroxene-garnet-rutile and U=10 - 243 ppm, Th/U = 0.003 - 0.013. This domain yields a $^{206}Pb/^{238}U$ weighted mean age of 347 ± 4 Ma (MSWD = 3). REE patterns are more variable in this domain. The positive Ce anomaly persists but the Eu anomaly does not. Zircon rims with U = 39 - 333 ppm and Th/U = 0.006 - 0.095 yield a $^{206}Pb/^{238}U$ weighted mean age of 342 ± 3 Ma (MSWD = 2). The rim REE patterns are more uniform with no Eu anomaly. A sample of quartzofeldspathic gneiss yielded a population of round zircons that exhibit multiple CL domains as well. Zircon cores with U = 159 - 324 ppm and Th/U = 0.14 - 0.33 give $^{206}Pb/^{238}U$ ages ranging from 360 to 1414 Ma. Regression of the ^{204}Pb-corrected data yields an upper intercept age of 1973 ± 35 Ma (MSWD = 1), the inferred protolith age. REE patterns with positive Ce and negative Eu anomalies are consistent with an igneous origin. There is clear evidence in CL images for recrystallization of the core regions as well as growth of distinct rims. In addition, some low U zircon grains may be entirely metamorphic in origin. Lower U core and rim domains with U = 2 - 73 ppm, Th/U = 0.004 - 0.047, and a coesite-clinopyroxene-garnet inclusion suite give a $^{206}Pb/^{238}U$ weighted mean age of 357 ± 5 Ma (MSWD = 2). REE patterns are variable in the low U core regions but uniform in the rims; Ce and Eu anomalies are present in all REE analyses. Results from the suite of samples analysed demonstrate that variation in U/Pb age and REE patterns match the variation in domains defined by CL image analysis. Both zircon recrystallization and new zircon growth occurred during UHP metamorphism. The variation in U-Pb ages from coesite-bearing zircon in the 3 samples examined indicates that UHP metamorphism had occurred by 360 and persisted at least through 350 Ma.

ECLOGITES IN PERIDOTITES, WESTERN GNEISS REGION, NORWAY: CHARACTERISTICS AND ENIGMATIC Sm-Nd RESULTS

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Eclogites in ortho- and paragneisses of the Western Gneiss Region (WGR), a.k.a "country-rock" or "external" eclogites, yield Sm-Nd grt-wr-cpx and U-Pb zircon ages of 400 - 420 Ma and document Scandian high-pressure (HP) metamorphism in the WGR. Eclogites also occur within WGR peridotites near their margins and are referred to as "internal" eclogites. Such eclogites are compositionally distinct from external ones, yield significantly older Sm-Nd ages, and introduce additional complexity in interpretation of the geological evolution of the WGR.

Internal eclogites have a wide range in composition, *e.g.*, SiO_2, 40.4 - 52.7 wt%; Fe-number, 25.4 - 85.1, and include both *ne*- and *hy*-normative types. The large degree of scatter in element compositional plots and common mineralogical layering indicate that such eclogites do not represent melt compositions, thus precluding their use in petrotectonic modelling. The internal eclogites contain a HP assemblage of grt + omp + rt ± am ± ilm ± ap, in which some garnet grains show prograde compositional zoning and many contain inclusions of Al-rich amphibole. Minimum temperatures and pressures for the eclogite assemblage are 660 - 765 °C and 12.2 - 18.1 kbar, based on Fe-Mg partitioning between grt and cpx and the Jd content of cpx.

Sm-Nd mineral isochrons for internal eclogites yield pre-Scandian, but widely scattered, ages of 574 ± 38 Ma, Raudkleivane, Almklovdalen; 997 ± 33 Ma, Eikremsaeterfoss, Almklovdalen; 888 ± 37 Ma, Raubergvik (BRUECKNER & MEHTA, this study), and 599 ± 42 Ma, Gurskebotn (JAMTVEIT et al., 1991). Such ages may record one or more pre-Scandian HP events, hints of which are found in some external eclogites. Alternatively, the ages may be spurious, resulting from disequilibrium induced by the pervasive influx of fluids from surrounding gneisses into the margins of the peridotite bodies. Biotite in a retrograded, K-metasomatized eclogite yields a nearly concordant $^{40}Ar/^{39}Ar$ plateau age of 524 ± 2 Ma. However, the isochron suggests that excess argon may comprise ≥ 20 % of the ^{40}Ar, thus we infer that this apparent age does not constrain the cooling history of the internal eclogites. $^{40}Ar/^{39}Ar$ age spectra from amphibole in two retrograded samples indicate cooling to 500 °C by 446 ± 2 and 411 ± 5 Ma, consistent with Silurian-Devonian ages determined regionally.

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TECTONIC EVOLUTION OF THE NORTH QAIDAM UHP TERRANE

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The North Qaidam ultra-high pressure (UHP) metamorphic belt is a recently discovered UHP terrane (YANG et al., 2001), located within the Early Paleozoic Qilian orogenic belt on the northern margin of the Tibetan Plateau, Western China. The orogen preserves a Precambrian to Mesozoic history of continental rifting, ophiolite emplacement, arc convergence and continental collision. Three fundamentally different models have been proposed: (1) an early Paleozoic mega-accretionary complex, where the site of arc magmatism migrated progressively southward (SENGOR & NATAL'IN, 1996), (2) north-dipping subduction by a series of micro-plates (e.g. LI et al., 1978), and (3) a shallowing south-dipping subduction zone (e.g. GEHRELS et al., 2003). Each model makes predictions about timing of subduction, number and polarity of subduction zones, which can be tested in the context of the formation and exhumation of the UHP rocks. Pre-Mesozoic rocks can be divided into two units: (1) epidote-amphibolite grade late Proterozoic rocks (Dakendaben gneiss) which include the UHP eclogite-bearing gneiss, and (2) a suite of early Cambrian (545.5 ± 6.0 Ma) epidote-amphibolite facies ophiolitic rocks. The contact between the ophiolite and UHP gneiss is sharp but irregular; marked by discrete shear zones with top-N and top-NE sense shear indicators which become subhorizonital when the effects of Cenozoic thrusting are removed. This detachment is also isoclinally folded at a wave-length of 15 - 20 km, exposing UHP eclogite-bearing gneiss in the cores of antiforms. Middle Paleozoic granites (510 - 400 Ma, GEHRELS et al., 2003) intrude the belt placing a lower bound on the cessation of the ductile phase of deformation. Regional muscovite cooling ages of 460 - 365 Ma indicate that the metamorphic complex reached the middle crust in the Ordovician and a Devonian unconformity indicates that it was at the surface by ~365 Ma. Early Cenozoic imbricate thrust faults placed UHP rocks over unlithified Tertiary sediments of the Qaidam Basin and generated broad regional folding and repetition of UHP units. Results indicate generation of UHP rocks by the closure of a small back arc ocean behind a more established arc, favoring a hybrid model consistent with south-dipping subduction (SOBEL & ARNAUD, 1999) and the existence of multiple sutures within the Qilian orogen (LI et al., 1978). Furthermore, preliminary petrologic and geochronologic results indicate that exhumation to the surface occupied two distinct stages: (1) rapid exhumation of the UHP rocks to the lower/middle crust, (2) slow exhumation from the middle crust to the surface.

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TIMING OF ECLOGITE METAMORPHISM IN THE POHORJE MOUNTAINS, SLOVENIA, EASTERN ALPS.

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High-pressure metamorphism in the Pohorje Mountains of Slovenia (Austroalpine unit, Eastern Alps) affected N-MORB type metabasic and metapelitic lithologies. Thermodynamic calculations and equilibrium phase diagrams of kyanite-phengite-bearing eclogites reveal PT conditions of about 2.2 - 2.5 GPa at T= 660 - 720 °C, within the stability field of quartz. The eclogites contain a single population of spherical zircon with a low average Th/U ratio of 0.05. A coherent cluster of single zircon analyses yields a $^{206}Pb/^{238}U$ age of 90.7 ± 1.0 Ma that is in good agreement with Sm-Nd garnet–whole rock regressions of 90.7 ± 3.9 and 90.1 ± 2.0 Ma for two eclogite samples. The agreement between U-Pb and Sm-Nd age data strongly suggests an age of approximately 90 Ma for the pressure peak of the eclogites in the Pohorje Mountains. Inclusions of garnet, omphacite, rutile, magnesio-hornblende and quartz (identified by Raman micro-spectrometry) in unfractured zircon indicate high-pressure rather than ultrahigh pressure conditions. The analysed metapelite sample yields a Sm-Nd garnet-whole rock scatterchron age of 97 ± 15 Ma, supporting a single P-T loop for mafic and pelitic lithologies of the Pohorje area and a late Cretaceous high-pressure event that affected the entire easternmost Austroalpine basement including the Koralpe and Saualpe eclogite type locality in the course of the complex collision of the Apulian microplate and Europe.

THE EQUILIBRIUM REACTION ALBITE = JADEITE + QUARTZ - A RE-EXAMINATION IN PRESENCE OF SMALL AMOUNTS OF H_2O AND AT DRY CONDITIONS

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The breakdown reaction of albite, $NaAlSi_3O_8$ into jadeite and quartz is considered the transition into the regime of high pressure metamorphism. Results obtained by slightly "wet" (HOLLAND, 1980) and dry performed experiments (BELL, 1964) are discrepant. The re-examination was performed with a piston cylinder apparatus using synthetic albite glass as starting material. While in „wet" experiments the sample material was moistened by breathing into the filled capsule, the capsules loaded for dry experiments were heated to 800 °C for 5 hours before welding shut. The reaction was determined by differential pressure analysis (DPA) technique (MIRWALD, 2004) and controlled by additional quench experiments. The preliminary results are displayed in Fig. 1.

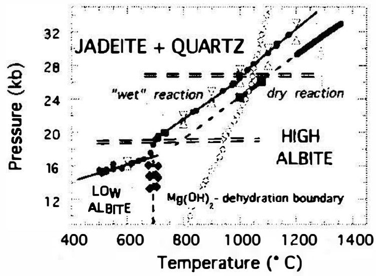

Fig. 1: The breakdown reaction of albite into jadeite + quartz under slightly „wet" and dry conditions.

Although the „wet" data (closed circles) grossly confirm the work by HOLLAND (1980) (open triangles), the detailed work revealed a complex fine-structure of the boundary: a pronounced inflection at 18 kbar / 680 °C including a triple point with the low-high albite transition boundary (closed diamonds), and a further weaker inflection at 27 kbar / 1000 °C. The dry reaction boundary (tick line: BELL (1964); closed squares: this study) determined between 1000 to 1350 °C is located at significantly lower pressures (2 - 3 kbar) indicating that albite is stabilised by H_2O. The inflections of the „wet" breakdown boundary are attributed to two PVT anomaly boundaries of H_2O (double dashed lines). This kind of effects have already been observed at the dehydration boundary of brucite, $Mg(OH)_2$ (open circles) (MIRWALD, 2004).

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DOLOMITIC MARBLES FROM ORGANI AREA IN THE EASTERN RHODOPE ULTRAHIGH-PRESSURE METAMORPHIC TERRANE, NE GREECE

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Dolomitic marbles are interbedded with migmatitic gneisses in the Organi area of the Kimi ultra-high pressure (UHP) metamorphic complex in Greek Eastern Rhodope. The marbles have the mineral assemblage: Cal + Mg-Cal + Dol + Ca-Dol + Ol + Di + Spl + Phl ± Hbl + Ti-Chu + Chl + Srp. Diopside, spinel, phlogopite and pargasitic hornblende are present in minor amounts. Ti-clinohumite, chlorite and serpentine are products of retrograde hydration metamorphism replacing olivine, spinel and phlogopite.

Calcite and dolomite are compositionally heterogeneous, widely ranging in compositions. Compositions in calcite range from almost pure calcite to Mg-calcite with X_{MgCO_3} = 0.13 mol, and in dolomite from pure dolomite to Ca-rich dolomite with X_{MgCO_3} = 0.34 mol. Within a single Mg-calcite grain there are domains of low Mg-calcite (X_{MgCO_3} = 0.00 to 0.03 mol) that are rich in Ca-dolomite inclusions (X_{MgCO_3} = 0.34 to 0.47 mol), and domains of high Mg-calcite (X_{MgCO_3} = 0.10 to 0.13 mol) that are free of inclusions. Calcite-dolomite geothermometry gives a temperature of 1085 °C from the Ca-rich dolomite with X_{MgCO_3} = 0.36 mol and 740 °C from the inclusion free homogeneous Mg-calcite domains with X_{MgCO_3} = 0.13. Textural relationships indicate that the Ca-dolomite inclusions and the low Mg-calcite host are decomposition products of the homogenous high Mg-calcite. The inclusion free domains are relics of the high Mg-calcite, that probably record peak temperatures (~740 °C) of a primarily low to medium pressure metamorphism. Assuming that pure calcite and low Mg-calcite was former aragonite, the association of these phases with Ca-rich dolomite indicates a subsequent UHP-UHT metamorphism for the Organi marbles, like that documented in the neighbouring diamondiferous metapelites.

Minimum pressures of 5 GPa are constrained from graphite-diamond transformation for temperatures of 1085 °C. At 6 GPa, the most Ca-rich dolomite (X_{MgCO_3} = 0.34) inclusions in low Mg-calcite (former aragonite), plot on the dolomite limb of the aragonite-dolomite solvus (BUOB et al., 2002) at 1150 °C. Peak P-T conditions did not cross the reaction curve Arg + Dol→ Mg - Cal. Calculated eutectoid composition of Mg-calcite has X_{MgCO_3} = 0.25 mol at 6 GPa and 0.30 mol at 8 GPa. Mg-calcites with X_{MgCO_3} ranging from 0.25 to 0.30 mol are not present in the dolomitic marbles. Peak P-T conditions for the UHP metamorphism are constrained within the aragonite + Ca-dolomite stability field with most realistic values ~6 GPa and ~1150 °C.

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GARNET-SPINEL METAPERIDOTITES AND SPINEL-GARNET PYROXENITES FROM ORGANI-KIMI AREA IN THE EASTERN RHODOPE ULTRAHIGH-PRESSURE METAMORPHIC TERRANE (N.E. GREECE): IMPLICATION FOR MANTLE PROCESSES IN CONVERGING PLATE SETTING

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In East Rhodope, UHP metamorphism is recorded in crustal rocks of the uppermost Kimi Complex, with peak P-T conditions of ~ 6 GPa and ~ 1150 °C (Mposkos et al., this volume). Boudins of garnet-spinel metaperidotites containing spinel-garnet pyroxenites occur within the UHP crustal rocks near the Kimi and Organi villages. The metaperidotite has the mineral assemblage: Ol + Opx + Cpx + Spl + Grt + Hbl. Grt ($Grs_{13-17}Prp_{58-62}Alm_{22-24}Sps_{1-2}Uv_{1.6-2.3}$) is rarely preserved as inclusions in olivine, orthopyroxene, spinel and hornblende. Two pyroxene and three spinel generations record successive decompression and cooling of the former garnet peridotite. Opx-1 and Cpx-1 contain exsolution lamellae of spinel and clino- and orthopyroxene, respectively Opx-2 and Cpx-2 are exsolution free. Spl-1 with Cr# [Cr/(Cr+Al)] 0.27 - 0.48 forms replacing garnet. Spl-2 (Cr# 0.12 - 0.19) grows around Spl-1, interstitially between Px-2 and as exsolution lamellae in Cpx-1 and Opx-1. Spl-3 (Cr# 0.03 - 0.05) forms symplectites with enstatite + diopside / or hornblende. Spl-Grt clinopyroxenites occur as mm to cm thin layers within the peridotites. They are interpreted as HP cumulates crystallized in the garnet pyroxenite stability field and subsequently deformed and recrystallized at high temperatures and pressures. Pyroxenites contain Grt + Cpx + Spl ± Ol + Hbl + Ilm. Two clinopyroxene generations record post-magmatic recrystallization processes. Cpx-1 shows zoning with decreasing Al_2O_3 from 3.5 wt% in the core to 2.5 wt% in the rim. Garnet lamellae and garnet + spinel lamellae are exsolved from the core of Cpx-1 at two successive stages of cooling and decompression. Cpx-2 is homogeneous and exsolution-free. Cpx2 is similar in composition with the exsolution free Cpx-1 rims.

Due to the continuous change of the chemical composition of the primary minerals during accent and cooling, the record of maximum P-T conditions of the original garnet peridotite is largely erased. Recalculated Cpx-1 and Opx-1 compositions from metaperidotite yielded temperatures and pressures of 1060 °C and 2.2 - 2.5 GPa, respectively. The gradual decrease of Cr# in Spl-1 toward the rim from 0.45 to 0.15, the continuous decrease of the Cr# in the matrix Spl-2, the formation of Cpx and Opx and Spl-2 exsolution lamellae in Opx-1 and Cpx-1 of the metaperidotite and the garnet exsolutions in Cpx-1 of the pyroxenite, indicate successive cooling, and possible decompression within the enlarged garnet-Cr bearing spinel peridotite stability field. Indicators for a possible subduction path are not present in the metaperidotite and pyroxenites. The Grt-Spl metaperidotites and the associated Grt-pyroxenites represent mantle fragments intruded into the crustal rocks during/or after peak pressure conditions during accent.

VARIETY IN CHEMICAL ZONATION OF GARNET IN ECLOGITE FROM NOVÉ DVORY, CZECH REPUBLIC

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Garnet-peridotite body associated with eclogite in Nové Dvory, Czech Republic, belongs to the Gföhl Unit of the Bohemian Massif, and compositional zoning of garnet in eclogite from this body was analyzed. Previous works suggested that most grains of garnet in eclogite of the Gföhl Unit are retrograde type in which Mg# [= Mg/(Fe+Mg)] decreases from core to rim, but the present study revealed that chemical zonation of garnet in some eclogites of Nové Dvory has complex characters.
A kyanite-bearing eclogite (ND6b) contains a large garnet grain (≈5 mm in diameter) which has a chemical zonation of increasing Ca content and slightly decreasing Mg# from core ($Prp_{58}Alm_{21}Grs_{21}$, Mg# = 0.73) to rim ($Prp_{41}Alm_{17}Grs_{42}$; Mg# = 0.71). On the other hand, another part (ND6c) of this eclogite sample contains a large oval-shaped garnet grain of ≈10 mm length which shows a kind of prograde-type zonation: Ca content and Mg# increase from core ($Prp_{51}Alm_{23}Grs_{26}$; Mg# = 0.69) to rim ($Prp_{48}Alm_{16}Grs_{36}$; Mg# = 0.75). These two samples ND6b and ND6c were taken from one specimen, but they contain garnets with different zoning patterns.
Other two types of garnet were found from one thin section of a kyanite-free eclogite sample (ND120). One is prograde-type garnet increasing Mg# from core ($Prp_{29}Alm_{47}Grs_{24}$; Mg# = 0.38) to rim ($Prp_{40}Alm_{38}Grs_{22}$; Mg# = 0.51), and the other is retrograde type decreasing Mg# from core ($Prp_{56}Alm_{25}Grs_{19}$; Mg# = 0.69) to rim ($Prp_{39}Alm_{36}Grs_{25}$; Mg# = 0.52). The compositions of these two types of garnet coincide with each other at rim parts. Retrograde-type zoning is predominant in a large garnet grain (> about 5 mm), and pyrope content of the core reaches about 60 mole%, which is similar content to that of garnet in peridotite. The retrograde-type garnet may have grown in a small peridotite xenolith enclosed within the host basaltic rock. The prograde-type garnet may have grown in the "basaltic" matrix upon increrase in temperature.
Thus, garnet showing prograde-type zonation was newly found from eclogite in Nové Dvory peridotite body that experienced UHP conditions of about 1100 °C, 5 GPa (MEDARIS et al., 1990; NAKAMURA et al., 2004), but different zonation patterns are observed in the same sample. Therefore, it is still questionable whether the Nové Dvory peridotite body has experienced subduction or not before the UHP metamorphism, but a simple decompression and cooling history cannot account for the above complex zonal structures of garnet.

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CHEMENDA-TYPE EXHUMATION DURING NON-STEADY STATE SUBDUCTION: MODEL AND LATE CRETACEOUS EVOLUTION OF EASTERN ALPS

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The Chemenda model (CHEMENDA et al., 1995, EPSL, 132: 225–232) predicts exhumation of previously subducted continental crust metamorphosed at UHP/HP metamorphic conditions mainly driven by (1) buoyancy of subducted material, and (2) associated surface erosion of the subducted wedge. Thrust surfaces in the footwall and a major normal fault in the hangingwall confine, therefore, the uplifting UHP/HP metamorphic wedge. Clastic material mainly derived from the surface of the uplifting subducted wedge fills a flexural sedimentary basin located on top of the lower plate in front of the UHP/HP wedge. A cross-section through an orogen exposes, therefore, the following units: (1) the non-subducted lower plate rocks with a collapse basin at the top, (2) the exhumed, previously subducted wedge with a nappe stack, which is dominated by cover rocks at the leading edge front and exhumed metamorphic, mostly polymetamorphic basement rocks, all metamorphosed at HP/UHP conditions at the rear front – all units were accreted from the footwall plate – and (3) the upper plate with collapse-type basins at top only in the case when extension-induced subsidence exceeds uplift. This is not the case in a setting of steady-state subduction, but in the non-steady state case when retreat of the subduction zone triggers extension in the upper plate unit.

The Austroalpine (AA) basement-cover nappe complex of the Eastern Alps likely represents a superb field example to test the non-steady state Chemenda model. The AA nappe complex received its final internal structure largely by middle–late Cretaceous tectonic processes as subduction of the Piemontais-Ligurian Ocean beneath the AA units started. The Lower AA and lower part of Middle AA basement-cover nappes represent the footwall of the UHP/HP wedge and were accreted to the exhuming UHP/HP wedge at ca. 80 Ma during a pronounced stage of thrusting. The Middle AA Eclogite-Gneiss units represent the exhuming UHP/HP wedge, which was subducted to depths corresponding to ca. 1.0 GPa in the north and max. ca. 3.0 GPa in southernmost exposures (JANAK et al., 2004, Tectonics, 23, TC5014) at ca. 95 - 90 Ma (THÖNI, 1999, Schweiz. Mineral. Petrogr. Mitt., 79, 209–230). Most pronounced exhumation of the HP/HP wedge occurred between 87 and 84 Ma, as cooling ages indicate. In the hangingwall, a series of ductile low-angle normal faults separates the UHP/HP wedge from uppermost Middle AA and Upper AA nappes representing the upper plate. Sinistral, transtensional, normal low-angle faults were most active between 87 - 84 Ma during formation of collapse basins (Gosau basins) on top of the upper plate, which we explain by disturbance of steady-state subduction by oceanward retreat of the subduction zone. The tectonic unroofing of the UHP/HP wedge continuously increased to and was most pronounced at the rear end of the wedge, so that more than 50 km of overburden was cut out.

ELECTRON BACKSCATTERED DIFFRACTION STUDIES ON OMPHACITE FROM THE ECLOGITE ZONE OF THE TAUERN WINDOW, AUSTRIA: IMPLICATIONS FOR THE EXHUMATION OF ECLOGITES IN EXTRUSION WEDGES

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The question how extremely dense eclogites are exhumed in orogens remains a lively debated controversy in tectonics. A widely held opinion is that buoancy is the main driving mechanism and that buoyancy forces lead to the formation of a so-called extrusion wedge, which is bounded by a lower thrust and an upper normal fault. We have tested this hypothesis by studying the deeply exhumed Eclogite Zone in the Tauern Window of the Austrian Alps.
The Eclogite Zone is part of the Pennine nappe edifice of the Tauern Window and is sandwiched between metasedimentary rocks of the Venediger nappe below and ophiolithic rocks of the Glockner nappe above. While maximum pressures in the Venediger and Glockner nappes were 10 – 12 kbar, the Eclogite Zone was subjected to distinctly higher pressures of 20 - 25 kbar. Because the Eclogite Zone is bounded by lower pressure units on both sides it has been proposed that it was exhumed in an extrusion wedge, i.e. it should be bounded by a top-N thrust below and a top-S normal fault above. The validity of this assumption can be tested because the high-pressure textures should have different asymmetries in a profile across the Eclogite Zone. Our approach was to use Electron Backscattered Diffraction measurements on omphacite along N-S profiles across the Eclogite Zone to resolve any systematic differences in the pattern of their crystallographic preferred orientation (CPO). Omphacite shows strong CPO patterns with distinct asymmetries. The sense of asymmetry of the CPO patterns consistently yielded a top-N sense shear and does not change in any systematic fashion. This finding does not support an extrusion wedge interpretation of the Eclogite Zone. Field work shows greenschist/blueschistfacies top-N thrusting at the base of the Eclogite Zone and greenschist/blueschistfacies sinistral strike-slip faulting at the top of the Eclogite Zone. The omphacite CPO patterns together with deformation/metamorphism relationship from the basal thrust zone show that the top-N thrust operated from 80 km up to mid crustal levels. However, the omphacite CPO's at the top of the Eclogite Zone do not show any geometric relationship to the sinistral strike-slip fault. This makes any interpretations as to how the exhumation of the Eclogite Zone was structurally accomplished difficult.

ORIGIN OF ECLOGITE AND GARNET PYROXENITE FROM THE MOLDANUBIAN ZONE OF THE BOHEMIAN MASSIF, CZECH REPUBLIC AND ITS IMPLICATION TO OTHER MAFIC LAYERS EMBEDDED IN OROGENIC PERIDOTITES IN THE WORLD

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Eclogite and related mafic rocks occur as layers or lenses in many mantle derived peridotite masses in orogenic zones in the world. A popular hypothesis for the origin of such mafic layers is that they represent crystal precipitates from mafic magmas flowing in the upper mantle at various depths (SUEN & FREY, 1987). However, some mafic rocks have been suggested to be of gabbroic origin from their geochemical and mineralogical signature such as positive Eu anomaly and the presence of corundum (e.g., KORNPROBST et al, 1990). The primary igneous mineralogy of these mafic rocks has typically been obliterated through subsolidus recrystallization at various metamorphic conditions and, therefore, their igneous origin must be sought through whole rock geochemical signature. I examined a large data base collected from literature on the eclogites and garnet pyroxenites embedded in garnet and spinel peridotites enclosed in the Gfoehl gneiss and granulites, Bohemian massif (MEDARIS et al, 1995; and others). These rocks may be divided into two sub-groups: the magnesian group (Mg# > 70) and the less magnesian group (Mg# < 62). It was found out that the whole rock compositions of the magnesian group lie on a single straight line with a positive slope on the oxide ratio plot – CaO / MgO vs SiO_2 / MgO. It may be shown that the straight line represents a projection of a mixing plane of olivine, An-rich plagioclase and clinopyroxene – the gabbroic assemblage. The well-defined linear relationship led the author to conclude that the magnesian group of eclogite and garnet pyroxenite, some of which contain kyanite, represents metamorphosed gabbros that had precipitated from basaltic magmas at shallower levels in the Earth. To test this hypothesis, this method of oxide ratio plot was applied to mafic rocks from other well-characterized orogenic peridotites such as Ronda (Spain), Beni Bousera (Morocco), and Horoman peridotites (Japan). It was found out that the magnesian group mafic rocks (Type II), including garnet pyroxenites and olivine-gabbroic granulites, all lie on straight lines on the CaO / MgO - SiO_2 / MgO oxide ratio plot. The linear relationship suggest that the observed compositional variation of these mafic rocks is ascribed to modal variations of original gabbroic minerals whose compositions were rather constant for each locality, which in turn suggests that a dominated process in the formation of original gabbros was *not* likely the fractional crystallization of magmas but some other mechanical processes of differentiation such as crystal sorting in magma chambers.

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BLUE JADEITITE FROM SHOGAN, SE IRAN

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In south-eastern Iran the Sanandjan – Sirjan metamorphic belt is divided in an amphibolite facies northern part with Palaeozoic crustal rocks and a southern belt with high-pressure metamorphic coloured mélanges. The separation of the two metamorphic belts is made up by an andesitic volcanic arc sequence, which did not undergo metamorphism and only shows minor alteration effects. The southern belt with high-pressure relics is juxtaposed to a sequence of non metamorphic ultramafic to mafic rocks. ^{40}K-^{40}Ar whole rock ages of gabbros and diabases range from 130 to 140 Ma (GHASEMI et al., 2002).
Within the metamorphic belt two typical associations can be identified. One is composed of series of amphibolites, micaschists, marbles and greenschists, with a metamorphic amphibole age of 202 Ma (GHASEMI et al., 2002). All these rocks underwent a late HP-LT overprint. Green amphiboles often show minute glaucophane rims. The other rock association comprises a coloured mélange composed of glaucophanites, marbles and garnet micaschists in a serpentinitic matrix. Micaschists just north of the Sikhoran ophiolites show metamorphic ages around 80.7 ± 1.5 Ma (GHASEMI et al., 2002). The blueschists show glaucophane, albite, phengite, sometimes lawsonite and rutile. In rare cases omphacitic clinopyroxene was found. Within this metamorphic belt large ultramafic bodies with chromite lenses are wide spread. These mainly dunitic ultramafics contain talc, enstatite, forsterite and antigorite. The associated chromites are rich in kammererite. Along the contacts of the ultramafics to the blueschists, magnesite lenses developed. In one of these magnesite lenses suspicious bluish veins occur. These veins are composed of lavender coloured pure jadeite. Additional phases are winchitic amphibole, lawsonite and Ba-bearing K-feldspar. The jadeitites are relatively rich in Ni and Li. Estimates of P-T conditions indicate pressures significantly higher than published for similar metasomatic rocks with blue jade from Itoigawa-Ohmi in Japan (MORISHITA, 2005).

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RELICS OF HIGH - PRESSURE METAMORPHISM IN THE BITLIS MASSIF (VAN REGION, E TURKEY)

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In south-eastern Anatolia, north of the Arabian Plate, part of the Anatolide-Tauride block constitutes the Bitlis Massif. During Mesozoic and Tertiary times, its palaeogeographic position was in the north, separated from the Arabian Platform by the southern branch of the Neo-Tethys Ocean. It forms an arcuate metamorphic belt, about 30 km wide and 500 km long. The massif is made up of Precambrian to Cretaceous rocks, which rest directly on top of Cretaceous to Eocene flysch and ophiolitic mélanges that are related to the suture between Arabia and Eurasia. Our investigations revealed that this massif has to be considered as a nappe complex.
Similarly to the Menderes massif, old eclogitic rocks, which suffered additionally a granulitic metamorphism, were found in the Kesandere section. These new findings fit well with the former findings by OKAY et al. (1985) and document the complex pre-Mesozoic metamorphic evolution of the Bitlis complex.
Below the Bitlis complex, Cretaceous ophiolitic mélanges occur. Contacts north of the complex, at Gevas, clearly dip southwards. Along this northern contact, glaucophane, relics of carpholite in chloritoid-bearing schists and pseudomorphs after aragonite in marbles document a low-temperature high-pressure (LT - HP) metamorphic evolution. Towards the south, the basal contact re-emerges, overriding Eocene melange sequences. There, contacts dip northwards and fresh carpholite occurring in Triassic marbles also indicates a LT – HP imprint. The lowermost metasediments of the Bitlis complex document a HP evolution. Similarly, some of the underlying Cretaceous and Tertiary meta-olistostromes and mélanges contain low-grade LT – HP metamorphic minerals. It is obvious that the area at the eastern termination of the Bitlis massif was involved in a subduction-related setting. A situation very similar to western Anatolia must be envisaged. The findings of carpholite and other HP minerals in the Bitlis complex add to the plate tectonic scenario of a continuous long-lived suture zone, extending from Western Anatolia (Lycian nappes, Afyon zone, Menderes Massif) to Eastern Anatolia. The present association of low-grade LT – HP continental rocks on top of ophiolitic rocks pleads for a complex bimodal setting. Basement and platform sediments of the promontory of the Arabian continental margin were involved in an accretionary wedge to suffer LT – HP metamorphism and then thrust over ophiolitic members of an oceanic suture.

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HIMALAYAN ECLOGITES, PAKISTAN: AN UPDATE

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The finding of eclogites in the Himalaya, and especially the realization that they are of UHP type, has forced a dramatic change of view regarding the nature of India-Asia collision and the style of subsequent tectonometamorphism. Important details constraining the timing of collision such as: the change in rate of plate motion; the age of the youngest marine sediments in the suture zone; the age of the final magmatism in the arc; initiation of denudation and sedimentation or change in oxygen isotope signal of benthic foraminifera (caused by the disruption of circum-equatorial ocean circulation) were unaffected by the new results. However, tectonic models requiring a shallow angle of subduction to produce the long-recognised inverted metamorphic sequences, recently rejuvenated in a series of papers promoting a channel flow mechanism, are put into question. New field and petrographic studies of eclogites reveal important details critical to the understanding of the evolution of the collision.

The new fieldwork shows a much wider distribution of eclogites than previously realised. The eclogites sit as part of a continental sequence (basement gneiss, meta-granite, metasedimentary cover) thus emphasizing the fact that it is the Indian Plate that was subducted to UHP conditions. The age of UHP metamorphism (dating of coesite-bearing zircon), combined with dating of retrograde and even final shallow-depth cooling (by fission track methods) indicates both rapid subduction and exhumation at rates of several cm / a. This short-term ‚dunk' to mantle depths is reflected very clearly in the fine-grained nature of most preserved eclogites. Garnet grains are mostly 0.2 - 0.5 mm in diameter but are still compositionally zoned. Clearly, the number of nuclei, and their size, is a direct reflection of the rapid overstep of the reaction boundary and the short time for the whole of the growth process. The fine-grained nature of these eclogites may be one of the reasons it took so long to identify them. The information from eclogites in Pakistan is perfectly compatible with what is known from NW Indian UHP eclogites and confirms that the subduction-controlled processes of the India-Asia collision probably lasted until about 40 Ma by which time these units had undergone amphibolite and greenschist facies overprints and were at shallow depths. This part of the history of the India-Asia collision is totally separate in style from the subsequent thickening-related Barrovian followed by HT metamorphism. The change from steep to low-angle subduction, as already pointed out with the discovery of coesite eclogites in 1998, is most likely related to a slab breakoff process that may be thus critical in allowing the subsequent shallow-angle underthrusting of the leading edge of the Indian Plate to cause crustal thickening. In this sense, deep continental subduction, UHP metamorphism and slab breakoff are necessary precursors for the channel flow mechanism and thus explain the time gap between the eclogite facies metamorphism in the NW Himalaya (the first part of India to collide) and the crustal-type metamorphism in the central part of the Himalaya.

CHARACTERIZATION OF MICRODIAMONDS IN PELITIC GNEISSES FROM THE KOKCHETAV MASSIF, KAZAKHSTAN – WHY NO 2nd STAGE GROWTH?

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Abundant microdiamond occurs in dolomite marble and pelitic gneiss in the Kokchetav UHPM terrane, northern Kazakhstan. In the dolomite marble, microdiamonds have been classified into three types (S-, R- and T-types) by its morphology with other characters, type S (Star-shaped grain consisting of core and rim) occupies over two thirds of microdiamond grains (ISHIDA et al., 2003). On the basis of cathodoluminescence, C-isotope, laser Raman spectroscopy and micro-Laue diffraction, those microdiamonds grew at two different stages: the 1st stage growth of R-type and the core of S-type, and the 2nd stage growth of T-type and the rim of S-type. YOSHIOKA et al. (2001) reported extremely high concentration of microdiamonds in dolomite marble (2700 carat / ton). Another representative diamond-bearing rock type in the Kokchetav Massif is pelitic gneiss, whose microdiamonds are in strong contrast to those in dolomite marble.

In pelitic gneisses, the morphologies of microdiamond are variable and differ from those of dolomite marble. The dominant morphology is rounded to cuboidal form with rugged surface (R-type, more than 80 %). Rounded grains with smooth surface, cubo-octahedron, and trigonal plate (spinel twin) are also observed. S-type, dominant in dolomite marble (polycrystalline grain with core and rim crystals) is rare in pelitic gneiss. Most micro-diamonds are translucent and yellowish with exception of spinel twin which is transparent and colorless. Different forms of diamonds are observed even in the same garnet grain. Microdiamond (size from 1 30 μm) often forms composite inclusions with biotite, phengite, calcite and graphite.

On the laser Raman spectroscopy, FWHM (Full Width at Half Maximum) of Raman band of microdiamond varies with the type of rocks; however, no correlation with peak position, intensity, morphology, and grain size was detected. The difference in FWHM of Raman band represents the crystallization environment of diamond to some extent. Morphology of microdiamond is controlled by growth and / or dissolution. R-type and spinel twin are considered to show growth form at the same stage, because they are included in the same garnet grain; their size and FWHMs are similar to each other; spinel twin has no resorption evidence. In contrast, rounded grain with smooth surface may show the resorption after diamond growth.

The absence of S-type diamond is a great difference from the microdiamond in dolomite marble, and indicates that fluids play different roles in both two diamond-bearing rocks; 1) carbon dissolved into aqueous fluid in pelitic gneiss, and 2) carbon precipitated from fluid to form microdiamond at the 2nd stage in dolomite marble.

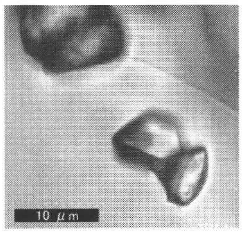

Fig. 1. Photomicrograph of microdiamond in garnet in pelitic gneiss.

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ZIRCON-INCLUSION MINERALOGY OF THE DIAMOND-GRADE ECLOGITE IN THE KOKCHETAV MASSIF, NORTHERN KAZAKHSTAN

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In order to determine the stability field of hydrous phases in the subducting crust in deep mantle, we have systematically investigated mineral inclusions in zircons and compositions of major silicates in diamond grade eclogites from Kumdy-Kol of the Kokchetav Massif of northern Kazakhstan. These eclogites contain Grt + Cpx + Rt + Coe / Qtz + Zo + Am ± K-spar ± Bi. Minor phengites occur as inclusions in Cpx, and zircon. Clinopyroxenes are zoned; the cored augite contains high K_2O up to 0.24 wt% and has phengite inclusions whereas the rimmed omphacite contains secondary K-feldspar (Kokchetavite?) inclusions. Phengite may have been consumed during prograde reaction, and K would have been fixed in Cpx or in the fluid or melt phase. The peak metamorphic condition was estimated at about 950 °C and the minimum pressures at 5 GPa defined by the diamond stability. No hydrous phase including phengite should be stable in these P-T conditions in the MORB system.

More than 500 zircons were separated from the studied high K augite bearing eclogite from the Kumdy-kol area. Approximately 200 zircons were mounted on epoxy disc and polished; mineral inclusions from 78 zircons on the polished surface were examined. Inclusions of Cpx, phengite and garnet were identified in the zircon cores, whereas garnet, rutile, quartz and composite inclusions are in the rims. Zircon rims overgrew on the edge of matrix minerals including quartz. Textural characteristics indicate that zircon cores grew at the peak UHP stage whereas the rims grew in the quartz stability field during decompression. The composite inclusions have assemblages of Ab + Phe + Ep, Rt + Ilm, Qtz + Rt, and Rt + Ab. The three-phase composite inclusion of Ab + Phe + Ep has triple-junction grain boundary, suggesting crystallization from fluid or melt in the zircon. Parageneses of mineral inclusions in both core and rim of zircon delineate a phengite-consuming reaction as follows: Phe + Cpx + Coe = Grt + Rt+ Qtz + melt / fluid. With continuous growth of zircon from the core to rims, phengite was consumed, and new garnet, rutile and fluid or melt were formed.

RAMAN SPECTROSCOPIC STUDY OF SYNTHESIZED Na-BEARING MAJORITIC GARNETS: CHARACTERIZATION OF TRANSITION ZONE GARNETS

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Majoritic garnets in diamond have been considered as the sample from mantle transition zone (e.g. MOORE & GURNEY, 1985). For non-destructive, in-situ Raman analysis, GILLET et al. (2002) systematically checked chemistry and Raman peak of various majoritic garnets in diamond. They treated majoritic component as number of excess-silica than 3.0 per formula unit. However, in the basaltic system, majorite garnets also have significant amounts of sodium and it's substitution is coupled with Si and Ti as follows; Na +Ti = Ca +Al (RINGWOOD & LOVERING, 1970), Na +Si = Ca + Al (SOBOLEV & LABRENTAV, 1971; RINGWOOD & MAJOR, 1971) or Na + Si = Mg + Al (GASPARIK, 1989). Each component in garnet is defined as follows; Mj (majorite) component = ((Si - 3) - Na) / 2) ≥ 0, NaSi ($Na_2MSi_5O_{12}$ where M = Ca, Mg, Fe^{2+}) component = (Na - T) / 2 ≥ 0, and NaTi component = Ti / 2. OKAMOTO & MARUYAMA (2004) conducted UHP experiments in the MORB + H_2O system (KNCFMATSH) at 10 - 19 GPa. They show that 1) Mj and NaTi component are constant and lower than 0.1 at T = 900 °C, and 2) NaSi component increases drastically above 15 GPa. In order to understand the relation between Raman spectra and chemistry of majoritic garnets, OKAMOTO & MARUYAMA (2004)' run charges were newly analyzed. Above 15 GPa, there is a characteristic sharp peak at 910 $cm^{-1}$and broad shoulder between 800 and 900 cm^{-1} as well as broad band near 960 cm^{-1} GILLET et at (2002) concluded that the former peak at 910 cm^{-1} is the only reliable signature for the majoritic garnet (Si > 3) and the latter two broad peaks are diagnostic feature for Ti rich garnet (TiO_2 > 1 wt%) as well as peak at 1030 cm^{-1} However, our additional Ti-free experiment at 16 GPa, 1200 °C clearly revealed that Na-bearing majoritic garnet has a significant shoulder at 800 - 900 cm^{-1}

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UHP METAMORPHIC CONDITIONS IN GARNET-BEARING PYROXENITES FROM LANTERMAN RANGE (NORTHERN VICTORIA LAND, ANTARCTICA): PETROLOGY AND P-T PATH

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Abundant lenses and pods of ultramafic and mafic rocks (KLEINSCHMIDT et al., 1987), including eclogites s.s. (RICCI et al., 1996), within a metasedimentary sequence of dominant gneisses and minor quartzites are present at the Lanterman Range (Antarctica). A common evolution characterized by three metamorphic stages have been identified for mafic and felsic rocks: (1) an eclogite stage at ≤ 850 °C and ≥ 2.6 GPa (≈ 500 Ma); (2) a medium-pressure amphibolite stage at 630 - 750 °C and 0.7 - 1.0 GPa (498 Ma); (3) a low-pressure amphibolite stage at 500 - 650 °C and 0.3 - 0.5 GPa (490 - 486 Ma) (PALMERI et al., 2003 and references therein).

Ultramafic boudins mainly consist of serpentinized peridotite and minor amphibole-rich fels. Rare garnet-bearing pyroxenites are also present. They are composed of orthopyroxene, garnet, olivine, clinopyroxene, amphibole with accessory spinel, rutile and secondary chlorite, serpentine and talc. Detailed petrographical analyses allow to reconstruct the igneous protolith and five metamorphic stages. The protolithic minerals are represented by Opx_0, ± Cpx_0 and Spl_0 ±Cam_0, found as tiny inclusions in poikiloclastic Grt_I. Metamorphic stage I consists of the ultrahigh pressure assemblage Grt_I + Opx_I + Ol_I + Cpx_I forming centimetric medium-grained levels. Stage II is characterized by millimetric fine-grained levels of idioblastic Grt_{II}, Cpx_{II}, Opx_{II} ± Cam_{II} and Ol_{II}. Stage III is defined by keliphytic coronas around Grt_I with an inner zone of Opx_{IIIa} + Cpx_{III} + Spl_I ± Cam_{IIIa}, and an outer zone, in contact with Ol_I, of Opx_{IIIb} ± Cam_{IIIb}. Cam_{IV} poikiloblasts enclosing resorbed Grt, Cpx, Opx and Ol of both stage I and II, characterize stage IV Stage V is a typical greenschist facies association with Tr + Mg-Chl + Srp ± Tlc. The mineral inclusions in porphyroclastic Grt_I indicate that the protolith formed in the spinel lherzolite P-T field (T ≈ 700 - 1400 °C, P ≈ 0.3 - 2.4 GPa). During the cambro-ordovician Ross orogeny, pyroxenites were tectonically amalgamated with supracrustal units, including felsic and MORB-like basalts, together with experienced UHP metamorphism. P-T estimates indicate that the UHP metamorphism (stage I) occurred at 750 - 850 °C and 2.6 - 3.4 GPa which are similar to P-T conditions estimated in mafic and felsic rocks. The exhumation history, as documented by stage II to V, followed an early near-isothermal path and a later cooling-unloading evolution.

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XENOLITHS OF ORTHOPYROXENE ECLOGITE AND CELSIAN CORONA-BEARING KYANITE ECLOGITE IN KIMBERLITE FROM SOUTH INDIA

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Eclogite xenoliths from two diamondiferous kimberlite pipes (KL2 and P10) of the Wajrakarur Kimberlite Field (1050 to 1100 Ma) in the eastern Dharwar Kimberlite Province have been studied. The KL2 pipe has intruded the 2.6 - 2.5 Ga old Closepet Granite, and contains abundant xenoliths of eclogite some of which are kyanite-bearing. A rare sample of orthopyroxene eclogite has been recovered from this pipe in which the core of garnet is characterized by microscopic triangular arrays of needles or blebs of Al-rich orthopyroxene, clinopyroxene and sphene consistent with an origin by exsolution parallel to the isometric form {111} Some of the exsolved needles are symplectic between orthopyroxene and clinopyroxene. Omphacite contains arrays of exsolved needles or blebs of orthopyroxene and garnet, and spectacular skeletal to feather-like inclusions (<20 µm long) of a chlorine-rich Na, Mg, Al silicate. Independent grains of orthopyroxene and Ti-phlogopite are also found in the orthopyroxene eclogite. Kyanite eclogites show tabular grains of kyanite which are invariably mantled by hydrated Ca-Al silicates with an occasional ring of celsian, which contains ~38 wt% BaO and <1 wt% CaO + Na_2O + K_2O. In all eclogites of KL2 pipe omphacite Na_2O contents are typically between 3 to 6 wt%, and garnet has widely variable composition with end members in the ranges of $Prp_{22-78}Grs_{3-47}Alm_{10-30}Sps_{0-1}Adr_{0-5}Uv_{0-3}$. Garnet and omphacite grains are mostly homogeneous without chemical zoning. Phase relations in the ACF projection (A = Al_2O_3 + Cr_2O_3 - Na_2O - K_2O; C = CaO and F = FeO + MgO + MnO) exhibit systematic increase of Ca-tschermak's component in omphacite from orthopyroxene eclogite through simple eclogite to kyanite eclogite. Thermometry in KL2 eclogites using Grt-Cpx Fe-Mg exchange calibration of KROGH (1988) gives temperatures mostly in the range of 920 - 1030 °C.
The P10 pipe is intrusive into a granitoid pluton within the 3.5 2.6 Ga old Peninsular Gneissic Complex. Eclogites of this pipe are characterised by chromian omphacite (2 to 4 wt% Cr_2O_3) and chromian garnet (4 to 6 wt% Cr_2O_3) but lack in either kyanite or orthopyroxene. Garnet has low calcium contents (<5 wt% CaO), and in one sample paucity of calcium relative to chromium results in 6 mole% knorringite component along with $Prp_{68}Alm_{14}Uv_{11}Sps_1$. PT calculations using Grt-Cpx thermometer of KROGH (1988) and Cr-in-Cpx barometer of NIMIS & TAYLOR (2000) give temperatures around 1100 °C and pressures in the range 31 to 36 kbar for P10 eclogites.

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CHEMICAL AND ISOTOPIC ALTERATION TRENDS PRESERVED DURING SUBDUCTION ZONE METAMORPHISM

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Analyses of the halogen and cation concentrations in fluid inclusions and stable isotopic composition (O, N) of eclogitic rocks revealed that subduction zone metamorphism in cold slab environment had little effects on the chemical and isotopic trends acquired prior to subduction. PHILIPPOT et al. (1998) showed that chlorine variability along a typical oceanic section charaterized by high-salinity brines in the gabbroic layer and relatively diluted aqueous fluids in the low-temperature basaltic layer have been preserved in HP and UHP meta-ophiolitic sequences from the Alps. More recently, BUSIGNY et al. (2003) showed that the HP and UHP coesite-bearing metasedimentary rocks of the Schistes Lustrés Nappe of the western Alps preserved the same N content and isotopic composition as their unmetamorphosed pelagic sedimentary protoliths. In this study, we present new results on the composition of individual salt-bearing inclusion fluids present in HP and UHP rocks of the Alps (Italy) and Dabieshan (China). The highly-saline brines were investigated for their trace element and halogen content using high-resolution synchrotron analysis at the European Synchrotron Research Facility (ESRF) following the experimental protocol developed by PHILIPPOT et al. (1998), MENEZ et al. (2002) and CAUZID et al. (2004). We show that the inclusions fluids preserve chemical patterns characteristic of hydrothermal or magmatic environments and therefore reamined essentially unmodified by subduction zone metamorphism. These results are discussed in light of the oxygen stable isotope data of the host rocks preserving $\delta^{18}O$ values inherited from meteoric water infiltration (Dabieshan) or oceanic hydrothermal alteration (Alps).

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MINERALOGY OF ULTRAHIGH-PRESSURE ROCKS FROM THE NE GREENLAND CALODONIDES

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The collision of Laurentia and Baltica at the final closure of the Iapetus Ocean during the Caledonian Orogeny resulted in the generation of ultrahigh-pressure (UHP) metamorphism at approximately 400 Ma in the Western Gneiss Region of Norway and ~50 Ma later in NE Greenland. The UHP terrane in Greenland is known from an island (Rabbit Ears Island) in Jøkelbugt off the northeast coast (78° 00' N, 18° 04' E). Here, eclogites occur as banded mafic boudins, surrounded by quartzofeldspatic orthogneiss with leucocratic pegmatites locally occurring in the boudin necks. Individual blocks are up to 50 x 100 metres in size and are traceable along the length of the island. Garnet rich paragneisses also occur. UHP mineral assemblages were identified in the host orthogneiss and in decimeter scale layers of kyanite-eclogite found in the mafic boudins. The UHP mineral assemblage in the kyanite-eclogite is garnet + omphacite + kyanite + phengite + rutile + coesite. The host gneiss has a disequilibrium assemblage of quartz + plagioclase + garnet + clinopyroxene + amphibole + biotite + kyanite + titanite + coesite. Solid inclusions in zircons were identified using laser Raman spectroscopy and Energy-Dispersive Spectroscopy (EDS). Zircons from both the eclogites and the gneisses are clear, sub-spherical and range in size from 100 to 400 micrometres in diameter. Inclusions in more than 1700 zircons were individually analysed using Raman spectroscopy, and from them, seven coesite inclusions were identified. The coesites are all clear, round crystals with diameters of 15 - 50 micrometres. While most zircons have multiply inclusions (> 4), coesite usually occurs on its own or with just one more. Further analysis using EDS shows that one coesite is part of a composite inclusion with clinopyroxene. The coesites occurred in three eclogite samples and one gneiss sample. In both the eclogite and the gneiss, zircons are mainly found enclosed in kyanite crystals but some grow at the grain boundaries of garnet and omphacite. Other eclogite facies minerals such as garnet, omphacite, kyanite and rutile were identified using EDS. They are abundant in zircons from all samples, garnet and omphacite having the greatest occurrences. Although the rocks are retrogressed, UHP minerals are best preserved and easily identified as inclusions in zircon.

CORONITIC METAGABBRO FROM GRESSENBERG, KORALPE, AUSTRIA: TEXTURES AND REACTIONS OF AN ECLOGITE FACIES HYDRATION EVENT

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A boulder of metagabbro from Gressenberg, at display at the Geopark Glashütten (Koralpe, Austria), shows partial transformation to reddish-green eclogite. The first transformation step of the original clinopyroxene (cpx) - orthopyroxene (opx) – plagioclase (plag) assemblage is a domainal decomposition that mainly affects former plag and opx.

Plagioclase domain: The cores of these domains consist of more albitic plag2, with little fibrous zoisite (zo) and kyanite (ky) or kyanite-quartz (qz) intergrowths. Towards the rims, the zo decreases drastically and cpx replaces plag2 as the interstitial phase (ky-cpx-zone). Some former plag-plag grain boundaries, particularly if close to former opx, now consist of corundum (cor).

Orthopyroxene domain: The opx first develops a corona of cpx, cor and spinel (sp), within which corundum gets later replaced (rimmed) by kyanite, and the spinel also by kyanite, but more often and characteristically by garnet (grt) on a mycron to sub-mycron scale. The thin garnet rims around spinel can be BSE-brighter or –darker than spinel, depending on whether this texture is found close to the plag-domain or immediately adjacent to opx. The first more coarsely grained garnet appears at a later stage between the opx-corona and the plag-domain. At an even more advanced stage the corona can be dominated by grt and cpx, and garnet is also found further towards the core of opx. In other cases, cpx advances further towards the core of opx and garnet stays more or less restricted to the outer corona.

Even in an advanced stage of corona formation, when all spinel has been replaced by garnet, relatively coarse grained Al-phases are still visible at the inner and outer margin of the opx-corona, typically with kyanite at the outer (plag-)side and corundum at the inner (opx-) side of the corona, both rimmed by garnet. Garnet overgrowing the margins of former plag-domains typically contains the fine kyanite needles of that domain.

Clinopyroxene domain: Relict igneous cpx experiences little alteration in the fist replacement stage and, except for the grain margins, still shows opx- and ilmenite (ilm) precipitates of the post-magmatic cooling stage. A gradual change towards a more omphacitic composition is observed from core to rim. Grain boundaries of former magmatic cpx and plag show minor development of sp, cor and ky in the outer part of the omphacitic cpx-rim. In some instances skeletal garnet growth is observed along former igneous cpx-plag grain boindaries. This was the only other instance where quartz (qz) was observed: either within grt or between grt and cpx.

The above textures can be explained by the hypothesis that Ca and Al advance towards and react more rapidly with opx than Si, which creates cpx, sp and cor before ky and grt can form in the opx corona. This is corroborated by the observation that zo and sometimes qz can be found only in the cores of plag domains, not in the rims.

PETROLOGY OF METAPELITES AND METABASITES OF THE UHP-KIMI COMPLEX NEAR KIMI, RHODOPES, NE GREECE

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Evidence of a former ultrahigh-pressure metamorphism has been found in metapelites and metabasites from several locations in the Kimi complex of the Rhodope Metamorphic Province (RMP), NE Greece (MPOSKOS & KOSTOPOULOS, 2001, PERRAKI et al., 2004).
The Kimi complex is dominated by granitic to tonalitic orthogneisses, amphibolites and marbles, with intercalated metapelites, metabasic granulites and eclogites, pegmatites and late subvolcanic intrusives. The orthogneisses in particular host large boudins of ultramafic rocks, amphibolites and granulitic rocks.
The metapelites that contain mircodiamond-bearing garnet are now garnet-kyanite gneisses and schists with two generations of kyanite (prograde ky_1 and retrograde ky_2), retrograde growth of biotite from muscovite and matrix plagioclase, quartz and rutile. Garnet is xenomorphic, with flat zoning profiles, indicating diffusional homogenization. The assumed former (U)HP-paragenesis has been obliterated, by a medium to low pressure overprint, which is reflected in the P-T conditions derived of about 12 - 14 kbar and 720 – 800 °C. Relicts of crystallographically oriented rutile needles as well as rare µm-sized quartz and apatite crystals in garnet indicate an extraordinary prior garnet composition. A significant phosphorus-content of a few wt% up to now is the only repeatedly confirmed possibly UHP trace element characteristic of these garnets.
The metabasites are mainly amphibolites, more rarely granulites and - in exceptional cases - still eclogites. Many of the basic granulites show medium- to coarse-grained symplectite textures, indicating a prior eclogite stage, but now also contain coarse grained amphibole, plagioclase, biotite and often kyanite. Pyroxene in the granulites often contains amphibole lamellae oriented along the cleavage planes, sometimes accompanied by minor quartz. Minor chemical zoning with decreasing Na from core to rim is common, as well as marginal replacement by plagioclase and amphibole. Garnets are usually small, clear and subidiomorphic, with no chemical zoning. Eclogitic pyroxenes contain up to 40 % jadeite component and are continuously zoned with decreasing X_{jd} towards the rims. Based on kyanite inclusions in omphacite, high, but not ultrahigh pressures can be calculated. Eclogite garnets ($Pyr_{43}Gro_{15}Alm_{42}$) have a flat zoning profile.
Granulite- and amphibolite-facies overprint is so predominant in the region, that high- or even ultrahigh-pressure minerals or parageneses are very rarely preserved.

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THE *P-T-d* EVOLUTION OF THE ECLOGITE-FACIES AUSTROALPINE SIEGGRABEN UNIT (EASTERN ALPS)

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The sequence of Alpine tectonometamorphic events was studied in the eclogitic Austroalpine Sieggraben Structural Complex (SSC) in the Eastern Alps. Although, the age of formation of this high-*P* complex is unknown, U-Pb zircon ages from orthogneiss bodies show discordant ages with a lower intercept at ca. 105 Ma and an upper intercept age of ca. 312 Ma. These age data indicate that the eclogite-facies SSC represents a strongly attenuated pre-Alpine continental crust fragment, which was subducted within a collisional wedge of the Meliata-Hallstatt Ocean passive margin during the Eo-Alpine event.
Thermobarometry of the Sieggraben eclogites, performed by simultaneous calculation of all possible reactions within the peak metamorphic assemblage garnet + omphacite + clinozoisite + barroisite + quartz with the program THERMOCALC v 3.1. (HOLLAND, 2001, written comm.) yields 580 – 650 °C and 1.4 – 1.9 GPa and low $a(H_2O)$. The *P-T* conditions of adjacent metapelites are 630 ± 30 °C and 0.6 ± 0.2 GPa. Calculations by using the software THERIAK-DOMINO (DE CAPITANI, 2004, written comm.) yielded the same results.
Eclogite-facies D1 microstructures are represented by parallel oriented aggregates of omphacite and zoisite, omphacite-barroisite and zoisite or barroisite and zoisite. During subsequent isothermal exhumation (D2), as indicated by *P-T* data from the surrounding metapelites, symplectitic intergrowths of clinopyroxene (Jd_{3-22}) and plagioclase in the eclogites and high-*P* amphibolites formed. Microstructurally, the exhumation stage D2 was enhanced by dynamic strain softening of omphacite (Jd_{38}) and zoisite into aggregates of minor clinopyroxene (Jd_{18-31}) and zoisite. Dynamic recrystallization of omphacite, barroisitic hornblende, plagioclase and quartz ribbons at medium-*T* (D2) was followed by low-*T* quartz recrystallization and calcite twinning. The textures indicate dislocation creep as the principal micromechanism of ductile deformation of clinopyroxene, amphibole, plagioclase and quartz, and mechanical twinning in calcite. The observed textures are mainly related to the medium-*T* (ca. 600 - 500 °C) mesoscopic fabrics of the D2 stage (foliation, layering, mineral and stretching lineation). Exhumation occurred along a detachment fault by top-to-the SSE extensional unroofing of the eclogitized SSC now overlying the low-grade *MP* / *HP* Grobgneiss and Wechsel nappes. The extensional exhumation of the Sieggraben *HP* complex around 100 Ma is obviously related to the start of the subduction of the South-Penninic oceanic crust below the Austro-Alpine – Centro-Carpathian continental margin (PUTIŠ et al., 2005).

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METAMORPHIC RECORD OF BURIAL AND EXHUMATION OF OROGENIC LOWER AND MIDDLE CRUST: NEW TECTONOTHERMAL MODEL FOR THE DROSENDORF WINDOW

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A continuous, but attenuated section through orogenic lower and middle crust overthrust by a second lower-crustal complex was distinguished at the eastern margin of the Bohemian Massif. This indicates the existence of two lower-crustal "autochthonous" extrusions into middle crust that is not compatible with the model of "allochthonous" lower crustal klippen remaining after flat thrusting of the Gföhl nappe from large distances. The base of the lower crust is represented by a granulite exhumed from ca. 15 kbar and 800 °C. A hangingwall complex of layered amphibolites gradually passes into amphibolite bearing paragneisses (the Monotonous unit) and micaschists intercalated with marbles at the top (the Varied unit). The metamorphic grade and anatexis decreases upwards and the micaschists preserve a prograde path to ca. 8 kbar and 700 °C. This sequence is overthrust by a second lower crustal strongly migmatitized Raabs complex marked by an eclogite-bearing belt at the base. The garnet zoning of eclogite indicates burial from 10 kbar to min. 15 kbar. In all units were identified relics of a steep metamorphic fabrics reworked by folding and a moderately west-dipping foliation. The conditions of 7 - 10 kbar and ca. 750 °C for the flat foliation were obtained in all units indicating that exhumation of the lower crust into middle crustal depth occurred earlier, probably during the development of steep fabrics. The intense flat reworking is interpreted as a result of thrusting of the whole assembly over the middle crustal Brunian indentor.

THE TIMING OF PARTIAL MELTING AND UHP METAMORPHISM IN THE KUMDY-KOL REGION (KOKCHETAV MASSIF, NORTHERN KAZAKHSTAN)

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The Kokchetav Massif is the type locality of microdiamonds in metamorphic rocks of the Earth's crust (SOBOLEV & SHATSKY, 1990). Drilling data indicate that diamondiferous rocks in the Kumdy-Kol microdiamond deposit are interlayered with granite gneisses, and migmatized garnet-biotite gneisses. It could be supposed that some part of granite gneisses and migmatite have been formed on melting of diamondiferous rocks. High equilibrium temperatures and geochemical data of diamondiferous rocks suggest their partial melting.
To determine the age of partial melting and relationship between the UHP rocks and migmatite five samples were collected for geochronology with precise locations in an underground mining gallery of Kumdy-Kol microdiamond deposit. They are related both to diamond-free zone and diamond-bearing zone. Studied rocks were affected by partial melting and preserve migmatitic structures. UHP indicator minerals are not preserved in these rocks; migmatization has destroyed almost completely previous mineral assemblages. Samples of rocks were crushed and the heavy mineral fraction including zircon was extracted using routine techniques, and zircon grains were hand picked from concentrate. Zircon was analysed for U, Th and Pb using the Sensitive High-Resolution Ion-Microprobe Reverse Geometry (SHRIMP RG) at Stanford-USGS Micro Analytical Center.
The internal structures of near central zircon parts revealed by cathodoluminescence and secondary electron microscopy mainly consist of core and rim domains. The apparent $^{206}Pb/^{238}U$ age for core domains (524 ± 6 Ma) and rim domains of zircons (522 ± 7 Ma) are the same within analytical error. The mean age of all zircons is 523 ± 4 Ma. Migmatites ages are slightly younger than the U-Pb zircon ages of metamorphic peak (~530 537 Ma) (CLAOUE-LONG et al., 1991, HERMANN et al, 2001). These data indicate that the partial melting took place during exhumation of diamondiferous rocks from the UHP peak to amphibolite-facies conditions.
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ECLOGITE-FACIES TRANSFORMATIONS OF ZERMATT-SAAS OPHIOLITIC GABBRO AND TROCTOLITE (CREPIN, VALTOURNANCHE, ITALIAN WESTERN ALPS)

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Metagabbro and metatroctolite from the Zermatt-Saas unit of the western Alps are coronitic rocks showing variable degrees of metamorphic transformation from igneous protoliths (plagioclase, olivine, Ca-clinopyroxene and spinel rocks) to completely eclogitized rocks.
Major and trace element analyses, a throughout study of microstructures and thermodynamic modelling of equilibrium assemblages have been performed, in order to unravel the metamorphic evolution of these metabasites and the mechanisms regulating the development and preservation of the high-pressure assemblages.
Evidence has been found that in completely transformed troctolite, fine-grained jadeitic clinopyroxene and clinozoisite replaced igneous plagioclase. Small kyanite crystals, together with micas (phengite and paragonite), chloritoid and garnet, forming irregular coronas at the former plagioclase-olivine interface, have been found towards olivine microdomain. Olivine was mainly transformed to talc. Large tremolite crystals are also common, together with omphacite, phengite, chloritoid, chlorite, kyanite and even rare quartz. Cr-rich clinopyroxene was partially to completely overgrown by omphacite. The latter is here and there overgrown by Cr-rich chloritoid and talc. In incompletely eclogitized rocks, igneous mineral relics are rimmed by eclogite-facies complex coronas consisting of talc + clinopyroxene + chlorite + garnet between olivine and plagioclase, and of omphacite when grown between clinopyroxene and plagioclase.
The variable degree of development of eclogite-facies reactions appears to be related with the intensity of the oceanic alteration that took place before eclogitization. This conclusion is in agreement with the fact that the oceanic metamorphism leads mainly to the development of low-grade hydrous assemblages, which presumably favoured here the chemical homogenization of the igneous microdomains and enhanced the kinetics of subsequent eclogite-facies metamorphic reactions. Computations of P-T pseudosections for the various microdomains of these rocks have provided P-T estimates of $P > 2.0$ GPa and $T \approx 600$ °C for the eclogite-facies reequilibration.

GEOCHEMISTRY AND GEOCHRONOLOGY OF E HIMALAYA ECLOGITES

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Compared to other collisional belts, the Himalaya is relatively poor in high pressure (HP) metamorphic rocks. Rare eclogite bodies of Eocene age have been described from two areas in the NW part of the belt (see MASSONNE & O'BRIEN, 2003, for a review), while granulitized eclogites have been reported in the E Himalaya (LOMBARDO & ROLFO, 2000).

The E Himalaya eclogites occur at the top of the Main Central Thrust zone in the Kharta region of S Tibet and record two superposed metamorphic events: A first eclogitic (T = 600 - 650 °C ?; P = 1.2 - 1.4 GPa ?) and a second granulitic (T = 750 - 770 °C; P = 0.55 - 0.65 GPa).

Geochemically, the E Himalaya eclogites have a basaltic (olivine tholeiite) composition showing a limited variation in SiO_2 contents (from 47.3 to 48.9 wt%), and low to medium K_2O (0.25 - 0.56 wt%) and MgO (5.57 - 7.50 wt%) contents. Ti content is moderate to high (1.47 - 2.83 wt% TiO_2) as well as the Fe content (FeO_{tot} = 11.48 - 15.39 wt%), pointing to Fe-rich dolerites. $^{87}Sr/^{86}Sr$ ratios and ε_{Nd} values are in the ranges of 0.70445 to 0.71515 and of +2.36 to +3.94, respectively

The timing of the HP event in the E Himalaya is difficult to constrain because of the widespread HT overprint and the poor preservation of HP assemblages. However, zircons could be separated and analysed by the U-Pb SHRIMP method. The zircons display complex systematics. A few analyses from low-U domains with low Th/U ratios (0.02 - 0.03) yield young $^{206}Pb/^{238}U$ ages from 12 to 15 Ma. Ages ranging from 88 to 110 Ma are interpreted to represent a Cretaceous protolith age of the mafic rock, while Proterozoic ages (1.8 Ga) are attributed to inherited components.

The basaltic protolith of the E Himalaya eclogites is possibly related to the Cretaceous Rajmahal Trap volcanism, widespread in NE India and here reported for the first time in the Higher Himalaya Crystallines. Because no evidence was ever found in the Nepal Himalaya for a metamorphic event between the Tertiary Himalayan orogeny and the Early Paleozoic metamorphism and plutonism (LE FORT et al., 1986), the Kharta eclogites must be Precambrian if they are not Himalayan in age. Even if the age of eclogitization was not recorded by the zircons, a Cretaceous protolith age for the Kharta eclogites definitely rules out the possibility that the age of eclogitization is Early Paleozoic or Precambrian, and corroborates the hypothesis put forward by LOMBARDO & ROLFO (2000) that the Kharta eclogites are of Tertiary age. The metamorphic ages of 13 - 14 Ma could record the end of the HT-LP fluid circulation and thus be linked to extrusion along the Main Central Thrust.

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DIACHRONOUS UHP METAMORPHISM IN THE KOKCHETAV MASSIF

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The Kokchetav massif consists of two UHP blocks: the diamond-baring Kumdy-Kol (4 - 6 GPa, 950 – 1000 °C) and the coesite-bearing Kulet (3.8 - 4.0 GPa, 650 – 700 °C). Extensive geochronological work on the diamond-bearing unit established an age of 528 - 530 Ma for the UHP peak, whereas only a few scattering Ar-Ar ages were produced for the Kulet area, where no infonnation is available on the time of the metamorphic peak.

Garnet-kyanite-micaschists from Kulet have been investigated to detennine the conditions and age of metamorphism. Textural observations suggest that the peak metamorphic assemblage garnet + phengite + kyanite + coesite ± jadeite + rutile records pressures of 3.8 - 4.0 GPa at temperatures of maximum 730 °C. A first sample contains garnet porphyroblasts with polycrystalline quartz inclusions, which together with the composition of phengite are indicators of UHP metamorphism. The garnet displays a bell-shaped zoning in Mn and a U-shaped zoning in Mg, which are in line with prograde garnet growth. A sharp core-rim zoning in trace element (Y and HREE) is also observed. Monazite recovered from this sample contains inclusions of kyanite, phengite and rutile. It displays limited zoning in back-scattered electron imaging, whereas it is homogeneous in REE composition. It has a typical REE pattern strongly enriched in light with respect to heavy rare earth elements and a small negative Eu-anomaly Partitioning of trace elements between monazite and garnet compared to previous works (HERMANN & RUBATTO, 2003) suggest equilibrium between monazite and the UHP garnet rim. Monazite was dated by SHRIMP ion microprobe at 500 ± 3 Ma (95% c.l.).

A second sample contains garnet with coesite and widespread polycrystalline quartz inclusion. Monazite in this sample forms symplectite-like aggregates with apatite and phengite. These symplectites are likely to be the product of breakdown of an UHP phase, most probably bearthite, as previously described in the Dora Maira whiteschists (SCHERRER et al., 2001). U-Pb dating of monazite yielded scattered ages partly due to the small grain size and contamination from apatite. The major population defines an age of 508 ± 6 Ma (2σ).

The ages of both monazite populations are indistinguishable within error, but significantly younger than the age of the zircon fonned at the UHP peak and in the Kumdy-Kol, diamond-bearing rocks. Together with the different metamorphic conditions recorded in the two areas, and published Ar-Ar and U-Pb data, there is enough evidence to suggest a diachronic UHP metamorphism between the Kulet (lower grade and younger) and Kumdy-Kol (higher grade and older) unit.

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MELT- VERSUS FLUID-INDUCED METASOMATISM IN SPINEL TO GARNET WEDGE PERIDOTITES (ULTEN ZONE, EASTERN ITALIAN ALPS): CLUES FROM TRACE ELEMENT, Li AND Be ABUNDANCES

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We present a trace element study of peridotite samples from the Ulten Zone (Upper Austroalpine, Eastern Alps), which are exposed inside Variscan migmatites and record the transformation of spinel peridotites to garnet - amphibole peridotites. This change occurred in response to corner-flow inside a mantle wedge, causing the tectonic slicing of lithospheric mantle into a subducted continental slab. All samples show similar trace element signatures, featuring LREE, LILE and light element enrichments with respect to HREE and HFSE. These characteristics imply the recycling of subduction-related crustal components in various wedge domains. A change from melt to fluid as metasomatic agent occurred at the transition from spinel to amphibole ± garnet peridotites. This is suggested by the lack of amphibole in the spinel peridotites, by their high temperatures of equilibration, and by several geochemical parameters. The spinel-facies clinopyroxene has low LILE/HFSE (Pb/Nb from 10 to 51) and high Li/Be; moreover the spinel-facies pyroxenes are Li-enriched compared with the coexisting olivine (up to 25 ppm Li in cpx; about 3 ppm Li in opx). These features suggest interaction of spinel peridotites with melt enriched in slab components. The amphibole + garnet peridotites display high LILE-HFSE fractionation (cpx Pb/Nb from 391 to 443), low Li/Be and variable LILE and LREE enrichments. Relevant features of the amphibole + garnet peridotites are bulk-rock positive anomalies in Cs, Ba, Pb and U. Bulk Li and Be in these rocks are twice the Primitive Mantle (PM), thus reflecting addition of a crustal component to the mantle rocks. The coupled increase of water and incompatible elements in these rocks indicate that metasomatism was caused by the infiltration in the mantle wedge domains above the subducting slab of an aqueous fluid sourced from the crustal rocks. The trace element signature acquired at eclogite-facies remains essentially unchanged during retrogression and further hydration. All these features concur to the conclusion that during their entire history the Ulten peridotites were percolated first by melts and then by aqueous fluids adding recycled components sourced by the same subducting crustal reservoir to the mantle wedge.

BURIAL AND EXHUMATION OF ECLOGITES IN CONTINENTAL ACCRETIONARY WEDGE: AN INDENTATION MODEL OF ECLOGITE FORMATION IN VARISCAN COLLISIONAL ZONE

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Numerous eclogite boudins surrounded by orthogneisses, metavolcanics and metapelites form a unit separating a Neoproterozoic foreland from the Variscan orogenic root at the NE margin of the Bohemian Massif. Eclogites record peak conditions of 15.5 kbar and 700 °C (indicating burial to 55 km) and near-isothermal exhumation to 40 km, whereas the enclosing metapelites show an almost complete *P-T* loop with peak pressure conditions at 11 kbar and 640 °C. These different paths suggest differential burial and exhumation of rocks with tectonic amalgamation at mid-crustal levels. Structural features show viscous pure shear-dominated deformation of gneiss-eclogite blocks at deep crustal levels and essentially non-coaxial partitioned deformation of these blocks and their volcano-sedimentary matrix at shallower levels. Based on U/Pb zircon ages (561 - 633 Ma, 2004 Ma), calc-alkaline intrusive rocks associated with the eclogites are interpreted as a part of the lower crust of the Neoproterozoic Brunian continent. The eclogite protolith ages, geothermal gradients deduced from prograde and peak *P-T* conditions and geological structures are compared with coherent eclogite-bearing crustal units of the subducted Saxothuringian lithosphere and thickened Variscan (Moldanubian) orogenic root. Based on this comparison, a new model suggests the development of HP rocks at the tip of Brunian lithospheric indentor which penetrated a weak orogenic root in the west with Cambro-Ordovician protolith ages. Subsequent exhumation of HP blocks enclosed in a weak metasedimentary matrix was controlled by ongoing indentation and is similar to that of block-matrix flow in sedimentary or serpentinite wedges. The block-matrix relationship is a characteristic feature of the eclogite-micaschist wedge along the entire eastern margin of the Variscan collisional front.

A NEW OCCURRENCE OF DIAMONDIFEROUS ROCKS IN KOKCHETAV MASSIF (NORTHERN KAZAKHSTAN)

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Three localities of diamondiferous metamorphic rocks have been known in the Kokchetav massif until the present time (SHATSKY & SOBOLEV, 2003). The new locality of diamondiferous rocks which represents a new type was discovered two km west of the Barchi Lake. Eclogite, garnet-kyanite-biotite gneisses, garnet-kyanite micaschists, garnet-clinopyroxene and carbonate rocks occur within this area. Relatively poor outcrop conditions did not allow to present more precise information about the structural settings. Garnet-kyanite-biotite gneisses and schists occur within granite-gneisses. In addition the diamondiferous gneisses are characterized by quartz, phengite and potassic feldspar. Microdiamonds are widely scattered as inclusions in kyanite, garnet and zircon, and are predominantly of cubo-octahedral or octahedral morphology. Diamond size varies from 2 to 40 µm. In the rock matrix graphite flakes appear. In some cases abundant graphite was observed as inclusions in kyanite cores succeeded by diamond in kyanite rim.
Garnets from all samples show chemical zonation patterns. Ca content increases and Fe decreases from core ($Grs_{7.7}Pyr_{22.3}Alm_{70}$) to rim ($Grs_{23.6}Pyr_{20}Alm_{56.4}$).
Garnet-kyanite-biotite gneisses are characterized by high alumina content (up to 19%) in contrast to diamondiferous rocks of Kumdy-Kol deposit. They are enriched in LREE with a negative Eu anomaly and relatively flat HREEs. According to Zr/Hf (37.8 - 40.4), Nb/Ta (11.8 - 14.5), Sm/Nd (0.17 - 0.26) the gneisses are close to upper continental crust. Diamondiferous rocks are depleted in Sr compared to upper crust composition.

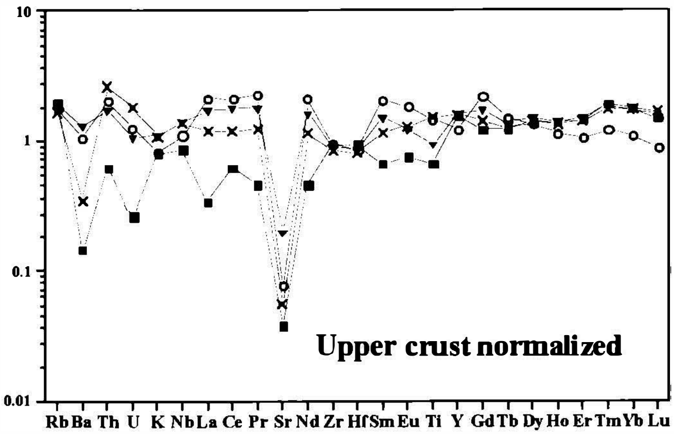

Fig. 1. Multi-element plot of the composition of the garnet-biotite-kyanite gneisses

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TRANSMISSION ELECTRON MICROSCOPIC STUDY OF QUARTZ RODS WITH INTERGROWN AMPHIBOLE WITHIN OMPHACITE IN ECLOGITES FROM THE SULU ULTRAHIGH-PRESSURE METAMORPHIC TERRANE, EASTERN CHINA

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Oriented quartz rods in clinopyroxene have been observed in eclogites and garnet clinopyroxenites from several ultrahigh-pressure (UHP) metamorphic terranes. They are often interpreted as an exsolution phase from supersilicic clinopyroxene, which is stable at UHP, and are therefore used as an indicator of UHP metamorphism (LIOU, 1998; TSAI & LIOU, 2000). However, PAGE et al. (2004) argued that the presence of quartz precipitates in clinopyroxene does not necessarily indicate UHP metamorphism. In this study, we used conventional petrographic tools and transmission electron microscopy to study quartz precipitates in omphacite from six eclogite samples collected near Donghai in the Sulu UHP metamorphic terrane, eastern China. The constituent minerals of the eclogite are garnet + omphacite + amphibole + rutile ± zoisite ± quartz ± phengite ± kyanite ± apatite ± talc. Few palisade quartz, presumably after coesite, occurs as inclusions in omphacite and garnet. The oriented quartz rods in omphacite host are generally ~1 μm wide and 10 - 50 μm long. They are intergrown with bluish-green calcic amphibole. It appears that thicker rods of quartz are accompanied with larger grains of amphibole. Both quartz and amphibole precipitates have a preferred orientation with host omphacite: $(010)_{Omp}$ // $(010)_{Qtz}$ and $[001]_{Omp}$ // $[001]_{Qtz}$, and $(010)_{Omp}$ // $(010)_{Amp}$ and $[001]_{Omp}$ // $[001]_{Amp}$. On the basis of their microtextures and mineral association, we propose a two-stage growth mechanism for the quartz and amphibole precipitates in omphacite: (1) very fine quartz rods exsolved from a supersilicic clinopyroxene during decompression, creating grain boundaries between quartz rods and host, (2) growth of amphibole and quartz along the grain boundaries with fluid participation and at the expense of omphacite during retrograde metamorphism.

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METHANE (CH_4)-BEARING FLUID INCLUSIONS IN THE MYANMAR JADEITE

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Fluid inclusion studies in jadeitites therefore provide important constraints on the composition of the metamorphic fluid present during formation of the jadeitites in deep subduction zone environments. CH_4 is a common fluid species in hydrothermal systems in the oceanic crust and commonly forms either by reactions involving magmatic CO_2 or during serpentinization of olivine and/or other mafic phases (KELLEY & FRÜH-GREEN, 1999). So far there is only indirect evidence for the presence of CH_4 in subduction zones from shallow (1 - 3 km depth) CH_4-rich plumes emanating from the accretionary prisms in convergent margins. Recent investigations to constrain the retention and loss of volatile elements such as CH_4 during subduction showed that fluxes of carbon into subduction zones are larger than returned to the surface, thus indicating that CH_4 could occur in deeper levels of subduction zones (SADOFSKY & BEBOUT, 2003).
A combined hydrogen-carbon-isotope and fluid-inclusion study has been carried out on high-pressure jadeitites from the famous jadeite tract Myanmar. CH_4-bearing fluid inclusions were found in jadeites containing CH_4 and H_2O. Microthermometric results yield lower temperature limits for the entrapment of these fluid inclusions of ca. 300 – 400°C. The bulk composition of the fluid inclusions is mostly H_2O (87 - 94 mol.% H_2O) and the isotopic composition of methane and water in the inclusions is characterized by $\delta^{13}C(CH_4)$ values ranging from -30.1 ‰ to -25.5 ‰, and $\delta D(H_2O)$ values ranging from -56.3 ‰ to -49.8 ‰. The stable isotope data would be indicative of an abiogenic mechanism of CH_4 formation which could be due to either CH_4 of primordial origin (mantle degassing), CH_4 production during serpent-tinization (Fischer-Tropsch synthesis) or thermal maturation of subducted organic carbon.
Due to the lack of evidence (no Ni-Fe alloys, low hydrocarbon fractions) for primordial CH_4 and for the formation of CH_4 by Fischer-Tropsch synthesis during serpentinization, the occurrence of the jadeite veins in this paleo-subduction zone thus most likely point to the formation of these CH_4-bearing fluid inclusions by abiogenic thermal maturation of subducted organic carbon. These also data show that CH_4 not only occurs as shallow CH_4-rich plumes in accretionary prisms of recent subduction zones but also occurs in deeper portions of at least the upper 20 km of subduction zones.

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DISCOVERY OF K-TOURMALINE IN DIAMOND-BEARING QUARTZ-RICH ROCK FROM THE KOKCHETAV MASSIF, KAZAKHSTAN

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Potassium tourmaline coexisting with microdiamond was newly discovered in tourmaline-K-feldspar-quartz rock at Kumdy-kol in the Kokchetav UHP Massif, northern Kazakhstan. Tourmaline is a chemically robust mineral, and retains information of each metamorphic stage. Tourmalines from the Kokchetav Massif, however, have been regarded as retrograde mineral until now. The discovery of diamond in tourmaline, which will be discussed here, indicates that tourmaline was stable under diamond-grade UHP conditions.

The rock sample containing K-tourmaline consists mainly of quartz, K-feldspar, and tourmaline (up to 25 vol%, ca. 1 mm coarse grained euhedral to subhedral), with small amounts of titanite, phengite, chlorite, zircon, biotite, apatite and hematite. Microdiamonds are included in zircon and tourmaline. Tourmaline in this sample is potassium-analogue of dravite, displays clear chemical zonation and K_2O content reaches 2.76 wt%. Such chemical compositions have never been reported before. Representative microprobe analyses of the core show K_2O 2.62 wt%, Na_2O 0.73 wt%, CaO 1.24 wt%, MgO 8.65 wt%, FeO 3.35 wt%, TiO_2 1.12 wt%, Al_2O_3 31.07 wt%, SiO_2 36.45 wt% and the chemical formula is written as $(K_{0.575}Ca_{0.280}Na_{0.186})_{1.041}(Mg_{2.226}Fe_{0.382}Ti_{0.146})_{2.755}Al_{5.969}Si_{5.987}O_{18}(BO_3)_3(OH)_4$. K_2O is concentrated in the core (2.76 wt%, $X_{K\text{-dravite}} = 0.55$) and decreased from the mantle to the rim (0.47 wt%, $X_{K\text{-dravite}} = 0.11$). Na_2O increases at the mantle from 0.59 - 1.73 wt%; CaO ranges from 1.24 wt% (core) to 3.26 wt % (rim). Mg increases at the mantle; Ti is higher in the core.

Twenty seven microdiamond grains were confirmed in three thin sections with laser Raman spectroscopy. Diamond is included only in K_2O-rich part (core), and flaky euhedral graphite sometimes occurs in the rim part. Quartz, K-feldspar, phengite, zircon, calcite, and aggregates of anhedral graphite also occur in the core and the mantle.

Occurrence of microdiamond inclusion suggests that the core part of tourmaline formed under UHP conditions. Flaky graphite in the rim demonstrates crystallization out of the diamond stability. This indicates K-rich tourmaline was stable under UHP conditions. The chemical zonation from mantle to rim corresponds to retrograde pattern, and it is consistent with the occurrence of graphite. Formation of diamond-bearing tourmaline-rich rock requires boron enrichment under UHP conditions. Boron may be carried by an aqueous fluid of dehydration origin of phyllosilicates through UHP metamorphism. Moreover, the tourmaline in this study is an example of diamond-grade borosilicate and gives great implications to B-enrichment through fluid effect during UHP metamorphism. Thus tourmaline is expected to retain information about fluid in crustal rock subducted to great depths.

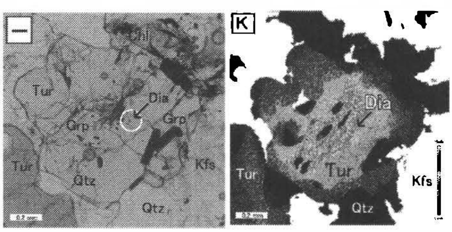

*Fig. 1 Left: photomicrograph of K-tourmaline.
Right: characteristic X-ray image of K of tourmaline.*

MINERALOGY OF MICRODIAMONDS FROM METAMORPHIC ROCKS AND CONDITIONS OF THEIR FORMATION

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The problem of diamond formation connected with metamorphic rocks is attracting numerous investigators. This type of diamond occurrences can provide the huge mass of diamonds like Popigaisky and Kumdy-Kol ones. The majority of publications in this direction are devoted preferably to petrography of HPHT rocks and inclusions. We have tried to systemize knowledge about metamorphic diamonds finds and provided investigations of metamorphic diamonds structural and physical properties features, mineralogy of carbon systems at the occurrences (SHUMILOVA, 2003).

According to geological settings and typomorphic features of metamorphic diamonds we have established that among metamorphic diamond bearing objects three types of diamonds exist: 1- impactly metamorphosed (formed by shock HPHT influence); 2- regional metamorphic (formed at static HPHT); 3- metasomatic (formed with fluid phase at quite low PT-conditions). As for the first type, the mechanism of diamond formation is known exactly, it is a solid transformation by martensite transition.

The situation with the regional diamond type is not so simple. According to modern experimental data on diamond synthesis the static solid transition graphite–diamond (direct transition) can be possible only at pressure higher then 8 GPa and temperature – more then 1400 °C. It means that the regional metamorphic type of diamonds could be possible at the same ultra high P-T conditions. It is important to know that the limits of pressure and temperature used before by geologists were automatically accepted from another experimental diamond formation mechanism – crystallization through dissolved carbon of metal melts, which allows to produce diamond at essentially lower pressure – 4 GPa. Thus, the geological metamorphism conditions earlier used are not quite correct as they were taken from another mechanism. The right P-T conditions could be provided not only with lithostatic pressure but with tectonic processes on grains boundaries level. We have established presence of cubic modification of graphite within granulites of Kola peninsula, the cubic graphite can be formed by transition mechanism within the pressure limit 15 - 30 GPa (SHUMILOVA, 2003). It means that UHPT-conditions could be possible not only at huge depths.

The geological features of the metasomatic diamond type were described by LAVROVA et al. (1999) in detail. The geology says rather about fluid diamond formation that accords to our mineralogical investigations of Kumdy-Kol diamonds and graphite.

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THE NEOARCHAEAN GRIDINO ECLOGITES-BEARING COMPLEX, BELOMORIAN MOBILE BELT (BMB), THE FENNOSCANDIAN SHIELD, RUSSIA

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The Neoarchaean Gridino eclogites-bearing complex (GEC) have been found in the BMB (Fig. A) of the Fennoscandian Shield (VOLODICHEV et al., 2004). The eclogites together with amphibolites, epidosites, kyanite-garnet-biotite gneisses, gabbroids, meta-ultramafites and marbles are the components of polygenic migmatised mélange (Fig. B). The migmatites and meta-matrix of this complex is represented by tonalites, trondjhemites, Qu-diorites and Bi-Amph-gneisses.

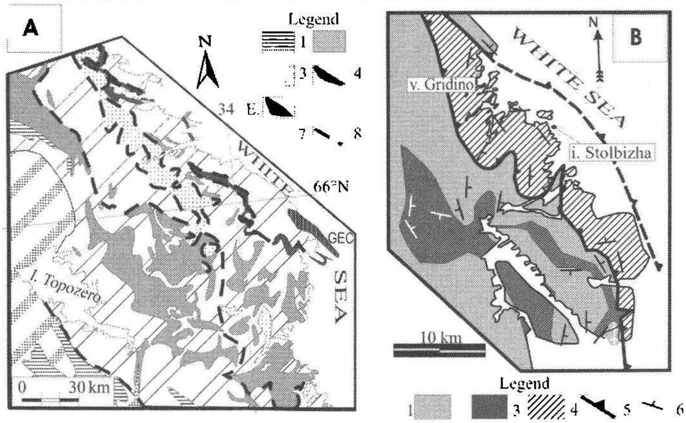

Fig. A. Location of the GEC in the BMB. 1 – Paleo-proterozoic supracrustal rocks; 2–7 – Archaean complexes: 2 – greenstones; 3 – para-gneisses ; 4 – ophiolite-like; 5 – GEC 6 – TTG and magmatites from BMB (2.9-2.7 Ga); 7 – TTG Karelian craton (3.2-2.7 Ga); 8 – assumed overthrusts

Fig. B. Location of the GEC:
1 – ca. 2.7 Ga granites; 2 – TTG
3 – Archaean greenstone complex
4 – Neoarchaean GEC
5 – assumed thrust fault
6 – strikes of the gneissosity

The eclogite consists of omphacite with 27-31 % Jd, homogeneous garnet – 20-22 % Prp (F = 0.67-0.68) and accessory rutile, zircon. The eclogites were formed at T = 740-865°C and P = 14.0-17.5 kbar. Four stages are distinguished in the trend of retrograde decompressional transformations, leading to formation of symplectic apoeclogites and garnet- clinopyroxene amphibolites. The age of zircons from eclogites and symplectite eclogites was determined by U-Th-Pb isotopic method (WHITEHOUSE et al., 1999) on the NORDSIM. Zircons are represented by small, isometric, multifaceted grains, transparent, unzoned, colorless, are typical for growth under high-pressure conditions. To confirm their genesis in eclogites the distribution of REE in zircons was determined on the ion microprobe. The results have confirmed their growth on the eclogitic stage. Nearly concordant data have been obtained with the best estimate age in 2720 ± 8 Ma. The GEC is cut by post-tectonic trondhjemite veins dated at 2701.3 ± 8.1 Ma and gabbronorite dykes (2.4 Ga). These results confirm the Neoarchaean age of the studied eclogites.

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SiO_2 EXSOLUTION AND PRECURSOR SUPERSILICIC PYROXENE REVISITED, AND A POTENTIAL NEW UHPM END-MEMBER: "SUPERSILIPYX"

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Supersilicic pyroxene in the form of needles of SiO_2 exsolved from omphacite was first recorded in an eclogite from Rendelven in S.E.Greenland by Smith & Cheeney (1980) and was deduced to indicate very high pressure there (a new UHPM province, if not the first). Subsequently the same texture was found in a "deduced-coesite" eclogite from Essdalen, S.W.Norway by Smith (1984) and was thus related to the Norwegian coesite-eclogite-province, and hence to UHPM. In Smith (1984, 1988) the two provinces were argued to be the same Caledonian province. Since then, exsolved SiO_2 needles have been discovered by many workers at various localities, and most recently in Slovenia (Janák et al., 2004). Instead of the usual quartz, Zhang et al. (2005) also found relict coesite which nicely confinns in nature the correspondence of supersilicic pyroxene and coesite P-T conditions already established by experiment (e.g. Mao, 1971, Gasperik, 1985). The question of how a pyroxene can be supersilicic has been frequently mentioned and the general consensus has always been a deduced exsolution from "Ca-Eskola's molecule" (Ca-Es) $\{^{viii}\#_{0.5}\ ^{viii}Ca_{0.5}\ ^{vi}Al\ ^{iv}Si_2\ O_6\}$ (where # = vacancy), which could give 1.5 SiO_2 + 0.5 $^{viii}Ca\ ^{vi}Al\ ^{iv}Al\ ^{iv}SiO_6$ (Ca-Ts) (Ca-Tschermak's pyroxene) (Smyth, 1980). This necessarily increases the "tschermakitic" substitution in the residual pyroxene. Since the natural residual pyroxene is often an almost stoichiometric omphacite, it is suggested here that this is not the only possible solution.

Supersilicic was defined by Smith (1982) by S > (N+D), and subsilicic by S < (N+D), with respect to the SA(ND) triangular diagram (where S = Si; A = Al + Fe^{3+} + Cr - Na; N = 2Na; D(divalents) = (Ca + Mg + Fe + Mn)) which had been especially conceived (Smith, 1976) in order to force jadeite to plot with diopside and all other stoichiometric pyroxenes except (Ca, Mg, Fe, Mn)-Ts, i.e. where (N+D)=S and A = zero. The diagram has been updated into the SHA(ND) tetrahedron (Smith, 2005, this conference) to include rutile, Li-, K-, Ni- or Mn^{3+}-pyroxene, majorite, Na-P garnet, protons and a new hypothetical inosilicate end-member *C2/c* pyroxene described here and called: "supersilipyx" $\{^{viii}\#\ ^{vi}Si\ ^{iv}Si_2\ O_6\}$ This mineral, which is not a tectosilicate like coesite or stishovite, is highly unlikely to be able to exist alone, but in solid-solution in a multicomponent omphacite it would only need a few octahedral ^{vi}Si atoms (as known to exist in majoritic garnet) and an equal number of M2 vacancies (as recognized in Ca-Ts). Decompression of a supersilicic pyroxene (i.e. a solid-solution of "supersilipyx" + stoichiometric omphacite) will lead to exsolution of pure SiO_2 as coesite or quartz without increasing the tschermakitic component of the residual pyroxene host phase. Subsilicic pyroxene is not possible for various reasons (over-charged or over-occupied M2 ± M1, under-occupied tetrahedra) unless Si is replaced by AlH or MgH_2 or H_4. These could be ways of introducing protons into pyroxene, known since Rossman & Smyth (1990), but these crystal-chemical mechanisms are more interesting in garnet (Smith, 2005, this conference).

THE "SHAND" DIAGRAM, A POSSIBLE SUBSILICIC PROTONATED GARNET, AND A POTENTIAL NEW UHPM END-MEMBER: "SUBSILIGAR"

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A most effective way of examining the stoichiometry of garnet and pyroxenes is the SAND diagram (Smith, 1982, 1988), initially devised by Smith (1976) for forcing jadeite to plot with diopside when dealing with eclogite-facies mineral and bulk-rock compositions. This plot takes advantage of the extreme mathematical constraint provided by all perfectly stoichiometric garnets $X_3Y_2Z_3O_{12}$ and pyroxenes $X_4Z_4O_{12}$, namely that they all have the same formula R_8O_{12} where R = any cation excepting H^+ On a linear plot of (ND) *vs.* S they all plot at the same point at the centre. In the SA(ND) triangle with A at the apex, they all plot on the same line between diopside and corundum (the "Gt-Px line", or "R_8O_{12} line"), with all non-majoritic garnets (Gt) exactly at the half-way position between all "Tschermak's molecule" (Ts) pyroxenes and all non-Tschermak pyroxenes (Px). The diagram is updated here to include all elements, especially P^{5+}, Zr^{4+} Ti^{4+} V^{3+}, Mn^{3+}, Ni^{2+}, K^+, Li^+ & H^+ (because of the last it is renamed here the SHAND plot):
S (for Si *et al.*) = $R^{4+} + R^{5+}$ (e.g. $Si^{4+} + Ti^{4+} + P^{5+}$),
H (for H only) = H^+,
A (for Al *et al.*) = $R^{3+} - [R^+ - R^{5+}]$ (e.g. $Al^{3+} + Cr^{3+} + Mn^{3+} + Fe^{3+} - [Na^+ + K^+ + Li^+ - P^{5+}]$),
N (for Na *et al.*) = $2\bullet[R^+ - R^{5+}] + R^{5+}$ (e.g. $2\bullet [Na^+ + K^+ + Li^+ - P^{5+}] + P^{5+}$),
D (for divalents) = $Ca^{2+} + Mg^{2+} + Mn^{2+} + Fe^{2+} + Ni^{2+}$
(ND) = N + D; all in cation proportions on the basis of O = 12.
The special point Px is very constrained as $R^+ = R^{3+}$, $R^+ + R^{3+} = R^{2+}$ and $R^+ + R^{2+} + R^{3+} = R^{4+} + R^{5+}$ It is more difficult to conceive of a supersilicic (S > ND) garnet than the supersilicic pyroxene "supersilipyx" $\{^{viii}\# \; ^{vi}Si \; ^{iv}Si_2 \; O_6\}$ (where # = vacancy) proposed by Smith (2005, this conference). The replacement of Si by AlH or MgH_2 was also suggested there (i.e. a substitution mechanism very different from that in hydrogarnet where Si = H_4) as a way of creating subsilicic pyroxene or garnet ((S < ND) as in forsterite, periclase & spinel). By placing Si in the octahedra, majoritic garnet neatly provides a way of creating subsilicic garnet, especially by the substitution of $^{vi}R^{4+}$ by $^{vi}R^{2+}H^+_2$ such that some octahedra are not $R^{2+}O_6$ but $R^{2+}O_4(OH)_2$ as in tri-octahedral micas. If one operates the Si = MgH_2 substitution on pure majorite in both octahedral and tetrahedral sites, the following formula is obtained: $^{xii}Mg_3 \; ^{vi}Mg_2H_2 \; ^{iv}Si_2 \; ^{vi}MgH_2 \; O_{12}$ = $Mg_6Si_2O_{12}H_4$ = serpentine + 3•periclase = 2•forsterite + 2•brucite = the composition of norbergite. This garnet is called here "subsiligar" It follows that with the Si = MgH_2 substitution, one can create a subsilicic garnet with the composition:
$^{xii}(Mg_{3p+3q+3r}) \; ^{vi}(Mg_{q+r} \; H_{2r} \; Al_{2p} \; Si_q) \; ^{iv}(Mg_r \; H_{2r} \; Si_{3p+3q+2r}) \; O_{12}$
= (p pyrope + q majorite + r norbergite) where $(p+q+r)$ = 1 or 100 %. Such an UHPM garnet could exsolve enstatite from the majoritic component and also norbergite, or serpentine + periclase, or forsterite + brucite, or these potential species could combine in a different way (e.g. to exsolve chondrodite, humite or clinohumite).

FROM MICROINCLUSIONS TO MAPPING AND MOBILITY (1983-2005): AN OVERVIEW OF RAMAN MICROSCOPY APPLIED TO ECLOGITES

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Raman Microscopy (RM) applied to eclogites seems to have begun in 1983 with the need to clarify the identity of two-phase SiO_2 microinclusions discovered in eclogite-facies rocks in Italy and Norway (BOYER et al., 1985a). This example has become a classic method in UHPM studies as it combined several beneficial possibilities of RM: (1) non-destructive physico-chemical analysis; (2) no special sample preparation; (3) analysis under the surface of transparent media; (4) analysis of a ~1 μm^3 volume; and (5) distinction of polymorphs (SMITH & CARABATOS-NEDELEC, 2001, NASDALA et al., 2004). After the original work on coesite / quartz, RM became widely used in many countries to distinguish between calcite / aragonite, sanidine / orthoclase / microcline & graphite / diamond / lonsdaleite / ??? and to study order / disorder phenomena in eclogite-facies rocks. A short time after it was applied to identifying run products in experimental petrology on UHPM minerals, e.g. AlF-rich titanite (BOYER et al., 1985b). Since RM can also analyse liquids and gases, it has been used to determine fluid inclusions (especially gases) in eclogites. Raman shifts can be caused by chemical exchanges that, when calibrated, can lead to semi-quantitative analysis of, for example, the jadeite % in omphacite or the pyrope % in hexary garnet (SMITH & PINET, 1989). More recently Raman mapping has shown its power to image phase distinctions and phase transformations, as well as elemental chemistry, in Norwegian symplectite, in zoned Guatemalan jadeite, and in metamictised zircon and complex carbon intergrowths from Kazakhstan (e.g. SMITH, 2004). Since 1999 Mobile RM (MRM) has been applied to analysing archaeological artefacts *in situ*, but this was not of great interest to eclogites. However the new possibility of "hand-held" analysis with a battery-powered mini-RM has led to "ultra-MRM" of Rock Art inside caves (SMITH, 2005); this means that it is now possible to distinguish the Jd % or Pyr % of eclogite minerals *in situ* in the field.

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THE EO-ALPINE HIGH-PRESSURE BELT IN THE EASTERN ALPS: A KINEMATIC EXHUMATION MODEL AND ITS TECTONIC IMPLICATIONS

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The eo-Alpine (Cretaceous) collision between the Austroalpine and the Adriatic microplates caused subduction and subsequent exhumation of HP-rocks along the so called eo-Alpine high-pressure belt (EHB). The EHB is an about 400 km long E-W striking zone restricted to the southern part of the Austroalpine realm in the Eastern Alps. HP-rocks occur at several locations within a ductile high-strain zone and show a rather uniform cooling age pattern related to exhumation between roughly 110 and 70 Ma (THÖNI, 1999). MORB-type rocks in the easternmost occurrences are the only evidence of the presence of oceanic crust. This observation could be interpreted as an oceanic subduction in the eastern part linked to continental subduction in the western part.
Recent data from a multidisciplinary approach provide new insights into the exhumation history of the western part of the EHB (SÖLVA et al., 2005). Within the Texel Gruppe (Northern Italy), HP-rocks were extruded SE-ward in the central part of a ca. 20 km thick eo-Alpine transpressive high-strain zone, which was active from 95 70 Ma exhuming rocks from eclogite facies to sub-surface conditions.
Similar geochronological and structural data from other parts of the EHB suggest that a similar mechanism may be responsible for exhumation along the whole Cretaceous belt. The presence of a continuous collision zone, but single HP-occurrences with different maximum burial depths indicates that vertical motion varied substantially along-strike.
In the Koralpe/Saualpe/Pohorje (KSP) complex, representing the largest occurrence of HP-rocks within the eastern part of the EHB, structural data point to northwestward thrusting of the HP-unit onto low-metamorphic units, opposite to the extrusion direction within the western EHB. Lower and upper plate within the subduction/exhumation zone must therefore switch their relative position somewhere in between the Texel complex and the KSP complex. An oblique continental collision zone with irregular plate boundaries and along-strike changes in crustal rheologies may explain (i) the differences in vertical motion along the EHB and (ii) the flip in polarity of hanging wall and footwall. In this scenario HP-rocks are located at "restraining bends" in a steep ductile shear zone with lateral and vertical displacement (e.g. CAMACHO & McDOUGALL, 2000), accompanied by shortening across the shear zone.

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THE ARROYO CHARCON, AN UNUSUAL ECLOGITE FROM THE ESCAMBRAY MASSIF, CUBA: PETROLOGY AND ZIRCONOLOGY

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In the Escambray Massif (EM) of Cuba, well known for Mesozoic HP/LT metamorphic rocks SOMIN et al. (1975), DOBRETSOV et al. (1987) and SOMIN et al. (1992) described apparently coherent bodies of eclogite placed within blueschist metasediments. One of these bodies near Arroyo Charcon (ACH) is a lens 1 m wide and 5 m long. The rock is composed of fresh garnet and omphacite; paragonite and deerite are subordinate phases; rutile, sulphide and zircon are accessories. Quartz, phengite and clinozoisite are present as small inclusions inside garnet and rutile. Microprobe analyses show two-stage evolution of the rock. Garnet I (cores) associated with chlorite reflects the first stage of uncertain (probably LT) parameters. The outer, wider garnet II zones and omphacite gave $P = 14 - 16$ kbar and $T \leq 600$ °C. These results are close to those of SCHNEIDER et al. (2004) on other eclogite bodies of the EM.
The Zr-content at 820 ppm in the ACH eclogite is unusually high. The zircons have complex morphologies. SEM photos show they originally had rounded form due probably to sedimenttary transport; later metamorphic overgrowths are expressed as flat facets on some of the zircons. CL images demonstrate oscillatory zoning in many grains, some sharply limited cores and the rare, thin metamorphic rims. In one case phengite was detected inside zircon. These observations show mostly magmatic, rarely metamorphic origin of the zircons. At the same time, the evidence of reworking indicates an alien, clastic origin for the parent grains.
U-Pb zircon dating in Santa Barbara, USA, using a multistep CA-TIMS procedure (MATTINSON, 2005) revealed 245 Ma as a mean age of the least soluble zircons, the possibility of younger event ab.110 Ma, plus older material of at least 375 Ma. SHRIMP-2 dating was done independently at St-Petersburg (VSEGEI) and Perth. A range of ages clustered around 245 Ma was obtained in both cases; the age range is 270 - 140 Ma (VSEGEI) and 256 201 Ma (Perth) due evidently to differences in grain selection and analytical quantity. Determination of the metamorphic rims' exact age remains our next goal.
We infer a mixed origin of the ACH eclogite and probable Central-American provenance of its Jurassic and older zircons. Sedimentation of terrigenous material on the ocean bottom and heavy mineral concentration by currents are a possible source for such abundant deprival zircon in the ACH eclogite.

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DIAMONDS AND Fe-CARBONATE INCLUSIONS IN GARNETS FROM PELITIC GNEISSES OF THE ULTRA-HIGH PRESSURE METAMORPHIC KIMI COMPLEX IN CENTRAL AND EAST RHODOPE GREECE

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Micro-Raman investigation on diamond inclusions in garnet from pelitic garnets of the UHP metamorphic Kimi complex in Rhodope, revealed two types of diamonds. Microdiamonds with a typical sharp peak at 1332 cm^{-1} and FWHM 3.5 to 5 cm^{-1} and diamonds with a broad peak at 1333 cm^{-1} with FWHM from 21 to 29 cm^{-1} interpreted as nanodiamonds. They are associated with an additional peak at 1308 cm^{-1} interpreted by PERRAKI et al (2005) as possible lonsdaleite(?). Microdiamonds occur either as single crystal grain inclusions in garnets or most frequently, they are associated with a carbonate phase. Nanodiamonds are present in composite inclusions in garnet, consisting of CO_2 + nanodiamond, CO_2 + nanodiamond + carbonate, CO_2 + nanodiamond + carbonate + mica (possibly phengite) and nanodiamond + carbonate + phengite.

Raman spectra of the carbonate inclusions are characterized by peaks at 1086 – 1090 cm^{-1} for the V1 vibration and at 287 – 296 cm^{-1} for the lattice mode vibration. Microprobe analyses on carbonate phases of inclusions exposed to the surface of polished thin sections showed that the carbonates are predominantly siderites with substitutions of Fe^{2+} mainly by Mg and less by Ca and Mn. Another type of carbonate inclusions in garnet was also detected, though this type is rarely in association with nanodiamonds. It is characterized by Raman peaks at 1090 – 1094 cm^{-1} for the V1 vibration and at 305 – 318 cm^{-1} for the lattice mode vibration. Microprobe analysis showed that this type is a Fe-Mg carbonate with much higher Mg content than the former one.

The coexistence of siderite with micro- and / or nanodiamond, CO_2 and phengitic mica in garnet inclusions of the metapelites in Rhodope metamorphic province indicates that diamond is crystallized from C-O-H + silicate supercritical fluids/or melts rich in Fe, Al, Mg, and less in K, Ca and Mn. Such fluids can be formed by dehydration melting at the peak P-T conditions or at the first stages of decompression but still at UHP conditions. Supercritical C-O-H (+ silicate) fluids for diamond crystallization are also referred by STÖCKHERT et al. (2001) and DOBRZHINETSKAYA et al. (2003) in Erzgebirge and Kokchetav massif respectively.

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CONSTRAINING THE P–T PATH OF A MORB-TYPE ECLOGITE USING PSEUDOSECTIONS AND GARNET ZONING: AN EXAMPLE FROM THE BOHEMIAN MASSIF

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A MORB-type eclogite from the Moldanubian domain in the Bohemian Massif retains evidence of its prograde path in the form of inclusions of hornblende, plagioclase, clinopyroxene, titanite, ilmenite and rutile preserved in zoned garnet. Prograde zoning involves a flat grossular core followed by a grossular spike and decrease at the rim, while Fe/(Fe+Mg) is also flat in the core and then decreases at the rim. In a pseudosection for H_2O-saturated conditions, garnet with such a zoning grows along an isothermal burial path at ca. 750 °C from 10 kbar in the assemblage plagioclase-hornblende-diopsidic clinopyroxene-quartz, then in hornblende-diopsidic clinopyroxene-quartz, and ends its growth at ca. 17 - 18 kbar. From this point there is no pseudosection-based information on further increase in pressure or temperature. Then with garnet-clinopyroxene thermometry the focus is on the dependence on, and the uncertainties stemming from the unknown Fe^{3+} content in clino-pyroxene. A Fe^{3+}-contributed uncertainty of ± 40 °C combined with a calibration and other uncertainties gives a likely result of 770 ± 90 °C at 18 kbar. The implication from this prograde path is that the rock started burial to eclogite conditions at an elevated temperature at lower crustal conditions.

Pseudosection-modelling suggests that decompression to ca. 12 kbar occurred under H_2O-undersaturated conditions (ca. 1.3 modal% H_2O) that allowed the preservation of the majority of garnet with symplectitic as well as relict clinopyroxene. The modelling also shows that a MORB-type eclogite decompressed to ca. 8 kbar ends as an amphibolite if it is H_2O-saturated, but if it is H_2O-undersaturated it contains assemblages with orthopyroxene. Increasing H_2O-undersaturation causes an earlier transition to SiO_2-undersaturation on decompression, leading to the appearance of spinel-bearing assemblages. Granulite-facies-looking overprints of eclogites may develop at amphibolite-facies conditions.

ECLOGITE AND STRESS

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Material properties and state of stress in subduction zones are poorly constrained by geophysical evidence. Valuable information can be provided by the structural and micro-structural record of exhumed (U)HP metamorphic rocks for depths down to > 100 km. Despite being cycled through a high strain-rate mega-shearzone, many exhumed (U)HP meta-morphic rocks appear not to be significantly deformed at (U)HP conditions, and others were exclusively deformed by dissolution precipitation creep (STÖCKERT, 2002). In both cases experimental flow laws for dislocation creep pose an upper bound to the magnitude of stress as a function of temperature along the entire trajectory. The inferred maximum differential stresses are generally on the order of 10^0 or 10^1 MPa for the peak temperatures recorded by the rock. The natural record implies (1) strongly localized deformation, (2) predominance of dissolution precipitation creep and fluid-assisted granular flow in the shear zones, suggesting Newtonian behaviour, (3) low magnitude of differential stress, which (4) is on the order of the stress drop inferred for earthquakes, and consequently (5) negligible shear heating. Numerical 2D experiments based on this concept and using best guess flow laws have demonstrated the evolution of a subduction channel and the feasibility of rapid exhumation by return flow (GERYA et al., 2002; STÖCKHERT & GERYA, 2005). The P-T-t paths and structural patterns obtained in the simulations compare well with the natural record. Among the volu-metrically important minerals in (U)HP metamorphic rocks, only omphacite in foliated eclogites shows widespread evidence of deformation by dislocation creep. Laboratory experiments on jadeite indicate a significantly lower flow strength in the dislocation creep regime compared to diopside. Based on the results on jadeite, a relatively low flow strength of omphacite solid solution in the dislocation creep regime is anticipated, in accordance with the natural record. Eclogites may be comparatively weak. The (U)HP metamorphism of eclogite cannot be due to very high mean stress $\sigma_{ii}/3$, i.e. tectonic overpressure. While undeformed (U)HP metamorphic rocks indicate a low level of stress along their *entire* path, the record of crystal plastic deformation in (U)HP metamorphic rocks only means that the respective stress levels were reached at a single stage of their history or at a site of stress concentration. Probably most important in subduction zones, high stresses are suspected to built up episodi-cally by quasi-instantaneous loading near the tips of seismic rupture planes, or by dilatation due to rapid phase transformation (LENZE et al., 2005). A typical average shear stress along the plate interface cannot be inferred from such features.

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WATER IN OMPHACITE OF ECLOGITE FROM THE SOUTHERN TIANSHAN

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The late Paleozoic western Tianshan high pressure (HP) and low temperature (LT) belt extends for about 200 km along the southern central Tianshan suture zone. It is part of the orogenic belt formed by subduction/collision between the Yili-Kazakhstan-Kyzylkum and the Tarim-Karakum plates. Eclogite facies rocks occur as lenses, as laminae, massive blocks or as thin layers intercalated with blueschists and marbles. PT estimates of the eclogite facies mineral assemblage garnet + omphacite ± phengite + quartz ± Na-amphibole indicate T = 490 - 570 °C at P = 18 - 21 kbar.
We studied omphacite samples from an eclogite (sample NO. SW32-36) of the Akeyazhi area from the southern Tainshan, western China. There are granoblastic crystals and fibroblastic aggregates of omphacite. The former has relatively higher jadeite- and lower aegirine-components when compared with the latter. Moreover, the large omphacite crystals are generally zoned with the jadeite-component increasing and the aegirine-component decreasing from core to rim. Fibroblastic omphacite shows a similar composition when compared with the rim of granoblastic crystals, generally the aegirine-component is higher while jadeite-component is lower. The compositional zoning of omphacite implies prograde growth conditions.
Out of doubly polished thin sections (0.1 mm thick) inclusion- and crack-free omphacite crystals with at least 150 - 200 µm in their shortest dimension were extracted, cleaned with ethanol and dried at 100 °C for 3 hours. Using a Nicolet Magna-IR 750 and IR-plan Advantage Fourier Transform Infrared Microscopic Spectrometer, omphacite was measured from 3000 to 4000 cm^{-1} with an IR light source, KBr beam-splitter and a MCT detector at room temperature; 128 scans were accumulated for each spectrum with 4 cm^{-1} resolutions. Apertures of 100 × 100 µm were used for selecting sample areas for measurement.
Four hydroxyl absorptions occur at the regions 3650 - 3660, 3620 - 3630, 3510 - 3520 and 3430 - 3440 cm^{-1} It implies that a hydrous component commonly exists in the omphacites. The bands centered at 3430 - 3440 cm^{-1} are blunt, which is attributed to the overlapping of water molecules (H_2O). Our data show that OH concentration in the fibroblastic omphacites is lower than in the granoblastic omphacites. However, the large omphacite crystals have comparatively high OH and low H_2O concentrations in the rim, while relative low OH and high H_2O concentrations were recorded for the core.
The results of IR studies on omphacite crystals suggest that the comparatively high H_2O and low OH concentrations measured in the core of the omphacites, indicate the presence of fluid inclusions. It further indicates that the OH solubility increased with increasing pressure during prograde growth of the omphacites. This indicates that H_2O, which was released by dehydration of blueschists during the transition from blueschist to eclogite, participates and promotes the formation of eclogite. In the earlier stage, fluid inclusions were trapped as H_2O during pervasive fluid flow. However, during later stages, OH was incooperated into the omphacite structure because the H_2Ocontent had decreased as the result of the formation of omphacite veins.

DATING ECLOGITES IN THE EASTERN ALPS: APPROACHES, RESULTS, INTERPRETATIONS

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In the Eastern Alps, eclogites occur at different levels:
(i) In the structurally lower part of the orogen (the Pennine unit as exposed in the *Tauern window*) eclogites (ca. 2 GPa / ≤ 630 °C) formed as a result of subduction of the Piemont-Liguria ocean below the Austroalpine domain. ^{40}Ar ^{39}Ar ages from phengite favour an Eocene (50 - 40 Ma), rather than a Late Cretaceous / Early Cenozoic age for this high-P metamorphism.
(ii) Variscan, partly MORB-type eclogites, forming constituents of the N Apulian (Austroalpine) crust, occur in the central *Ötztal basement* (2.7 GPa / 730 °C; mean Sm-Nd age: 347 ± 11 Ma), the eastern *Silvretta* (ca. 350 Ma), and the *Ulten* high-grade crystalline (336 - 332 Ma).
(iii) In the southern Austroalpine units, metabasic eclogites and high-P metapelites are known from the *Texel complex* (1.3 GPa / ca. 520 - 600 °C), the *Schober / Kreuzeck* areas (1.8 GPa / ≤ 690 °C), and the *Saualpe-Koralpe-Pohorje* region (2 - 2.5 GPa / ≥ 700 °C). The latter originate from Permian MORB-type gabbros and basalts, whereas the Schober and Texel eclogite protoliths probably represent elements of the pre-Permian crust. The similar tectonic position and near-identical ages suggest a common subduction-exhumation history for this „eo-Alpine high-pressure belt" (THÖNI & JAGOUTZ, 1993). It resulted from burial of the distal passive Neotethyan Meliata margin and, further west, pre-Alpine Austroalpine crust, along a continent-to-ocean subduction zone during Late Mesozoic Apulia–Europe convergence. Peak metamorphism and initial decompression / exhumation is dated by the Sm-Nd, Lu-Hf, U-Pb and Rb-Sr systems as close to 90 Ma, with uplift rates in the range of 3 - 4 km / Ma for the time 90-80 Ma B.P

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TECTONOTHERMAL EVOLUTION DURING EXHUMATION OF THE UHPM KIMI COMPLEX NEAR XANTHI, RHODOPE, NE GREECE

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The tectonothermal history of an UHP area north of Xanthi was investigated using microstructures, rheology, thermobarometry and a fluid inclusion study of metamorphic index minerals like kyanite, garnet, pyroxene and quartz. The Kimi-complex of Xanthi is separated by detachments from the adjacent Sideronero Complex and consists of a variety of lithologies that have been subject to a continental subduction process. The area exhumed during Cretaceous and Tertiary times due to the collision of Europe with Apulia. The lithological sequences consist of marbles, paragneisses, orthogneisses, metabasites and ultrabasites. These crustal rocks and its mantle-derived associations experienced UHP metamorphism, supported by the occurrence of metamorphic microdiamonds in grt-ky-micaschist. The metamorphic zircon age of such a micaschist suggests UHP metamorphism at 152.8 ± 2.4 Ma (LIATI et al., this volume). The exhumation process was dominated by SW-directed thrusting, subsequently transformed into a fold and thrust belt under amphibolite facies conditions. Folding is accompanied by sinistral strike-slip tectonics. NW-SE striking foliation planes (S1) contain indicators for SW-directed shear in x-z section (parallel to the NW-dipping stretching lineation) and for sinistral shear in y-z sections (perpendicular to the stretching lineation). The fold geometry is characterized by NE-SW striking upright to SE-vergent folds with NE-dipping fold axes. Folding results in clear repetitions of the lithological units on a meter- to km-scale.
P-T data range between 580 - 630 °C and 10 - 12 kbar for metabasites and up to 900 °C and 18 kbar for metapelites. The metamorphic conditions for the formation of the ductile cleavage planes in metapelites are about 780 860 °C and 13 15 kbar. Garnets up to several centimetres in diameter grew prior to the amphibolite-facies overprint. Kyanite occurs within ductile cleavage planes and also within pressure shadows of garnets. The quartz matrix in metapelites is completely recrystallized due to high-temperature intracrystalline deformation processes. Feldspar shows also evidence for intracrystalline deformation and recrystallization. High-density CO_2-inclusions in kyanite and garnet rims give pressure conditions for mineral formation of ~ 10 kbar. Primary fluid inclusions in kyanite show variable degrees of fill and homogenisation temperatures, which is interpreted as variable density loss by leakage. Quartz enclosed within pyroxene contains high-density aqueous inclusions, suggesting pressures up to 15 kbar. A high number of H_2O-CO_2 fluid inclusions in quartz hosted by garnet have only low densities, similar to matrix quartz, where decrepitation textures of former fluid inclusions indicate density loss during relatively isothermal decompression. Transgranular fluid planes within matrix quartz from metapelites contain $CO_2 \pm N_2 \pm CH_4$ and represent a late stage of fluid entrapment below 2 kbar at a shallow crustal level.

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$a(H_2O)$ CALCULATIONS IN ECLOGITE-FACIES ROCKS

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Subduction of crustal materials is accompanied by metamorphic reactions liberating fluids. Fluid inclusions in eclogite minerals range from dilute solutions to chloride-rich brines; however, the effect of salinity variations on the stability of hydrous phases in subduction zones is poorly understood. TROPPER & MANNING (2004) carried out experimental investigations on the influence of saline brines on the reaction paragonite = jadeite + kyanite + H_2O (1). The shift of this reaction to lower P constrains a-X relations in the system H_2O-NaCl and indicates that $a(H_2O)$ is consistent with the H_2O-NaCl activity model of ARANOVICH & NEWTON (1996) which involves NaCl dissociation as a function of P, T and ρH_2O. In addition, the experimental results now permit use of appropriate paragonite-bearing or -absent assemblages to quantify $a(H_2O)$ in high-P metamorphic environments, such as the Austroalpine units (Sesia Lanzo Zone, Dent Blanche Nappe) in the Western Alps. For example, jadeite and kyanite in a partly equilibrated metapelite from Val Savenca in the Sesia Lanzo Zone formed during the Eo-Alpine high-P metamorphic event at 1.7 - 2.0 GPa, 550 – 650 °C. The absence of paragonite requires an upper limit of $a(H_2O)$ of 0.3 - 0.6. Calculations with the assemblage white mica + omphacite + kyanite in better equilibrated samples, yield a very small $a(H_2O)$ of < 0.02. These data show that significant dilution of the coexisting fluid must have occurred. Petrologic investigations of Sesia Lanzo eclogites from Val Ianca show that paragonite occurs as inclusions in garnet cores but gives way to omphacite + kyanite toward rims, suggesting a decrease in $a(H_2O)$ from ca. 1.0 to < 0.81. In addition to textural constraints, it is also possible to calculate $a(H_2O)$ from fluid inclusion (FI) data. Calculation of $a(H_2O)$ of paragonite-bearing eclogites from the Austroalpine Mt. Emilius unit in the Dent Blanche nappe (1.1 - 1.3 GPa, 450 – 550 °C) yielded $a(H_2O)$ of 0.62 - 0.72, based on H_2O-NaCl fluid inclusion data from omphacites by SCAMBELLURI et al. (1998). Calculation of reaction (1) with the obtained $a(H_2O)$ shows no incompatibilities with the observed phase assemblage, indicating that paragonite + omphacite are stable relative to omphacite + kyanite.

This study shows that the presence or absence of paragonite yields at least limiting constraints on $a(H_2O)$ whereas the assemblage white mica + omphacite + kyanite allows an exact determination of $a(H_2O)$. Prerequisite is an independent estimate of P or T Fluid inclusions can also be used to obtain informations on $a(H_2O)$ as long as the FI / host relations are clear.

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INCIPIENT ECLOGITIZATION BELOW 300 °C PRESERVED IN GUATEMALAN LAWSONITE-ECLOGITE

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Early Cretaceous lawsonite-eclogites and related HP rocks occur as tectonic inclusions within serpentinite mélange south of the Motagua fault zone, Guatemala (HARLOW et al., 2004; TSUJIMORI et al., 2005). Petrologic and microtextural analyses of four types of mafic HP rocks – jadeite-bearing lawsonite eclogite (JdEC), Type I, II lawsonite-eclogites (Type I LwEC, Type II LwEC), and garnet-bearing lawsonite-blueschist (Grt-LwBS) – reveals three metamorphic stages formed during four deformational phases. The prograde stage represents an incipient eclogitization and is preserved mainly in prograde garnet of all rock types along with older S_1-S_2 foliations. Rarely it occurs in the matrix of the JdEC and Type II LwEC with S_2. The assemblage is Grt [X_{Mg} = ~ 0.22] + Omp [~ 52 % Jd] (or Jd [~ 83 % Jd]) + Lws + Rt + Qtz ± Phe [3.6 Si pfu]; some also have Chl, Ilm, and rare Fgl. Primary impure jadeite occurs in the JdEC. Lawsonite inclusions in garnet of Type I LwEC contain rare pumpellyite inclusions. The presence of syn-metamorphic brittle deformation, inclusion of precursor pumpellyite, the Fe-Mg distribution coefficient between omphacite inclusions and adjacent garnet (Ln(K_D) = 2.7 4.5), and the Grt-Cpx-Phe thermobarometry suggest that the eclogitization initiated at T = ~ 300 °C and P > 1.1 GPa, and continued to T = ~ 480 °C and P = ~ 2.6 GPa. In contrast, retrograde eclogite-facies assemblage is best preserved in the Type II LwEC and is characterized by reversely zoned rims of garnet and Omp + Gln + Lws + Rt + Qtz ± Phe [3.5 Si pfu] within S_3 foliation; this Gln and Lws contain rutile inclusions. The Grt-Cpx-Phe thermobarometry yields P = ~ 1.8 GPa and T = ~ 400 °C. Intense deformation and recrystallization along with a PT drop and hydration may have been caused by initiation of exhumation. Furthermore, the latest blueschist-facies assemblage (Gln + Lws + Chl + Ttn + Qtz ± Phe ± Ab) along S_4 crenulations locally replaces earlier mineral assemblages as observed in the Grt-LwBS. In summary, these petrologic characteristics indicate: (1) the basalt-eclogite transformation may have occurred at T = ~ 300 °C in a cold subduction zone, and (2) formation of a lawsonite-bearing eclogite assemblage that may not have passed through precursor blueschist-facies. During subduction, dehydration of Chl + Ab + Lws ± Pmp to form Grt + Omp within the lawsonite stability field may be more effective than the glaucophane-forming reaction; lawsonite-eclogitic mineral assemblage may form directly from altered basalt. Instead abundant retrograde glaucophane was formed by hydration during exhumation.

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A NEW THERMODYNAMICAL DATASET FOR Mn-RICH MINERALS: APPLICATION TO THE ECLOGITIZED OCEANIC Mn DEPOSIT OF PRABORNA (WESTERN ALPS, ITALY)

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The Mn-ore deposit of Praborna is embedded in the Zermatt-Saas meta-ophiolites (Western Italian Alps). It is located in the Saint-Marcel Valley (Aosta Valley), where the ophiolites have been metamorphosed in high-P low-T conditions (2.0 GPa and 550 °C; MARTIN et al., 2004) during the Alpine orogeny. This deposit has been described as metamorphosed mineralized cherts, overlying the oceanic crust of the Liguro-Piedmont branch of the Tethys that opened during Jurassic between Europe and Adria (Africa). The ore displays a banded structure towards the gneiss contacts, with development of variable petrological assemblages, pointing out complex redox reactions at the high-P peak as well as during retrogression. The ore itself consists in thick quartz-braunite and quartz-piemontite-spessartine layers. Other more-or-less abundant phases are: i) amphiboles (sodic-calcic, ranging from tremolite and winchite to glaucophane, rare richterite; mangano-cummingtonite), ii) clinopyroxene (diopside-jadeite-aegirine solid solutions), iii) micas (Mn-bearing phengite and phlogopite); iv) feldspars (albite, Ba-rich microcline); v) other Mn-minerals (rhodonite, calcite-rhodocrosite s.s., hollandite); vi) accessories phases: rutile, barite, titanite, apatite, ardennite, romeite, (Ca,REE)-vanadates, androsite-(Ce). Although the Praborna mine has been studied by many authors, the origin of the ore and the petrological evolution at and after the high-P peak are still uncertain. The difficulty in studying such unusual Mn-rich parageneses, is the lack of thermodynamic data, which prevents modelling the P-T evolution. Therefore, we have built a new thermodynamic dataset, estimating the thermodynamic properties of our Mn-bearing phases (ΔH_f, S_0, V_{mol}, the C_P parameters, a^0 and κ), by using a combined polyhedra-analogous modelling. In fact, we have chosen the mineral most similar to the phase selected for estimation, generally the Fe analogue because of the chemical similarity between Fe and Mn. For estimating a particular thermodynamic parameter, we subtracted the contribution of the Fe polyhedra to this parameter (recalculated by linear regression, using phases from the database of HOLLAND & POWELL, 1998) and we added the Mn one. We used this new dataset to construct P-T and T-a(O_2) grids in simple (Mn-Si-O) and complex (NCFMASH+Mn) systems, and, thus, we obtained results that well agree with the experimental published data. The dataset also allows the construction of P-T pseudo-sections, by considering the chemical composition of some of the Praborna rocks, whose evolution is thus better constrained.

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SUPER-SILICIC GARNET MICROSTRUCTURES: AN UNUSUAL BUT POTENTIAL POWERFUL MICROSTRUCTURE FOR LITHOSPHERE EVOLUTION

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Fossil UHP continental subduction zones, now exposed at the surface of the earth, consist dominantly of subducted continental crust with subordinate mantle fragments (subduction zone- and / or relict peridotites (BRUECKNER & MEDARIS, 2000)) incorporated within them. In such terranes characteristic mineral indicators for UHPM conditions (CHOPIN, 2003), such as coesite, micro-diamond, ellenbergite or super-silicic garnet microstructures can be combined with more classical petrological techniques to make estimates about maximum exhumation depths of these fossil continental subduction zones. In principle the characteristic UHP mineral indicators / classical petrological techniques should be applied to all rock types: i.e. the subducted continental crust *AND* the intercalated mantle fragments. If this is not done the two rock types may originate from different depth levels putting severe constraints on possible exhumation mechanism

In this respect the super-silicic (or majoritic) garnet microstructure forms an unusual, but potential powerful, UHP mineral indicator. Sofar it has been recognized in mantle xenoliths, brought to the surface by kimberlite-related magmas, and in orogenic peridotites associated with UHP subduction zones formed by continental collision. In the latter case the super-silicic garnet microstructure is, however, only present within mantle fragments and not in associated subducted continental crust, indicating that the formation of super-silicic / majoritic garnet is either strongly controlled by bulk rock chemistry or that significant pressure (and / or age) differences exist between the various mineral / bulk rock compositions that together form the fossil UHP continental subduction zone. All available experimental evidence (FEI & BERTKA, 1999; GASPARIK, 2003) sofar, is consistent with the latter solution and clearly demonstrates that, when super-silicic garnet microstructures are found within fully recrystallized subduction zone peridotites, these mantle fragments cannot have been derived from the hanging wall of the subduction zone system as predicted by the model of BRUECKNER & MEDARIS (2000) and BRUECKNER & VAN ROERMUND (2004). Such findings would require hitherto unrecognized exhumation mechanism(s). Alternatively the super-silicic garnet microstructure may be unrelated to the age of the (continental) subduction event; i.e. the microstructure is related to lithosphere evolution of the hanging wall of the subduction system. PT constraints require that this lithoshere is cold and thick, most likely subcontinental.

A review of the occurrence, age and interpretation of supersilicic garnet microstructures will be given and discussed within the light of the text given above.

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EVIDENCE FOR ULTRA-HIGH PRESSURE (UHP) METAMORPHISM WITHIN PROTEROZOIC BASEMENT ROCKS ON OTRØY, WESTERN GNEISS REGION, NORWAY

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Vestiges of Scandian ultra-high pressure (UHP) metamorphism have been increasingly recognized in recent years within coastal rocks of the Western Gneiss Region (WGR) north of Nordfjord, western Norway (TERRY et al., 2000; VAN ROERMUND et al., 2002; ROOT et al., 2003). Here we present new field-, mineral-chemical- and microstructural evidence from the northern part of Otrøy island indicating that the Proterozoic basement rocks on Otrøy also underwent UHP metamorphism.

The Proterozoic Baltica basement rocks on northern Otrøy consist of E-W to NNE-SSW trending belts that consist of interlayered augen orthogneiss (often migmatitic) and well-layered (migmatitic) dioritic-granodioritic gneiss with abundant eclogites and subordinate garnet peridotites. The dominant foliation is subvertical, often with a well developed subhorizontal E-W amphibolite facies lineation. Previous studies (CARSWELL et al., 1985; KROGH & CARSWELL, 1995) concluded that incorporation of the garnet peridotite into the Caledonian basement rocks during the Scandian occured within the β-quartz stability field. In addition it is well known that the garnet peridotites contain Proterozoic (M1) and Caledonian (M2) mineral assemblages but microstructural criteria can easily be used to distinguish between both age generations. We have applied standard geothermobarometric techniques on newly discovered and old (re-studied) occurences of external Opx eclogites. These results were subsequently compared with similar M2 rock-types (garnet websterite) occuring within garnet peridotites. Previous studies also concluded that Al_2O_3 wt% values in Opx $\geq$ 0.6 roughly corresponding to 750 – 800 °C and 18 - 20 Kbar. This is in strong contrast to the results of this study in which for the external Opx eclogites values as low as 0.5 and for the internal (and recrystallised) garnet websterites values as low as 0.25 could easily be identified within EMP-cross sections across Opx grains adjacent to Grt. In combination with various established thermometers this corresponded in all cases to P-T estimates above the β-quartz / coesite phase boundary line indicating UHP metamorphic conditions. A supplementary search for the presence of other UHP index minerals that ought to be present in other rock types have sofar been unsuccesful. In our opinion this can be explained by the severe amphibolite facies retrograde metamorphic overprint that characterises most of the rocks.

We conclude that based on the internal and external orthopyroxene eclogites/pyroxenites results the basement rocks on Otrøy can be classified as UHP.

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ULTRAHIGH-PRESSURE ECLOGITES FROM POHORJE MTS. (EASTERN ALPS, SLOVENIA)

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Ultrahigh-pressure (UHP) metamorphism in the Eastern Alps has been recently documented in the eclogites from Pohorje Mts. of Slovenia (JANÁK et al., 2004). These eclogites occur in the southeastern part of Pohorje, near Slovenska Bistrica. The country rocks of eclogites are metaultrabasites (predominantly serpentinised dunite and harzburgite with garnet peridotite remnants), amphibolites, orthogneisses, paragneisses and micaschists. These rocks belong to the Lower Central Austroalpine basement unit of the Eastern Alps, exposed in the proximity of the Periadriatic fault.

Kyanite eclogites consist of garnet, omphacite, kyanite and zoisite as major primary phases. Garnet is unzoned with 48 - 53 mole% of pyrope and 19 22 mole% of grossular. Non-stoichiometric supersilicic omphacites contain up to 8 - 10 mole% of Ca-Eskola molecule. Their breakdown during decompression resulted in exolution of quartz rods that are oriented parallel to omphacite c-axis. Phengites contain up to 3.5 Si p.f.u. Quartz inclusions in garnet, omphacite and kyanite are surrounded by radial fractures and exhibit microtextures diagnostic for recovery after coesite breakdown. Secondary phases occur in the coronas, symplectites and fractures. These are diopside, amphibole and plagioclase after omphacite, biotite and plagioclase after phengite, and sapphirine, corundum, spinel and anorthite after kyanite. Pressure and temperature conditions for the formation of the peak metamorphic mineral assemblages have been assessed through a consideration of a) Fe^{2+}- Mg partitioning between garnet and omphacite, b) the equilibrium between garnet + clinopyroxene + phengite ± kyanite ± quartz / coesite assemblage. Calculated peak pressure and temperature conditions of 3.0 - 3.1 GPa and 760 - 840 °C are well within the coesite, i.e. the ultrahigh-pressure stability field. This is consistent with UHP metamorphic conditions recorded in the garnet peridotites from the same area (see JANÁK et al., this issue).

UHP rocks in Pohorje record the highest-pressure conditions of Eo-Alpine metamorphism during the Cretaceous orogeny in the Alps, implying a very deep subduction of the continental crust to at least 90 - 100 km depths. Subduction was intracontinental, dipping to the south or southeast; north-western parts of the Austroalpine (Lower Central Austroalpine) were subducted under south-eastern parts (Upper Central Austroalpine). The subduction zone formed in the Early Cretaceous in the north-western foreland of the Meliata suture after Late Jurassic closure of the Meliata Ocean and the resulting continental collision.

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NORTHEASTWARD EXPANSION OF THE NORTHERN ULTRA-HIGH PRESSURE (UHP) DOMAIN, WESTERN GNEISS REGION, NORWAY; EVIDENCE FROM A Fe-Ti GARNET PERIDOTITE/WEBSTERITE BODY

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To date ultrahigh-pressure (UHP) metamorphic rocks in the Scandinavian Caledonides are recorded in three domains within the Western Gneiss Region of Norway: Stadlandet-Nordfjord, Hareidland-Runde (ROOT et al., 2005) and Nordøyane-Otrøy (TERRY et al 2000; VAN ROERMUND et al. 2002; CARSWELL & VAN ROERMUND, 2003). Here we present field, mineral-chemical, microstructural and isotopic evidence that the northern UHP domain extends northeastwards to as far as Tornes on the mainland. An excellent preserved 1300 m^2 Fe-Ti type peridotite/websterite body at Svartberget lies along strike with similar occurrences between Raknestangen and Kolmannskog, thought to be of lower crustal origin (CARSWELL et al., 1983). The body comprises diopsidic clinopyroxene (Cpx) ($Wo_{47}En_{48}Fs_5$, Jd_{1-2}), orthopyroxene (Opx) (En_{84-86}, Al_2O_3 ~ 0.50 %), garnet (Grt) ($Pyr_{56}Alm_{29}Gross_{13}$) and olivine (5-20 % Fo_{83}). The main websterite body is cut by a network of coarse-grained (up to 20 cm) garnet-pyroxenite and garnetite veins consisting of unzoned diopsidic Cpx ($Wo_{46}En_{46}Fs_8$, Jd_4), Opx (En_{81-82}, Al_2O_3 ~ 0.16%), Grt ($Pyr_{50-52}Alm_{35}Gross_{11-13}$) and phlogopitic biotite (Phl_{85}). P-T estimates based on the Opx-Grt barometer of BREY & KÖHLER (1990) in combination with the Grt-Cpx thermometer of POWELL (1985) yield 2.6 GPa at 670 °C for the main body. Veins yield 6.4 GPa at 950 °C. Preservation of the markedly higher P-T conditions in the veins is considered to be due to the much larger grain size in the veins allowing lower Al_2O_3 values in Opx to be preserved.

Grt and Cpx in the veins contain multi-phase solid-inclusion assemblages of carbon, magnesite, dolomite, monazite, apatite, xenotime, titanite, pyrite, chalcopyrite, pentlandite, galena, Fe-oxides, orthite, gypsum, Ba-sulphates (+ Sr), Ca-sulphate (+ Sr), (unknown) W-, Al- and Al-Cl-silicates, Al-Fe-Mg-oxides, opx, cpx and grt. A micro-Raman spectroscopic study of the carbon is underway to verify the presence of micro-diamond.

Sm-Nd grt-cpx ages are 393 ± 3 Ma for the main body and 381 ± 6 Ma for the vein assemblage. ε_{Ndi} values are -3.5 and -8.5 respectively and indicate that the body was separated from the depleted mantle significantly before Scandian metamorphism. Sr-Nd systematics indicate that vein formation was concomitant with addition of crustal derived fluids. Together these data provide evidence of subduction of lower crustal rocks to ~200 kilometers depth with modification by C-O-H-rich crustal derived fluids (and diamond formation?).

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ALLANITE AS UHP PHASE IN SULU UHP ECLOGITES (CCSD): EVIDENCE FROM ELECTRON-MICROPROBE CHEMICAL DATING OF EPDIOTE-GROUP MINERALS

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Epidote-group minerals are common accessory minerals in eclogites. They are stable over a wide P-T range. Zoisite is certainly considered as a primary phase in UHP eclogite. However, there are debates on the occurrence of two other species, allanite and epidote under UHP conditions. Does allanite occur as a relict phase or as a UHP phase? Does epidote appear as a relict or as a secondary mineral in retrograde eclogites? In fact, a profound understanding of the behaviour of LREE in subduction zone processes needs to know in which phases LREE are incorporated, how stable these phases are and how they interact with subduction zone liquids.

Chinese Continental Scientific Drilling (CCSD) provides us an opportunity to make a systematic study on distribution of REE-bearing accessory minerals in the Sulu UHP eclogites. Aggregates of epidote, allanite, apatite and thorite are observed in the rocks. Allanite grains are cored by apatite, and mantled by epidote; micro-inclusions of thorite are found within the apatite core or allanite, or at the contact between them; allanite transforms progressively to epidote; epidote reveals zoned texture, which is represented by variations in Fe and Al contents. Electron-microprobe analyses reveal that the apatite contains up to 1 wt% $LREE_2O_3$ and 0.5 wt% ThO_2, particularly allanite incorporates not only LREE, but also as high as 2.1 wt% ThO_2.

High-resolution spot U, Th, Pb analyses of epidote and allanite on the electron microprobe are powerful geochronological tools. Results give an age of 485 Ma for the epidote mantle, and an age of 236 Ma for the allanite core, which is interestingly similar to the UHP metamorphic age in the Dabie-Sulu terrane.

Relationships and chemical dating of epidote and allanite indicate that there is a continuous transition from epidote to allanite. The latter is stabilized due to the presence of LREE, deriving possibly from the breakdown of primary LREE- and Th-bearing apatite in the course of UHP metamorphism: (Th,REE)-apatite + Epidote (UHP) $\rightarrow$ allanite + thorite + apatite.

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TIMING OF PROGRADE METAMORPHISM IN THE DABIE SHAN UHP COMPLEX: U-Pb AND Sr SYSTEMATICS OF PRE-UHP TITANITE

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Prograde mineral relics that formed during the subduction stage are rarely preserved within UHP metamorphic rocks. Such relics, however, may provide crucial geochronological information that allows to constrain subduction rates and the time span between subduction and the early phases of exhumation of UHP rocks. This is essential to understand the processes that occur in the lithosphere and in the upper asthenosphere during collision.
U-Pb dating of titanite has the potential to constrain successive stages of the burial and exhumation history: (1) especially in marbles, due to large viscosity contrasts between titanite and carbonate, prograde titanite may escape strain induced recrystallization, (2) the U-Pb system in titanite may remain closed even during high temperatures (> 1000 °C), (3) correlation of titanite with metamorphic reactions, deformation fabrics, and U-Pb data allows to establish a dated PTd-path.
We analyzed a relictic prograde titanite from calcsilicate rocks from the Dabie Shan UHP complex (eastern China). It survived UHP metamorphism and recrystallization and HT-deformation events related to exhumation. The calcsilicate rocks also locally preserve UHP peak pressure conditions (P > 40, T > 750 °C). The prograde titanite are porphyroclastic megacrysts in a strained calcite matrix, with a margin rich in rutile inclusions, that formed at the expense of the titanite megacryst by the reaction titanite + CO_2 = rutile + calcite (aragonite) + quartz (coesite).
Nine subsamples yield concordant $^{206}Pb/^{238}U$ data constraining titanite formation, and give an upper age limit for UHP metamorphism at 245 ± 5 Ma (2σ), thus beeing only ca. 5 Ma older than UHP peak conditions. Assuming that the megacryst had formed at ca. 10 - 12 kbar, the average vertical subduction rate would be 1.7 cm / a, though the PT-range of the formation of the prograde titanite megacryst is not well confined.
The Sr and Nd isotopic compositions (and chemical composition) are homogenous among the subsamples of the titanite megacryst, but fundamentally different from titanite in the calcite matrix. The $^{87}Sr/^{86}Sr$ value in the titanite megacryst is higher than 0.70712, whereas calcite yields a value as low as 0.70457, indicating that calcite probably changed its Sr isotopic composition during later fluid-infiltration and recrystallization. This demonstrates that Pb is likely to have been isotopically homogeneous, and that the U-Pb system of the titanite megacryst remained closed. There is no indication for a heterogeneous initial Pb isotopic composition, which could have induced excess scatter among the age data.

A PIVOTING MICROPLATE MODEL FOR SUBDUCTION EVERSION AND EXHUMATION OF UHP TERRANES

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In eastern Papua New Guinea (PNG), Pliocene exhumation of high and ultrahigh-pressure (HP–UHP) rocks is intimately linked to a pivoting microplate. The present day tectonic setting of this region is the result of rapid, oblique convergence between the Australian (AUS) and Pacific plates. Counter-clockwise (CCW) rotation of the Woodlark microplate (WLK) relative to the AUS plate within this larger tectonic framework led to the inception and westward propagation of sea floor spreading (SFS) in the Woodlark Basin beginning ca. 6 Ma. West of the rift tip, metamorphic core complex formation is associated with rapid exhumation of Late Miocene–Pliocene HP–UHP metamorphic rocks formed during prior subduction. Tectonic reconstructions of the AUS–WLK plate boundary zone in eastern PNG suggest the SFS system exploits the former subduction thrust and are in accord with the documented southeastward transition from convergence, to sinistral strike-slip faulting, to divergence. Plate tectonic based calculations suggest that removal of the upper plate (WLK) via CCW rotation and synchronous exhumation of lower plate rocks from beneath mylonitic shear zones is sufficient to exhume rocks from > 100 km depths.

The microplate rotation model provides a testable hypothesis by which to assess its applicability to older UHP terranes. Evidence for microplate rotation should be recorded in along-strike structural transitions as predicted and documented in eastern PNG. Geographic polarity of the transition is dependent upon the clockwise v CCW rotation of the upper plate, while the shear sense in the transitional strike-slip zone is a function of relative plate motions. The model also predicts generalized spatial patterns of stretching lineations and metamorphic grade as seen in PNG. Increasing pressure gradients from south to north as well as from west to east may be associated with an overall W-plunging antiform. Regional patterns of stretching lineations reflect changing flow patterns consistent with rotation.

We propose that the Qinling–Dabie terrane in eastern China may be an ancient example of a UHP terrane exhumed during subduction zone eversion associated with a pivoting microplate. The orogen is characterized by: 1) a W-plunging, antiformal dome associated with pressure gradients that increase from south to north as well eastward along strike; 2) stretching lineations that record changing flow patterns consistent with rotation; 3) the existence of a contemporary along-strike transition from transpression in the Qinling to extension in the Dabie Shan; and 4) available paleomagnetic data suggest ca. 60 degrees of relative rotation between the North and South China blocks.

ECLOGITE EVOLUTION IN THE ALPS AND NORWAY

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The Alps contain mafic eclogite-facies rocks in the Zermatt-Saas zone (ZS) associated with a blueschist facies overprint. The Western Gneiss Region (WGR) of Norway consists of quartzofeldspathic gneisses with eclogite bodies on the m - km scale, associated with an amphibolite facies overprint. Despite these differences the two regions share common features. Both regions were unroofed in part by shear zones dipping in the same direction as the subduction zones (to the W in Norway; to the SE in the Alps, (WHEELER & BUTLER, 1993)). These shear zones preserve tectonites predominantly at greenschist facies.

In the Alps, activity on the Gressoney Shear Zone is dated at 45 - 36 Ma (REDDY et al., 1999) which overlaps with, or immediately postdates, peak UHP eclogite facies metamorphism in the rocks beneath. Higher-pressure structures related to exhumation are not particularly obvious, though fabrics defined by both omphacite and glaucophane are present in the ZS. The time span of activity, though, shows that the shear zone operated throughout unroofing from UHP to greenschist facies pressures and was therefore the agent of exhumation.

In Norway, an intermediate stage of exhumation is preserved in the amphibolite facies gneisses of the WGR, with fabrics related to pure shear in a transtensional regime. Intense constrictional strains, with folding with hinges parallel to lineation in eclogites, show that the transtensional regime began at eclogite facies (FOREMAN et al., 2005).

The similar geometry of extensional shear zones in the two orogens does not necessarily diagnose a common driving force. In the Alps extension was synchronous with thrusting as indicated by the migration of the foreland basin, dated in detail by stratigraphy (WHEELER et al., 2001) An internal buoyancy force is thus required to produce the exhumation. Though the ZS eclogites are dense, they lie above quartzofeldspathic rocks of the Monte Rosa unit and may have been carried up on the back of those less dense rocks. In Norway, in contrast, overall (oblique) plate divergence led to extension.

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EXHUMATION OF THE SAUALPE ECLOGITE UNIT, EASTERN ALPS: CONSTRAINTS FROM $^{40}Ar/^{39}Ar$ AGES AND STRUCTURAL INVESTIGATIONS

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The Cretaceous-aged Eclogite-Gneiss unit and its tectonic overburden (Micaschist, Phyllite and Lower Magdalensberg units) of the Saualpe, Eastern Alps, have been investigated in order to constrain the mode of exhumation of the type locality of eclogites. $^{40}Ar/^{39}Ar$ ages of white mica from the eclogite-bearing unit suggest rapid, uniform cooling and exhu-mation between 86 and 78 Ma considered to represent Santonian-Campanian cooling and exhumation. Overlying units show upwards increasingly older ages with an age of 261.7 +/- 1.4 Ma in the uppermost low-grade unit (Lower Magdalensberg unit). We consider this Permian age as geologically significant and to record a Permian tectonic event. Rocks of phyllite and micaschist units along western margins of the Saualpe block yield amphibole and white mica ages ranging from 123 to 130 Ma. These are considered to closely date the age of nappe stacking. Biotite and amphibole of Micaschist and Eclogite-Gneiss units show variable contents of extraneous argon. Consequently, their ages are in part geologically meaningless whereas other samples yield meaningful ages. The ages of white mica from the Eclogite-Gneiss unit argue for cooling through ca. 400 °C during the time as the westerly adjacent Upper Creteceous Krappfeld-Kainach collapse basin type formed.

The Preims unit with paragneiss and marbles is considered to represent a large synmetamorphic shear zone at the base of the over-thrusting Eclogite-Gneiss unit. The unit comprises a flat-lying foliation and a SE-trending lineation. This zone is considered to represent a zone of top-NW thrusting. A major ductile low-angle normal fault with top to ESE shear has been detected between the Eclogite-Gneiss and overlying units, respectively between the Micaschist and Phyllite units. The ductile thrust at the base and the low-angle normal fault at top are considered to confine a NW-ward extruding high pressure wedge. This observation argues for rapid exhumation of a subducted high-pressure wedge within a sub-duction channel. Rapid erosion of the exhu-ming wedge facilitated exhumation. Eroded sedimentary rocks are preserved within adja-cent Gosau basins, although only pebbles of low-grade rocks of the uppermost tectonic unit can be found in these basins.

ZIRCON U-Pb DATING, Hf AND O ISOTOPE STUDIES OF MARBLE-ASSOCIATED ECLOGITE IN THE DABIE-SULU OROGEN OF EAST-CENTRAL CHINA: CONSTRAINTS ON THE TIMING OF FLUID ACTIVITY DURING SUBDUCTION AND EXHUMATION OF CONTINENTAL CRUST

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Fluid activity during subduction and exhumation is a very important issue with respect to timing and mechanism of metamorphic zircon growth. This is elucidated by a combined study of zircon internal structure, U-Pb dating, Hf and O isotope analyses for UHP eclogite boudins enclosed in marbles from the Dabie-Sulu orogen in east-central China. CL imaging identifies two types of zircon that are metamorphically new growth and recrystallized detrital grains, respectively. Both of them have low Th and U contents with low Th/U ratios, yielding two groups of $^{206}Pb/^{238}U$ age at 243 ± 2 Ma and 225 ± 3 Ma, respectively. The metamorphically grown zircons are characterized by much lower $^{176}Yb/^{177}Hf$ and $^{176}Lu/^{177}Hf$ ratios of 0.000055 to 0.002116 and 0.000001 to 0.000033 than the detrital zircons, indicating their formation during eclogite-facies metamorphism. Therefore, the two groups of U-Pb age are responsible for timing of zircon growth with fluid availability in the HP-UHP-HP metamorphic processes. The formation of the first episode of metamorphic zircons is correlated with fluid activity during prograde HP eclogite-facies metamorphism. The growth of the second episode of metamorphic zircons is interpreted to date fluid activity during retrograde HP eclogite-facies metamorphism.

The metamorphically grown zircons in the eclogites from the Dabie terrane have negative $\varepsilon_{Hf}(t)$ values of -20.9 to -12.0, suggesting that the eclogite protolith is old crustal rocks. In contrast, the metamorphic zircons in the eclogite from the Sulu terrane are characterized by uniformly positive $\varepsilon_{Hf}(t)$ values of 8.1 ± 0.5, indicating the origin of its protolith from juvenile crust derived from depleted mantle. The metamorphic zircons from the eclogites show the very different $\varepsilon_{Hf}(t)$ values, suggesting they have diverse protoliths with localized fluid activities in the bulk processes of HP-UHP-HP metamorphism. Some of the newly grown and recrystallized zircons have the significant different Lu-Hf isotope compositions from each other despite their similarity in U-Pb age. All the eclogites have anomalously high $\delta^{18}O$ values, with 12.34 to 22.55 ‰ for quartz, 9.87 to 21.39 ‰ for garnet, 7.92 to 21.89 ‰ for omphacite, and 18.63 ‰ for zircon. The $\delta^{18}O$ differences between coexisting minerals are consistent with those expected from equilibrium fractionations at eclogite-facies temperatures, suggesting that the high $\delta^{18}O$ values are inherited from their protoliths. Thus the protoliths of marble-associated eclogites are a kind of marls or volcanic ash that was interlayered with the marble protolith.

ISOTOPIC (O, Sr, Nd, Pb) AND FLUID INCLUSION INVESTIGATIONS THROUGH VERTICAL SECTIONS OF ULTRAHIGH-PRESSURE METAMORPHIC ROCKS

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We investigated fluid inclusion and isotopic (O, Sr, Nd, Pb) characteristics on 66 selected drillcores (mainly eclogites) from the main hole and the pilot-holes of the Chinese Scientific Drilling Program (CCSD) in Donghai, East China, with depths ranging from 97 to 3000 m. The oxygen isotope data show that: (1) the rocks can be divided into two groups according to their $\delta^{18}O$ values: ^{18}O-depleted rocks (as low as $\delta^{18}O$ = -7.4 ‰ for garnet) that were produced by cold climate meteoric waters, and ^{18}O-normal rocks (with bulk $\delta^{18}O$ > +5.6 ‰) that may have preserved the O-isotopic compositions of their protoliths; (2) meteoric water/rock interaction has reached depths of at least 2700 m; (3) the oxygen isotope distribution pattern supports the hypothesis that granite intrusions were one of the heating engines which drove the hydrothermal circulation of meteoric water during the Neoproterozoic; (4) oxygen isotope equilibrium was mostly reached on a mm- to cm- scale regardless of the lithology, while isotope heterogeneity was observed between rock types at a scale of a few meters; (5) oxygen isotope distributions in the vertical sections favour an "in situ" origin of the UHP metamorphic rocks. Fluid inclusion data are related to oxygen isotopic compositions: rocks having depleted oxygen isotope compositions are dominated by high-salinity inclusions, whereas those with normal oxygen isotope composition are characterized by high density CO_2 fluids. The very negative $\delta^{18}O$ eclogites usually have higher hydroxyl-mineral contents than the higher $\delta^{18}O$ rocks, indicating higher water content during UHP metamorphism.

Sr-Nd-Pb isotopic data of eclogite and garnet peridotite demonstrate significant interactions between UHP metamorphic rocks (formerly subducted continental crust) and the eastern China mantle. Major- and trace-elements and Sr-Nd-Pb isotopic data from a continuous 3 m profile composed of amphibolite, gneiss, retrograde eclogite, and fresh eclogite show the following characteristics: (1) Eclogites and gneisses have distinct protolith sources, as indicated by their initial Nd and Pb isotopic compositions; the amphibolites, however, may be derived from either retrogressed eclogite or gneiss. (2) In the ε_{Nd}(240 Ma) vs. $^{87}Sr/^{86}Sr$ (240 Ma) diagram, most samples fall on an extension of the mantle array at the high $^{87}Sr/^{86}Sr$ end. The systematic upward decrease of ε_{Nd}(240 Ma) might indicate a systematic contamination of the mafic eclogite samples with gneiss-derived Nd. (3) Sr isotope anomalies occurring at the boundaries between eclogites and gneisses, and systematic overcorrection of in situ ^{208}Pb-growth in those samples with the highest $^{208}Pb/^{204}Pb$ suggest that retrogression after the UHP metamorphism, concentrated along the contacts, was associated with Rb-Sr fractionation and Pb-loss.

CALCULATED PHASE RELATIONS FOR UHP ECLOGITES AND WHITESCHISTS IN $Na_2O - CaO - K_2O - FeO - MgO - Al_2O_3 - SiO_2 - H_2O$

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Pressure-temperature grids in the system $Na_2O - CaO - K_2O - FeO - MgO - Al_2O_3 - SiO_2 - H_2O$ and its subsystems have been calculated in the range 15 – 45 kbar and 550 – 900 °C, using an internally consistent thermodynamic dataset and newly-developed models of complex solid solutions, with the software THERMOCALC. Minerals considered for the grids include garnet, omphacite, diopside, jadeite, hornblende, actinolite, glaucophane, zoisite, lawsonite, kyanite, coesite, quartz, talc, muscovite, paragonite, biotite, chlorite, and plagioclase, with kyanite, muscovite, coesite/quartz, and H_2O (and also garnet in the case of the full system) assumed to be present. Compatibility diagrams are used to analyse the consistency and validity of the grids. P-T pseudosections prove to be a powerful approach to model natural eclogites of different compositions and a whiteschist from UHP terranes in China.
Under water-saturated conditions, chlorite-bearing assemblages in Mg and Al-enriched eclogites are stable at lower temperatures than in Fe-enriched eclogites. The relative temperature stability of the three amphiboles is hornblende > actinolite > glaucophane (amphibole names used *sensu lato*). Talc-bearing assemblages are stable only at low temperature and high pressure in Mg and Al-enriched eclogites. For most eclogite compositions, talc coexists with lawsonite, but not zoisite, in the stability field of coesite.
Chlorite and lawsonite are two important H_2O-carriers in subducting slabs. Depending on bulk composition and P-T path, amphibole may or may not be a major H_2O-carrier to depth. In most cases, dehydration of a mineral takes place gradually, with H_2O content buffered by divariant or higher variant assemblages, rather than abruptly, as was predicted by intersection with univariant dehydration reactions in P-T projections with geotherms in various types of subducting slab. Therefore, fluid fluxes in subduction zones are likely to be continuous, with the rate of dehydration changing with changing P-T. Further, eclogites of different bulk compositions dehydrate differently. Dehydration of Fe-enriched eclogite is nearly complete at shallow depth, whereas Mg and Al-enriched eclogites dehydrate continuously down to great depth and may provide hydrous fluid for arc magmatism.

RUTILE THERMOMETRY: STATE OF THE ART AND OUTLOOK

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In a recent study we demonstrated that the Zr content in rutile is strongly temperature dependent if it is buffered by quartz and zircon. (ZACK et al., 2004). We analysed rutile-quartz-zircon assemblages of 31 metamorphic rocks spanning a temperature range from 430 to 1100 °C. Electron microprobe measurements of Zr concentrations in rutile vary from 30 to 8400 ppm, being highly dependent on metamorphic grade. No pressure dependence is observed. An uncertainty of absolute T of ± 50 °C is inherited from T estimates of the natural samples used.

To promote wide application of rutile thermometry, we selected relatively homogeneous rutiles (Zr variation less than 10% within a given sample) that span a range of Zr contents (100, 260 and 770 ppm) for distribution as secondary mineral standards. These rutiles were measured by isotope dilution MC-ICP-MS (ZACK et al., in prep), to create accurate calibration values for instrumental facilities (e.g. EMP, SIMS, LA-ICP-MS) for Zr in rutile determinations. The calibration of the Heidelberg SIMS facility through these three rutiles as well as titanites, MPI-DING glasses and NIST-SRM 610 glass show no matrix effect for Zr determination outside 15 % (2 sigma), thus SIMS analysis of Zr in rutile is straightforward.

Temperature information of ordinary high variance eclogites often can be retrieved only by Grt-Cpx Fe-Mg geothermometers. However, such calculations have large uncertainties (± 50 - 250 °C) because Fe^{3+} in omphacites can not be reliably obtained unless Mössbauer analysis are available (e.g. PROYER et al., 2004). Rutiles are an attractive alternative for geothermometry of such eclogites. Although absolute temperatures can be currently calculated only within ± 50 °C with rutile thermometry, relative temperature differences can be distinguished within ± 10 °C, as examplified by Trescolmen eclogites where two eclogites and one HP metapelite give identical Zr concentrations within counting statistical errors (ca. ± 2 %). As a next step we are currently investigating a wide range of low-variance eclogites where temperatures can be relatively well constrained, e.g. containing index minerals such as lawsonite, zoisite, glaucophane and/or allowing thermobarometry by the critical assemblage Grt-Omp-Ky-Phe-SiO_2 (RAVNA & TERRY, 2004). This will demonstrate if well-equilibrated rutiles are a common feature in eclogites and how closely rutiles show a general increase of Zr from low-T to high-T eclogites.

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HIGH PRESSURE AND LOWER TEMPERATURE METAMORPHISM ALONG THE NORTH-EASTERN MARGIN OF THE BOHEMIAN MASSIF

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Several occurrences of high-pressure low-temperature rocks are known from the northern border of the Bohemian Massif (Krkonoše-Jizera complex and Krušné hory Mts., CHÁB & VRÁNA, 1979; PATOCKA et al., 1996). We studied mafic and phyllitic rocks from three localities (•elezný Brod, Roprachtice and Rýchory) including nearby basement units. The rocks are strongly retrogressed into greenschist facies assemblages. Only some primary basalts or gabbros may have glaucophane. Blueschist facies assemblages in meta-basites involve one or more of the minerals: blue amphibole, epidote, albite, chlorite, titanite and aegirine. Surrounding phyllitic rocks contain porphyroblasts of chloritoid in fine-grained matrix composed of white mica, quartz and chlorite. Some chlorite forms porphyroblasts with interlayers of white mica.

Amphibole composition ranges between sodic and calcic amphibole. Some blue amphibole grains reveal a continuous transition towards rim to actinolite. This suggests equilibrium conditions between these two amphiboles after peak pressure or increase of temperature during metamorphism. Blue amphiboles have composition ranging from glaucophane to riebeckite with $X_{Al} = 0.37$ 0.75 and $X_{Mg} = 0.4$ 0.68. Calcic amphibole corresponds to actinolite. Analyzed sodic pyroxene, rich in aegirine (Di_{43-48}, Aeg_{40-45}) with low jadeite content (Jd_{8-12}), was found in metagabbro, where it replaces primary igneous pyroxene. Epidote is rich in Fe ($X_{Al} = 0.656 - 0.886$). Accessory biotite is rich in Fe ($X_{Mg} = 0.535 - 0.699$) and chlorite has $X_{Mg} = 0.37 - 0.622$. Surrounding phylites contain porphyroblasts of Fe-chloritoid ($X_{Mg} = 0.078 - 0.083$), chlorites ($X_{Fe} = 0.64 - 0.68$) and white mica (Si = 3.2a.p.f.u.). PT conditions, estimated based mineral compositions of blue amphibole, chloritoid, phengite, are confirmed by mineral assemblages in metabasites that are comparable with the epidote blueschist composition 6 of EVANS (1990). Textural relations indicate decompression to greenschist facies conditions that resulted in formation of actinolite, biotite, albite and chlorite.

Pelitic rocks from the adjacent basement units contain greenschist facies to lower amphibolite facies assemblages. Most of these rocks are characterized by the presence of porphyroblasts of albite that cross-cut older foliation. In one case a garnet- and chlorite-rich sample with relics of amphibole was found. Garnet is rich in Fe ($Alm_{67-72}Grs_{27-32}Py_{1.2-2.3}Sps_{1.2-2.5}$) and amphibole corresponds to taramite (Si = 6.1 a.p.f.u.) with $X_{Mg} = 0.34$ and $X_{Na} = 0.31$, where the B site is occupied by 0.508 Na p.f.u. Chlorite ($X_{Mg} = 0.38$) is always a retrograde phase in the rock. The presences of sodic-calcic amphibole as well as of porphyroblast of albite suggest medium-pressure conditions of basement rocks. However the relation to the blueschist event is not clear yet.

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DISCOVERY OF ECLOGITES AND EXTENSION OF SULU UMP BELT IN SOUTH KOREA

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The Korean peninsula is divided into three massifs separated by Imjinggang and Ogcheon belts, the three massifs are called as the Rangnim, Gyeonggi and Yeongnam massifs from north to south. Although the Imjinggang belt or Ogcheon belt or both were suggested to be the extension of the Sulu belt, our research seems not to support these suggestions. The Precambrian rocks in the three massifs are similar, and their petrological, metamorphic and geochronological characteristics are similar to the Precambrian basement of the North China craton. The Paleozoic Phyongnam and Taeback basins were developed on the Precambrian basements of the Rangnim, Gyeonggi and Yeongnam massifs have similar successions of strata to those of the Paleozoic basins of the North China, typically without Silurian-Devonian sedimentary succession.

The first eclogite sample, recently, was collected from Hongsung area in southwestern part of the Gyeonggi massif. The eclogites occur as lenses in granitic gneiss. Three metamorphic stages can be identified, representing three main metamorphic episodes. The first mineral assemblage is composed of Omp + Grt + Qtz + Ilm + Rut. The second mineral assemblage is Cpx + Hy + Plg, represented by symplectite around garnet and exsolution of omphacite. The third mineral assemblage is Amp + Plg, partially replacing the first and second mineral assemblages. But any coesite and other UHP mineral have not been found up to now. The estimated pressure and temperature by the first stage minerals are 15 - 18 kbar and 750 - 800 °C. The P and T conditions of three metamorphic stages constitute a clockwise PT path. The eclogite yields two SHRIMP U-Pb zircon ages: 231.2 ± 3.3 Ma and 887 ± 14 Ma, representing metamorphic age and protolith age. The garnet-amphibolite lenses (dyke?) within peridotite ponds in granitic gneiss are also identified to be retrograded eclogites, indicated by relict omphacite as inclusion in garnet. The estimated pressure and temperature of eclogite facies are 17 - 20.9 kbar and 830 - 860 °C. The peridotites are harzburgite and lherzolite. The estimated metamorphic temperature and pressure by Ca, Al in Opx for peridotites are 750 - 950 °C and 16 - 20 kbar. Their geochemical compositions show characteristics of continental mantle.

The main rocks of the Hongsung complex are granitic gneisses, lenses of ultramafic rocks and metabasites and marbles. A part of metabasites and ultramafic rocks are HP metamorphosed rocks, and their country granitic gneisses obtained SHRIMP U-Pb zircon ages of at 812 - 822 Ma. Therefore, the Hongsung complex and the Sulu belt have similarities, and should be separated from the Gyeonggi massif, although our study is preliminary, the boundary of the Hongsung complex and basement of the Gyeonggi massif is not clear.

TRIASSIC COLLISION OF WESTERN TIANSHAN OROGENIC BELT, CHINA: EVIDENCES FROM SHRIMP U-Pb DATING OF ZIRCON FROM UHP ECLOGITIC ROCKS

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A newly recognized ultrahigh-pressure (UHP) terrane in the Chinese Western Tianshan orogenic belt contains blueschists, eclogites and metapelites. This belt extends westward to the "South Tianshan" in Tajikistan, Kyrgyzstan, Kazakhstan and Uzbekistan for more than 2500 km in central Asia. New ion microprobe (SHRIMP) U-Pb dating of zircon from UHP eclogites and metapelites indicates Triassic ages for the collision in western Tianshan. Zircon from four eclogites yield magmatic ages of 310 ~ 413 Ma in the cores and one metapelite contained detrital zircon cores as old as 1886 ± 20 Ma. Zircon rims reveal peak metamorphic ages of 233 ± 4 ~ 225 ± 6 Ma. The geochronologial data suggest that a South Tianshan paleo-ocean was developed between the Tarim continent and the Yili-central Tianshan Craton before the Carboniferous (> 310 Ma). During the Permian-Triassic subduction and continent collision, oceanic basalts and Proterozoic continental materials underwent HP/UHP metamorphism. A new tectonic evolution for HP-UHP metamorphic rocks of the Chinese Western Tianshan orogenic belt represented by HP-UHP metamorphic eclogitic rocks is proposed in the light of recent palaeomagnetic, paleontologic, sedimentary and stratigraphic studies. Before the Late Carboniferous, a South Tianshan paleo-ocean occurred between the Tarim and Yili-central Tianshan cratons. The 310 ± 5 Ma age for the protolith of the eclogites is interpreted as the formation age of this ocean. The northward docking of the Gondwanan Karakoram-Qingtang block to the Cathaysian (Eurasian) Kunlun block was suggested to occur during the Carboniferous-Triassic in the western Kunlun area adjacent to the Chinese western Tianshan. At this time, the south Tianshan paleo-oceanic crust began to subduct northward beneath the Yili-central Tianshan plate to produce arc volcanic rocks in the southern active margin of Yili-central Tianshan craton. According to SHRIMP U-Pb zircon dating of low-P granulites resulted from arc magmatic intrusion, the subduction started at about 290 - 280 Ma (LI & ZHANG, 2004). At last, the south Tianshan oceanic and some continental crustal materials were subducted to mantle depth to form UHP metamorphic rocks (ZHANG et al., 2002; 2003), then exhumed during the Early Triassic collision between the Tarim and Yili-central Tianshan plates (233 ± 4 ~ 225 ± 6 Ma).

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GARNET CLINOPYROXENITE AND ASSOCIATED ECLOGITE FROM THE SULU UHP TERRANE, EASTERN CHINA: ORIGIN AND METAMORPHIC EVOLUTION

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Garnet clinopyroxenite (Grt + Cpx + Ilm ± Ol) and minor eclogite from Rizhao occurs as lenses or layers in serpentinized, mantle-derived peridotite body that is faulted against gneiss in the Sulu ultrahigh-pressure (UHP) terrane, eastern China. The Grt clinopyroxenites have Al_2O_3 vs. MgO plots within the field of mantle xenoliths and are characterized by mantle isotopic compositions of $^{87}Sr/^{86}Sr$ (0.7038 - 0.7044), $^{143}Nd/^{144}Nd$ (0.5127 - 0.5128), $\delta^{18}O$ in Grt (4.83 5.64 ‰) and Cpx (4.99 - 5.64 ‰). Garnets exhibit LREE depleted pattern characterized by increasing in abundance from La to Sm with maxima at the middle REE (Sm-Eu-Gd). In contrast, all Cpx show humped patterns. The crossovers of Grt and Cpx patterns are in Nb to Sm. Clinopyroxenites vary from those rich in megacrystic and/or porphroblastic Grt through Ilm-rich, coarse-grained Cpx-bearing to Grt-poor fine granoblastic varieties. Megacrystic garnets 2 - 14 cm across contain inclusions of Cpx, Ilm ± Dol with minor Spl; the Cpx inclusions show exsolved lamellae of Grt, Ilm ± Amp. Garnets show large variation in composition, and contain high Grs component: megacryst ($Alm_{18-25}Grs_{34-51}Prp_{26-47}$), porhyroblast ($Alm_{20-25}Grs_{36-47}Prp_{28-43}$), exsolution ($Alm_{19-20}Grs_{32-66}Prp_{16-47}$) and matrix ($Alm_{18-24}Grs_{46-57}Prp_{22-32}$). Cpx is diopside containing < 2 wt% Al_2O_3 and < 0.8 wt% Na_2O. Coarse-grained Cpx contain abundant exsolution of Grt + Ilm, Amp + Ilm, and Spl + Ilm + Amp. Exsolved garnet and ilmenite in Cpx may be up to 25 vol% and 4 vol%, respectively. The coexisting Cpx host and Grt rods yields recrystallization temperatures of 1000 ± 50 °C at an assumed *P* of 5 GPa. The exsolved phases were recrystallized to form fine-grained matrix assemblage at 800 ± 50°C and 3 GPa. Typical eclogites consist of Grt ($Alm_{38-41}Grs_{26-39}Prp_{24-32}$) + Omp ($Jd_{24-29}$) + Coe/Qtz + Rt with porphyroblastic texture. Coarse-grained garnets (up to 5 mm) contain inclusions of quartz pseudomorphs after coesite and exsolved rutile rods. Rare strong foliated eclogite contains additional zoisite and very minor Omp; orientated grs-rich, coarse-grained garnets are wrapped by elongated laths of zoisite (0.5 - 2 mm long, 0.02 - 0.15 mm wide), garnet and apatite. Mg-Fe partitioning of Grt-Cpx yields equilibrium - *T* of 690 - 720 °C at a minimum *P* (3 GPa).
One Ilm-rich Grt clinopyroxenite was used for high *P* experiments at 5 and 15 GPa at 1400 °C. The results indicate the titanium solubility in garnet and Grt_{Ti}/Cpx_{Ti} ratio have a pronounced positive correlation with pressure and the coexisting Cpx contains low Ti, and shows no significant pressure effect. Petrological data and experiments suggest that the parental phase of exsolved Grt + Ilm and Cpx host probably was a majoritic garnet, and coupled substitutions of $Ca^{2+}Ti^{4+} \rightarrow 2Al^{3+}$ and $Si^{4+}Mg^{2+} \rightarrow 2Al^{3+}$ increase the majorite component with pressure. The protolith of Grt clinopyroxenite was derived from very deep convecting mantle and was included within host peridotite in the upper mantle. During Triassic continent subduction, the Grt pyroxenite-bearing peridotite was inserted into the subducting slab, and subjected to UHP metamorphism together with host gneissic country rocks.

PETROLOGY OF UHP METAMORPHIC ROCKS FROM THE MAIN HOLE (0 - 2050 m) OF CHINESE CONTINENTAL SCIENTIFIC DRILLING PROJECT

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The main hole of the Chinese Continental Scientific Drilling Project (CCSD) in southern Sulu recovers more than 80 % core samples of eclogite, orthogneiss, paragneiss, ultramafic rock and minor schist at depth interval of 100 - 2050 m. Recovered eclogite cores are distinguished to quartz-, rutile-, phengite-, kyanite-rich and normal eclogites. Ultramafic cores contain garnet + olivine + clinopyroxene + orthopyroxene ± Ti-clinohumite ± phlogopite assemblages The gneisses and schists contain an amphibolite-facies paragenesis, but their zircons have coesite, garnet, omphacite (or jadeite) and phengite inclusions, indicating these rocks together with eclogite and ultramafics have been subjected to *in-situ* UHP metamorphism. When the data from surface outcrops and shallow drill holes are considered together, we suggest that a huge supracrustal rock slab (> 50 km long × 100 km wide × 5 km depth) was subducted to a depth > 100 km, and then exhumed to the surface. Using available geothermobarometers, P-T estimates of 678 - 816 °C and 3.1 - 4.4 GPa for eclogites and 700 - 930 °C and 3.8 to 5.0 GPa for garnet-peridotite were obtained. Such wide P-T ranges and the recognition of a retrograde compositional zoning of garnet, omphacite and phengite suggest that true peak UHP metamorphic compositions have not been well preserved due to re-equilibration during early retrograde metamorphism.

DEFORMATION OF THE UHP METAMORPHIC ROCKS IN THE SULU UHP METAMORPHIC BELT, CHINA: FROM MICRON TO CRUST SCALE STRUCTURES

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Sulu UHP metamorphic belt extending over 500 km in eastern China is part of the Qinling-Dabie-Sulu collisional orogenic belt resulted from the collision between the North China plate and the Yangtze plate during the Late Triassic. Coesite-bearing eclogite, gneisses and marbles are exposed along entire length of the Sulu UHP belt. Seismic reflection profiling revealed three main features of the crust structure across the UHP belt: stacked thrust sheets dipping to the south, a major detachment at the base of the thrust sheets and a normal fault cross-cutting the thrust sheets. Deep continental drilling (CCSD) and surface geology reveal that the stacked thrust sheets consist of over 10 km of UHP metamorphic rocks. The UHP rocks are interlayered granitic gneisses and paragneisses with minor amount of layers or lenses of ultramafic rocks and eclogites. On a mesoscopic scale the UHP rocks show isoclinal folding with various orientation. The major detaclunent crops out in the north of the UHP stacked thrust sheets as a 10 km wide high pressure (HP) mylonite zone that can be traced 200 km to the east, and is exposed at Yangkou as an UHP ductile shear complex. The UHP shear complex consists of interlayered granitic and eclogitic mylonites with well developed foliation and lineation. The UHP phase minerals, such as omphacite, kyanite, phengite and K-feldspar, show irregular undulatory extinction, kinks, subgrains and dynamic recrystallization indicative to dislocation creep being a major deformation mechanism. TEM study reveals dense dislocations, tilt walls, dislocation network and recrystallized grains with low dislocation density. The UHP deformation is estimated to take place at 624 °C and 3.3 GPa. Timing of the deformation is constrained by zircon age of 225 ± 3.2 Ma from an eclogite dike that crosscuts the mylonite. The normal faulting is observed in the region to relate to the Late Jurassic to Cretaceous extension and basin development. We suggest that the exhumation of the UHP rocks is due to back thrusting of the detached UHP slab in a compression regime but not normal faulting in an extension regime.

FLUID ACTIVITY DURING EXHUMATION OF DEEP-SUBDUCTED CONTINENTAL CRUST: CASE STUDIES FROM THE DABIE-SULU OROGENIC BELT

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A great deal of studies have been devoted in past two decades to the composition and flow of fluid in HP and UHP metamorphic rocks that formed during subduction of oceanic crust. It has been recognized that a great deal of fluid was released during subduction of oceanic crust, resulting in arc magmatism, quartz veining and metamorphic mineralization of syn-subduction. However, knowledge concerning the origin of retrograde fluid is still incomplete, and sometimes misleading because it was simply ascribed to external origin by ignoring exsolution of internal fluids. With the advance in the study of stable isotopes, fluid inclusions and petrological phase relationships in HP to UHP metamorphic rocks that formed during the deep subduction of continental crust, it becomes clear that the compositional differences in continental and oceanic crusts result in differences in the mobility and amount of fluid within metamorphic products in the processes of subduction and exhumation.

A large number of studies involving stable isotopes, fluid inclusions and petrological phase relationships have been accomplished in past a few years with respect to the mobility and amount of metamorphic fluid in Triassic UHP metamorphic rocks from the Dabie-Sulu orogenic belt in east-central China. The results demonstrate that the fluid activity during the exhumation of deeply subducted continental crust has the following effects: (1) amphibolite-facies retrogression due to pervasive fluid flow; (2) formation of HP quartz veins within eclogites due to channelized fluid flow; (3) partial melting of overlying crustal rocks due to focused fluid flow, producing syn-exhumation magmatism within the UHP slabs of orogenic belt. In particular, the aqueous fluid released by decompression exsolution of hydroxyl from UHP minerals is characterized by low salinity and is capable of resulting in pervasive and channel flow.

Although the process of continental subduction is characterized by the relative lack of fluid with a limited mobility, heterogeneity in protolith composition and water concentration is found to result in the local activity of metamorphic fluid. During exhumation of deeply subducted continental crust, particularly, significant amounts of aqueous fluid became available from decomposition of such hydrous minerals as lawsonite, zoisite and phengite, decrepitation of primary fluid inclusions, and exsolution of structural hydroxyls from nominally anhydrous minerals. This kind of metamorphic fluid has recently attracted widespread interests and thus been one of the most important targets in deciphering the geological processes concerning metamorphism, magmatism and mineralization in collisional orogens.

ECLOGITES FROM THE CCSD - DIFFERENT P-T PATHS AS INDICATION FOR A SUBDUCTION CHANNEL ENVIRONMENT

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Four phengite-bearing eclogites, taken from different depths (464, 579, 1899, 1991 metres, samples B218, B301, B1008 and B1039, respectively) of the CCSD borehole (XU, 2004) in the Sulu ultrahigh pressure (UHP) terrane, eastern China, were carefully studied with the polarising microscope and the electron microprobe. The compositional zonation of garnet and omphacite is moderate, whereas phengite compositions generally vary significantly in a single sample from core to rim by decrease of Si contents and increase of the Na / (Na+K) and Fe / (Fe+Mg) ratios. Various geothermobarometric methods were applied to constrain the P-T conditions of these eclogites on the basis of the compositional variability of the above minerals. The derived P-T path for sample B218 shows a pressure decrease starting at ~3.0 GPa (close to 600 °C) with slightly falling temperatures to reach finally conditions of ≤ 1.8 GPa and 500 °C accompanied by formation of corona textures around omphacite and garnet. Kyanite-bearing eclogite B310 did not allow to construct a P-T path but the temperatures of an early eclogite stage are ~100 °C higher than those of the other three samples. Eclogites B1008 and B1039 show similar but complicated P-T paths which start at about 650 °C and 3.6 - 3.9 GPa (stage I), followed by a pressure decrease to about 3.0 GPa and a moderate to significant temperature rise (stages II and III) by up to 100 °C. Subsequently, the temperatures decreased to about 500 °C (stage IV) at pressures close to 2.0 GPa or less. During the final metamorphic stage recorded in the CCSD eclogites (stage IV and younger) fluids partially rich in potassium, probably of hydrous nature, penetrated the rocks. However, these fluids caused minor changes only. Among the newly formed minerals are andradite and magnetite pointing to relatively high fO_2 values of the fluid phase.
We think that the above findings (different P-T paths, heating and cooling events at moderately decreasing pressures, relatively small volumes of interacting fluids) can be best explained by mass flows in a subduction channel environment. However, this environment implies that the assembly of UHP rocks of the CCSD site, eclogites, quartzofeldspathic rocks, and peridotites, cannot represent a crustal section that was already coherent at UHP conditions as it is the common believe currently. The coherency was attained after significant exhumation of these UHP rocks possibly at a depth level close to 60 km corresponding to 1.8 GPa of stage 4.

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ECLOGITES IN THE EASTERN ALPS: HIGH-PRESSURE METAMORPHISM IN THE CONTEXT OF THE ALPINE OROGENY

by

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The Alpine orogene formed during the convergence of the African and European plates, which has been more or less continuous since Cretaceous times. The geology of the Eastern Alps is complex, however, because of the existence of more than one oceanic realm and several microplates between Africa and Europe, and also because the interplay between shortening processes and lateral movements makes it difficult to determine the plate tectonic arrangement through time.

Models of Alpine tectonics have developed rapidly during recent decades, mainly as a result of modern structural, stratigraphic, petrological and geochronological investigations which, together with deep reflection seismic profiling and tomographic studies, have provided new insights into the present-day structures. Contrasting interpretations on the evolution of the Alpine orogen still remain, however, further complicated by the use of different nomenclatures. This summary of the geology of the Alps is based on the tectonic interpretation by SCHMID et al. (2004) and on the recent review of Alpine metamorphic history by OBERHÄNSLI (2004) together with all literature cited therein.

In a geographical sense the Alps are divided into the Southern Alps (to the south of the Periadriatic Lineament), the Eastern Alps, the Central Alps (approximately between NFP-20 WEST and NFP-20 EAST), and the arc of the Western Alps (Fig. 1). These divisions are each characterised by different paleogeographic elements that were incorporated at different stages in the Alpine tectonic evolution, resulting in distinct geological structures and a specific geomorphology.

1. Plate tectonics

The Alpine orogen is subdivided into plate tectonic units reflecting the Mesozoic to Paleogene paleogeography (Fig. 1, 2). In their simplest form the plate tectonic units involved in the Alpine orogen are the European continent, the Alpine Tethys ocean, the Apulian microcontinent and the Meliata ocean (FROITZHEIM et al., 1996).

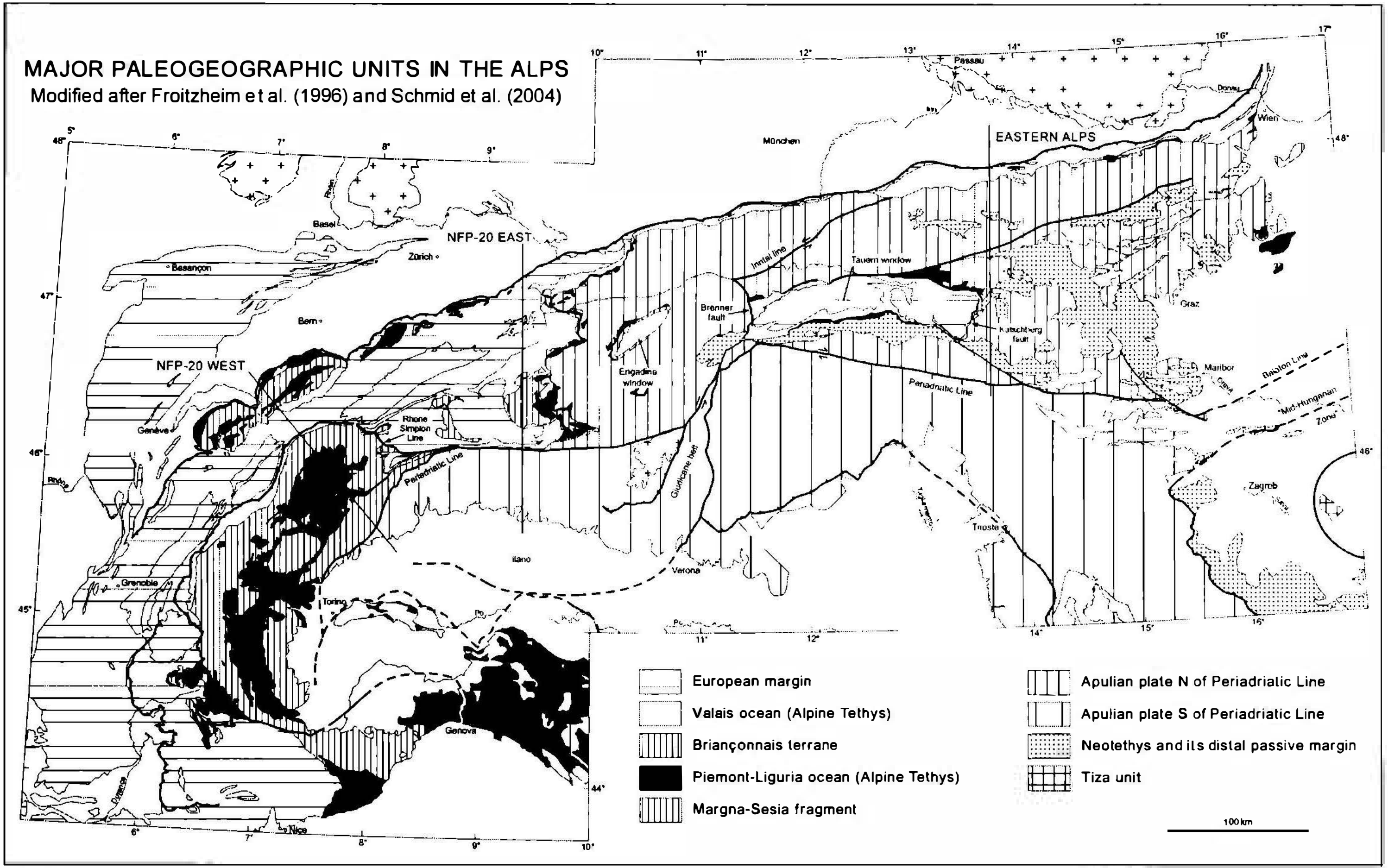

Fig. 1

Map of the major paleogeographic and tectonic units in the Alps adapted from SCHMID et al. (2004).

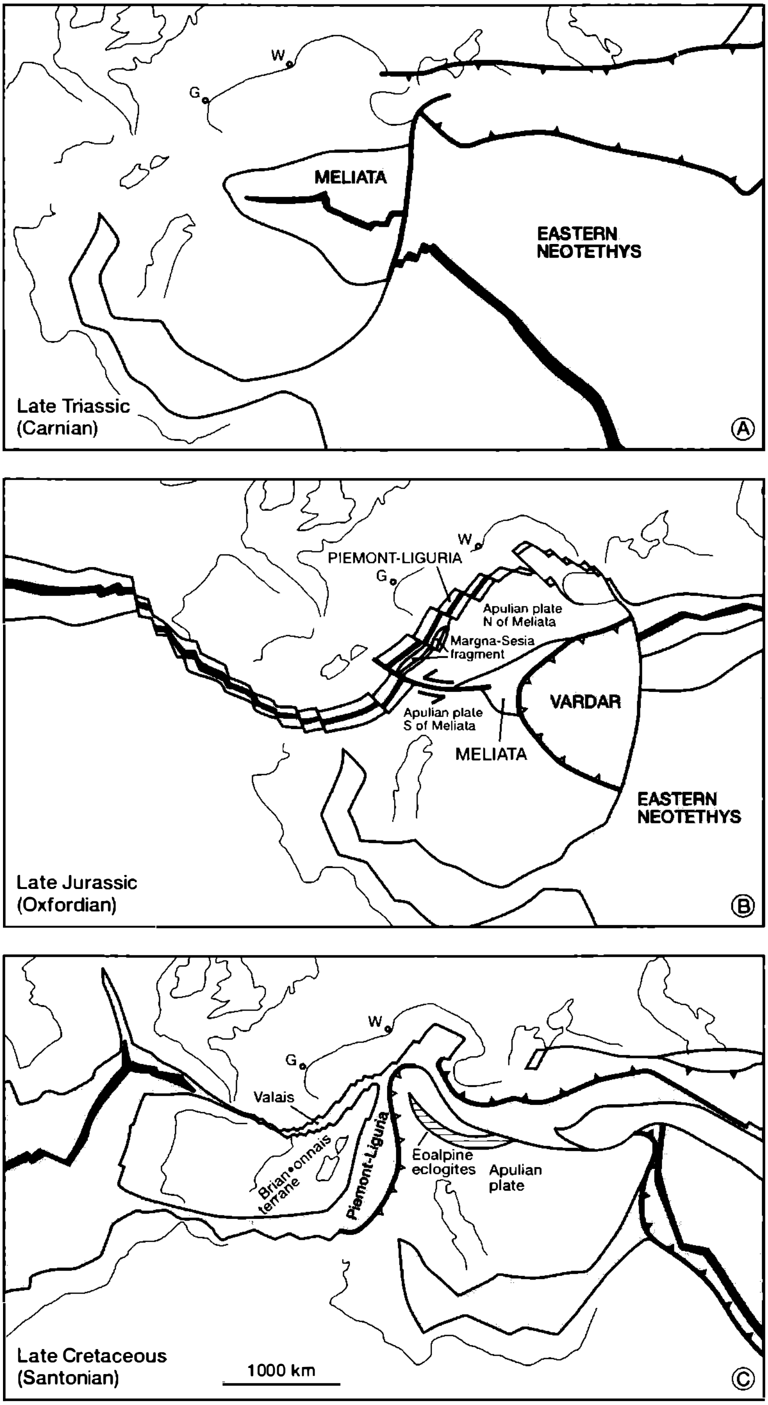

Fig. 2

Paleogeographic reconstruction for a) Late Triassic, b) Late Jurassic and c) Late Cretaceous times. G: Genève, W: Vienna adapted from SCHMID et al. (2004).

The Meliata ocean opened during the Triassic (KOZUR, 1992) when, according to STAMPFLI & BOREL (2004), it formed as a back arc ocean at the western end of the Tethys ocean bay, related to the closure of the Paleotethys ocean. During the Jurassic the Vardar ocean opened and the Meliata, Vardar and Neotethys oceans formed a continuous basin. The closure of the Meliata ocean started in the Jurassic and continued until Lower Cretaceous times, with the subsequent continental collisions being referred to as the eo-Alpine event. The geometry of these oceanic basins, their relationships and the plate tectonic arrangement during their closure is still under discussion (e.g. CHANELL & KOZUR, 1997; GAWLIK, et al., 1999; NEUBAUER et al., 2000; CSONTOS & VÖRÖS, 2004). Melange zones with material from the Triassic ocean are preserved in the Dinarides and in the Pannonian basin, whereas fragments with a Jurassic blueschist facies metamorphic imprint can be found in the Western Carpathians (DAL PIAZ et al., 1995). However, no oceanic Meliata suture is preserved in the Alps and outcrops of this realm are extremely scarce, only being found in the easternmost part of the Eastern Alps. Recent interpretations suggest that the eo-Alpine event in the Alps was related to intracontinental subduction within the Apulian microplate, which took place in the continuation of an oceanic subduction zone further to the southeast (THÖNI & JAGOUTZ, 1993; KURZ & FRITZ, 2003).

The Alpine Tethys ocean was related to the opening of the Atlantic ocean and consisted of two subbasins (FRISCH, 1979). At first the Piedmont-Ligurian ocean developed in the Jurassic and separated Apulia from Europe. During the Lower Cretaceous spreading in the Valais ocean cut off the Brianconnais microcontinent from southwestern Europe, while in the east the two oceans merged into a single basin (FROITZHEIM et al., 1996). The subduction of the Alpine Tethys started in the Upper Cretaceous and lasted until the Eocene. During the related continental collisions, which are referred to as the Alpine orogenic event, Europe acted as the lower tectonic plate and Apulia as the upper one. The suture zone of the Alpine Tethys is represented by the Penninic Nappes and can be traced all along the Alps.

2. Tectonic units

This description of the tectonic units of the Alps is based on the map and sections published by SCHMID et al. (2004) (Plate 1, Fig. 3; numbers in the text refer to these figures). From bottom to top (from N to S, or NW to SE, respectively) the Alps are made up of the following tectonic units:

2.1 Units derived from the (Mesozoic to Paleogene) European continent:
The European continent consists of a deeply eroded Variscan (Late Devonian to Carboniferous) metamorphic continental crust, rich in plutonic rocks (41 north of the Alpine front), covered by Carboniferous to Eocene sedimentary sequences (39, 40). This crust is still in contact with its lithospheric mantle; it dips beneath the Alps and contains the Late Eocene to Neogene Molasse basin (2, 38) which is the northern peripheral foreland basin of the orogene. The External massifs (41) represent windows in the European plate within the Western and Central Alps. They comprise basement rocks and Late Carboniferous to Cretaceous cover sequences. The Helvetic and Ultrahelvetic Nappes (36, 37) are a thin-skinned fold and thrust belt formed exclusively of detached cover sequences. The Helvetic Nappes at the northern margin of the Central Alps are well known, whereas in the Eastern Alps they are present only as thin slices.

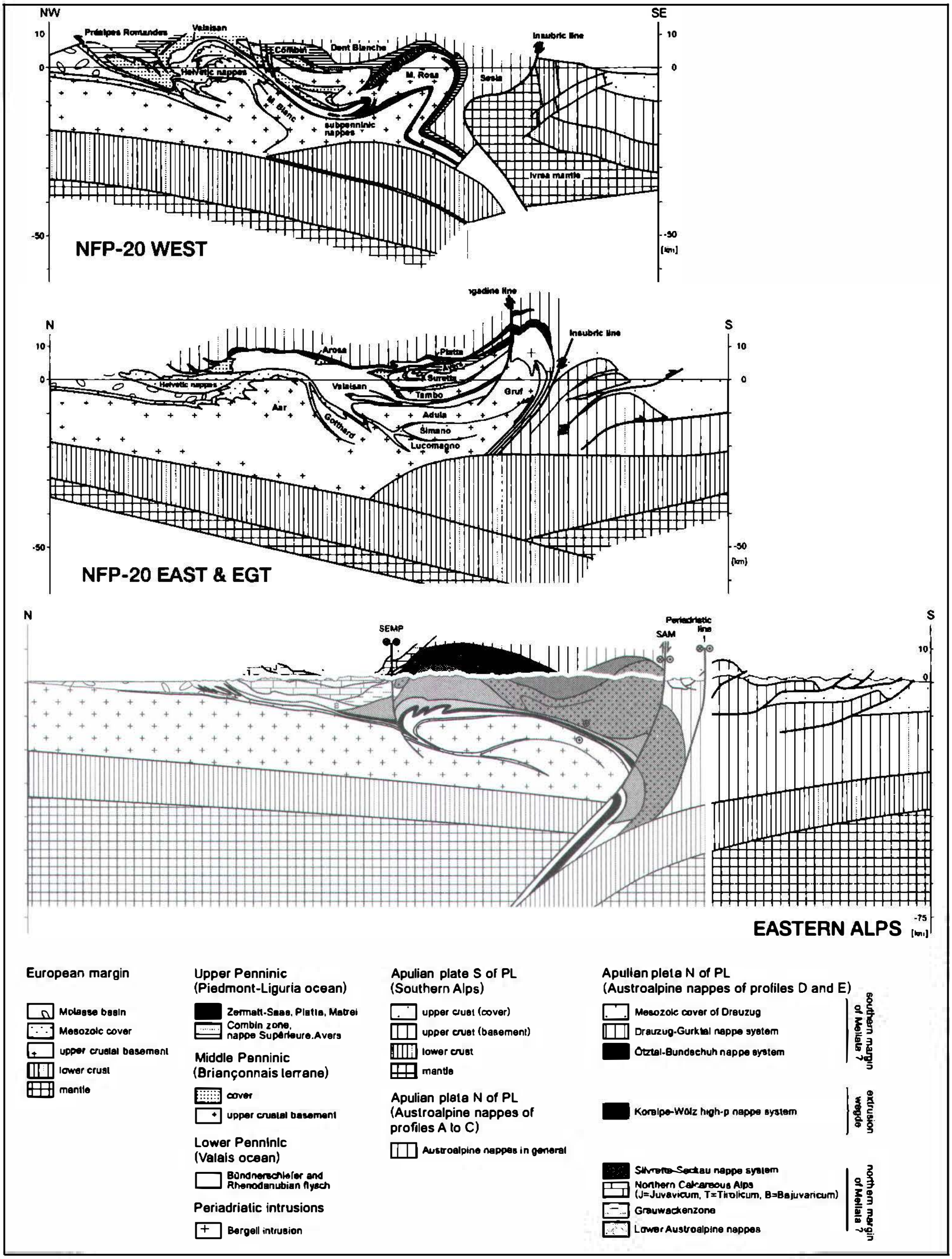

Fig. 3

Sections through the Western, Central and Eastern Alps adapted from SCHMID et al. (2004).

Plate I

Tectonic map of the Alps adapted from SCHMID et al. (2004). Doted squares show the areas of Saualpe-Koralpe-Pohorje region and Tauern Window, which will be visited during the excursions.

The Sub-Penninic Nappes (33, 34) represent the distal European margin, forming ductilely deformed basement and cover nappes which lost contact with their lithospheric mantle and served as the basement for the Helvetic Nappes. They form the Gotthard, Travetsch and Adula Nappes in the Central Alps and also, contrary to many earlier publications, the Venediger Nappe system in the Tauern Window of the Eastern Alps. This interpretation is based on the conclusion that the crustal material of the Venediger Nappe system was not separated from the European margin by an oceanic basin (e.g. FROITZHEIM et al., 1996; KURZ et al., 2001). The eclogitic Sub-Penninic basement units (35) (Adula Nappe, Cima Lunga Nappe and Eclogite Zone of the Tauern Window) contain material derived from the Alpine Tethys ocean and developed in a tectonic accretion channel (KURZ et al. 1998a; ENGI et al., 2001; KURZ & FROITZHEIM, 2002).

2.2 Penninic Nappes:

The Penninic Nappes comprise three paleogeographic elements: the Piedmont-Ligurian ocean, the Brianconnais microcontinent and the Valais ocean.

The Piedmont-Ligurian ocean opened in Upper Jurassic times. Its initial sea-floor formed by exhumation of the subcontinental mantle of the Apulian microplate (FROITZHEIM & MANATSCHAL, 1996). These mantle rocks are overlain by Jurassic radiolarites, aptychus limestones and Cretaceous calcareous turbiditic metasediments. The Brianconnais microcontinent was a part of the European distal margin until it was cut off by the opening of the Valais ocean in the Cretaceous. The Valais oceanic crust comprises Cretaceous ophiolites overlain by Cretaceous to Eocene calcareous turbiditic metasediments. Towards the east the Valais ocean merged into the Piedmont-Ligurian basin thus forming a single oceanic basin in the east (e.g. STAMPFLI, 1994; FROITZHEIM et al., 1996). Although this situation in the east makes any subdivision of the Piedmont-Ligurian from the Valais basin there somewhat artificial (KURZ et al., 2001), characteristic successions, analyses of the source areas of the clastic sedimentary successions and the age and chemical characteristics of the ophiolitic rocks allow the differentiation of elements from the northern or southern part of this joint oceanic basin.

The Penninic Nappes can be subdivided into the Upper, Middle and Lower Penninic Nappes, whereby each consists mainly of one of the paleogeographic elements mentioned above.
The Lower Penninic Nappes (31, 32) consist predominantly of material from the Valais oceanic province and from the northern parts of the joint oceanic basin in the east. The Lower Penninic Nappes make up large parts of the Central Alps and the central part of the Lower Engadine Window. The lower nappes of the Rhenodanubian flysch zone (32) represent a continuation of the Central AlpineValais basin sediments into the Eastern Alps (KURZ et al., 1998b); they comprise Cretaceous flyschoid sediments deposited in a basin along the European margin. The Glockner Nappe system of the Tauern Window, consisting of calcareous flyschoid metasediments and metaophiolites, is thought to be a southern continuation of the lower nappes of the Rhenodanubian flysch zone.
The Middle Penninic Nappes (27, 28, 29, 30) are mainly derived from the Brianconnais microcontinent and are common in the Western and Central Alps. The easternmost nappes to include material from the Brianconnais microcontinent are represented by the Tasna Nappe of the Lower Engadine Window.

Rocks derived from the Piedmont-Ligurian ocean and the accretionary wedge along the southern margin of the oceanic basin towards the Apulian microcontinent made up the Upper Penninic Nappes (26). They are widespread in the Western and Central Alps and continue into the Apennines (9). In the Eastern Alps the Upper Penninic Nappes form the uppermost tectonic elements in the Engadine and Tauern windows (e.g. the Arosa Zone, the Matrei Zone, and the Reckner Complex) as well as the whole of the Rechnitz Window Group. In the northern part of the Eastern Alps the Ybbsitz klippen belt (DECKER, 1990) is a remnant of the Piedmont-Ligurian ocean, containing the typical sequence of serpentinites, Jurassic radiolarites and aptychus limestones. It is in contact with the Kahlenberg Nappe of the Rhenodanubian flysch zone, which is also interpreted to be an Upper Penninic Nappe (FAUPL & WAGREICH, 1992).

2.3 Apulian microcontinent:

The Apulian microcontinent consists of a Cadomian continental crust (NEUBAUER, 2002) with Paleozoic metasedimentary sequences and with magmatic activity related to rifting and subduction processes lasting until the Carboniferous. During the Variscan orogeny large parts of this crust were affected by metamorphic processes and synorogenic magmatism. Post-orogenic Permo-Carboniferous sediments were deposited locally. In the Permian the area was affected by lithospheric extension expressed by basaltic magmatic underplating, intense acidic magmatism and related high-temperature / low-pressure (HP/LT) metamorphism. More than 3 km of Permo-mesozoic sediments were subsequently deposited on top of the thermally subsiding micro-continent, which formed a broad carbonate shelf towards the Meliata ocean in the southeast and, from the Jurassic, was bordered to the north by a passive continental margin facing towards the Piedmont-Ligurian oceanic trough (Fig. 2). In the Alps the Apulian microcontinent is represented by the Margna-Sesia fragment and by the Austroalpine and Southalpine units, the latter two being separated by the Periadriatic lineament.

The Margna-Sesia fragment (25) (FROITZHEIM et al., 1996) rifted apart from the Apulian micro-continent during the Middle Jurassic. In the late Cretaceous it was incorporated in the accretionary wedge and subducted along the Apulian margin.

The Austroalpine unit forms a complex nappe stack of crustal material which can be subdivided into Lower and Upper Austroalpine units (Fig. 4). The Lower Austroalpine unit (24) formed the continental margin towards the Piedmont-Ligurian ocean and was affected by tectonism during the opening and closing of this oceanic realm (Alpine event). It overlies the Penninic Nappes of the Eastern Alps. The Upper Austroalpine unit represents an eo-Alpine nappe pile. Its lower-most unit is the Silvretta-Seckau Nappe system (23) consisting of a basement with a dominating Variscan metamorphic imprint and remnants of Permotriassic cover (parts of 19). During the eo-Alpine event it was overprinted by sub-greenschist to greenschist facies conditions.

To the north the Silvretta-Seckau Nappe system is overlain by the nappes of the Greywacke zone (18), which consists of greenschist facies metamorphic Paleozoic sequences, and the Juvavic (15), Tirolic (16) and Bajuvaric (17) nappe systems. The latter form the Northern Calcareous Alps, comprising unmetamorphosed to lowermost greenschist facies metamorphic Permo-mesozoic sediments deposited on the shelf facing originally towards the Meliata ocean, with the sequences of the Juvavic Nappe system representing the most distal shelf towards the oceanic basin.

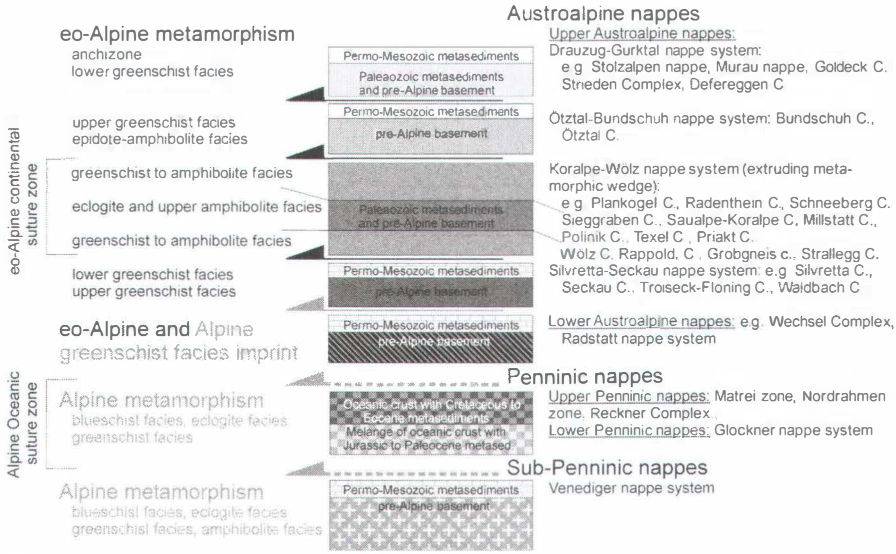

Fig. 4

Schematic nappe stack of the southeastern part of the Eastern Alps with information on the metamorphic grade and correlation with nappes from the western part of the Austroalpine units.

To the south the Silvretta-Seckau Nappe system is overlain by the Koralpe-Wölz Nappe system (22) which represents an eo-Alpine metamorphic extrusion wedge (SCHUSTER et al., 2004). Its Permomesozoic cover was completely stripped off during an early phase of the eo-Alpine orogenic event (Lower Cretaceous) and it therefore consists exclusively of polymetamorphic basement nappes with a Permotriassic HTLP (SCHUSTER et al., 2004) and an eo-Alpine LTHP metamorphic overprint (e.g. HOINKES et al., 1999).

The Ötztal-Bundschuh Nappe system (21 and parts of 19) shows a similar lithological composition to the Silvretta-Seckau Nappe system, but is positioned on top of the Koralpe-Wölz Nappe system. The overlying Drauzug-Gurktal Nappe system (20) is made up of a Variscan metamorphic basement, Paleozoic metasediments and Permomesozoic sequences (parts of 19). Within the Ötztal-Bundschuh and Drauzug-Gurktal Nappe systems the eo-Alpine metamorphic grade decreases upwards from amphibolite facies at the base to diagenetic conditions at the top of the nappe pile.

The Southalpine unit (11, 12, 13, 14) shows minor deformation concentrated along its margins. Its major part is in contact with a subcontinental lithosphere; this contact is visible at the surface in the Ivrea Zone in the Western Alps (11). The Southalpine unit is considered to be a southern external retro-arc orogenic wedge within the Alpine orogenic system (e.g. SCHMID et al., 1996). In the southeast the Southalpine unit continues into the External Dinarides (8).

2.4 Meliata zone:

The Meliata zone of the eastern Alps contains remnants of the Meliata oceanic basin. These include serpentinites, basic volcanic rocks and deep water Triassic sediments, redeposited in Jurassic metasediments. These rocks can be correlated with those from the Meliata zone in the Western Carpathians (MANDL, 2000).

The Meliata zone occurs as tiny klippen within the eastern part of the Eastern Alps between the Tirolic and Juvavic Nappe systems of the Austroalpine unit. They show a sub greenschist facies metamorphic imprint but no indications of subduction related HP/LT metamorphism. Material from the Meliata oceanic basin is also present as detritus in Cretaceous sediments of Austro-alpine units (FAUPL & WAGREICH, 2000) and in the Haselgebirge, an evaporite tectonite at the base of the Juvavic Nappe system.

The Periadriatic intrusions (5) comprise calkalkaline tonalities, granodiorites and granites, and minor alkaline basaltic dikes. They are mostly Oligocene in age and related to the break-off of the Alpine Tethys oceanic lithosphere from the distal European margin (DAVIS & VON BLANKENBURG, 1995). Their intrusion is closely associated with contemporaneous strike-slip movements along the Periadriatic lineament.

3. Distribution and timing of high-pressure metamorphism within the Alps

The convergence of Africa and Europe led to the formation of the Alpine orogenic belt by "tectonic progradation" (FRISCH, 1979) from south to north. This process started with an intra-continental subduction within the Austroalpine unit in the Lower Cretaceous which was followed by the Upper Cretaceous-Eocene subduction of the Piedmont-Ligurian and Valais ocean and prograding continental collisional events that continued until recent times. This mechanism produced high-pressure metamorphism in different tectonic units, decreasing in age from south (internal) to north (external).

A brief summary of this evolution is given below. Detailed reviews of the metamorphic conditions and the timing of metamorphism in the individual units, together with maps showing the distribution of the metamorphic grade, are given by FREY et al. (1999) and OBERHÄNSLI (2004).

3.1. Eclogite formation in the eo-Alpine subduction zone:
In the Alps the eo-Alpine eclogites only occur in the Koralpe-Wölz Nappe system of the Austro-alpine unit. None of these eclogites are metamorphosed remnants of oceanic crust from the Maliata ocean. Most of them derived from pre-existing amphibolites and only a minor part (in the Saualpe-Koralpe Complex) formed from Permian gabbros and basalts intruded into meta-sedimentary rocks (MILLER & THÖNI, 1997). Furthermore, the absence of blueschist facies metamorphic precursor assemblages or associated rocks argues against eclogite formation as a consequence of oceanic subduction (GAWLIK et al., 1999; NEUBAUER et al., 2000) and in favour of a continental subduction setting, possibly in the lateral continuation of an oceanic subduction zone (THÖNI & JAGOUTZ, 1993, KURZ & FRITZ, 2003; JANAK et al., 2004).

The following description of the eo-Alpine event is based on the interpretation proposed by SCHUSTER (2004). At the end of the Jurassic the Austroalpine unit showed the following zoning. Firstly, in the northwest, the Lower Austroalpine unit formed a passive margin towards the Alpine Tethys. Next came the future Silvretta-Seckau Nappe system, overlain by the lower nappes of the future Greywacke zone and by the Bajuvaric Nappe system.

Further to the southeast was the future Koralpe-Wölz Nappe system, with the uppermost nappe of the Greywacke zone (Noric Nappe) overlain by the future Tirolic Nappe system and the already existing Juvavic Nappe system above. To the south of a system of Jurassic sinistral strike-slip faults, the future Ötztal-Bundschuh and Drauzug-Gurktal Nappe systems and the Southalpine unit where located. The latter tree units shifted to the south of the Juvavic Nappe system during the activity of the Jurassic sinistral strike-slip faults. During the lowermost Cretaceous the system of strike slip faults was transformed into a southeast-dipping continental subduction zone. When the subduction started (in the Beriassian, ~140 Ma) the cover of the tectonic lower plate in the northwest (the uppermost nappe of the Greywacky zone, Tirolic and Juvavic Nappe systems) was stripped off from its basement (the future Koralpe-Wölz Nappe system) and thrust towards the northwest. The basement was subducted below the tectonic upper plate to the southeast, with maximum depths being reached in the middle Cretaceous (THÖNI 1999, 2002). The Koralpe-Wölz Nappe system subsequently formed by exhumation in a extrusion wedge, by thrusting in the lower part of the wedge and normal faulting in the upper part.. The main part of the nappe was exhumed in a pro-wedge geometry (e.g. Saualpe-Koralpe and Sieggraben Complexes), whereas to the southwest (Texel Complex) and southeast (Millstatt Complex) of the recent Tauern Window a retro-wedge geometry developed. During normal faulting late-orogenic to post-orogenic basins (sediment basins of the Gosau Group) formed on top of the upper plate and on top of the Bajuvaric, Tirolic and Juvavic nappe system, which form the Northern Calcareous Alps.

From the late Eocene onwards the Austroalpine unit was affected by deformation caused by the exhumation of Penninic and Sub-Penninic Nappes within windows (GENSER & NEUBAUER, 1989; FÜGENSCHUH et al., 1997) and by lateral extrusion towards the east (RATSCHBACHER et al. 1989). During these processes a system of normal and strike slip faults developed, with remarkable vertical displacements in some places, cutting through the eo-Alpine nappe pile and exerting a strong control on the present day geographical distribution of eclogite occurrences.

In the Koralpe-Wölz Nappe system eclogite-bearing complexes can be traced from the Texel Complex southwest of the Tauern Window to the eclogite type locality in the Saualpe-Koralpe Complex, east of the Tauern Window (HAUY, 1822), and to the Sieggraben Complex at the eastern margin of the Alps. For the westernmost Texel Complex minimum pressures are 10-12 kbar at 550°C (HOINKES et al., 1991; SÖLVA et al., 2001). For the Prijakt Complex and the Polinik Complex to the south of the Tauern Window minimum pressures of approximately 15 kbar were reported by LINNER (1995) and HOKE (1990) respectively. Data on the eclogites from the Millstatt Complex to the southeast of the Tauern Window are >12 kbar at 600-630 °C (TEIML & HOINKES, 1996). In the northern part of the Saualpe-Koralpe Complex peak pressures of 15-20 kbar and 600-700°C have been recorded (MILLER, 1990; THÖNI & MILLER, 1996; MILLER & THÖNI, 1997), whereas for the southern part UHP metamorphic conditions with pressures > 30 kbar at 750-800°C were reported (Pohorje mountains, Slovenia; JANAK et al., 2004). Finally, for the eclogites of the Sieggraben Complex temperatures of 670-750°C at about 15 kbar were determined (NEUBAUER et al., 1999; PUTIS et al., 2002).

These data show regional trends: 1) The highest PT conditions were reached in the Saualpe-Koralpe Complex to the east of the Tauern Window, whereas to the west and to the east lower conditions have been determined. 2) Within the Saualpe-Koralpe Complex a southward increase

in maximum P and T can be recognised. This is consistent with a southward subduction direction in the Cretaceous (FLÜGEL & FAUPL, 1987; FRANK, 1987).
The timing of the eclogite facies metamorphism is best constrained by Sm-Nd garnet ages from the Saualpe-Koralpe and Texel Complexes indicating an age between 110 and 90 Ma. However many reliable data scatter around 95 Ma (Cenomanian) (for a review see THÖNI, 1999, 2002).

3.2. High-pressure metamorphism in the Alpine subduction zone:
The high-pressure rocks in the Alpine subduction zone formed as a result of the successive subduction of the Piedmont-Ligurian ocean, including the Margna-Sesia fragment, the Brianconnais microcontinent, the Valais ocean and, finally, the European margin, below the Apulian microcontinent.

Subduction of the Piedmont-Ligurian oceanic crust beneath the northern margin of Apulia started in the Upper Cretaceous. The continental Margna-Sesia fragment located within the ocean must have entered the subduction zone quite early, because eclogite facies metamorphism is documented within the Sesia Zone of the Western Alps at the Cretaceous-Tertiary boundary (60-70 Ma) (RUBATTO et al., 1999; DAL PIAZ et al., 2001; HANDY & OBERHÄNSLI, 2004).

In the Upper Penninic Nappes of the Western and Central Alps an eclogite facies imprint and locally UHP conditions were attained (approx. 28 kbar at 600-650°C; REINECKE, 1998; VAN DER KLAUW et al., 1997; AMATO et al., 1999), but only blueschist facies conditions were attained in the eastern part of the Central Alps and in the Eastern Alps (OBERHÄNSLI, 2004). In the Eastern Alps the Idalpe ophiolite in the Engadine Window experienced blueschist facies conditions of 7-9 kbar and c. 350°C (HÖCK & KOLLER, 1987). Within the Tauern Window the Matrei zone and the Reckner Ophiolite Complex experienced a blueschist facies metamorphic imprint, with conditions of 10 kbar pressure and c. 350°C, dated at approx. 50-45 Ma (DINGELDEY et al., 1997; HEIDORN et al., 2002). The blueschist facies imprint in the Rechnitz Window Group reached minimum pressures of 6-8 kbar at 330-370°C (KOLLER, 1985). An age of about 57 Ma has been suggested for the HP-imprint by Ratschbacher et al. (2005), based on an Ar-Ar measurement on amphibole. Although the subduction of the Piedmont-Ligurian ocean may have started in the Cretaceous the preserved high-pressure rocks are Paleocene to Lower Eocene (45-60 Ma) in age (e.g. DINGELDEY et al., 1997, CLIFF et al., 1998; RUBATTO et al., 1999; GEBAUER, 1999).

The subduction of the Brianconnais below the Upper Penninc Nappes started in the Eocene (SCHMID et al., 1996). Radiometric age data on the high-pressure rocks from the Middle Penninic Nappes are in the range of 30-40 Ma (e.g. GEBAUER et al. 1997; DUCHENÈ et al. 1997; RUBATTO & HERMANN, 2001). In the Western Alps the Middle Penninic Nappes show a metamorphic zoning with eclogite facies and local UHP conditions (c. 28-35 kbar and 700-750°C Dora Maira massif; CHOPIN et al., 1991) in the more internal units, and blueschist followed eventually by greenschist facies conditions towards the external units. In the Central Alps only blueschist facies conditions have been observed to date.

Since the youngest sediments derived from the Valais oceanic basin, which experienced high-pressure metamorphism, are Lutetian (40-48 Ma) in age, the peak of the metamorphic imprint in the Lower Penninic Nappes has to be younger than 45 Ma (FROITZHEIM et al., 1996). In the Lower Penninic Nappes eclogitic facies metamorphism is only documented in some localities of the Western and Central Alps (Versoyen and Antrona; BOUSQUET et al., 2002) and in the Tauern Window of the Eastern alps (Glockner Nappe; PROYER et al., 1999; DACHS & PROYER, 2001). Large parts of the Western and Central Alps experienced blueschist facies conditions, whilst in the Eastern Alps blueschist facies metamorphism is documented locally from the Engadine and Tauern Windows.

In the Sub-Penninic Nappes eclogites occur in the southern, tectonically uppermost, nappes, whereas large areas experienced a blueschist facies imprint. The age of the high-pressure imprint is Eocene (35-45 Ma) (DROOP et al., 1990; BECKER, 1993; GEBAUER, 1999; ZIMMERMANN et al., 1994; RATSCHBACHER et al., 2005) and a subsequent greenschist to upper amphibolite facies thermal overprint is characteristic. In the Central Alps, the Adula Nappe and the attached Cima Lunga unit experienced maximum conditions of 35 kbar at 850-900°C (NIMIS & TROMMSDORFF, 2001). For eclogites from the Eclogite Zone, located in the Tauern Window of the Eastern Alps, peak conditions of 20-22 kbar and 600-625°C have been reported (HOLLAND, 1979; HOSCHEK, 2001).

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ALPINE ECLOGITES IN THE TAUERN WINDOW

by

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1. Geologic setting

The Tauern Window (TW) represents the largest exposed section of the lowest major tectonic unit in the Eastern Alps (the "Penninic" unit, see Plate 1 of SCHUSTER & KURZ, this volume). It represents an exhumed section of the nappe stack that developed in a subduction zone during closure of the Penninic ocean in the Upper Cretaceous and Tertiary (Fig. 1). From base to top, the Penninic nappe stack includes (KURZ et al., 1998, 2001):

(1) *The Venediger Nappe (VN) and the Wolfendorn Nappe:* these nappes comprise a pre-Variscan basement intruded by Variscan granitoids (the "Zentralgneis") with a cover sequence of Jurassic metacarbonates ("Hochstegen Marble Formation") and Cretaceous metapelites and metapsammites ("Kaserer Group", sedimentation up to Eocene) (FRISCH, 1980, 1984; LAMMERER, 1988). The Wolfendorn Nappe mainly forms a duplex of the cover sequences of the Hochstegen Marble Formation and the Kaserer Group, underlain by thin slices of former continental basement.
(2) *The Storz and Riffl Nappes* comprise Variscan and Alpidic polymetamorphic basement rocks covered by metapelites and graphitic quartzites of the Murtörl Group, which was assumed to be of either late Paleozoic or, more likely, Cretaceous age (KURZ et al., 1998, and references therein). The nature of the tectonic contact between the Venediger Nappe and the Riffl Nappe (Fig. 1a) has been highly debated and is interpreted by FRISCH (1977, 1980) to be related to the Variscan orogeny.
(3) *The Eclogite Zone* (EZ) is restricted to the central southern TW and is characterized by a Mesozoic volcano-sedimentary sequence of a distal continental slope that has experienced HP metamorphism. The Eclogite Zone is tectonically positioned above the Venediger Nappe Complex and is overlain by the Rote Wand-Modereck Nappe (Fig. 1a-c). Where the Eclogite Zone is absent, however, the Rote Wand-Modereck Nappe is overthrust directly onto the Venediger Nappe (Fig. 1a).

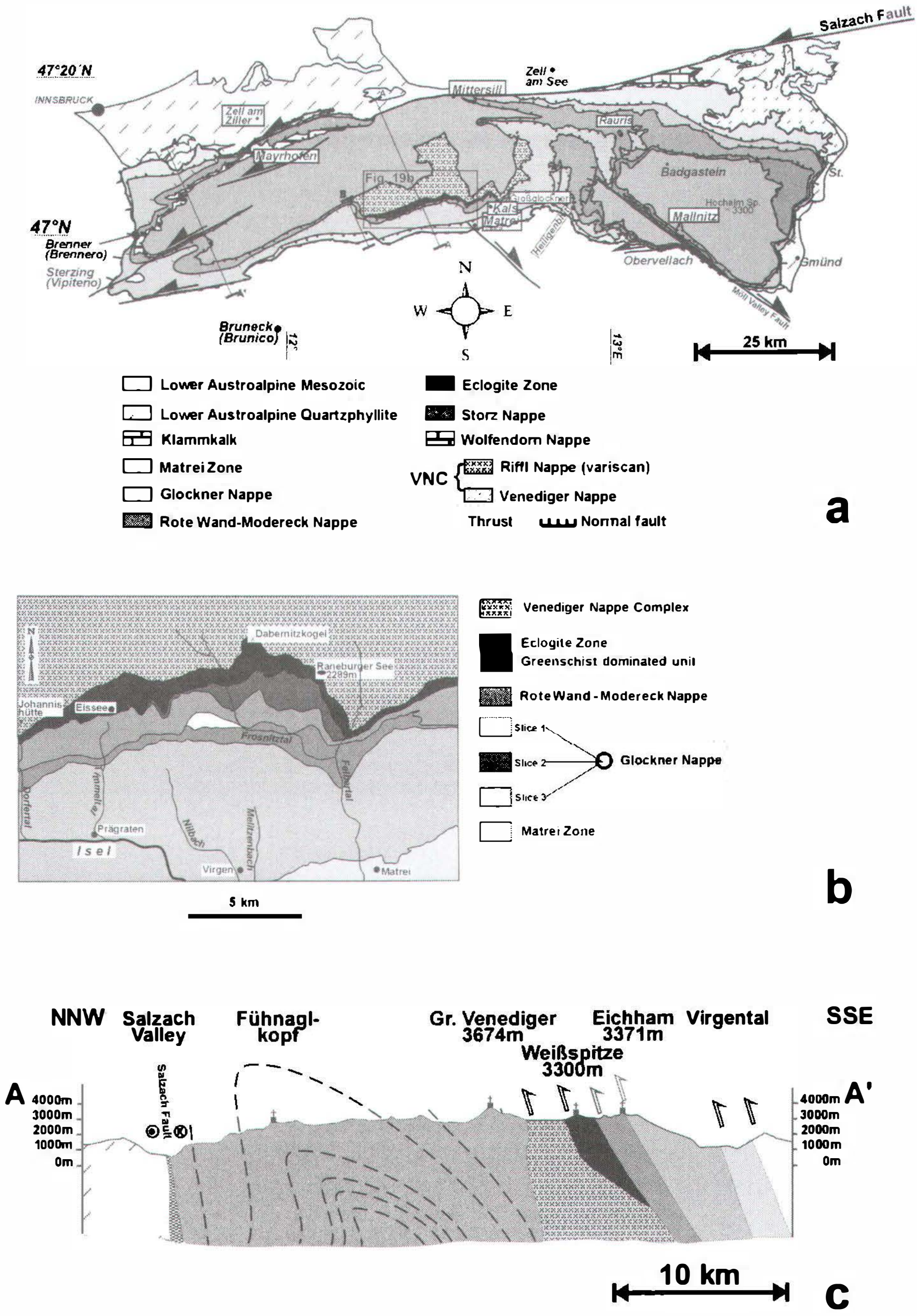

Fig. 1

a) Geologic overview of the Tauern Window (according to KURZ et al., 1998, 2001); b) Simplified geologic map showing major tectonic units in the southern Großvenediger area. The excursion area (2nd and 3rd day in the Eclogite Zone) is in the Dorfer and Timmeltal areas close to the western edge of the figure; c) Simplified geologic profile across the TauernWindow in the Großvenediger section (line A-A' in Fig. 1a).

(4) *The Rote Wand-Modereck Nappe* (RMN) is formed by basement rocks of the Rote Wand-Modereck Lamella that are covered by Permian to Triassic quartzites, Triassic metacarbonates, Jurassic breccias, calcareous micaschists and metatuffs as well as Cretaceous metapelites and metapsammites.

(5) *The Glockner Nappe* (GN) comprises an oceanic basement made up of an incomplete ophiolitic sequence of serpentinites, ultramafic rocks, MORB-type metabasics (greenschists and amphibolites) of supposed Jurassic to Cretaceous age (BICKLE & PEARCE, 1975; HÖCK & MILLER, 1980), covered by or intercalated with a sequence of quartzites, micaceous calcitic marbles and calcarous schists (the "Bündner Schists").

Terrigenous sequences have been observed locally, for example in the central and western parts of the TW. It is very important to note that the base of the Glockner Nappe is made up of former oceanic lithosphere, while the cover sequences of several other nappes within the TW are underlain by continental basement. Hence the separation of the Glockner Nappe from the Rote Wand-Modereck Nappe in the footwall is only possible if serpentinites and other remnants of former oceanic lithosphere are intercalated between meta-sediments.

(6) *The Matrei Zone* is interpreted to represent an accretionary wedge that is characterized by metamorphic flysch sediments (mainly calcareous and carbonate-free micaschists), breccias and olistoliths, mainly of Austroalpine derivation (FRISCH et al., 1987).

(7) *The Klammkalk Zone* comprises calc-schists, massive marbles and thin-bedded green phyllites; it forms a low-grade metamorphic equivalent to the "Bündnerschiefer" of the Glockner Nappe.

(8) *The Lower Austroalpine nappe* stack, in the hanging wall of the Penninic nappe stack, comprises pre-Alpine continental basement units and Permian to Mesozoic cover sequences, predominantly derived from a rifted, passive continental margin.

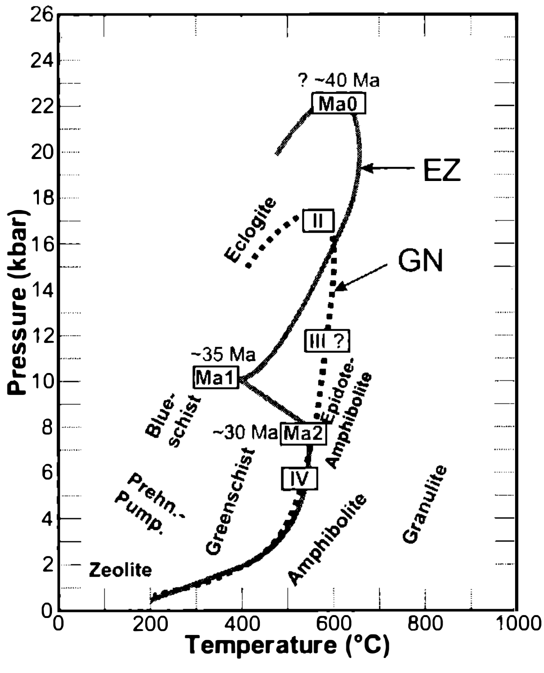

Fig. 2

P-T paths recorded from HP-rocks of the Eclogite Zone (EZ) and Glockner Nappe (GN). See Tables 1 and 2 for data sources and references.

2. Tectonometamorphic evolution

2.1. HP evolution

The rocks exposed within the EZ in the southern Großvenediger area have been affected by a multiphase tectonometamorphic evolution. Inclusions in garnet from eclogites (Ep, Chl, Pa, Bt, Phe, Qtz, Ab - see Tab. 1a for mineral abbreviations used in the text) and from metasediments (rhombic form-relics of Pa+Zo+Qtz interpreted as pseudomorphs after lawsonite by FRY (1973), Tab. 1b), document a pre-eclogite stage of prograde metamorphism in greenschist-to-blueschist facies. The eclogite facies rocks were then buried to a depth of at least 65 km, as has been concluded from the HP parageneses of eclogites (Tab. 1a), associated metapelites (Tab. 1b) and metacarbonates (Tab. 1c), which all yielded similar PT paths with peak conditions of ~20 kbar, ± 600°C (Ma0 in Fig. 2).

Omphacite microstructures, in particular shape fabrics and crystallographic preferred orientations (CPOs) (Fig. 3), indicate that the final phases of the prograde evolution are characterised by flattening strain (documented by S-type omphacite CPOs). L-type CPOs formed at the pressure peak and along the exhumation path and document a constrictional strain geometry.

In the tectonically higher RMN and GN eclogite facies metamorphism is only locally recorded and former eclogites are much more affected by retrogression (KURZ et al., 1996; STURM et al., 1997; PROYER et al., 1999; DACHS & PROYER, 2001, 2002). The pre-eclogite stage in such retrogressed rocks is nevertheless still recognizable by inclusions preserved in garnet cores (e.g. ?magmatic augite and chromite, Plag, Chl, Akt, Barr/Glau, etc., Tab. 2) pointing to an early greenschist (?ocean-floor) and blueschist stage. Generally, eclogite facies assemblages documenting P-T conditions of ~17 kbar / 570 °C (Tab. 2, II in Fig. 2) can only be observed in the southern sections of these nappes, which would be related to a more distal (southern) paleogeographic position.

2.2. Post-HP evolution

The major tectonic units of the TW (from the VN at the base, up to and including the GN) were subsequently affected by blueschist facies metamorphism (Tab. 1-2, Fig. 2). Generally, the P and T of this stage are not well constrained due to the subsequent strong overprinting by Barrovian-type metamorphism ("Tauern crystallization").
In the southern Großvenediger area, ZIMMERMANN et al. (1994) derived 450°C and 10-15 kbar for this stage from Alpine HP-veins in garnet amphibolites of the VN. Reliable quantitative P-T estimates for this blueschist stage are not available from rocks of the EZ. However, ZIMMERMANN et al. (1994) argue for conditions of P > 10 kbar and T < 450°C, based on ^{40}Ar-^{39}Ar dating on phengites from the VN, EZ and GN in the Großvenediger section, suggesting that all three tectonic units cooled below the K-Ar closure temperature of white mica (~ 400°C) at 34.4 ± 2.6 Ma (Ma1 in Fig. 2). From the occurrence of crossite and low-jadeitic pyroxene in metabasites from higher structural levels of the GN, HOLLAND & RAY (1985) determined P > 8 kbar and T = 400-450 °C for this stage.

Stage	Eclogites of the EZ	Parageneses / Textures /Reactions	P, T estimates	Ref.[1)]
Pre-eclogite	Relics in Grt-cores	Ep, Chl, Pa, Bt, Phe, Qtz, Ab, Fe-Barr, Ilm, Mt, Ap	prograde greenschist- to Ep/Amph-facies	1, 2, 3, 4, 23
Eclogite Ma0	E1: coarse-grained, gabbroic eclogite	Omph$_1$(Jd$_{34}$)+Grt(Py$_{33}$)+Ky+Tc+Qtz±Rt±Ap±Pyr (Omph$_1$, Ky, Tc inclusions close to grt-rims)	P ~19 - 22 kbar T ~ 590 - 650 °C a_{H2O} ~ 1	1, 2, 5, 8, 9, 10
	E2: fine-grained, "cataclastic" eclogites	Omph$_2$(Jd$_{47}$)+Grt(Py$_{38}$)+Ky+Tc+Qtz±Rt±Ap±Pyr relictic coarse Omph$_1$ →Omph$_2$		
	E3: banded kyanite-talc eclogites	Omph$_2$+Grt+Ky+Tc+Rt+Qtz±Pa±Ap±Pyr		
	E4: fine-grained epidote eclogite-mylonites	Omph$_2$+Grt+Ep±Dol/Mag±Pa/Phe		
	E5: banded eclogite-mylonites	layers of Omph$_2$+Grt+Ep+Pa/Phe+Qtz alternating with bands of Ep+Omph+Grt+Qtz, Ep+Dol, Omph+Qtz, Ep, Carb +Qtz		
	Synmetamorphic veins	Qtz+Ky+Omph$_{(1,2)}$ ±MgCtd±Tc±Qtz±Zo/Ep± Rt±Ap±Mag		1, 2, 6
Blueschist Ma1	eclogite retrogression	Glau+Ep±Law stable (2), Omph/Grt → Glau/Barr±Pa, Rt → Sph±Ilm, Ky → Pa±Ep ^{40}Ar-^{39}Ar dating on Phe: 34.4 ± 2.6 Ma	P = 10 - 15 kbar[2)] 300 < T < 450 °C[2)] P > 10 kbar, T < 450 °C	1, 2, 10, 11, 11
	in greenschists of Glockner Nappe:	Law-pseudomorphs crossitic amph, jadeitic Px	P > 4 kbar, T = 300-350 °C P > 8 kbar, T = 400-450 °C	23, 12 19, 13
Greenschist / Amphibolite Ma2	eclogite retrogression	Act+Ab+Chl±Ep±Phe±Sph±Carb±Qz±Mt Grt → Chl±Ep±Carb±Bt, Omph → Sym(Ab+Di),	P = 6 - 10 kbar T ~ 550°C	14, 17

Table 1a

Summary of mineral assemblages, parageneses and P-T estimates for eclogites of the Eclogite Zone (south-central TW). Eclogite types E1 - E5 are according to MILLER (1977).

Stage	Metapelites of the EZ	Parageneses / Textures /Reactions	PT estimates	Ref.
Pre-eclogite		rhombic form-relics (Pa+Zo+Qtz) as inclusions in Grt: pseudomorphs after ?Law (Law+Ab → Pa+Zo+Qtz)	? prograde blueschist facies	1, 3, 5
Eclogite Ma0	Metapelites with Omph-relics	Grt(Py$_{24-35}$)+Phe$_1$(Si up to 3.47 apfu)+Qtz±Tc± Omph(Jd$_{42-54}$) ±Ky±Zo±Pa±Ru	P ~ 20 kbar at T = 600°C	3
	Grt-Ctd quartz-mica schists	Grt+Ctd+Ky+Phe$_1$+Qtz+Zo/Ep±Dol±Zn-Stau	P = 19 ± 2 kbar, T = 590 ± 20°C	16
		Grt+Ctd+Phe$_1$(Si up to 3.33 apfu, zoned)+Ky+Ru+Qtz	P ~ 25 kbar, T ~ 600 °C	7
late-eclogite		early decompression	P ~ 16 kbar, T < 550 °C	7
Blueschist		not clearly discernible in metapelites		
Greenschist / Amphibolite Ma2	Metapelites with Omph-relics	Omph → Sym; Omph+Ky → Pa+Zo/Ma±Sym;	P = 7.5 ± 1 kbar, T ~ 525°C	3, 4
		Tc+Phe$_1$ → Bt+Chl+Qtz;	P = 6-7 kbar, T = 500-550°C	18
		Grt+Phe$_1$ → Bt+Plag±Phe$_2$(Si=3.06-3.15 apfu) ±Chl±Cal Ky+Zo → Ma+Qtz	P = 9-10 kbar, T ~ 550 °C	8
	Grt-Ctd quartz-mica schists	Grt+Phe$_1$ → Bt+Chl		16
late alteration		Sudoite+Kaolinite	P ≤ 3 kbar, T = 200-350 °C	16

Table 1b

Summary of mineral assemblages, parageneses and P-T estimates for metapelites of the Eclogite Zone (south-central TW). For references and mineral abbreviations see next page and below.

Mineral abbreviations (Tables 1-4 and text):

Ab albite, Act actinolite, Amph amphibole, Ap apatite, Barr barroisite, Bt biotite, Cal calcite, Chl chlorite, Cpx clinopyroxene, Ctd chloritoid, Di diopside, Dol dolomite, Ep epidote, Glau glaugophane, Gr graphite, Grt garnet, Hbl hornblende, Ilm ilmenite, Carb carbonate, Kfs K-feldspar, Ky kyanite, Law lawsonite, Mag magnesite, Ma margarite, Mt magnetite, Ol oligoclase, Omph omphacite, Pa paragonite, Phe phengite, Phl phlogopite, Plag plagioclase, Pyr pyrite, Px pyroxene, Qtz quartz, Sph sphene, Stau staurolite, Sym symplectite, Rt rutile, Tc talc, Tr tremolite, Win winchite, (C)Zo (clino)zoisite

Other abbreviations and symbols:

apfu atoms per formula unit, —> transforms/reacts to (texturally mostly also rimmed by)

Stage	(Impure) Marbles of the EZ	Parageneses Textures Reactions	P, T estimates	Ref.
Pre-eclogite		not preserved		
Eclogite Ma0	Marbles with HP relics	Cal−Qtz±Omph(Jd_{10-32}) ±Zo±Dol±Qtz ±Phe_1(Si = 3.32-3.47 apfu); Omph inclusions in Tr/Akt-cores	P > 10 kbar at 550°C	1, 3
	Siliceous dolomites	Di+Tr_1(coarse-grained)+Dol+Cal+Qtz±Zo	P = 18-25 kbar, T ~ 600°C, a_{H2O} ~ 1	15
	Kyanite-Zoisite marbles	Ky−Zo−Dol−Qtz, Zo+Phe_1(Si~3.36 apfu)−Dol+Cal+Qtz		16
Blueschist Ma1	Marbles with HP relics	? Inclusions in Tr/Akt-cores Omph → Barr−Ab+Cal (±Di); Phe_1 → Phe_2(Si 3.1 apfu)	P, T uncertain	3
Greenschist Amphibolite Ma2	Marbles with HP relics	Tr(with relics of Omph Barr in core preserved)−Cal+Plag(Ab_{98})±Dol±Qtz±Zo±Phe_2	T ~ 530 (Cal/Dol)	4
	Siliceous dolomites	Ta−Tr_2(fine-grained)−Dol+Cal+Qtz±Zo±Chl	P = 8 - 15 kbar, a_{H2O} = 0.2-0.8	15
	Kyanite-Zoisite marbles	Ky−Dol−Phe_1−Zo → Chl+Ma+Pa+Cal+Phe_2	P = 3-10 kbar, T = 450-550°C	16

Table 1c

Summary of mineral assemblages, parageneses and P-T estimates for (impure) marbles of the Eclogite Zone (south-central TW). For references and mineral abbreviations see below and previous page.

Stage	Retrogressed eclogites of the Grossglockner area	Parageneses Textures Reactions	P, T estimates	Ref.
Pre-eclogite I	Relics in Grt-cores	magmatic Augit, Chromit, ?Ilm greenschist Act, Plag, Chl, Cal, Sph blueschist Act → Barr, primary Augit → Omph, Aegirine-Augit, Win/Glau	prograde greenschist facies (ocean floor ?) → blueschist facies: P ~ 6 kbar, T ~ 400 °C	20, 21
Eclogite II	retrogressed eclogites	Grt-Omph($Jd_{40-60}Ae_{5-20}$)-Pa-Glau-Zo-Qtz-Rt±Phe(Si = 3.3-3.43 apfu) ±Dol	P ~17 kbar, T ~ 570°C	21
		Grt: strong compositional hiatus between core ($Alm_{36}Py_4Gr_{31}Sp_{29}$), and rim ($Alm_{60}Py_{18}Gr_{21}Sp_1$) → natural diffusion couple allows to constrain time of metamorphism ~ 1 Myr and age of HP-event ~ 40 Ma	diffusion modelling → fast exhumation rates in the order of several cm yr^{-1}	22
late-eclogite III		growth of coarse-grained Barr	still in eclogite facies ?	20, 21
Blueschist		not clearly discernible in retrogressed eclogites		
Greenschist / Amphibolite IV	further eclogite retrogression and hydration	Omph → Sym(Cpx, Amph, Ab), Glau → Sym. rims: Pa+Ep−Mt around Grt, CZo around Pa, Cpx around Qtz, Rt → Ti-hematite → Sph fully hydrated Amph+Plag+Chl+Ep+Sph±Cal±Qtz	P = 5 - 6 kbar T = 500 - 530°C	21

Table 2

Summary of mineral assemblages, parageneses and P-T estimates for retrogessed eclogites of the Grossglockner area of the TW. For references and mineral abbreviations see below and previous page.

[1] References (Tables 1-2)

1 MILLER (1977), 2 HOLLAND (1979), 3 DACHS (1986), 4 DACHS (1990), 5 FRANK et al. (1987), 6 THOMAS & FRANZ (1989), 7 STÖCKERT et al. (1997), 8 HOSCHEK (2001), 9 HOSCHEK (2004), 10 KURZ et al. (1998), 11 ZIMMERMANN et al. (1994), 12 FRY (1973), 13 HÖCK (1974, 1980), 14 RAITH et al. (1977), 15 FRANZ & SPEAR (1983), 16 SPEAR & FRANZ (1986), 17 HOERNES & FRIEDRICHSEN (1974), 18 HOSCHEK (1982), 19 HOLLAND & RAY (1985), 20 PROYER et al. (1999), 21 DACHS & PROYER (2001), 22 DACHS & PROYER (2002), 23 RAITH et al. (1980)

[2] estimated from omphacitic pyroxene in Alpine HP-veins of garnet amphibolites from the Venediger Nappe (footwall of Eclogite Zone, Ref. 11)

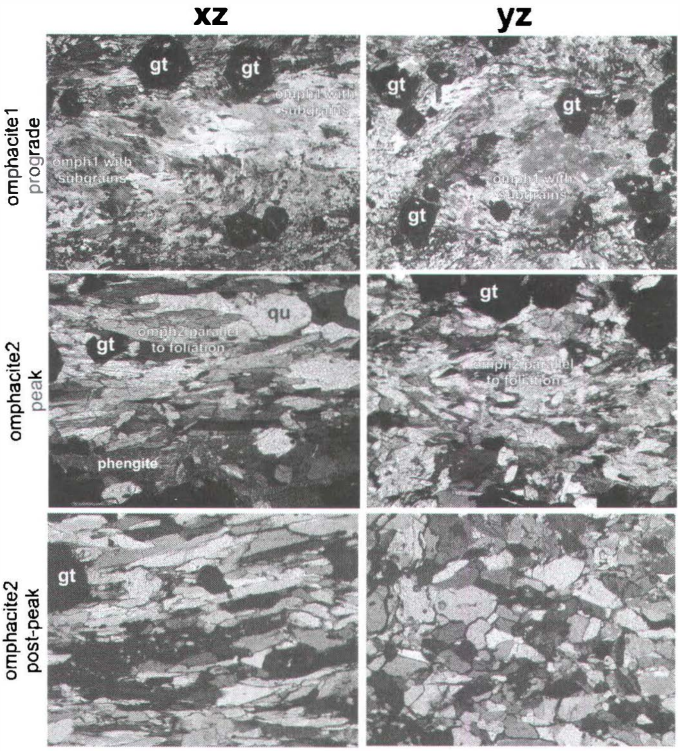

Fig. 3a

Representative microstructures of Eclogite Zone eclogites at distinct stages of pressure vs. temperature evolution (crossed polarizing filters; long axis of photographs represents ~4 mm; gt-garnet; qu-quartz).

Top: coarse-grained, weakly foliated eclogite, showing Omph1 with subgrains. Centre: Eclogite mylonite with remnants of Omph1, surrounded by fine-grained dynamically recrystallized Omph2. Bottom: Eclogite mylonite showing dynamically recrystallized Omph2 with shape preferred orientation in X-Z (left) and equigranular fabric in Y-Z (right).

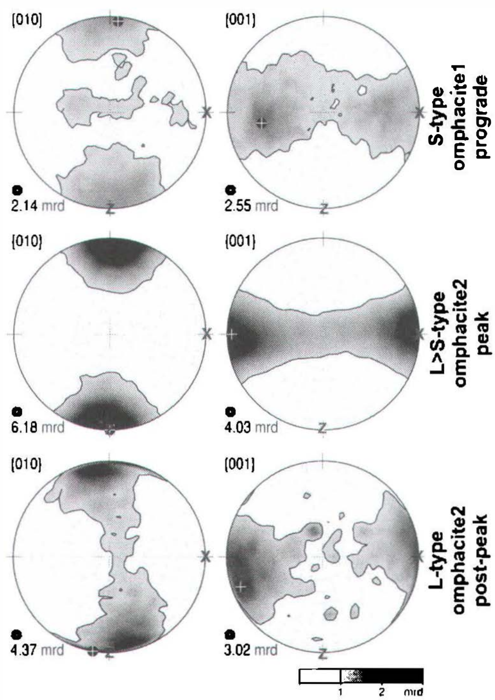

Fig. 3b

Representative crystallographic preferred orientations (CPO) of Omph at distinct stages of pressure vs. temperature evolution. CPOs have been analysed by neutron texture goniometry at Forschungszentrum Jülich (Germany). Recalculated pole figures {001},{010} describe orientation of the poles to the (001) and (010) omphacite planes, including the equivalent (00-1) and (0-10) poles. X marks trace of foliation and lineation; Y is at centre of pole figure, Z is vertical; lower-hemisphere equal-area projection; mrd-multiples of random distribution; white cross marks position of maximum.

Within the VN and GN of the western and eastern TW, peak pressures of up to 10-12 kbar have been evaluated for the blueschist event (SELVERSTONE et al., 1984, 1992; SELVERSTONE, 1993; CLIFF et al., 1985; DROOP, 1985; FRANK et al., 1987).
Within the basal GN of the Grossglockner area this phase of metamorphic overprinting is not clearly discernible in retrogressed eclogites (PROYER et al., 1999), but is evidenced by pseudomorphs after lawsonite and high-Si phengites in metabasites and calc-schists (HÖCK, 1974, 1980; FRANK et al., 1987).
Finally, the entire nappe pile was affected by Barrovian-type upper greenschist to lower amphibolite facies metamorphism ("Tauern crystallisation"), with peak conditions of ~ 7 kbar, 500-550°C in the EZ and RMN of the southern Großvenediger area (e.g. DACHS, 1990; Ma2 in Fig. 2) and 5-6 kbar, 500-530°C in the Grossglockner region (DACHS & PROYER, 2001; IV in Fig. 2). Corresponding mineral isograds run approximately parallel to the outline of the TW and are concentrically arranged, such that metamorphic grade increases from the periphery towards the interior of the window (see HOINKES et al., 1999 for further details and references).

In contrast to supposed Cretaceous ages, phengite $^{40}Ar^{39}Ar$ mineral ages between 32 and 36 Ma from the EZ (ZIMMERMANN et al., 1994) and of 38 Ma from the RMN (HANDLER et al., 2001; KURZ, unpublished data) are interpreted to represent cooling ages related to Eocene blueschist facies metamorphism (Ma1 in Fig. 2). Assuming a similar age for the blueschist event in the GN of the Grossglockner area, the diffusion modelling of DACHS & PROYER (2002) on a garnet overgrowth textures preserved in retrogressed eclogites indicates that the eclogite facies event in the TW (at least in the Grossglockner area) is not older than ~ 40 Ma. KÜHN et al., (this volume) report multi-mineral Rb/Sr ages for eclogites of 31.5 ± 0.7 Ma.
Alpine low-Si micas of all tectonic units, on the other hand, record younger ages < 27 Ma for the late cooling of the entire nappe pile (Ma2, IV in Fig. 2) with the youngest ages, down to 14 Ma, in the western and eastern TW (e.g. ZIMMERMANN et al., 1994; INGER & CLIFF, 1994).

3. Summary of the geodynamic evolution

The Eclogite Zone (Tauern Window, Eastern Alps, Austria) represents one of only a few examples of high-pressure units where both the prograde and the retrograde metamorphic evolution are documented. The eclogites are associated with rocks of continental origin and occur as layers and boudins on a scale of a few centimetres to several metres in thickness. The southward subduction of a single lithospheric slab, comprising the Penninic oceanic units in the south and the European margin in the north (represented by the Venediger Nappe Complex), resulted in nappe stacking within the Penninic units of the Tauern Window. After the consumption of the Penninic oceanic basin the European margin was incorporated into the subduction zone, which resulted in eclogite facies metamorphism in the Eclogite Zone and in the southern structural sections of the Rote Wand - Modereck Nappe. The Eclogite Zone ascended towards the surface and was emplaced on the subducted European margin, which is mainly exposed in the Venediger Nappe Complex. According to recently published geochronological data, this phase of continental collision and related Alpine high-pressure metamorphism and nappe stacking within the Penninic units is inferred to having occurred in the Paleogene (approximately 45-40 Ma) (KURZ et al., 2001). The main deformational phase related to nappe stacking occurred during the Eocene.

The change from flattening along the prograde path to constrictional strain at the pressure peak is interpreted to be controlled by the force balance between slab pull (related to a subducted oceanic slab) and the buoyancy of adjacent subducted continental crustal material in which the eclogites are included. At a certain lithospheric level the buoyancy forces related to the subducted continental part exceeded the externally applied slab pull forces related to the oceanic part. This is assumed to happen in an array where the subducted continental rocks are entirely surrounded by high-density lower crustal and upper mantle material, resulting in the buoyancy-driven extrusion of low-density continental material between two lithospheric plates (Fig. 4). That part of the subducted slab that is in buoyant equilibrium will therefore be affected by constrictional strain (KURZ, 2005).

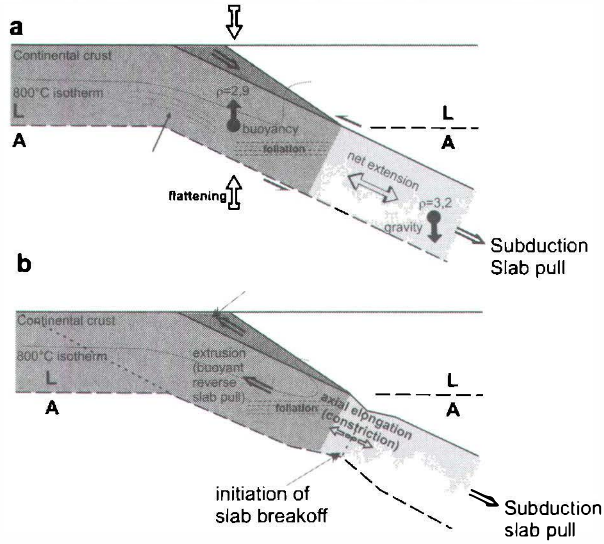

Fig. 4
Schematic cross section through a convergent plate margin showing qualitatively the force balance within the downgoing slab (a) and the mechanism of slab breakoff initiation with the related crustal deformation processes (b).

4. Excursion Locations

First Day

Itinerary: Seggau - Graz - Klagenfurt - Spital a.d.Dr. Mölltal Heiligenblut - toll road "Großglockner Hochalpenstrasse" Fuscher Törl Edelweißspitze Franz-Josefs-Haus Heiligenblut - Winklern - Iselsberg Pass - Lienz - Matrei - Virgental - Prägraten - Hinterbichl.
Object of excursion: Introduction to the geology of the TW, retrogressed eclogites in the Großglockner area.
Topographic maps: Österreichische Karte 1:50000, sheet 153, Grossglockner, Alpenvereinskarte Großglocknergruppe 1:25000 (published by Österreichischer Alpenverein).
Geologic maps: HÖCK, V. & PESTAL, G. (1994): Geologische Karte der Republik Österreich 1:50000, sheet 153, Grossglockner, Geologische Bundesanstalt Wien.
CORNELIUS, H. P. & CLAR, E. (1934): Geologische Karte des Großglocknergebietes 1:25000, Geologische Bundesanstalt Wien.
CORNELIUS, H. P. & CLAR, E. (1935): Erläuterungen zur geologischen Karte des Großglockner-gebietes 1:25000. Geologische Bundesanstalt Wien, 34 p.
GPS: GPS coordinates are given according to the grid UTM (WGS84).

Fig 5

Locations Edelweißspitze (1) and Gamsgrube (2) in the Großglockner area of the Hohe Tauern.

Location 1: Fuscher Törl (2404 m), RMN: geologic overview

The bus will be parked at Fuschertörl on the "Großglockner Hochalpenstrasse" and we intend to walk up to the Edelweißspitze (2580 m, GPS coord. 0335512/5221195) which will take us ~ 30 minutes (it is usually very windy there, so please take appropriate clothes and shoes with you). The main purpose of this stop is to get a first impression of the geology of the TW.

The huge dome-like structure of the TW can be seen to the north and, if the weather is clear, Zell am See, with its lake marking the northern border of the TW, is visible down in the Salzachtal valley. The white rocks further to the N already belong to the Northern Calcarous Alps of the Austroalpine Nappe Complex.

On the way up to Edelweißspitze we find yellowish dolomites, on the northern flank are outcrops of grey to light coloured quartzites and quartzitic schists intercalated with dark graphitic schists containing kyanite and chloritoid + chlorite. This flat lying sequence represents upper-Triassic sediments of the RMN (local name "Seidlwinkl-Trias") that underwent upper greenschist facies metamorphism (T around 500°C).

Location 2: Franz Josefs-Haus (2400 m), GN: retrogressed eclogites of locality "Gamsgrube"

(GPS coord. 0328388 / 5217240)

The area around Franz-Josefs-Haus is probably the most touristic place along the "Großglockner Hochalpenstrasse" because it is close to Austria's highest peak, the Großglockner (3798 m), and allows a visit of one of the largest glaciers in Austria (the "Pasterze"). We will leave the bus for ~1.5 hours and walk along the footpath to the Hofmannshütte (2444 m). This path was closed several years because of rock avalanches, but has recently been reconstructed and now runs through several tunnels for public safety.

The rocks encountered around Franz-Josefs-Haus are typical greenschists ("prasinites") of the GN (Ab/Ol, Chl, ± Act/Hbl, Ep, ± Bt ± Carb ± Sph ± Phe), that might contain rhombohedral aggregates of Czo+Chl (pseudomorphs after lawsonite). The prasinites dip moderately to steeply towards the southeast because we are already in the southern part of the metamorphic dome, and represent MORB-type oceanic crust (BICKLE & PEARCE, 1975; HÖCK & MILLER, 1980). The other main rock types of the GN along the path are brownish to grey calc mica schists ("Bündner Schists", Cal, Phe, Qtz, ± Dol ± Bt ± Zo ± Chl ± ore ± graphitic-pigment) with occasional bands of relatively pure marbles and garnet mica schists.

At the Gamsgrube location is a band of rather inaccessible eclogitic amphibolite with an average thickness of ~ 20 m, running from near Hofmannshütte along the steep slope due north towards Fuscherkarkopf (from 2400 m to over 3000 m). This band is underlain by graphitic garnet-micaschists and overlain by carbonaceous garnet-micaschists and greenschists of the Bündner Schist country rocks (PROYER et al., 1999). The early workers in the Großglockner area already recognized the eclogitic nature of these rocks and used the term "eclogitic prasinites" for them (CORNELIUS & CLAR, 1939).

Boulders of this rock type can be found directly above Hofmannshütte on the footpath from Hofmannshütte to Oberwalderhütte. The most striking feature in hand specimen is the fine-grained reddish garnet set in a dense dark green foliated matrix. STURM et al. (1997), PROYER et al. (1999) and DACHS & PROYER (2001) performed a detailed petrographical study on these retrogressed eclogites, revealing a four-stage metamorphic evolution with peak pressures of ~17 kbar and temperatures of ~570 °C, followed by the main greenschist/amphibolite facies event ("Tauerncrystallization") constrained at P = 5 - 6 kbar, T = 500 - 530°C (Tab. 2).
Some petrographic characteristics of the retrogressed eclogites from the Gamsgrube location are shown in Figs. 6a,b. Representative microprobe analyses of minerals from this and the following locations are given in Tab. 3.

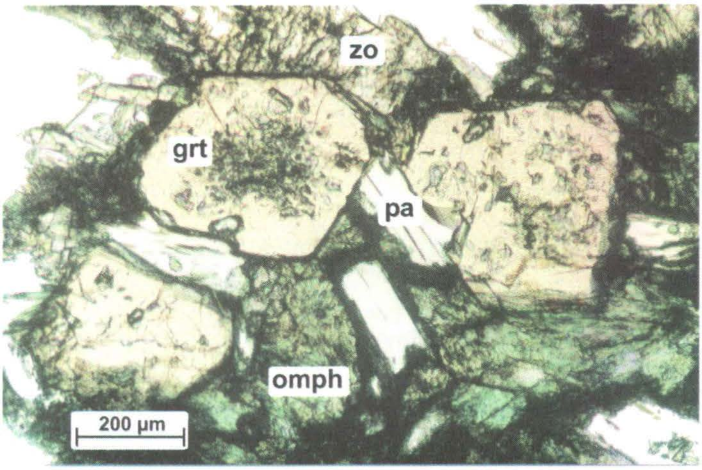

Fig. 6a
Eclogite paragenesis from Gamsgrube: garnet (grt), omphacite (omp), paragonite (pa) and zoisite. Additional dolomite, glaucophane, quartz and phengite are not within view. Dark areas show incipient breakdown to extremely fine grained symplectite.

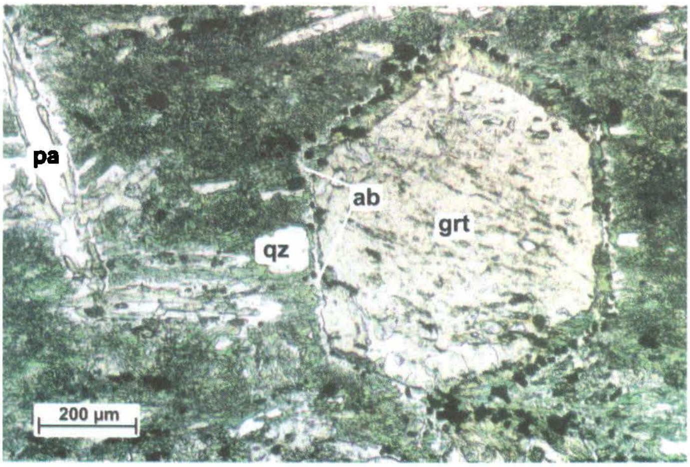

Fig. 6b
Gamsgrube: Replacement of idiomorphic garnet by polycrystalline rims of pargasitic amphibole + epidote (inner rim) and albite (ab) + magnetite (outer rim). Note the lack of corrosion of garnet along grain boundaries with matrix quartz (qz) and the light green rims of diopside around quartz grains. Paragonite (pa) is rimmed by clinozoisite and albite.

Another interesting feature found in this band of retrogressed eclogites was described by DACHS & PROYER (2001, 2002, their sample G5): the matrix assemblage in this rock is Grt + Omph + Pa + Glau + Zo/CZo + Phe + Dol + Qtz + Rt. The inclusion assemblage of Grt changes from core (Ep/CZo, Pa, Cal, Amph, Chl), where they are numerous and minute, to rim (CZo, Omph, Dol, Qtz), where they are few and coarse-grained (Fig. 7a).

The discontinuity in the inclusion texture, as visible under microscope, coincides with an abrupt change in chemical zoning, mainly in X_{Fe} and X_{Mn} from which times of diffusion can be calculated (Fig. 7b). Diffusion modelling on this overgrowth texture gave the fastest exhumation rates ever reported in the TW, of the order of several cm yr^{-1} (DACHS & PROYER, 2002).

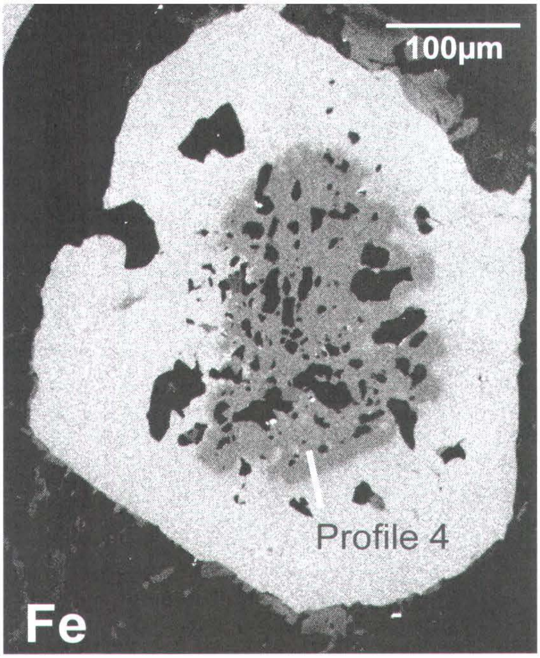

Fig. 7a
Eclogite garnet with discontinuous growth zoning from the Dorfertal.

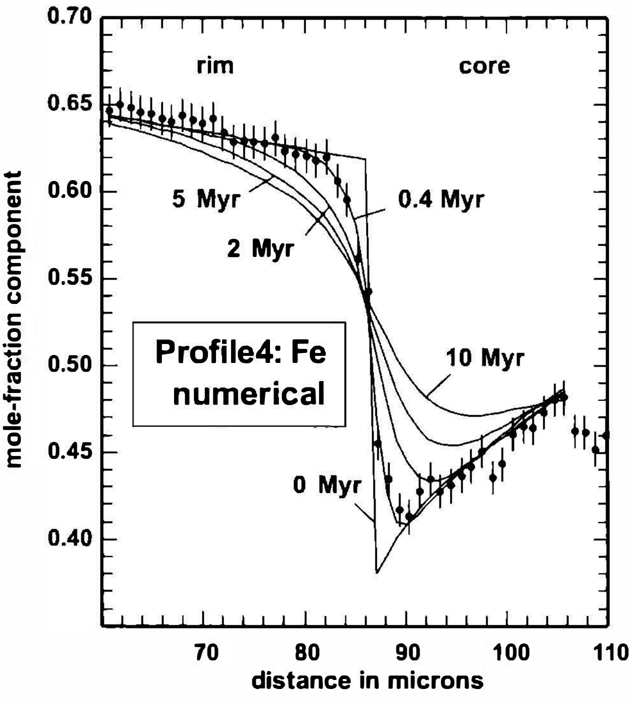

Fig. 7b
Result of numerical diffusion modelling for a detailed zoning profile for Fe, giving a best fit time span of 1.2 Ma from prograde growth of the eclogitic rim until diffusion closure at around 500°C during exhumation.

We return to the bus and continue the itinerary to Hinterbichl (~ 2 hours drive time), where accommodation will be provided.

Mineral	Location 2 retrogressed eclogites (GN)							Location 3 retrogressed eclogites (EZ)							Loc 4 marble with HP-relics (EZ)			
Mineral	Grt-c[1]	Grt-r	Omph	Phe	Pa	Glau	Dol	Grt-r	Omph-i-grt	Omph	Glau	Ep	Ky	Pa	Omph	Barr	Tr/Act	Ab
Stage	II	II	II	II	II	II	II	Ma0	Ma0	Ma0	Ma1	Ma0	Ma0	Ma0	Ma0	Ma1	Ma2	Ma2
SiO_2	37 42	37 7	56 08	51 58	47 51	57 72	0	38 77	55 91	55 83	57 56	38 19	36 75	48 87	55 35	53.94	56 34	67.84
TiO_2	0 22	0 09	0 05	0 17	0 04	0 03	0	0 01	0	0 049	0 06	0 14	0 013	0 12	0	0 02	0	0
Al_2O_3	20 75	20 72	9 8	27 96	38 63	11 43	0	22 03	7 81	9 89	10 31	25 34	62 38	37 87	7.82	6.64	0.61	19
Cr_2O_3	0	0	0	067	0	0	0	0 08	0 053	0 048	0 1	0 03	0 05	0 02	0	0	0	0
FeO	2296	28.54	8 49	2 43	0 55	8 13	10 91	22 96	12 17	8 92	8 57	10.14	0 91	1.09	4.93	4.29	5.2	0 11
MgO	1.22	1 8	6 37	3 52	0 36	11 06	15 6	9 71	5 91	6 84	13 51	0 35	0	0.15	11.85	20.53	22.69	0.07
CaO	11.74	9.42	11 23	0 16	0 14	0 89	29 91	5 09	9 13	10 31	1 9	22 52	0	0.24	14.92	8.18	12.44	0.22
MnO	5 30	1 05	0 11	0	0	0	0 39	1 2	0 2	0 097	0 06	0 13	0 01	0 01	0.06	0 02	0.26	0
Na_2O	0 04	0 02	7 56	0 65	7 21	6 8	0	0	9 32	8 66	6 02	0 02	0	7 37	5.24	4 16	0.05	11.79
K_2O	0	0	0	9 51	1 06	0 03	0	0	0	0	0 06	0	0	0 7	0 02	0.02	0.02	0.05
Total	99 65	99 34	99 69	96 65	95 5	96 09	56 81	99 85	100 5	100 64	98 15	97 99	100 21	96 44	100 19	97.8	97 61	99 1
Oxygens	12	12	6	11	11	23	2	12	6	6	23	12 5	5	11	6	23	23	8
Si	2 987	3.022	2 020	3 382	3 035	7 970	0	2 955	1 994	1 974	7 814	3 004	0 993	3 092	1.967	7.404	7.826	2.995
Ti	0 013	0 005	0 001	0 008	0 002	0 003	0	0 001	0	0 001	0 006	0 008	0	0.006	0	0.002	0	0
Al	1 952	1 957	0.416	2 160	2 909	1 860	0	1 979	0 328	0 412	1 649	2 349	1 987	2.823	0.327	1.074	0.100	0.989
Cr	0	0	0	0 035	0	0	0	0 005	0 001	0 001	0 011	0 002	0 001	0 001	0	0	0	0
Fe3	0 053	0	0 069	0	0	0 005	0	0 104	0 327	0 230	0 166	0 667	0 021	0	0.101	0.245	0.009	0.004
Fe2	1.480	1.913	0 187	0 133	0 029	0 934	0 282	1 359	0 036	0 034	0 807	0	0	0 058	0.045	0.248	0.595	0
Mg	0 145	0 215	0 342	0 344	0 014	2 277	0 718	1 103	0 314	0 361	2 734	0 041	0	0 014	0.628	4 201	4.699	0.005
Ca	1 004	0 809	0 433	0 011	0 010	0 132	0 990	0 416	0 349	0 391	0 276	1 898	0	0.016	0.568	1.203	1.851	0.010
Mn	0 358	0 071	0 003	0	0	0	0 010	0 077	0 006	0 003	0 007	0 009	0	0 001	0.002	0 002	0.031	0
Na	0 006	0 003	0 528	0 083	0 893	1 821	0	0	0 644	0 594	1 584	0 003	0	0904	0 361	1.107	0.013	1.009
K	0	0	0	0 795	0 086	0 005	0	0	0	0	0 010	0	0	0 056	0 001	0.004	0.004	0.003
Cations	8	8	4	6 95	7	15 01	2	8	4	4	15 06	7 98	3	6 97	4	15 49	15.13	5.02
X_{Fe}[2]	0.5	0.64	0 45	0 618	0 965	0 03		0 46	0 33	0 39	0 186			0 908	0.28	0.596	0.1	0.99
X_{Mg}	0 05	0 07	0 07	1 542	1 944	1 83		0 37	0 32	0 22	1 463			1.915	0.09	0.478	0	0.01
X_{Ca}	0 33	0 27	0 48			1 951		0 14	0 35	0 39	1 81				0.63	1.82	1.67	0
X_{Mn}	0.12	0 02				0 29		0 03			0 23					0.06	0.11	

Mineral	Loc 5 coarse-grained gabbroic eclogites (EZ)						Loc 8 fine-grained banded eclogites (EZ)						Loc 9 fine-grained boudinaged eclogites (EZ)						
Mineral	Grt-r	Omph1	Omph2	Pa	Parg-r-grt	Mg-Hbl-sy	Grt-r	Omph2	Pa	Glau	Hast-i-grt	Ed-sy	Grt-r	Grt-c	Omph1	Omph2	Pa	Barr	Mg-Hbl
Stage	Ma0	Ma0	Ma0	Ma0	Ma1?	Ma2	Ma0	Ma0	Ma0	Ma0	Ma0	Ma2	Ma0	Ma0	Ma0	Ma0	Ma0	Ma1?	Ma2
SiO_2	37 67	55 76	57 31	49 05	41 23	48 58	37 96	57 41	48 73	59 93	43 64	47 23	39 36	37 9	55 9	56.65	46.14	50.28	51.82
TiO_2	0 02	0 1	0 03	0 1	0 022	0 08	0 17	0 02	0 07	0 04	0 329	0 463	0 041	0 2	0.069	0 07	0.08	0.302	0 224
Al_2O_3	21.6	10 58	15 19	38 39	19 26	11 23	21 61	12 32	39 24	12 11	12 18	10 61	22 31	20 79	7.94	11 3	40.68	11.31	4.42
Cr_2O_3	0	0 43	0 12	0	0	0 015	0	0	0 08	0 015	0	0 036	0 068	0	0.024	0 08	0	0.047	0.012
FeO	29.02	4.49	2 03	0 13	13 09	6 23	25 61	2 45	0 15	3.89	13 95	10 39	24 76	21 02	7 91	3.03	0.45	12.24	12.44
MgO	2 64	8.17	6 93	0 26	9 43	17 31	4 97	7 93	0 11	13 94	13 04	15 49	6 8	4.03	8.81	8.96	0.32	12.46	15 46
CaO	8 19	12 74	9 78	0 17	10 28	11.5	8 09	11 53	0 3	1 14	11 36	11 3	7 69	9.22	13 19	12 88	0 15	7.35	12.8
MnO	0 89	0 02	0 04	0	0 26	0	1 4	0	0 02	0 005	0 078	0 107	0 357	6 96	0	0.04	0	0 078	0.26
Na2O	0 01	7 47	8 76	7 45	3 81	2 62	0 01	8 55	7 16	7 02	3 28	2 95	0 021	0 01	7 14	7 23	7.29	4.2	0.857
K2O	0 01	0	0 01	0 82	0 71	0 28	0	0 01	0 53	0 02	0 175	0 139	0	0	0	0	0.64	0.262	0 124
Total	100.05	9976	1002	96.37	98 092	97 845	9982	100 22	96 39	98 11	98 032	98 715	101 41	100 13	10098	100 24	95 75	98.529	98.417
Oxygens	12	6	6	11	23	23	12	6	11	23	23	23	12	12	6	6	11	23	23
Si	2 986	1 979	1.991	3.091	6.004	6 796	2 97	2 001	3 064	7.948	6.366	6 688	2.994	2.974	1.978	1.991	2.937	7 065	7.386
Ti	0 001	0.003	0 001	0.005	0.002	0.008	0.01	0.001	0.003	0.004	0 036	0 049	0.002	0.012	0 002	0 002	0.004	0.032	0.024
Al	2.018	0.442	0 622	2.851	3 305	1.851	1.993	0 506	2 908	1.893	2.094	1.771	2	1.923	0.331	0.468	3.052	1.873	0.742
Cr	0	0.012	0.0[illegible]3	0	0	0.002	0	0	0.004	0 002	0	0 004	0.004	0	0.001	0 002	0	0.005	0.001
Fe3	0 009	0.097	0	0	0 298	0 338	0 049	0 069	0	0 003	0 502	0 437	0.006	0.106	0.199	0.037	0	0.461	0.362
Fe2	1 915	0 036	0 059	0 007	1.296	0.391	1 626	0 002	0.008	0 429	1.2	0 793	1.569	1.274	0 035	0 052	0.024	0.977	1.121
Mg	0.312	0 432	0.359	0.024	2 047	3 61	0 58	0 412	0 01	2 756	2 836	3 27	0 771	0.472	0465	0.469	0.03	2.61	3.285
Ca	0 696	0.484	0 364	0 011	1.604	1.724	0 678	0 431	0 02	0 162	1 776	1 714	0.627	0 775	0.5	0 485	0.01	1.106	1.955
Mn	0 06	0 001	0 001	0	0 032	0	0 093	0	0 001	0 001	0 01	0 013	0.023	0 463	0	0.001	0	0.009	0.031
Na	0.002	0.514	0.59	0 91	1.076	0.711	0 002	0 578	0 873	1.805	0 928	0 81	0.003	0.002	0.49	0.493	0 9	1.144	0.237
K	0.001	0	0	0.066	0.132	0 05	0	0	0 043	0 003	0 033	0 025	0	0	0	0	0.052	0.047	0.023
Cations	8	4	3.99	6.97	15.8	15.48	8	4	6 93	15	15 78	15 57	8	8	4	4	7.01	15 33	15.17
X_{Fe}[2]	0.64	0.43	0.6	0 909	1.996	1.204	0.55	0.51	0 936	0.052	1.634	1.312	0.52	0.43	0.31	0.46	1.063	0.935	0.614
X_{Mg}	0 11	0 09	0	1.942	1.309	0 647	0 19	0 07	1.972	1.84	0 46	0.459	0.26	0.16	0.19	0.04	1.989	0.937	0.128
X_{Ca}	0 23	0 48	0.4		2	2	0.23	0.42		1.966	1.96	1.98	0.21	0.26	0.5	0.5		1.97	2
X_{Mn}	0.02				0 39	0 1	0 03			0 13	0 3	0 2	0.01	0.15				0.27	0.25

1) -c: core, -r: rim, i-grt: inclusion in Grt, r-grt: rim around Grt, -sy: in symplectite

2) X_{Fe}, X_{Mg}, X_{Ca}, X_{Mn} for Grt; X_{Jd}, X_{Ae}, X_Q for Omph; Al^{IV}, Al^{VI} for Phe and Pa; Al^{IV}, Al^{VI}, $(Ca+Na)_B$, X_{Fe} for Amph; X_{Fe} for Dol; X_{Ab}, X_{An}, X_{Or} for Plag

Table 3

Representative chemical analyses and formulas for minerals from locations 2, 3, 4, 5, 8 and 9.

Second Day

Itinerary: Using "Venediger Taxi" minibuses we will climb up from Hinterbichl to Dorfertal - Johannishütte (2121 m). After having viewed the locations here we will return to Hinterbichl around noon. After some refreshment and having picked up our equipment for staying overnight we will again use the "Venediger Taxi" and go to Prägraten - Bodenalm (1955 m). From here we will take the footpath to the Eisseehütte (2500 m) in Timmeltal (~ 2.5 hours walk), where we will stay overnight. Please be properly equipped for alpine conditions (mountain-boots, warm clothes, and gloves etc.).

Object of excursion: eclogite lenses and HP-metasediments of the EZ in the Dorfertal-section of the southern Großvenediger area; cross-section through lithologies of GN, RMN and EZ.

Fig. 8

Locations in the Dorfertal (3, 4) and the Timmeltal (5 - 9) of the Eclogite Zone.

Topographic maps: Österreichische Karte 1:50000, sheet 152, Matrei in Osttirol, Österreichische Karte 1:50000, sheet 151, Krimml, Alpenvereinskarte Venedigergruppe 1:25000 (published by Österreichischer Alpenverein).

Geologic maps: FRANK, W., MILLER, CH. & PESTAL, G. (1987): Geologische Karte der Republik Österreich 1:50000, sheet 152, Matrei in Osttirol, Geologische Bundesanstalt Wien.

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Geology along Dorfertal (from south to north)

Because the rocks dip steeply towards south, the route from Hinterbichl (1330 m) up to Johannishütte (2121 m) offers a cross-section from tectonically higher to tectonically lower units (from the GN, through RMN and EZ down to the upper VN - Fig. 2c). The metamorphic grade increases northwards accordingly from ~ 450°C in the area south of Hinterbichl to ~ 530°C in EZ and VN rocks at Johannishütte, as determined by calcite-dolomite geothermometry (DACHS, 1990) and phase relations in metasediments and metabasics (e.g. HOSCHEK, 1980; RAITH et al., 1977).

The steep flanks at the beginning of the valley are made up of a thick prasinite layer from the GN (Ab, Ep, Chl, Amph (act.Hbl-Barr), ± Bt ± Cal ± Qtz ± Phe ± Sph ± Pyr ± Mt; DACHS et al., 1991), which is quarried for building stone and as ornamental stone. The prasinites intercalate with brown-weathered calcareous schists (Cal/Dol, Phe, Qtz, ± Pl ± Chl ± Zo ± Grt ± Bt ± Tur ± Ap), with mainly tectonic contacts. Former pelitic horizons in these Bündner Schists are present as thin layers of (garnet-)mica schists (Phe, Qtz, ± Grt, Pa, Chl, Bt, Zo, Cal, Dol, Plag, Pyr). A large serpentinite body outcrops at 1760m, surrounded by brown calcarous mica schists, and is also quarried. At the contact with the Ca-rich metasediments a rodingite series is developed (grossular/andradite Grt, Di, Ep, Tr, Calc, Chl, etc., DIETRICH et al., 1986); along strike a number of such serpentinite bodies can be mapped and this tectonic horizon is considered to form the base of the GN in this area. The rocks underlying the RMN again comprise greenschists and calcareous mica schists similar to the GN, with a thin Permo-Triassic sequence at the base consisting mainly of quartzites or quartzitic schists (Qtz, Phe, Plag, ± Chl, Cal, Dol, Pyr) and marbles, with a maximal thickness of around 50m at Zopetscharte (Cal, Dol, Phe, Zo, Tr, Chl, Qtz). This unit rests upon mica schists and paragneisses (i.e. meta-arkoses: Plag, Kfs, Qtz, Phe, Bt, Chl, Zo/Ep) with some garnet amphibolites interfolded, which are considered to be the continental basement of the RMN (KURZ et al., 1996, 1998). Rocks of the tectonically deeper EZ, which has its maximal thickness further east in the Timmeltal, are tectonically reduced in the Dorfertal section to a small horizon crossing the valley north of "Ochsnerhütte" at around 2070 m (for further details see Locations 3 and 4). Mica Schists with aplitic veins and gneisses at Johannishütte (2121 m) and further north already belong to the upper parts of the VN.

Location 3: Dorfertal, close to Johannishütte (2121 m), EZ: Eclogite lenses and host rocks
(GPS coord. 0297995 / 5214990, 2380 m)

From Johannishütte we follow the footpath to Zopetscharte. After ~ 30 min walk, at a point just below 2480 m, the path crosses a band of outcrop approximately 30m high that consists of brown calcarous and grey quartzitic schists with, in places, dark lensoid bodies of garnet-bearing banded eclogites that usually have dimensions ranging from several metres to tens of meters. Boulders from these banded, boudinaged eclogites can be found further down along the path where blocks of more coarse-grained varieties also occur.

Microscopic investigation reveals a paragenesis of Grt + Omph + Phe + Ep + Amph + Pa + Qtz. Garnets are up to 2 mm in size, with a smooth bell-shaped prograde compositional zoning (Mn, Fe and Ca decreasing to wards the rim), and inclusion-rich: Epidote and paragonite predominate in the cores, sometimes forming rhomb-shaped pseudomorphs after lawsonite, and omphacite enters in towards the rims. The amphibole is a greenish-blue barroisite. Omphacite and epidote are mostly alligned to the strong foliation, amphibole and paragonite only to a lesser degree (Fig. 9).

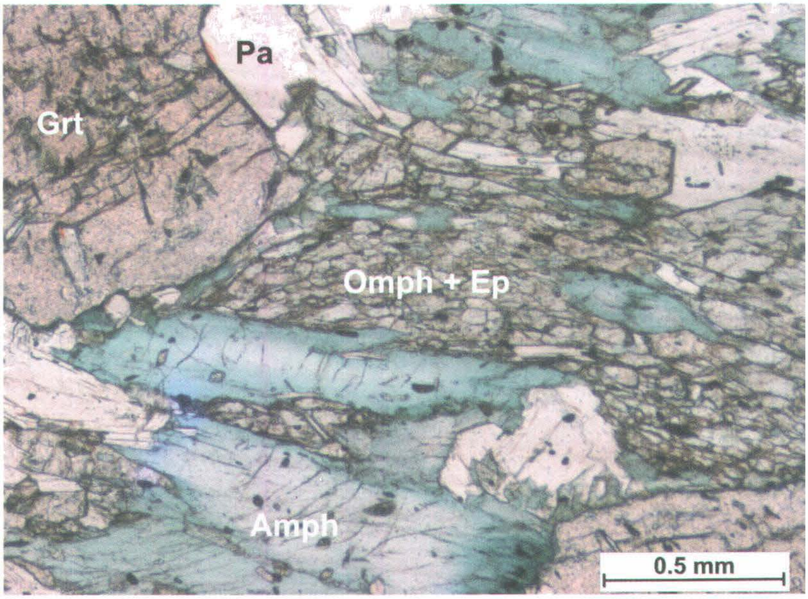

Fig. 9
Foliated eclogite from the Gastacher Wände, E of Johannishütte, with pale omphacite and epidote and bluish-green barroisitic amphibole.

Location 4: Dorfertal, EZ: Marble with Omph-relics
(GPS coord. 0297491 / 5214911, 2120 m)

About 250 m before Johannishütte along the eastern side of the road a thin marble outcrops within a sequence of mostly quartzitic schists. Following this marble layer along strike, a sequence of white carbonate-rich material is interfolded with dark-green amphibolitic material, crossing the river at 2090 m, where there is a little bridge with a footpath across it.

Under the microscope and as revealed by EMP-work. Cal, Qz, Tr are the main constituents and ± Tc-Zo-Dol-Chl-Phl-Sph can also be observed. That this marble experienced eclogite facies conditions can be inferred from the irregularly distributed brown symplectite patches (mainly fine-grained barroisitic Amph+Ab) that are always surrounded by pure albite rims. Omph is only rarely still present, either in the core of larger Tr-grains (in this case rimmed by Barr), or isolated in the Cal-rich matrix (then rimmed by Di). The omphacites preserved in Tr-cores were obviously decomposed in a two-stage process (DACHS, 1986):

$$\text{Omph} + H_2O + CO_2 \rightarrow \text{Barr} + \text{Ab} + \text{Cal} \quad \text{and}$$
$$\text{Barr} \pm \text{Cal} \rightarrow \text{Tr} + \text{Ab}$$

Third Day

Itinerary: From Eissehütte (2528 m) we will follow path 923 to Wallhorntörl (3045 m). In the area just below (Wallhornkar) will be the highest planned stop (Location 7). There will also be the possibility for interested colleagues to climb Weißspitze (3300m) which, however, requires some alpinistic skills. We will then return along path 923 and turn east to Eissee for the last stop at Location 9, before returning past Eisseehütte to Bodenalm where the minibuses will again pick us up and bring us down to Prägraten. From here back to Graz via Matrei in Osttirol, Lienz and Klagenfurt.

Object of excursion: eclogites and HP-metasediments of the central EZ in Timmeltal (Fig. 10)

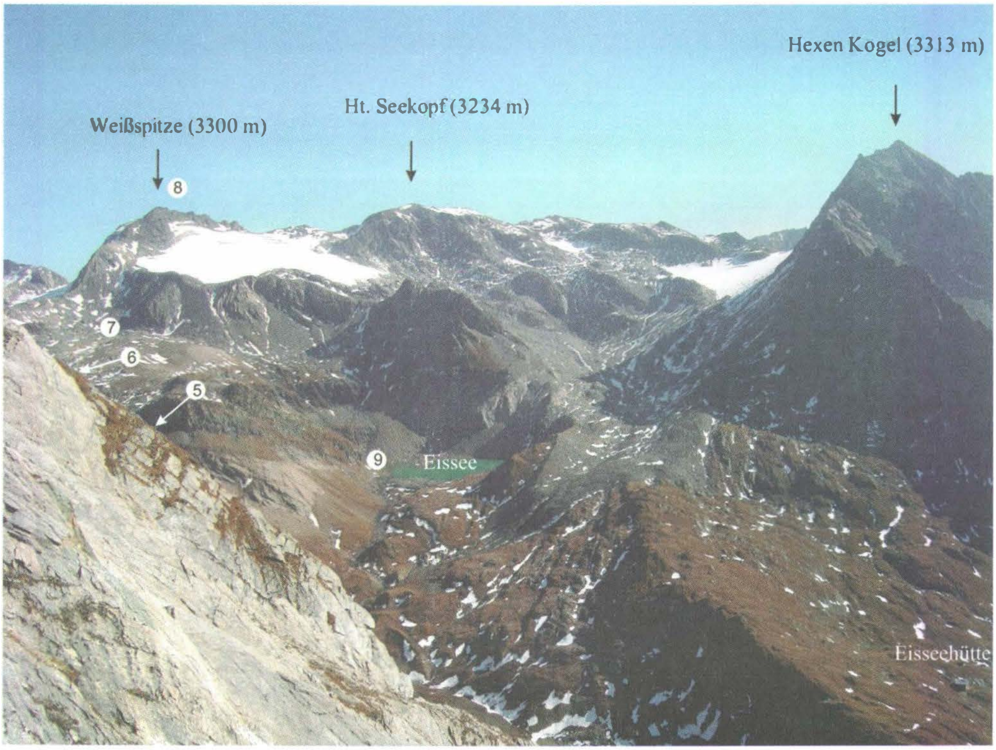

Fig.10

Central EZ of the upper Timmeltal with Eissee in the middle, seen from Zopetscharte (2958 m) looking towards the northeast. Eisseehütte (2500 m) is visible close to the lower right corner. The line marks the footpath. Numbers indicate the designated Locations (Locations 5 and 6 not in view). Light coloured rocks in the left foreground are a ~50 m thick marble (Permo-Trias of RMN), underlain by arkose-gneisses of Zopetspitze (3198 m).

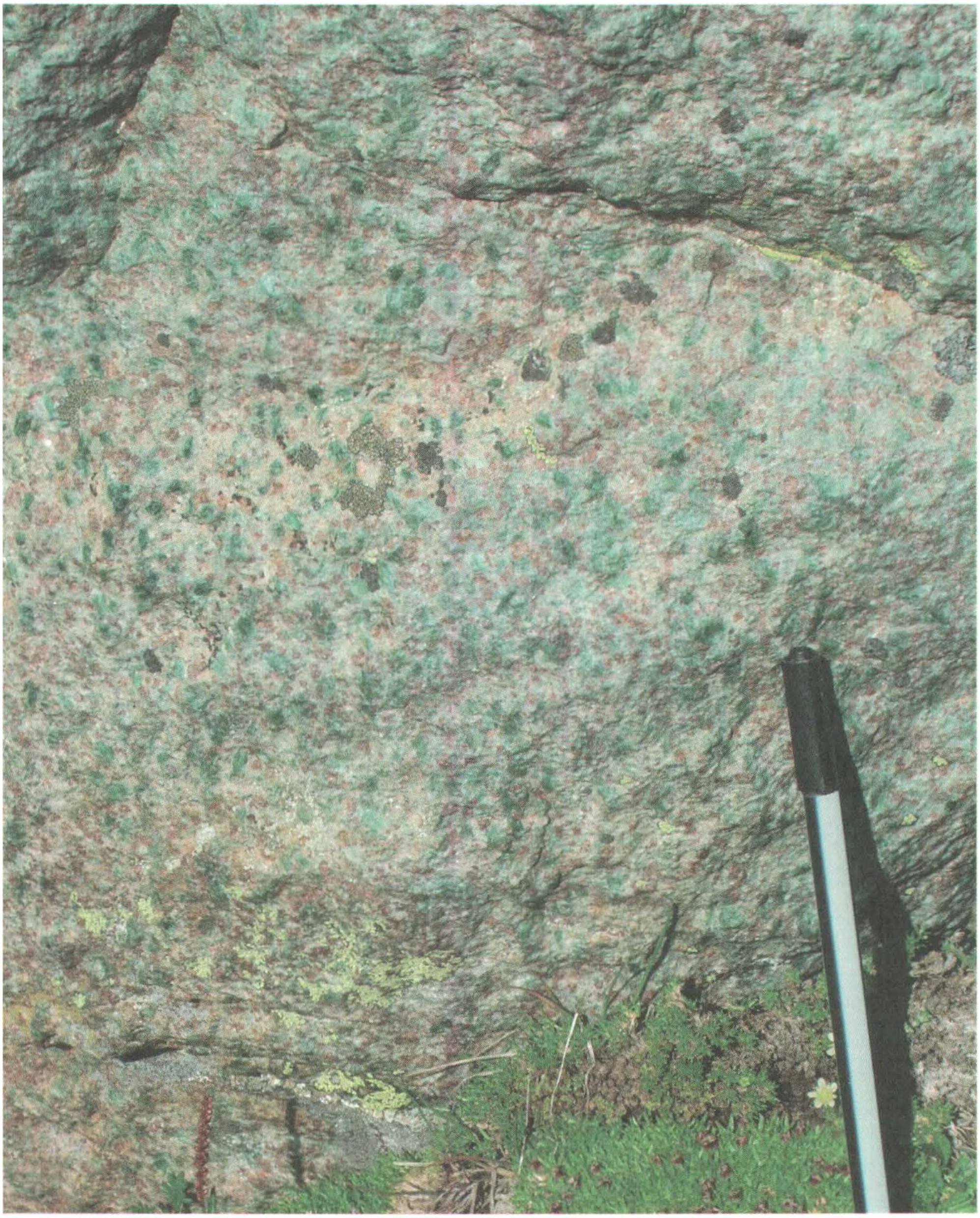

Fig. 11a

Large single grains of red garnet and green omphacite in a whitish matrix are typical features of the gabbroic eclogites of the Eclogite Zone.

Location 5: Upper Timmeltal: Coarse-grained gabbroic eclogites of the EZ (type E1, Tab. 1)
(GPS coord. 0300678 / 5215621, 2726 m)

The first stop along the footpath from Eissee to Weißspitze is a field of huge eclogite boulders (type E1 of MILLER, 1977) with spectacular coarse-grained omphacite crystals clearly discernible in hand specimen (Fig. 11a). The coarse grained omph I ($Jd_{44-52}Ae_{5-10}$, supposedly pseudomorphic after augite) shows dynamic recrystallization to a more jadeitic omph II ($Jd_{60}Ae_{0-2}$) along the margins, coexisting with garnet, paragonite, quartz and rutile, now embedded mainly in late stage symplectite (Fig. 11b). MILLER (1977) describes inclusions of talc and kyanite in the margins of garnets of this type, indicative of a prior metamorphic stage at pressures above the stability fields of paragonite (HOLLAND, 1979).

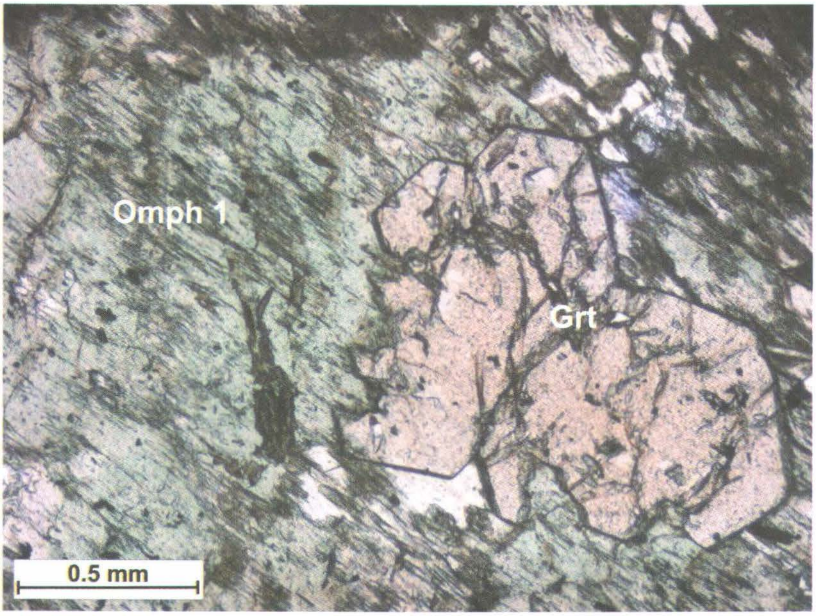

Fig. 11b Idiomorphic garnet intergrown with mm-sized grain of omphacite 1 in coarse grained gabbroic eclogite.

Location 6: Upper Timmeltal: Eclogite (micro)fabrics
(GPS coord. 0301012 / 5215945, 2862 m)

Syn-eclogitic deformation structures are difficult to reconstruct because the eclogites are often retrogressed to garnet-amphibolites and garnet-bearing greenschists during exhumation. The degree of retrogression of the eclogites is irregularly distributed, both within the Eclogite Zone and within individual eclogite bodies. Where the stretching and/or mineral lineation is defined by HP minerals (e.g. Grt, Omph, Ky, Glau), its orientation is variable in some places. A majority of mineral lineations, especially of Omph and Glau, dip to the S to SW. Associated sense-of-shear criteria indicate top-to-the north general shear. The variation of lineation orientations may be related to variable rotation of eclogite slices and boudins during later greenschist to amphibolite facies deformation. The penetrative eclogitic foliation, generally oriented subparallel to principal tectonic contacts, is transposed subparallel to the penetrative mylonitic foliation formed

under amphibolite facies metamorphic conditions. In general the foliation strikes east-west and dips to the south. This foliation is defined by the subparallel arrangement of actinolitic Hbl, Ep, Chl and locally Bt, and is also associated with a well-developed, E-trending, subhorizontal stretching lineation, defined primarily by actinolitic Hbl and Plag. In metapelites and meta-carbonates, the foliation orientation is close to that of the shear planes (C). It is transected by C´ and to a lesser extent by C´´ shear bands at scales of centimetres, decimetres and metres. These sense-of-shear indicators (shear bands and extensional crenulation cleavage) document top-to-the W displacement related to the exhumation of the Penninic nappe stack under amphibolite to greenschist metamorphic conditions.
The whole lithological sequence is affected by E-trending isoclinal folds (Fig. 12) and subsequently by open to tight E-W striking folds with subhorizontal axes. A final deformation is documented by km-scale (map-scale) N-trending open folds.

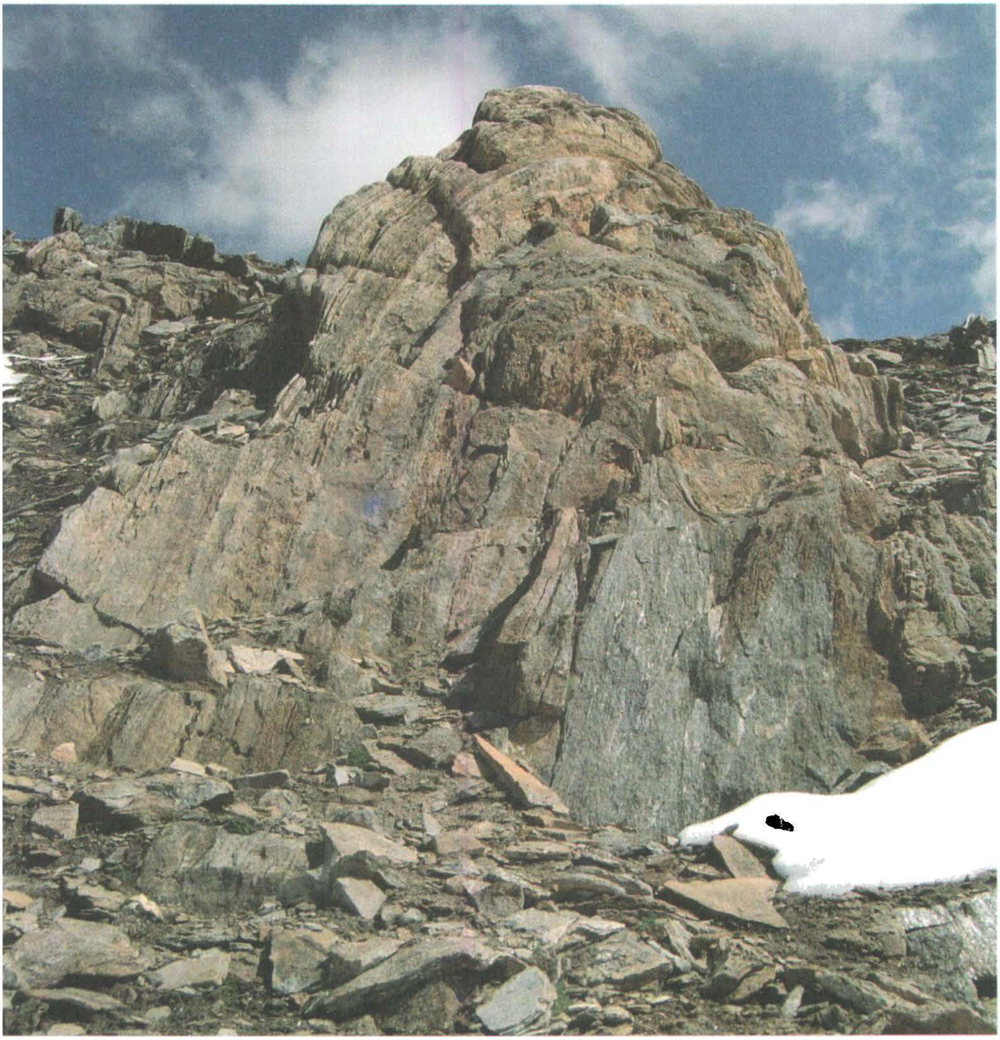

Fig. 12
Folded eclogitic metasediments near the Wallhornkar.

Location 7: Upper Timmeltal (Wallhornkar): Various eclogite types of the EZ , HP veins and sediments
(GPS coord. 0301451 / 5216381, 2950 m)

The area below the Wallhorn Törl (3060m) exhibits a profile through a metasedimentary sequence of garnet amphibolites (retrogressed eclogites), marbles, calc-schists, garnet-micaschists and quartzites with relict HP-minerals (see DACHS 1986, Tab. 4, Fig. 13). This evidence shows that the entire Eclogite Zone (eclogites and the intercalated metasediments) have been subject to high-pressure metamorphism.
Adjacent to the outcrops, moraine material also contains blocks of eclogite with kyanite-omphacite-quartz-rutile veins, similar to those that we will find higher up at the summit of the Weißspitze.

Profile [m]	Description
0	strong retrogressed eclogite, Omph+Grt largely decomposed, dark green parts (Barr, Amph, Plag, Chl, Zo, Rt, Il, Mt,±Phe-Bt-Pa) irregularly mixed with bright-green zones (Ep, Plag, Amph, Bt, Phe, Carb)
34	brown weathered, strongly foliated graphitic Grt-mica schist (Grt, Phel/2, Qtz, Chl, Pa, Zo, Cal, Dol, Ap, Rt, Gr)
43	amphibolite, in places with Grt
48	alternating bands of dark Grt-mica schists (Grt, Phe, Zo, Qz, Bt, Rt, Sph, Ap, Gr) and bright brownish calcarous-mica schists with quarzitic layers; s 185/45
53	coarse-grained Grt-amphibolite (Barr with Glau-cores, Grt with Omph inclusions, Plag, Chl, Bt, Pa, Phe, Qtz, Zo, Rt. s 176/60
62	yellow-brownish quartzite with limonite
63	concordant Grt-amphibolite
66	brown calcarous mica schist with cm-thick layers of Grt-mica schist. Late veins with Qtz, Fsp, Zo
67	s-parallel intercalated Grt-amphibolite (Grt, Amph, Plag, Chl, Phe, Sph)
85	bright-grey to yellowish strongly foliated Grt-mica schist (Grt, Qtz, Phe, Pa, Plag, Chl, Bt, Act, Tc, Rt, Sph) with s-parallel Qtz-veins
85.7	5 cm thick Grt-amphibolite band intercalated
86	dark-grey Grt-mica schists with Omph-relics (Grt, Phel/2, Tc, Pa, Zo, Ky, Qtz, Plag, Chl, Bt, Omph, Sym, Ma, Cal, Rt, Ap)
86.7	brown, limonite-pigmented quartzite
88	strongly retrogressed eclogite (Grt, Omph, Sym, Amph, Phe, Chl, Bt, Zo/Ep, Rt)
91.5	yellowish, quartzitic Grt-mica schist with Qtz-veins (Grt, Phe, Qtz, Plag, Pa, Chl, Bt, Rt, Sph). Grades into a Zo-quartzite (Qtz, Phe, Zo, FeS).
91.8	retrogressed eclogite (Grt, Omph, Sym, Plag) partly transformed to amphibolite (Amph, Plag, Phe, Pa, Chl, Tc, Zo/Ep, Qtz, Cal, Dol)
92.1	yellowish calcite marble
92.4	bright quartzitic Grt-mica schist with Qtz-veins. Grades into
92.9	white quartzite (Qtz, Phe, Zo, FeS). Without tectonic contact follows a (Fig. 10)
93.1	strongly retrogressed eclogite (Omph, Grt, Sym, Zo/Ep, Amph, Phe, Chl, Plag, Qtz)
93.4	bright quartzite
93.7	Qtz-bearing Cal/Dol-marble (Cal, Dol, Qtz, Tr, Zo, Chl, Plag)
95	brownish calc-mica schist with more pure carbonate layers
96.3	Ky-bearing, Grt-mica schist with Carb and Zo (Phel/2, Zo/Ep, Chl, Grt, Ky, Qtz, Ab, Cal, Dol, Rt, Il, FeS) grading into a
97	Cal-marble with Omph-relics (Cal, Phe, Zo, Tr, Tc, Chl, Qtz, Omph, Di)
97.7	Grt-amphibolite
98	Cal-marble, grading into a
99.3	Ky-Zo bearing Grt-mica schist (Grt, Phe, Zo, Qtz, Ky, Pa, Ma, Bt, Rt, Ap) with Qtz-veins
101	calc-mica schist with layers of pure Cal-marble
103	quartzitic, brown-weathered Grt-mica schist with Grt up to 2 cm in size and s-parallel layers of green Grt-amphibolite
105.5	bright quartzitic mica schist without Grt
109	dark graphitic Grt-mica schist
109-133	quartzites, quartzitic and graphitic mica schists, calcarous schists with layers of Grt-amphibolite

Table 4
Detailed lithological profile across a sequence of more or less strongly retrogressed high-pressure metasediments in the Wallhornkar; from DACHS (1986).

Fig. 13

Meters 92.1 (right) to 95 (left) from the metasedimentary sequence in the Wallhornkar (Table 4).

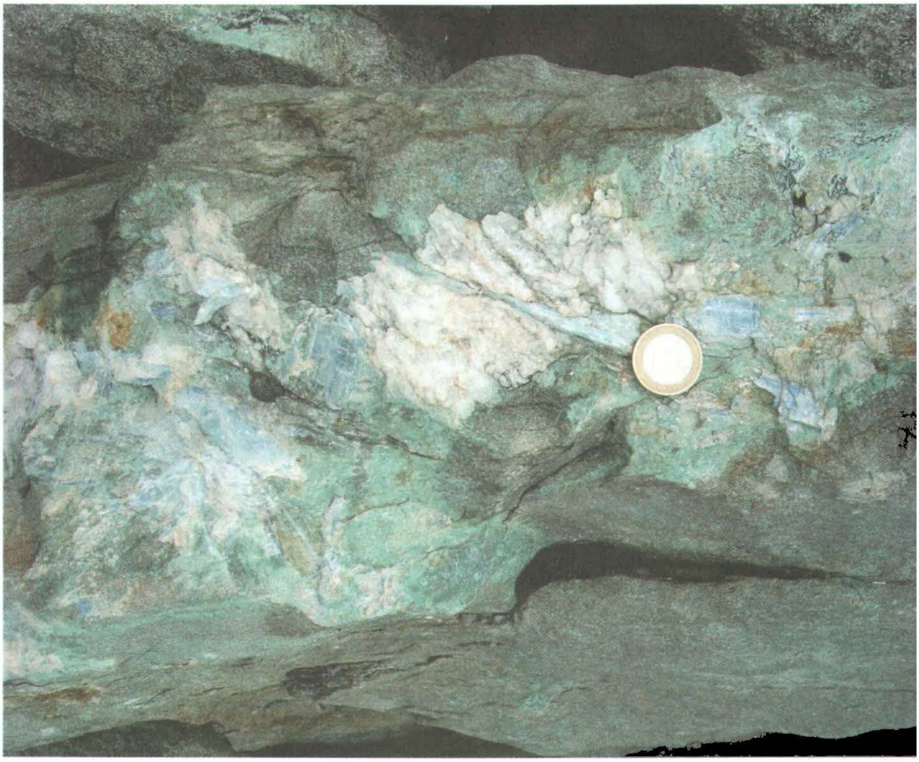

Fig. 14
Kyanite-omphacite-quartz-seggregation in eclogite from the Weißspitze.

Location 9: Upper Timmeltal (Eissee): Eclogite-boudins/Edelweiß
(GPS coord. 0301357 / 5215748, 2681 m)

The towering rock masses north of the Eissee consist of strongly boudinaged banded e (Fig. 15) with a paragenesis of Omph + Grt + Glau + Pa + Ru + Qtz. Greenish actino some albite form along cataclastic veins.

Along the eastern shore of lake Eissee, eclogite boudins are exposed in a matrix of mylonite, calcareous micaschists and metapelites. Symmetrically boudinaged eclogite locally document pure shear deformation as well as strain partitioning during deformatio amphibolite facies metamorphic conditions.

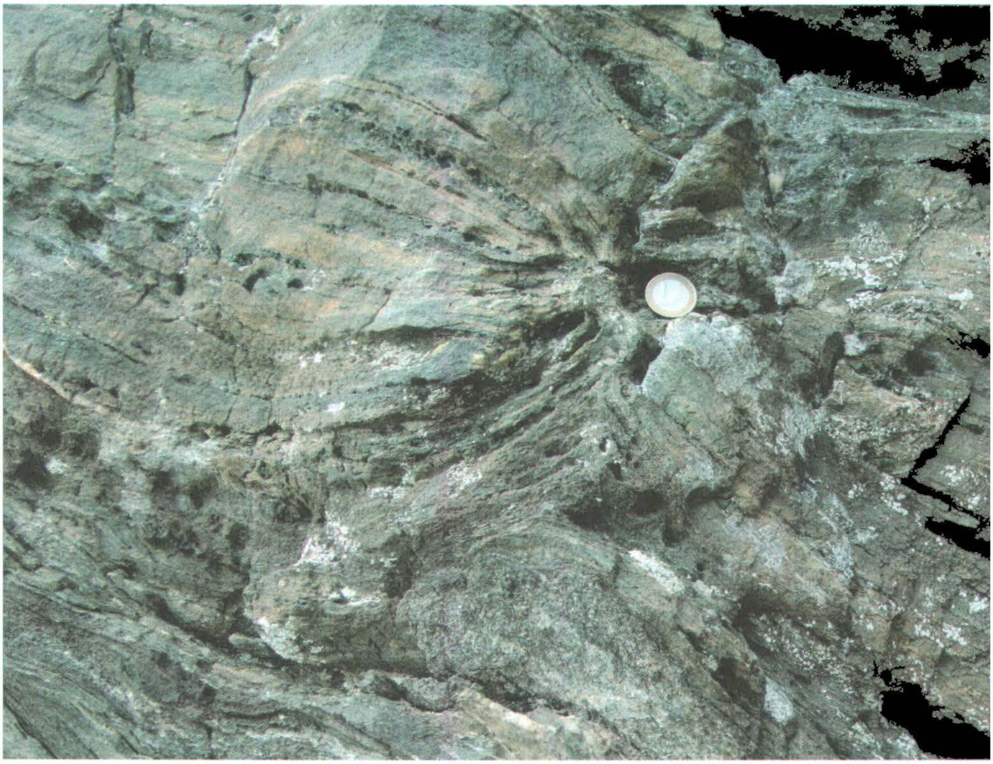

Fig. 15
Foliated and boudinaged eclogite from north of Eissee.

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ECLOGITES FROM THE KORALPE AND SAUALPE TYPE-LOCALITIES, EASTERN ALPS, AUSTRIA

by

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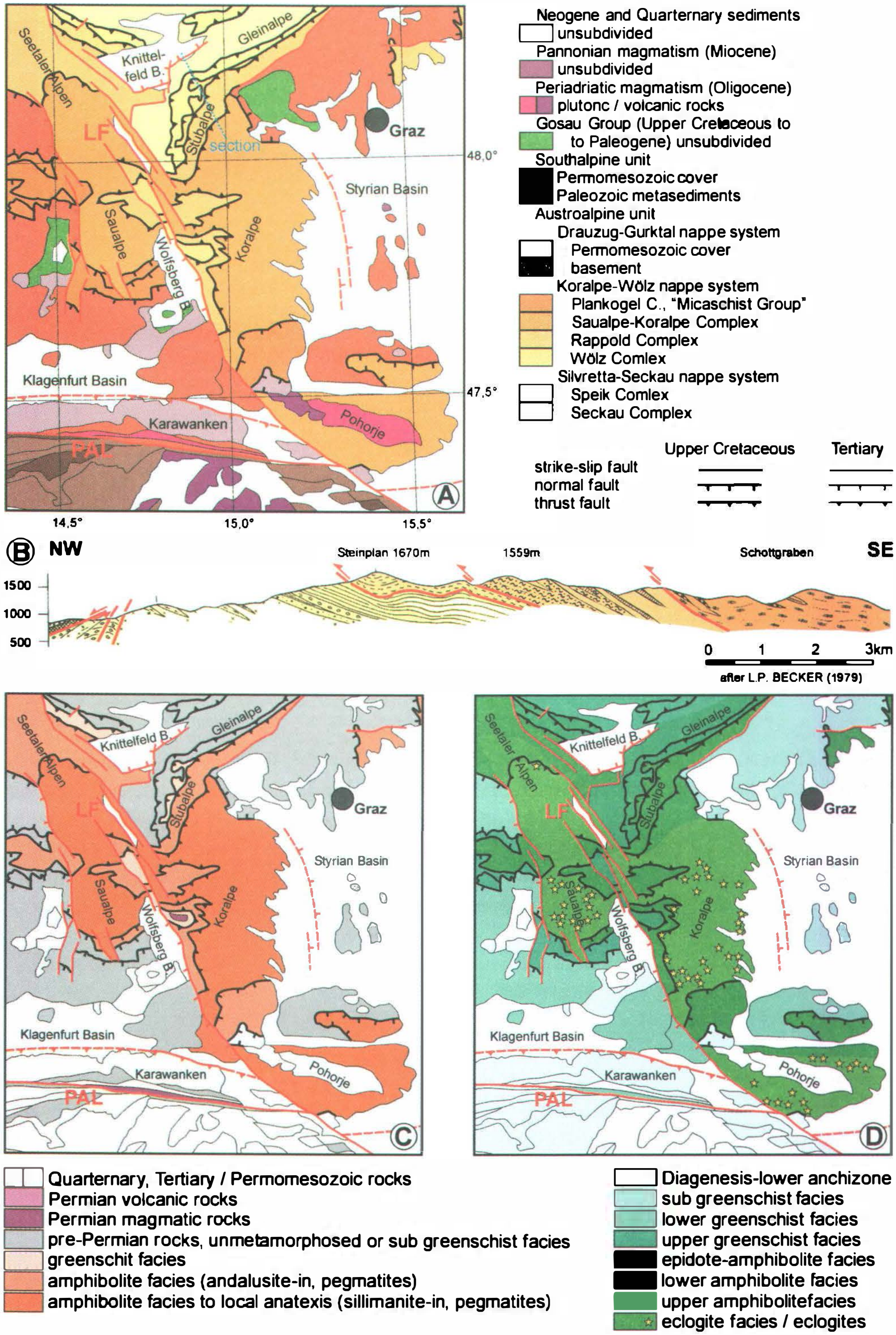
1. Geology of the Saualpe-Koralpe region

The area of interest is located in the Carinthia and Styria districts of Austria. Geographically it is dominated by two approximately N-S oriented mountain ridges: (i) the westerly ridge of the Saualpe and Seetaler Alps and (ii) the Koralpe and Stubalpe ridge that continues north-eastwards into the Gleinalpe and south-eastwards into the Pohorje Mountains. These two ridges are separated by the Lavant valley. The terrain morphology is characterized by valleys and basins at altitudes between 500 and 700 m, and by gently sloping mountains up to 2150 m high. Outcrops are few and restricted to rocky cliffs ("Öfen"). The area is bordered to the east by the Styrian basin, to the north by the Knittelfeld basin, to the southeast by the Klagenfurt basin and to the west by the Gurktaler Alps.

Tectonically the Saualpe-Koralpe region is an assembly of Austroalpine units (part of the Apulian microplate) with medium to high-grade metamorphic units, low-grade Paleozoic units with remnants of unmetamorphosed transgressive Permotriassic sediments in places, and unmetamorphosed Upper Cretaceous sediments. According to the nomenclature of SCHMID et al. (2004), this area forms part of the Upper Austroalpine unit and can be subdivided in several genetically linked nappe systems. These nappe systems are described below from north to south and from bottom to top with respect to their lithological content and their metamorphic history (Fig. 1, and Fig. 4 of SCHUSTER & KURZ, this volume).



Seetaler Alpen
Knittel-feld B.
Gleinalpe
Stubalpe
section
Graz
LF
Saualpe
Wolfsberg B.
Koralpe
Styrian Basin
Klagenfurt Basin
Karawanken
Pohorje
PAL
48,0°
47,5°
14,5°
15,0°
15,5°
A
Neogene and Quarternary sediments
unsubdivided
Pannonian magmatism (Miocene)
unsubdivided
Periadriatic magmatism (Oligocene)
plutonc / volcanic rocks
Gosau Group (Upper Cretaceous to
to Paleogene) unsubdivided
Southalpine unit
Permomesozoic cover
Paleozoic metasediments
Austroalpine unit
Drauzug-Gurktal nappe system
Permomesozoic cover
basement
Koralpe-Wölz nappe system
Plankogel C., "Micaschist Group"
Saualpe-Koralpe Complex
Rappold Complex
Wölz Comlex
Silvretta-Seckau nappe system
Speik Comlex
Seckau Complex
Upper Cretaceous
Tertiary
strike-slip fault
normal fault
thrust fault
B
NW
Steinplan 1670m
1559m
Schottgraben
SE
1500
1000
500
0
1
2
3km
after L.P. BECKER (1979)
C
D
Quarternary, Tertiary / Permomesozoic rocks
Permian volcanic rocks
Permian magmatic rocks
pre-Permian rocks, unmetamorphosed or sub greenschist facies
greenschit facies
amphibolite facies (andalusite-in, pegmatites)
amphibolite facies to local anatexis (sillimanite-in, pegmatites)
Diagenesis-lower anchizone
sub greenschist facies
lower greenschist facies
upper greenschist facies
epidote-amphibolite facies
lower amphibolite facies
upper amphibolitefacies
eclogite facies / eclogites

Fig. 1a, b
Tectonic map of the Saualpe-Koralpe-Pohorje area (a) and section in the northern part (b).
Fig. 1c, d
Maps showing the distribution of the Permotriassic (c) and eo-Alpine (d) metamorphic grades in the Saualpe-Koralpe-Pohorje area.

1.1. Lithological content and metamorphic history

The *Silvretta Seckau nappe system* (Seckau and Speik Complexes) is composed of paragneisses, migmatic paragneises, hornblende gneisses and amphibolites, of partly metavolcanic origin. Up to kilometre sized ultramafic bodies are locally present and eclogites are known from the northernmost part of the system; granitic intrusions of pre-Variscan and Variscan age also occur (FLÜGEL & NEUBAUER, 1984; NEUBAUER, 2002). Permo-Scythian transgressive sediments are preserved along the northern margins. Geochronological ages of the medium to high-grade metamorphism are Variscan (Upper Devonian to Carboniferous) (SCHARBERT, 1981; FARYAD et al., 2002), and the eo-Alpine overprint reached upper greenschist facies.

The overlying *Koralpe-Wölz nappe system* (Wölz, Rappold, Saualpe-Koralpe, Plankogel Complex and "Micaschist Group") has garnet-bearing micaschists and mostly mylonitic, kyanite-bearing paragneisses as its major lithologies, with intercalations of marbles, amphibolites, eclogites (only in the Saualpe-Koralpe Complex) and quartzites. Pre-Variscan and Variscan magmatic rocks have not yet been documented but granitic gneisses, (meta)gabbros, and partly spodumene-bearing meta-pegmatites with Permian intrusion ages are known to occur (GÖD, 1989; MILLER & THÖNI, 1997; THÖNI & MILLER, 2000; SCHUSTER et al. 2001). Permo-mesozoic sediments are absent. The Koralpe-Wölz nappe system is polymetamorphic, with a Permotriassic low-P/T imprint and an eo-Alpine high-P/T overprint. A prior amphibolite facies regional metamorphism of Variscan age is proven, at least for the Rappold Complex. Permotriassic as well as eo-Alpine P-T conditions increase upwards in the lower part of the nappe system and then decrease again (GREGUREK et al., 1997; SCHUSTER et al., 2004). Upper amphibolite facies conditions have been reached within the central Saualpe-Koralpe Complex in Permian times (0.38 GPa and 590 °C at 250-270 Ma; HABLER & THÖNI, 2001), and eclogite facies (2.4 GPa and 650-730°C at approximately 90-95 Ma; MILLER, 1990; MILLER et al., this volume) as well as subsequent amphibolite facies conditions have been determined for the eo-Alpine event.

Some types of paragneisses contain kyanite aggregates which can, within the less deformed rocks, be identified as pseudomorphs after (Permian) andalusite and sillimanite. The most spectacular rocks of this type, called "Paramorphoseschiefer", exhibit large idioblastic pseudomorphs after chiastolitic andalusite measuring up to 50 cm. The mylonitic, kyanite-bearing gneisses of the Saualpe region are called "Disthenflasergneisses" The "Plattengneiss", a blastomylonite of up to 700 m thickness, is a major element in the Koralpe and is composed of kyanite-bearing paragneisses and interlayered pegmatite gneisses. Meter to kilometre-sized lenses of eclogite, eclogite-amphibolite and (meta)gabbros occur within the paragneisses.

Discordant pegmatoids formed preferentially adjacent to this rigid rock type (NEUBAUER, 1991) during decompression after the eo-Alpine pressure peak.

The *Drauzug Gurktal nappe system* (Gurktal Nappe, Graz Paleozoic, North Karawanken) is mainly formed by anchizonal to greenschist facies Paleozoic metasedimentary sequences and by unmetamorphosed Permotriassic sediments (RANTITSCH, G. & RUSSEGGER, B., 2000).

The Southalpine unit follows to the south of the Periadriatic Lineament and is composed of anchizonal to greenschist facies Paleozoic metasediments and unmetamorphosed Permotriassic sediments.

The eo-Alpine nappe stack is discordantly overlain by Cretaceous, mostly clastic sediments of the Upper Cretaceous Gosau Group (Krappfeld, St. Paul and Kainach Gosau). Oligocene plutonic and volcanic rocks related to the Periadriatic magmatism occur in the Pohorje area.

1.2. Geodynamic and tectonic evolution

The *Silvretta-Seckau nappe system* is an external part of the Austroalpine unit with respect to the eo-Alpine subduction zone (SCHUSTER & KURZ, this volume). As a result of only greenschist facies metamorphic overprinting, pre-Alpine structures are well preserved in the northern part of this system whereas a penetrative ductile eo-Alpine deformation prevails in the southern part (FRANK, 1987).

The *Koralpe-Wölz nappe system* is interpreted as an extrusion wedge (SCHMID et al. 2004) that developed during the E-SE directed subduction (RATSCHBACHER, et al. ,1989) until 9095 Ma (THÖNI, 2002) and the subsequent exhumation from the internal part of the Austroalpine unit. Exhumation was characterised by penetrative deformation of the whole nappe system by NW-directed thrusting in the lower part of the wedge (KROHE, 1987) and SE-E directed extensional deformation in its upper part (KURZ et al., 2002). These post-peak metamorphic tectonics caused an inversion of the metamorphic grade in the lower part of the nappe system (Fig. 4, SCHUSTER & KURZ, this volume).

Sm-Nd garnet ages on eclogites from the Saualpe, Koralpe and Pohorje areas are in the range of 108-87 Ma (THÖNI, 2002). K-Ar and Ar-Ar muscovite ages are 85-90 Ma in the northern part of the nappe system (Gleinalpe-Stubalpe region), about 75 Ma in the central part (Saualpe-Koralpe region) and around 18 Ma in the Pohorje area to the south (MORAUF, 1982; SCHUSTER et al., 1999; FODOR et al., 2002). The same trend, with somewhat younger ages, is also shown by Rb-Sr data on biotites. Apatite fission track data from the Koralpe region are in the range of 35 to 40 Ma (HEJL, 1997), whereas about 11 Ma was measured from Pohorje (FODOR et al., 2002). These geochronological data indicate a maximum burial of the Saualpe-Koralpe Complex in the Cenomanian and Turonian, followed by rapid exhumation in the Coniacian and Senonian. From the Campanian to the middle Eocene the Koralpe area was affected by slow exhumation and cooling whereas the Pohorje area remained at much greater depths until the Miocene, when it was rapidly exhumed.

The history of the Drauzug-Gurktal nappe system indicates that it was part of the eo-Alpine tectonic upper plate (SCHMID et al., 2004). It shows an upward decrease of the eo-Alpine metamorphic grade until reaching diagenetic conditions in the Permomesozoic sediments at the top, indicating that it has not been buried since Permian times. It was affected by thrusting in the Lower Cretaceous (FRITZ, 1988; DALLMEYER et al., 1998), whereas in the Upper Cretaceous it was affected by ductile extensional deformation and normal faulting (NEUBAUER et al., 1995), as for the upper part of the Koralpe-Wölz nappe system. The extensional deformation led to the formation of basins and the deposition of the Gosau Group sediments, which are Santonian to Paleogene in age (e.g. EBNER & RANTITSCH, 2000). The formation of these sedimentary basins is also linked to the rapid exhumation of the eclogite bearing unit (KURZ & FRITZ, 2003).

Subsequent exhumation of the underlying Penninic and Sub-Penninic nappes within windows (GENSER & NEUBAUER, 1989; FÜGENSCHUH et al., 1997) and lateral extrusion of the orogene in the Miocene (RATSCHBACHER et al., 1989) generated a system of normal and strike slip faults. These faults have a major influence on the recent morphology and are responsible for the exhumation of the Saualpe-Koralpe Complex in the Pohorje region. The Styrian, Knittelfeld and Klagenfurt basin developed along these faults. The major strike-slip faults are the Periadriatic line or the Lavanttal fault.

2. Petrological characteristics of the eclogites

2.1. Mineral assemblages

The Koralpe, Saualpe and Pohorje eclogites are either quartz- or kyanite-rich and contain garnet, omphacite, quartz, kyanite, zoisite/clinozoisite, rutile, apatite, zircon, phengite, calcic-subcalcic amphiboles, paragonite, dolomite and sulfides (MILLER, 1990; MILLER & THÖNI, 1997; JANÁK et al., 2004; SASSI et al., 2004). Amphiboles may be in textural equilibrium with omphacite and garnet, but more frequently form poikiloblasts overgrowing the foliation defined by omphacite ± kyanite and zoisite. Retrogression is documented by (1) omphacite rimmed by symplectites of Na-poor clinopyroxene ± calcic amphibole and sodic plagioclase, (2) kyanite mantled by complex symplectites of corundum + anorthite ± spinel ± sapphirine ± Mg-staurolite, (3) symplectites of biotite + plagioclase after phengite, and (4) garnet replaced by a kelyphitic intergrowth of amphibole ± plagioclase ± epidote.
At the Bärofen and Gressenberg localities in the Koralpe the transition from gabbro to eclogite can be studied in situ. The gabbros are generally isotropic and medium to coarse-grained, but modal layering on a cm-scale is locally present. They are mainly composed of calcic plagioclase and clinopyroxene ± orthopyroxene ± olivine (HERITSCH, 1973; THÖNI & JAGOUTZ, 1992; MILLER & THÖNI, 1997).

2.2. Major and trace element whole rock composition

The Koralpe-Saualpe-Pohorje eclogites have a wide compositional range and can be subdivided into cumulate and basaltic types on the basis of the PEARCE (1983) Al_2O_3-TiO_2 discrimination diagram (Fig. 2).

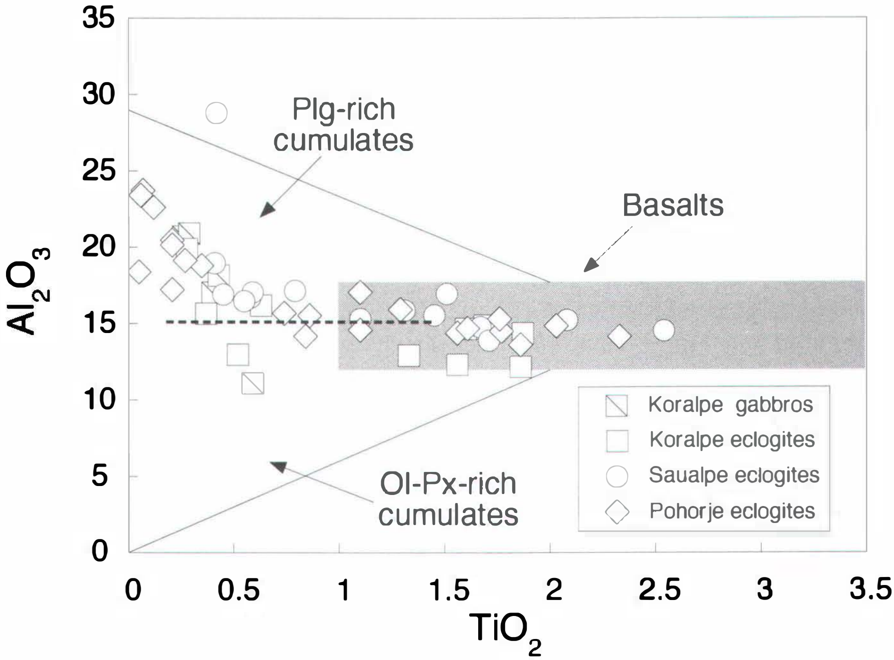


Fig. 2

Al_2O_3 - TiO_2 variation of the Koralpe, Saualpe and Pohorje eclogites, plotted on the discrimination diagram of Pearce (1983). Dashed line separates kyanite-bearing and kyanite-free eclogites. Data are from MILLER et al. (1988), MILLER & THÖNI (1997), SASSI et al. (2004) and unpublished data.

The cumulate eclogite types are Mg-rich and characterized by low TiO_2 (0.06 - 0.79 wt. %), generally high Al_2O_3 (up to 28.8 wt. %), and Cr contents ranging from 400 to 1240 ppm, resulting in a low modal abundance of rutile and quartz and in Mg-rich garnet and omphacite. The basaltic eclogite types, on the other hand, are quartz-rich and characterized by distinctly higher FeO and TiO_2 (1.10 - 2.70 wt.%), but a lower Cr_2O_3 content of 160-260 ppm. Kyanite is present in Al-rich compositions of both eclogite types, but modally much more abundant in the cumulate-type eclogites thought to be derived from plagioclase-rich cumulates (kyanite-rich eclogites, Fig. 2). The low-K characteristics indicate a tholeiitic affinity for all investigated samples. Highly variable Cr and Ni contents and the wide range in Mg-ratios [Mg# = Mg/(Mg + ΣFe)] of 0.54-0.84 clearly point to igneous fractionation during protolith generation.

In terms of immobile trace element concentrations and Nd isotopic compositions, the Koralpe-Saualpe-Pohorje eclogites and their gabbroic protoliths are comparable to N-MORBs. Sr and oxygen isotope systematics (MILLER et al., 1988) are best explained by variable, but mostly minor, seawater alteration (Fig. 3). All samples are light rare earth element (LREE)-depleted (La_N/Yb_N = 0.35 - 0.69). Some of the analysed metagabbros and cumulate-type kyanite-rich eclogites have lower and more variable incompatible trace element contents compared to basaltic-type quartz-rich eclogites (Fig. 4a) as well as positive Sr and Eu-anomalies (Eu/Eu*= 1.12-1.53). As argued by MILLER et al. (1988), THÖNI & JAGOUTZ (1992), MILLER & THÖNI (1997), SASSI et al. (2004) and MILLER et al. (2005), the eclogite precursor rocks represent a Permian (247 - 275 Ma) N-MORB-type gabbroic rock-suite evolving through fractional crystallization of olivine, clinopyroxene, orthopyroxene and plagioclase.

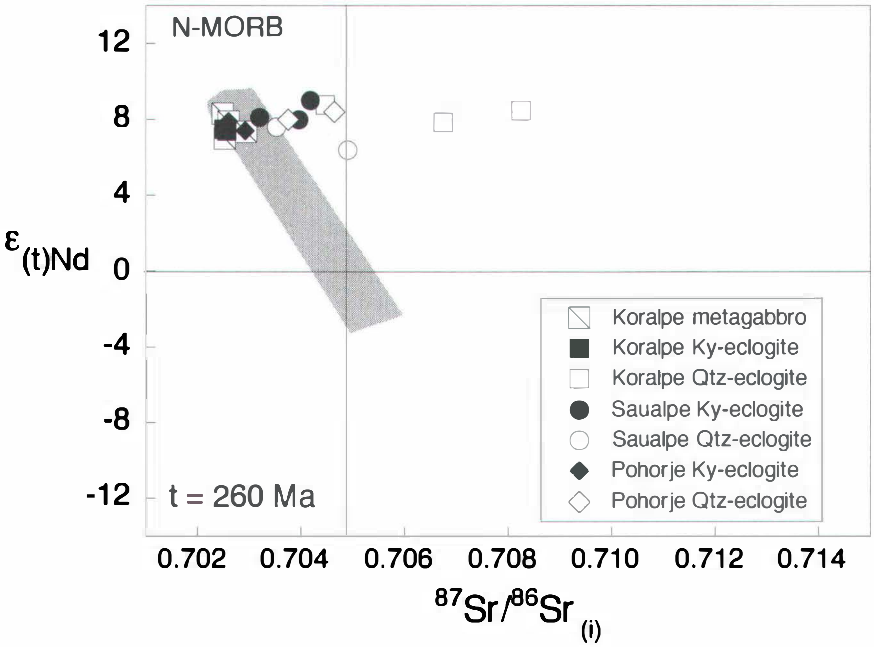


Fig. 3

Nd vs. Sr isotope correlation diagram of the Koralpe, Saualpe and Pohorje eclogites (data from THÖNI & JAGOUTZ 1992; MILLER & THÖNI 1997, SASSI et al. 2004). The gabbroic protoliths and most of the kyanite-rich eclogites plot on the Mantle array. The Sr isotopic composition of eclogites that plot to the right of the Mantle array could have been altered by reactions with seawater (e.g. MUEHLENBACHS 1986).

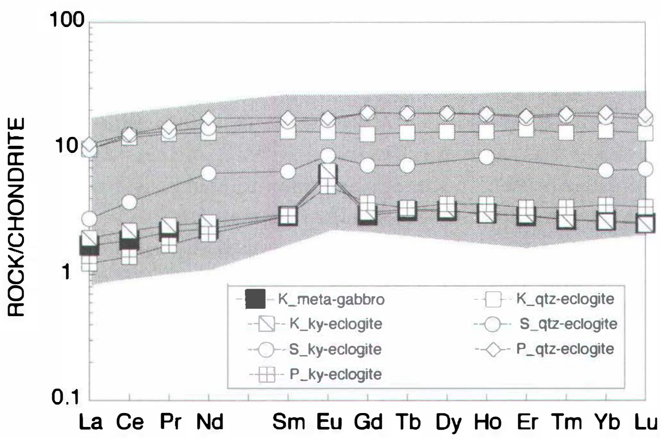


Fig. 4a

Chondrite-normalized (BOYNTON, 1984) rare earth element plot showing representative patterns of a Koralpe meta-gabbro, kyanite- and quartz-rich eclogites form the Koralpe (K), Saualpe (S) and Pohorje (P). The shaded area represents the range of all compositions reported for these eclogites and their gabbroic protoliths by MILLER et al. (1988), MILLER & THÖNI (1997), SASSI et al. (2004) and unpublished data.

2.3. Geothermobarometry

Despite recent advances in high pressure/ultrahigh pressure (HP/UHP) geothermometry, the precise determination of eclogite peak metamorphic conditions remains difficult. Geothermobarometric calculations are critically dependent on thermodynamic data sets, activity models and the quality of mineral chemical data, and do not yet permit an unambiguous determination of pressure and temperature. The thermometric evaluation of the temperature-dependent Fe^{2+}-Mg^{2+} partitioning between garnet and omphacite is based on the calibrations of KROGH RAVNA (2000) and POWELL (1985). A familiar problem with this exchange equilibrium is the absence of data on the Fe^{3+}/Fe^{2+} ratios in microprobe analyses of garnet and omphacite. The temperatures listed in Table 1 were calculated using stoichiometric charge balance for both minerals and indicate temperatures between 626-665°C according to the calibration of KROGH RAVNA (2000) and between 695-746°C according to that of POWELL (1985), at a nominal pressure of 2.4 GPa. Temperatures based on the Zr content of rutile coexisting with zircon (ZACK et al., 2004) range from 651-733°C.

KROGH RAVNA & TERRY (2004) and BRANDELIK & MASSONNE (2004) have formulated sets of internally consistent geothermobarometric expressions for reactions between the garnet-clinopyroxene-kyanite-phengite-quartz/coesite mineral assemblages where net transfer reactions involving the endmenbers grossular, diopside, muscovite, celadonite, kyanite, quartz/coesite define equilibrium pressure and temperature for kyanite-phengite-quartz/coesite-bearing eclogites. The results listed in Table 1 show that these invariant points range from 2.2 to 2.4 GPa when calculated according to BRANDELIK & MASSONNE (2004), and from 2.4 to 2.8 when using the geothermometric expressions of KROGH RAVNA & TERRY (2004). The results also show that all samples plot within the stability field of quartz.

Despite the absence of coesite and micro-diamond, JANÁK et al. (2004) claimed an UHP origin for the Pohorje eclogites based on mineral compositions and micro-textures such as quartz "exsolutions" in omphacite and quartz inclusions in garnet, omphacite and kyanite that are surrounded by radial fractures. As discussed by MILLER & KONZETT (in press), similar micro-textures are also present in Koralpe and Saualpe eclogites. However, these micro-textures cannot be taken as unambiguous evidence of former UHP conditions. In our opinion it is exclusively the presence of coesite and/or diamond identified by microbeam techniques that documents UHP conditions beyond any doubt. The metastable persistence of coesite and/or diamond up to surface conditions is frequently the result of their inclusion in mechanically strong host minerals, such as garnet and zircon, that act as pressure vessels around inclusions (e.g. PARKINSON, 2000). Because zircon is considered to be the closest analogue to diamond in its mechanical resistivity (CHOPIN & SOBOLEV, 1995) we selected this mineral in our attempt to find coesite in the Pohorje, Koralpe and Saualpe eclogites. Out of 252 zircon crystals so far investigated in polished thin sections or mounted in epoxy, fifteen contained inclusions of rutile, apatite, omphacite, garnet or magnesio-hornblende (Fig. 5). Only two zircons (Pohorje eclogite sample CM27/03 and Saualpe eclogite sample SKP17) contained quartz that was identified by micro-Raman spectroscopy (Fig. 6). Because zircon CM27/03 contains omphacite in addition to quartz and both zircon grains are unfractured we take this to indicate zircon growth during HP metamorphism in the stability field of quartz.

Table 1

Estimated PT conditions of Saualpe, Koralpe and Pohorje eclogites.

sample	locality	type	T1°C *2.4 GPa*	T2°C *2.4 GPa*	T3°C Zr (Rt)	T4°C P(GPa)	T5°C P(GPa)
SAUALPE							
GE2	Gertrusk	qtz	655	695	651		
SJ1	Jurkikogel	kya	635	716		693/2.25	724/2.49
SJ4 TS	Jurkikogel	qtz	626	688			
SK20	Kirchberg	kya	664	744			
SK 30TS	Kirchberg	kya	651	723			
SKP2	Kupplerbrunn	qtz	655	711	721		
CM06/03	Kupplerbrunn	kya	641	724			
88T35	Kupplerbrunn	kya	654	731		721/2.23	744/2.52
04T30	Kupplerbrunn	qtz	659	740			
04T31	Kupplerbrunn	kya	648	730			
SKP17	Prickler Halt	qtz	648	713			
SKP23	Prickler Halt	kya	639	717		705/2.22	729/2.47
SKP26	Prickler Halt	kya	639	719			
CM11/03	Grünburg	qtz	629	698			
CM12/03	Grünburg	qtz	647	717			
KORALPE							
94T44KH	Hohl	kya	630	708			
H42	Hohl	qtz	657	704			
H8	Hohl	kya	665	732			
CM5/04	Hohl	kya	642	722			
KBE	Bärofen	kya	624	698			
KK3	SE Kleinalpl	qtz	639	688			
KM10	Mauthner Eck	qtz	661	700	681		
CM1/04	Krumbach	qtz	660	708			
POHORJE							
CM15/01	Kebelj	qtz	644	703	701	696/2.21	707/2.47
CM16/01	Kebelj	qtz	647	702			
CM20/01	Kebelj	qtz	658	722	697	666/2.19	696/2.38
CM23/01	W Visole	kya	660	731			
CM25/01	W Visole	kya	636	747			
CM42/01	Turiska Vas	kya	648	741			
CM46/01	Jurisna Vas	kya	643	740			
RS03/01	N Visole	kya	653	746			
CM24/03	E Vranjek	kya	635	711		704/2.42	732/2.61
CM27/03	E Vranjek	kya	637	721	733	745/2.41	773/2.67
CM31/03	Visole	kya	665	758		760/2.43	785/2.80
CM40/03	Sv. Lenhart	qtz	651	699	713		

T1 = Krogh Ravna (2000); T2 = Powell (1985)

T3= Zack et al. 2004; Zr in rutile determined by LA-ICP-MS

T4/P= Brandelik and Massonne (2004)

T5/P= Krogh Ravna and Terry (2004)

The exhumation path is not well constrained with respect to P and T. The onset of lower-grade transformation is marked by the breakdown of omphacite to Na-augite ± Ca-amphibole + sodic plagioclase symplectites, by biotite-plagioclase symplectites that replace phengite and by plagioclase-corundum ± spinel symplectites formed at the expense of kyanite. The only mineral reactions that can be attributed to the intervening stage are texturally late amphibole poikiloblasts that coexist with garnet and omphacite. Model calculations show that this could have happened as the pressure dropped to approximately 2 GPa.

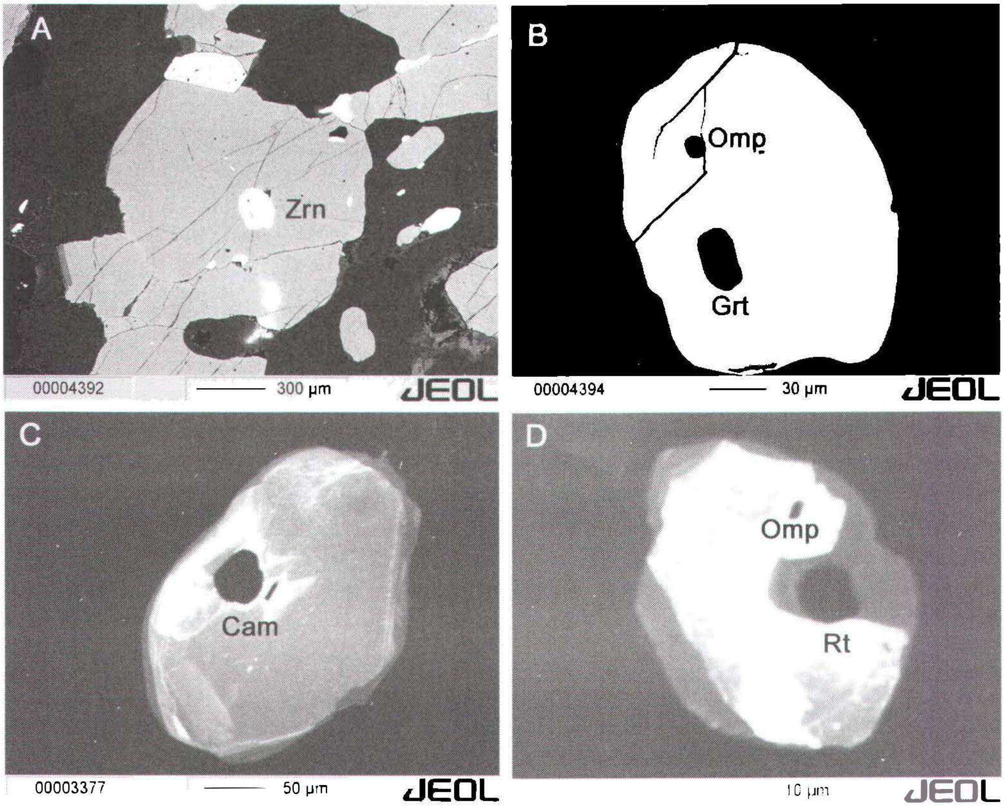
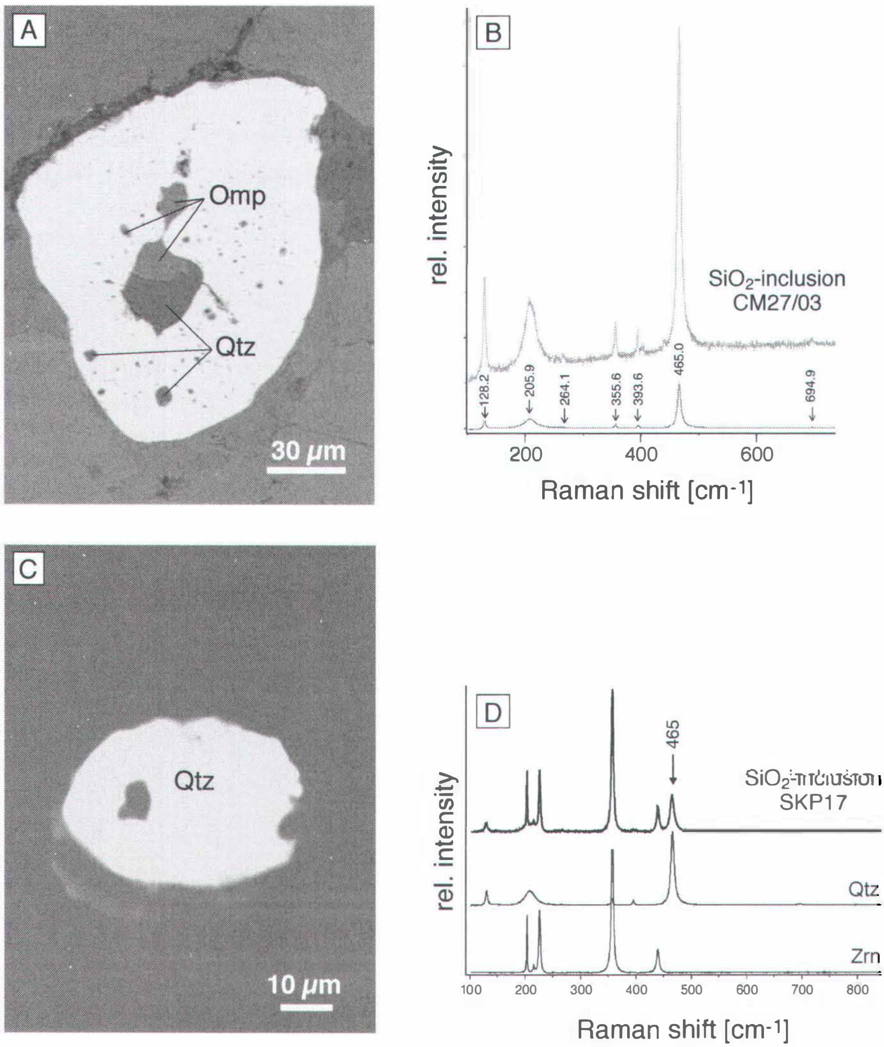


Fig. 5

Backscattered electron (BSE) and cathodoluminescence (CL) images showing (a) a zircon inclusion in garnet of sample SKP2 (Kupplerbrunn, Saualpe) containing inclusions of garnet and omphacite depicted in enlargement (b); (c) matrix zircon with inclusions of magnesio-hornblende, sample SKP23 (Prickler Halt, Saualpe); (d) matrix zircon with inclusions of omphacite and rutile, sample CM1/04 (Krumbach Graben, Koralpe).

Fig. 6

(a) BSE image of quartz and omphacite inclusions within unfractured zircon in kyanite-rich eclogite CM27/03 (E Vranjek, Pohorje). (b) Raman spectrum of the large quartz inclusion showing Raman bands at 465 cm⁻¹ diagnostic of quartz. (c) CL image of matrix zircon in quartz-rich eclogite SKP17 (Prickler Halt, Saualpe) containing an inclusion of quartz. (d) Raman spectrum of this inclusion showing Raman bands diagnostic of zircon and quartz. Raman spectra of zircon and standard quartz are shown for comparison.



2.4. Geochronology

In HP assemblages, especially those derived from mafic precursor rocks, the interpretation of geochronological results is a major challenge and requires a close link between isotope data and data from petrology and micro-textures. Conventionally, geochronometers are linked to the thermal evolution (via the "closure temperature", T_c) of a "system", and the data give little information about pressure. In HP rocks, however, knowledge of the time at which peak pressure conditions and maximum burial were effective is essential. Therefore, the main question for eclogite geochronology is: which point is dated along a pressure-dominated PT path? This includes the crucial point of linking trace element and radiogenic isotope diffusion behaviour with thermometric results inferred from major element distribution.

In meta-gabbroic eclogites whose protolith is derived from a LILE depleted source, several additional problems arise for geochronology, such as (1) very low (< 0.1 ppm) abundances of trace elements, such as Nd and Hf whose radiogenic isotope ratio must be determined precisely, or those which control the net radiogenic ingrowth (such as low U concentrations in zircon) (PAQUETTE & GEBAUER, 1991; THÖNI & JAGOUTZ, 1992); (2) isotopic disequilibrium between different HP phases, in particular between garnet and omphacite (MØRK & MEARNS, 1986; THÖNI & JAGOUTZ, 1992), resulting in spurious, and mostly too young "ages" These problems also represent a major limitation for geochronology in the Koralpe-Saualpe metabasic suite and will be addressed below.

Over the past two decades, it has been shown that eclogites can be dated, though with variable success, using the so-called "robust" isotope systems Sm-Nd, Lu-Hf (for garnet) and U-Pb (in zircon) (e.g., GRIFFIN & BRUECKNER, 1985; BECKER, 1993; DUCHÊNE et al., 1997; RUBATTO et al., 1999; MILLER et al., 2005). It seems that these isotopic systems are able to record mineral formation ages up to very high temperatures; cooling, on the other hand, can be dated by using the Rb-Sr and/or the ^{40}Ar-^{39}Ar technique for phengite.

At present, the age results for both protolith source and the subsequent evolution in time of the Koralpe-Saualpe type-locality eclogites can be summarized as follows: (1) The protoliths of the investigated eclogites were emplaced in Permian time within thinned continental crust, either as gabbros or basalts of MORB-type affinity; (2) Cretaceous HP conditions were effective in the Koralpe-Saualpe region up to 90-88 Ma B.P.; (3) fast exhumation, with exhumation rates in the range of 3-5 km/Ma, was operating in the time interval c. 90-80 Ma B.P., with a clear decrease in cooling rates after that time.

3. KORALPE EXCURSION

Location K1: Hohl (N46°43´32 E15°08´44)
Österreichische Karte 1:50.000, sheet 206 Eibiswald

Hidden in the forest is a residual hill consisting of coronitic kyanite-rich eclogite. The base of the hill is comprised of foliated quartz-rich eclogite with an intercalation of kyanite-garnet-phengite schist. Locally developed eclogite-facies shear zones show no evidence of large-scale displacements. Metamorphic textures and mineral compositions of the kyanite-rich eclogite are quite variable. Igneous relics have not been preserved, but the chemical composition and positive Eu anomalies clearly indicate a cumulate precursor rock (Fig 4b: samples H8 and 94T44KH). In addition, igneous textures have been locally preserved (Plate 1a): igneous clinopyroxene is frequently replaced by magnesio-hornblende or by an aggregate of fine-grained omphacite (X_{Jd} = 0.32-0.39). Inclusion-rich garnet ($Prp_{40-48}Alm_{33-37}Grs_{14-24}Sps_{0.7-1.2}$) forms porphyroblasts or aggregates aligned along former clinopyroxene-plagioclase boundaries. Former plagioclase domains consist of kyanite + zoisite ± quartz ± garnet. Rutile, apatite and Fe-sulfides are accessories.

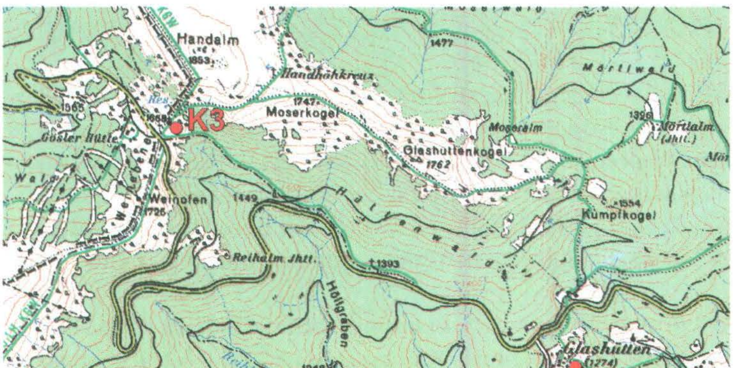


Fig. 7a
Locations Hohl (K1) and Bärofen (K2)

and

Fig. 7b
Weinebene (K3) and Glashütten (K4)

visited on the Koralpe excursion.

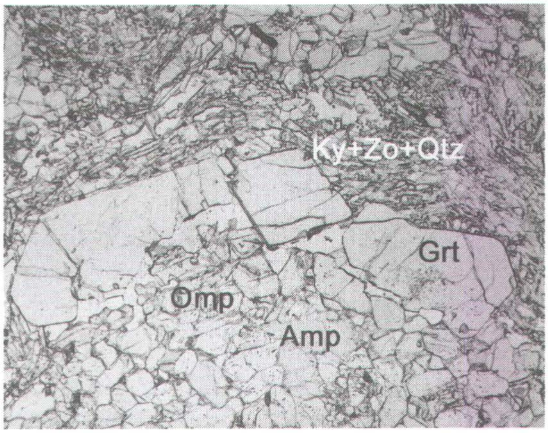


Plate 1a
Photomicrograph of coronitic Ky-rich eclogite CM5/03 from Hohl, Koralpe. A string of garnet separates former plagioclase and clinopyroxene domains that now consist of kyanite + zoisite + quartz and omphacite + magnesiohornblende + quartz, respectively.

The quartz-rich eclogite at the base of the hill is medium-grained, foliated and layered due to variable proportions of garnet ($Prp_{22-29}Alm_{46-49}Grs_{22-28}Sps_{0.8-1.0}$), omphacite ($X_{Jd}$ = 0.38-0.40), Ca-amphibole (magnesio-hornblende) and clinozoisite. These minerals coexist with quartz, minor phengite, rutile, apatite, zircon and pyrite. Bulk rock compositions are clearly enriched in incompatible elements relative to the overlying cumulate-type kyanite-rich eclogites of the same outcrop (Fig. 4b: samples H12 and 87T28).

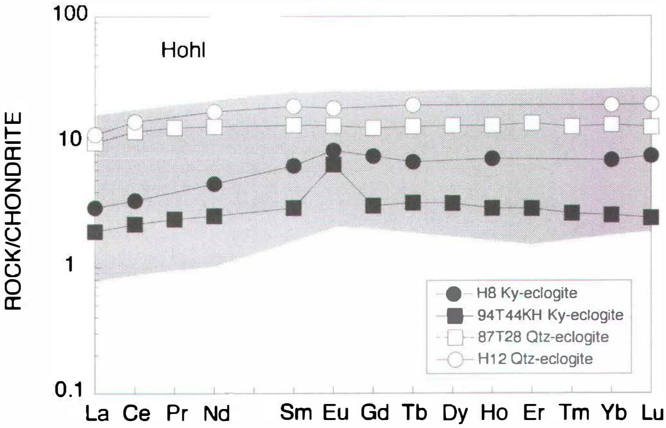
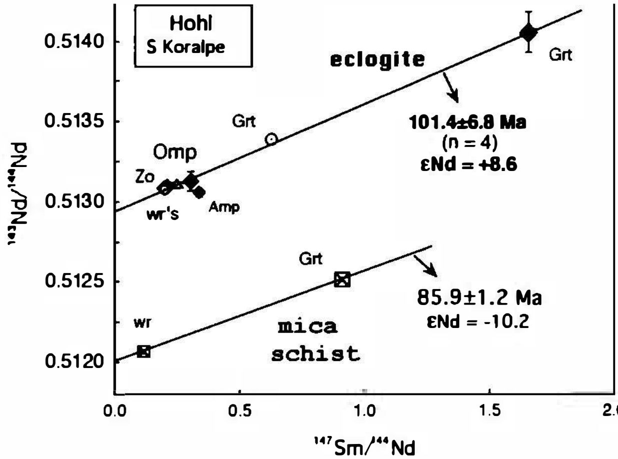


Fig. 4b
Chondrite-normalized (BOYNTON, 1984) rare earth element plot for Ky- and Qtz-rich eclogites from Hohl, Koralpe. Mineral abbreviations after KRETZ (1983).

The precise Nd isotope analysis of eclogite minerals from this outcrop is hampered by the low to very low Nd concentrations. Thus, Nd and Sm contents in garnet of quartz-rich eclogite 87T28 are only 0.022 and 0.059 ppm respectively (MILLER & THÖNI, 1997). Regression of whole rock + Zo + Omp + Grt data points of sample 87T28 yields an isochron age of 101.4 ± 6.8 Ma, but the Amp data point (Fig. 8) plots away from the regression. For three samples, initial ε_{Nd} values range between +7.5 and +8.8, indicating derivation of the magmatic protolith from a depleted mantle source.

The Sm-Nd whole rock-Grt age of the kyanite-garnet-phengite schist 94T47KH, sampled from a c. 0.30 cm layer within the quartz-rich eclogite, is 85.9 ± 1.2 Ma, ε_{Nd} = -10.1. Its Nd model age of 1.5 Ga is similar to model ages from other Koralpe metapelites (MILLER & THÖNI, 1997), indicating a Proterozoic mean crustal residence age for this material.

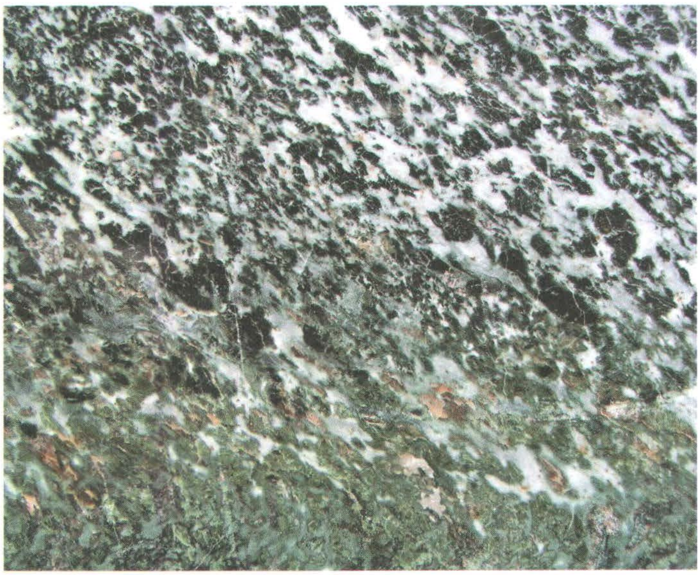
Fig. 8
Isochron plot of whole rock and mineral Sm-Nd data of three eclogite samples (upper part) and an intercalated Grt-Ky-Phe-schist (lower part) from Hohl locality, southern Koralpe. Full symbols depict eclogite 87T28 (see text): wr, Zo, Omp and Grt of this sample define an age of 101.4 ± 6.8 Ma (ε_{Nd} = +8.6; MSWD = 0.32), but overall uncertainties are high due to the extremely low Nd concentrations (Grt: 22 ppb Nd). Data from MILLER AND THÖNI (1997).



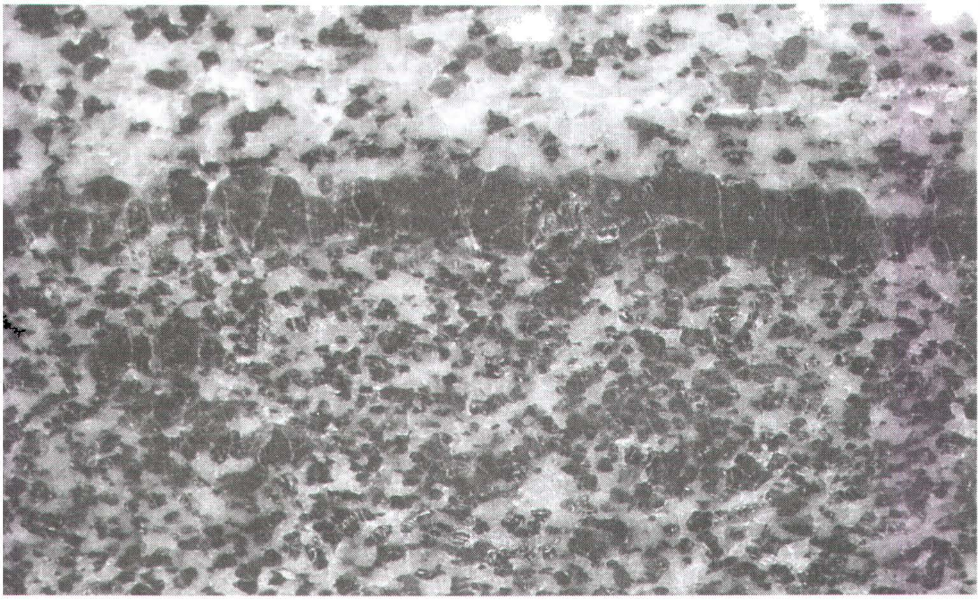
Location K2: Bärofen (N46°47′06 E15°05′13)
Österreichische Karte 1:50.000, sheet 189 Deutschlandsberg

In this spectacular outcrop, the gabbroic eclogite protoliths and the transition from gabbro to eclogite (Plate 1b) can be studied in situ (if one is lucky and somebody has provided a fresh outcrop by blasting) because partial preservation of igneous minerals and textures is ubiquitous.

Plate 1b
Photograph showing the transition of gabbro to eclogite to eclogite-amphibolite within a single block. Bärofen, Koralpe.

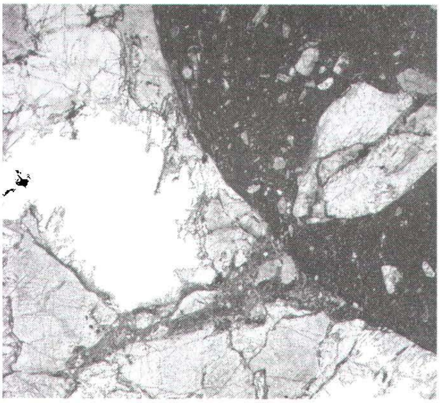


Bulk geochemistry and normative mineralogy of the gabbros are consistent with gabbro-norites, leuco-gabbronorites and olivine gabbros. Although most analysed samples have an isotropic, medium to coarse-grained igneous texture composed of plagioclase, clinopyroxene ± orthopyroxene ± olivine, distinct layering (Fig. 9) may also be observed.



ig. 9

hotograph of igneous layering resulting from differing proportions of plagioclase, olivine, ortho- and clinopyroxene eserved in the Bärofen gabbro, Koralpe.



Another interesting feature is the presence of pseudotachylite veins (Fig. 10) within the metagabbro. Whole rock chemical data show a good match between HFSE and REE of the kyanite-rich Bärofen eclogites with their protoliths (Fig. 4c), suggesting that these elements were immobile during HP metamorphism.

Fig. 10

Photomicrograph showing contact of gabbro with pseudotachylite/cataclasite. Bärofen, Koralpe.

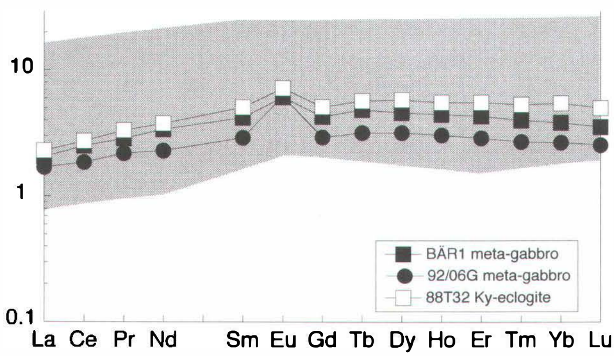


Fig. 4c

Chondrite-normalized (BOYNTON, 1984) rare earth element plot for two meta-gabbros and a coronitic Ky-rich eclogite from Bärofen, Koralpe.

Three gabbro samples from this locality were analysed by the Sm-Nd method (THÖNI & JAGOUTZ, 1992; MILLER & THÖNI, 1997). Whole rock (wr), plagioclase (Pl), and clinopyroxene (Cpx) analyses of sample Bär1 define an isochron corresponding to an age of 275 ± 18 Ma (MSWD = 0.12), resulting in an initial ε_{Nd} = +8.4 (THÖNI & JAGOUTZ 1992). The Depleted Mantle model age for this rock is 253 Ma. Plagioclase-clinopyroxene two-point regression for another two gabbro samples (MILLER & THÖNI, 1997) yielded 247.2 ± 14.4 Ma (sample Bär2) and 254.4 ± 8.7 Ma (sample 92T11B). Within analytical uncertainties, these ages and the corresponding initial ε_{Nd} values of +8.8 and +8.2 are identical with the results obtained on sample Bär1. Inclusion of all Bärofen wr, Pl and Cpx fractions (n = 9) in a single regression calculation results in: t = 257 ± 21 Ma; ε_{Nd} = +8.4, MSWD = 4.1 (Fig. 11). The initial $^{87}Sr/^{86}Sr$ ratios range between 0.70249 and 0.70278 when calculated for an age of 260 Ma, suggesting that the gabbro has more or less preserved its primary magmatic isotopic signature.

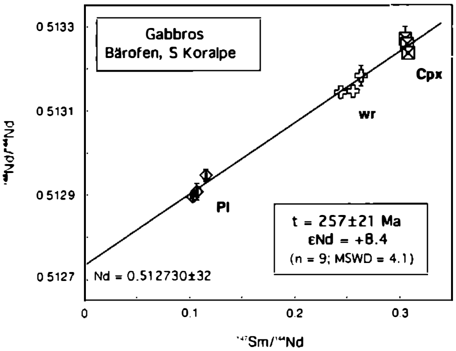


Fig. 11
Sm-Nd isochron plot showing results for handpicked plagioclase (Pl) and clinopyroxene (Cpx) fractions, and the whole rock (wr) for the three gabbro samples Bär1, Bär2 and 92T11B from Bärofen locality, Koralpe The mean regression age of 257±21 Ma (Upper Permian) is taken to indicate the time of crystallisation of the gabbro that was derived from a depleted N-MORB-type source (mean ε_{Nd} = +8.4).

In addition, a coronitic eclogite (88T32) was analysed from this outcrop. This sample yields an ε_{Nd} (260 Ma) of +8.4 and a corresponding $^{87}Sr/^{86}Sr$ ratio of 0.70258. As discussed by THÖNI & JAGOUTZ (1992), the Sm-Nd data of wr, garnet, clinopyroxene and amphibole show isotopic disequilibrium (Fig. 12), although wr and Grt yield a regression date of 93 ± 13 Ma (or of 88 ± 9 Ma if the data point for Zo is included; THÖNI & MILLER, 1997) that is close to new results obtained for well-equilibrated eclogites from the Saualpe and Pohorje (MILLER et al., 2005; THÖNI et al., in preparation).

A Ky-St-bearing Grt-mica schist sampled some 70 m away from the Bärofen eclogite outcrop yielded a Grt-wr Sm-Nd age of 88.7 Ma (MILLER & THÖNI, 1997). Inclusion of an impure garnet fraction in the regression (Fig. 12) results in an age of 89.5 ± 2.7 Ma (MSWD = 1.6; ε_{Nd} = 10.1).

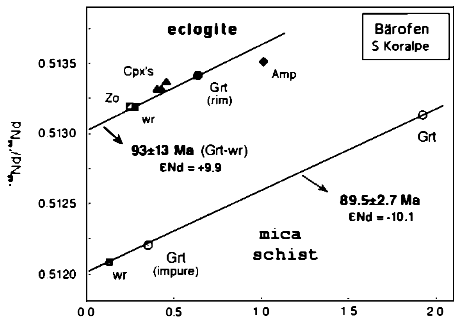


Fig. 12
Sm-Nd isochron plot showing mineral and whole rock data points for metagabbroic, coronitic eclogite 88T32 (upper part of the diagram; data from THÖNI & JAGOUTZ, 1992) and metapelite 90T11B (lower part of the diagram; MILLER & THÖNI, 1997) from Bärofen locality. Note the strong Nd isotope disequilibrium among the high-P minerals of the gabbro. The Grt fraction was handpicked from the largely inclusion-free rims only. The age result of 89.5 ± 2.7 Ma for the metapelite garnet (n = 3; MSWD = 1.6) is very similar those of other metapelite garnets from the Saualpe-Koralpe-Pohorje crystalline.

Mineral chemistry of precursor gabbros

Plagioclase compositions range from to An_{60} to An_{76} in unaltered domains of different samples. Incipient alteration results in cloudy areas consisting of extremely fine-grained kyanite, zoisite ± Ca-rich garnet ± sodic clinopyroxene. Clinopyroxene appears dark and cloudy due to exsolution of very fine-grained ilmenite in addition to exsolution of orthopyroxene (Fig. 13). The original composition prior to exsolution is not known; all analysed clinopyroxene grains are diopside ($Wo_{46-49}En_{43-46}Fs_{6-10}$) containing 4.1-4.6 wt% Al_2O_3, 0.2-0.4 wt% Cr_2O_3 and 0.7-0.9 wt% Na_2O. Orthopyroxene is relatively homogeneous bronzite (En_{71-76}) with 2.2-2.9 wt% Al_2O_3. Olivine has been replaced in most samples by Opx and spinel, but when still present its composition ranges between Fo_{76} and Fo_{79}.

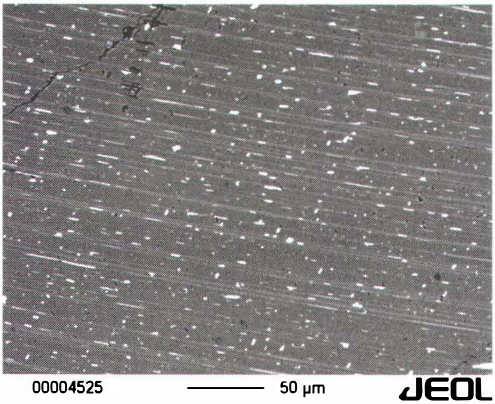


Fig. 13

BSE image of igneous clinopyroxene containing exsolution lamellae of orthopyroxene and ilmenite exsolutions. Bärofen, Koralpe.

Coronitic stage of gabbro-eclogite transformation

The breakdown of olivine to a complex aggregate of orthopyroxene (En_{82}), green spinel (50-64 mol% $MgAl_2O_4$) ± clinopyroxene ± garnet ($Prp_{43}Alm_{52}Grs_4Sps_1$) ± corundum (Fig. 14) starts along grain boundaries. The SiO_2, CaO and Al_2O_3 required for this reaction could have been released by the decomposition of plagioclase. Breakdown of plagioclase takes place along grain boundaries and at fractures and high-strain domains within the grains. Partly reacted plagioclase contains abundant kyanite and zoisite needles (Fig. 15), and small euhedral garnet or garnet aggregates strongly enriched in grossular (Grs = 53-91 mol%). In these altered domains, plagioclase composition becomes more sodic (An_{36} - An_{40}) as reactions proceed.

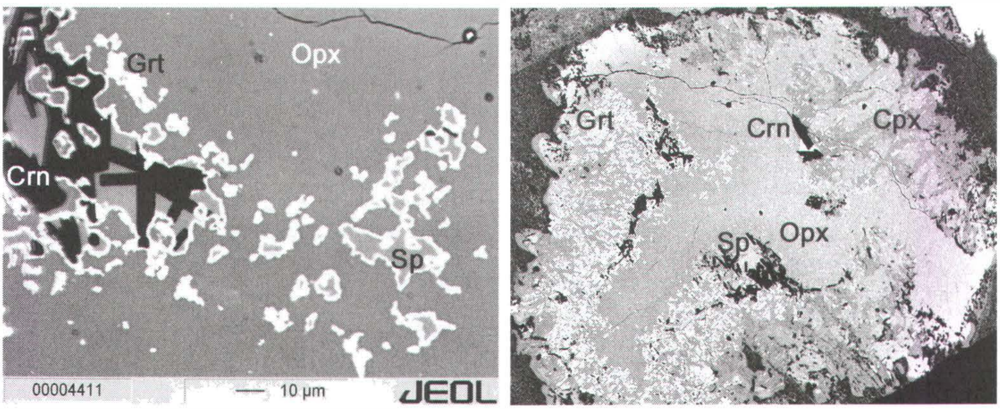


Fig. 14

BSE images of olivine pseudomorph in meta-gabbro sample Bär1, Bärofen, Koralpe. Olivine is replaced by orthopyroxene (Opx), clinopyroxene (Cpx), spinel (Sp), garnet (Grt) and corundum (Crn).

Igneous orthopyroxene has narrow coronas composed of sodic augite (X_{Jd} = 0.10-0.14) when in contact with plagioclase. Igneous clinopyroxene has reacted with plagioclase forming garnet coronas along grain boundaries. Corona garnet is strongly zoned with higher values of grossular (Grs_{75-81}) and Fe/(Fe+Mg) and abundant inclusions of kyanite ± zoisite on the plagioclase side, and lower values of grossular (Grs_{35-38}) and Fe/(Fe+Mg) and inclusions of rutile towards clinopyroxene. This texture suggests that kyanite and zoisite nucleated at an early stage of plagioclase decomposition, probably by the continuous reaction proposed by GOLDSMITH (1982)

$$Pl + H_2O = Ky + Zo + Qtz + (NaSiCa_{-1}Al_{-1})_{Pl}$$

that proceeds to the right with increasing pressure. Reactions responsible for the final breakdown of the igneous phases and the formation of eclogite involve recrystallization and extensive diffusion between different chemical domains through a set of complex continuous reactions.

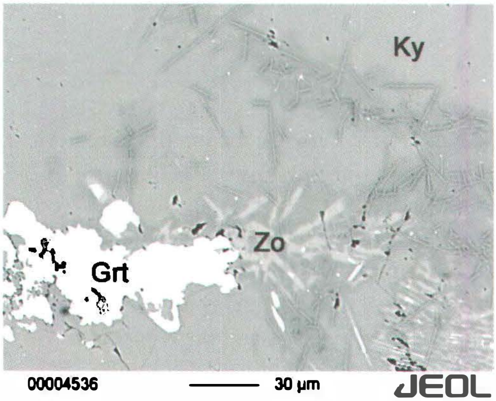


Fig. 15
BSE image of altered plagioclase domain in metagabbro sample Bär2, Bärofen, Koralpe. Calcic plagioclase has partly reacted to grossular-rich garnet (Grt), kyanite (Ky), zoisite (Zo) and Na-rich plagioclase.

Eclogitic stage of gabbro-eclogite transformation

Eclogite samples that preserve igneous textures still show string-like clusters of euhedral garnet separating former plagioclase and mafic mineral domains (Plate 2a). Plagioclase has been replaced by kyanite + zoisite ± garnet ± quartz, pyroxene and olivine domains have been replaced by fine-grained polygonal omphacite, quartz and magnesio-hornblende, with minor rutile. Garnet is often zoned, with decreasing X_{Ca} and increasing Mg(Mg+Fe) from core to rim, and contains numerous micro-inclusions of kyanite, zoisite, quartz, rutile and omphacite. Further recrystallization results in a polygonal fabric, increasing grain size and a loss of igneous textures.

Plate 2a
Photomicrograph of coronitic Ky-rich eclogite where strings of inclusion-rich garnet separate former plagioclase and pyroxene domains; Bärofen, Koralpe. Igneous plagioclase has reacted to Ky + Zo + Qtz, pyroxenes have been replaced by omphacite or recrystallized to a granular aggregate of omphacite + magnesiohornblende + quartz.

The preservation of igneous minerals and textures and the coexistence of sodic plagioclase and eclogite in a single block of the same outcrop suggest sluggish reaction kinetics. As pointed out by AHRENS & SCHUBERT (1975a, b), the presence of an intergranular fluid is a pre-requisite for the transformation of gabbro into eclogite within geological timescales at T < 600-800°C. Although the formation of hydrous phases such as zoisite and amphibole in the coronitic eclogites documents the involvement of fluid, the metastable persistence of gabbroic assemblages indicates that fluid flow was not pervasive. The fact that coronitic eclogites partly preserve igneous textures whereas well-equilibrated eclogites are strongly foliated suggests that deformation also enhanced reaction kinetics and aided recrystallization by dislocation creep, grain-size reduction and allowing ingression of catalytic fluid.

Eclogite microstructures and Crystallographic Preferred Orientations

The eclogites of the Koralm area form layers and lenses of 0.1 to 100 meters thickness. Most eclogites show a strong schistosity and a mineral lineation at outcrop scale, due to a shape preferred orientation of omphacite, zoisite, kyanite, and amphibole, and a compositional layering at millimeter-scale. Coarse grained eclogites without shape preferred orientation occur as boudins within schistose fine-grained eclogite mylonites. On a microscale, the eclogites show a clear succession of mineral parageneses related to several phases of their metamorphic evolution. The transformation of gabbroic parageneses into coarse-grained eclogitic assemblages occurred without penetrative deformation at a meso-scale. The coarse-grained boudinaged eclogites show a weak foliation. However, omphacite (omph1) shows several features of plastic deformation. Coarse grains are twinned, kinked and bent. Fine grains of recrystallized omphacite (omph2) are arranged along twin lamellae, cleavage surfaces and the grain boundaries of the coarse omphacites; locally, core and mantle textures have been observed. Several stages from coarse-grained eclogites to the formation of fine-grained eclogite mylonites (due to dynamic recrystallisation and secondary grain size reduction) have been observed. These mylonites show a compositional layering with monomineralic layers of garnet, zoisite, and omphacite. The fine grained garnets are interpreted to represent dynamically recrystallized grains (KURZ et al., 2004).

Omphacite crystallographic preferred orientations (CPOs) from the Koralm-Saualm Complex may generally be described by S-type fabrics. Within coarse-grained samples WK17-98a, WK20-97, WK51-97 in Fig. 16 the {001} poles are distributed along a girdle parallel to the XY plane of the finite strain ellipsoid (foliation plane). These textures show {001} maxima near the Y axis of the finite strain ellipsoid, i.e. perpendicular to the lineation, but parallel to the foliation plane. The {010} poles, oriented parallel to the b [010] axes, show very well developed clusters centred within the Z; the {100} poles are distributed along a girdle within the XY plane (foliation), with maxima near X. This type of CPO fabric ({100} and {001} girdle within the XY plane, {010} poles with a cluster centred in Z) is formed within a deformation geometry of axial compression. The omphacite CPOs within fine-grained eclogite mylonites (WK7-97, WK8-97, WK3-99, WK-HF2 in Fig. 16) may be characterized as S to transitional S>L types with a {001} girdle within the XY plane (foliation); clusters of {010} poles are centred in Z. However, the {001} poles show a tendency to form weak maxima centred in X (WK8-97, and especially WK7-97); accordingly, the {010} poles show a tendency to form a girdle within YZ (normal to the foliation plane).

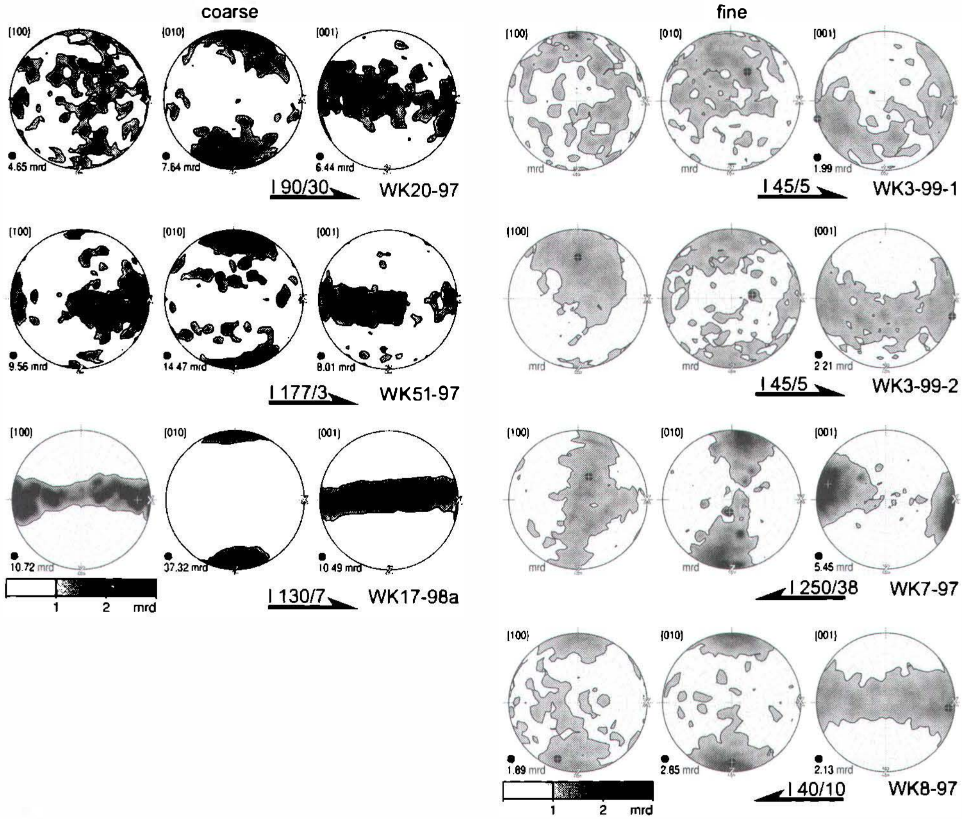


Fig. 16

CPOs (textures) of omphacite in deformed eclogites from the Koralm-Saualm Complex obtained from neutron diffraction. The recalculated pole figures ({001}, {010} and {100}) describe the orientation of the poles to the (001), (010) and (100) planes, including the equivalent (00-1), (0-10) and (-100) poles. Trace of the foliation and lineation (X direction) is horizontal (east-west in the pole figures), Y direction is at the centre of the pole figure, and Z direction is vertical; equal area projection, lower hemisphere; mrd: Multiples of Random Distribution; ï marks the position of the maximum. The asymmetry of figures of WK3-99 is due to cutting slightly oblique to the foliation and lineation. The order of the pole figures corresponds to the decreasing grain size of the related samples.

We assume that the deformation geometry from the pressure peak onwards is directly related to the mechanism of exhumation. Therefore, the evolution of CPOs depends on the tectonometamorphic evolution of these units, in particular the mode of exhumation. Hence, S-type fabrics predominantely occur within eclogites exhumed by crustal extension. This is associated with a flattening strain geometry and subvertical axial compression.

Location K3: Weinebene (N46°50´29 E15°01´01)
Location: OEK 50, sheet 188, Wolfsberg

At this location can be seen paragneiss with pseudomorphs of kyanite after andalusite, and Plattengneiss. Follow the road from Deutschlandsberg to the Weinebene, a saddle in the Koralm. From the Weinebene follow the footpath to the north, towards the Handalpe (N46°50´51 E15°01´16).

Along this path you may observe continuously increasing deformation of the gneisses and micaschists. The gneisses grade into mylonites (the so-called Plattengneiss) with a closely spaced schistosity, a N trending stretching lineation and secondary grain size reduction.
The Plattengneiss forms an important shear zone within the Austroalpine Nappe Complex of the Eastern Alps, which developed during the Lower Cretaceous collisional event (Eo-Alpine) within the Austroalpine unit. It has been investigated for regional tectonic reasons as well as in order to get general information about the evolution of microfabrics and the development of CPOs within high-grade shear zones.
The quarry exposes the typical, fine-grained mylonitic Plattengneis with a flat-lying foliation and a N-trending stretching lineation. The Plattengneis is composed of quartz, feldspar (K-feldspar and plagioclase), muscovite, biotite and kyanite. The feldspar is completely recrystallized during deformation and the quartz displays monomineralic layers with quartz shapes similar to those of granulites.

Plattengneiss Microstructures (for details, see KURZ et al., 2002)

Quartz typically forms layers and lenses within the Plattengneis (Fig. 17a). Within these layers and lenses, the quartz grains show an equant shape and are characterized by serrate and lobate grain boundaries typical of high temperature deformation (equigranular - interlobate fabric). The main mechanism of dynamic recrystallization is grain boundary migration recrystallisation. Subgrains commonly occur, and in many cases the subgrains show undulatory extinction. Some domains are characterised by uniformly sized quartz grains bordered by straight grain boundaries; these fabrics document partial annealing.
Feldspar (K- feldspar and plagioclase) occurs as single porphyroclasts within a fine grained matrix of quartz, white mica, biotite and plagioclase. The porphyroclasts are characterized by undulatory extinction and the development of subgrains (Fig. 17c). Very often large grains with undulatory extinction are surrounded by small, dynamically recrystallized grains (0.02 - 0.05 mm) forming core-and-mantle structures. The occurrence of subgrains and the development of core-and-mantle structures indicates medium to high-grade deformation conditions (above 500°C). The porphyroclasts are sometimes surrounded by asymmetrically arranged strain shadows; these kinematic indicators document a top-to-the-north sense of shear. The strain shadows are either filled with dynamically recrystallized feldspars, or with quartz grains.
In the paragneisses, garnet is partly boudinaged (Fig. 17d), which indicates strong extension in the X direction of the finite strain. The garnets are very often surrounded by biotite. In places, biotite crystallized in strain shadows is asymmetrically arranged around garnet cores. These fabrics also indicate a top-to-the-north sense of shear (Fig. 17d).
Crystallographic Preferred Orientations (CPO) of quartz have been investigated along a south-north oriented section across the Plattengneis of the Koralm Complex (Eastern Alps) (Fig. 18). The quartz c-axes form small circular distributions in the southernmost parts of the Koralm Complex, which represent the uppermost structural level of the Plattengneis (Fig. 19). Further to the north two maxima between the Y and Z directions of the finite strain can be interpreted in terms of preferred slip on the rhomb planes. These fabrics continuously grade into (type I and type II crossed) girdle distributions in a northward direction. A strong maximum near the Y axis with a tendency to be distributed along a single girdle and with three corresponding maxima of a-axes near the margin of the pole figure can be observed in the central and northern parts (Figs. 18, 19).

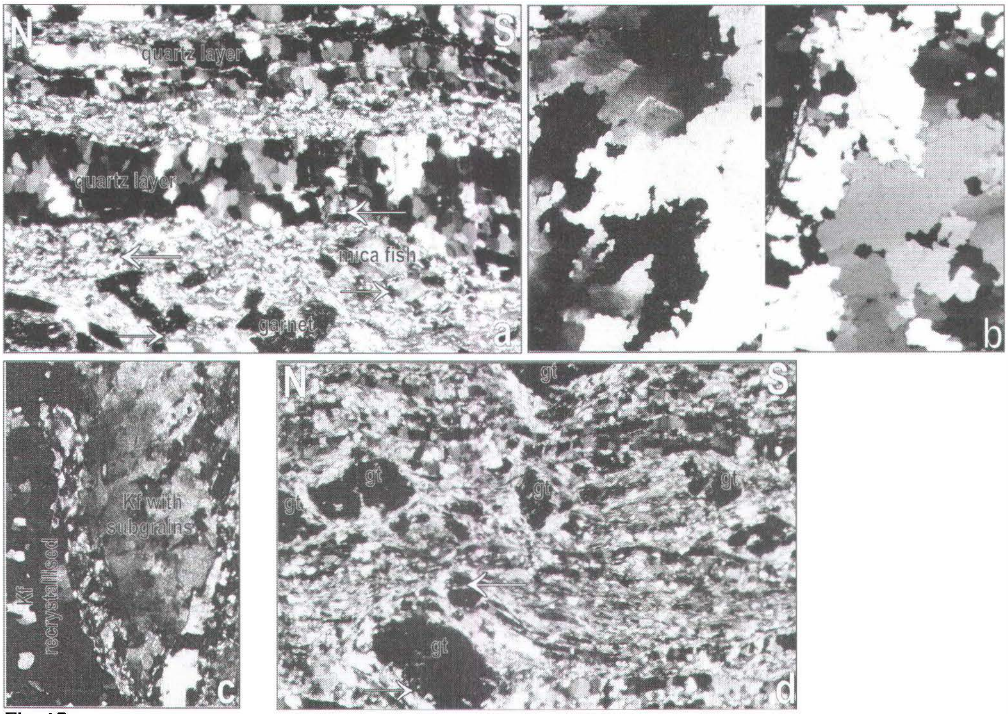


Fig. 17

Representative microstructures from the Plattengneis. a - Typical quartz layers parallel to the penetrative foliation showing HT microstructures. b - Quartz microstructures from transposed quartz vein; the quartz grains show typical lobate grain boundaries. c - K- feldspar (Kf) showing undulatory extiction and subgrain formation; dynamically recrystallized K- feldspar grains are developed along the margins of the host grain. d - Boudinaged garnets (gt) within metapelitic Plattengneis; asymmetric strain shadows around garnet indicate top-to-N sense of shear, and are filled with biotite; quartz within layer shows uniform grain size and partially straight grain boundaries.
a-d: crossed polarized Nicols. a, b, d: long axis of photograph about 4mm; c: long axis of photograph about 2mm.

Such CPO are characteristic of both high grade metamorphic conditions and high finite strain. The microstructures show that deformation within the Plattengneis shear zone was synmetamorphic. A continuous increase in peak temperatures from approximately 550°C to approximately 750°C, from the south to the central parts, can be inferred from geothermometric calculations. The temperatures then decrease again to approximately 650°C in the north. The corresponding pressures increase from 8 to 16 kbar, and then decrease to 10 kbar. The CPO changes that have been observed in the study area are best interpreted in terms of temperature dependence of the activation of glide systems within quartz aggregates. Together with the CPO-evolution, the temperature and pressure evolution indicates that exhumation rates for the central parts of the Koralm Complex were higher than for the northern and southern parts. We assume that the Plattengneis shear zone formed during the exhumation of the Koralm Complex, as a consequence of the strong exhumation of the eclogite-bearing high-pressure units in the footwall of this shear zone. Consequently, the kinematics of the Plattengneis shear zone is extensional rather than thrust-related.

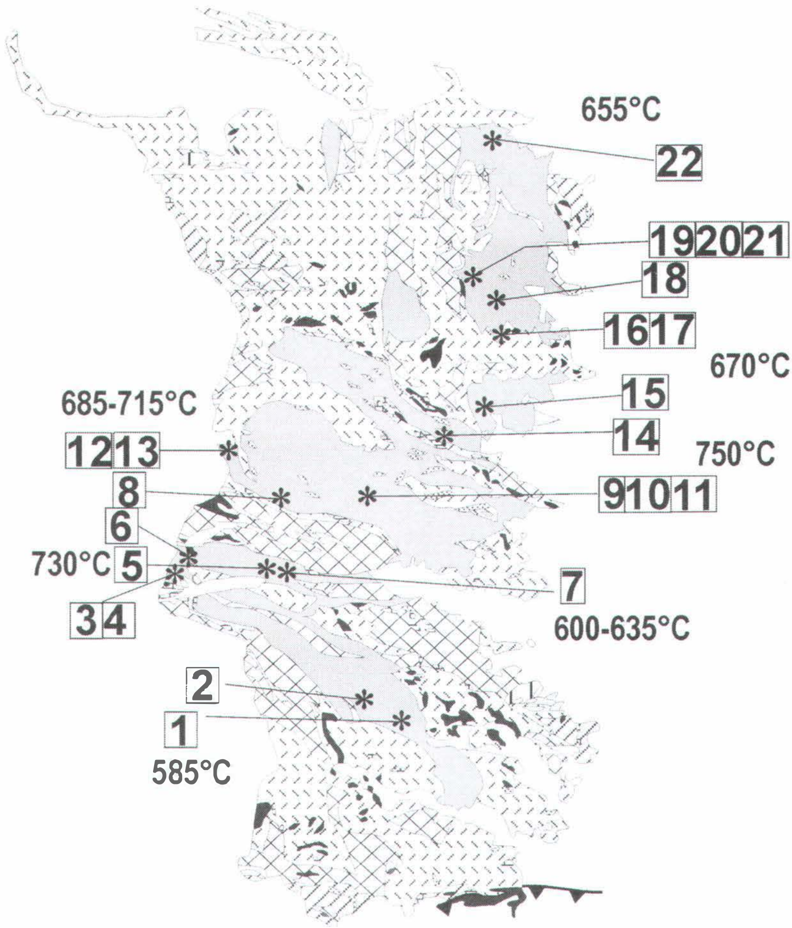


Fig. 18

Geological map of the Koralm area including the sampling sites for texture measurements; numbering corresponds to the pole-figure-numbers in Fig. 19 (from KURZ et al., 2002).

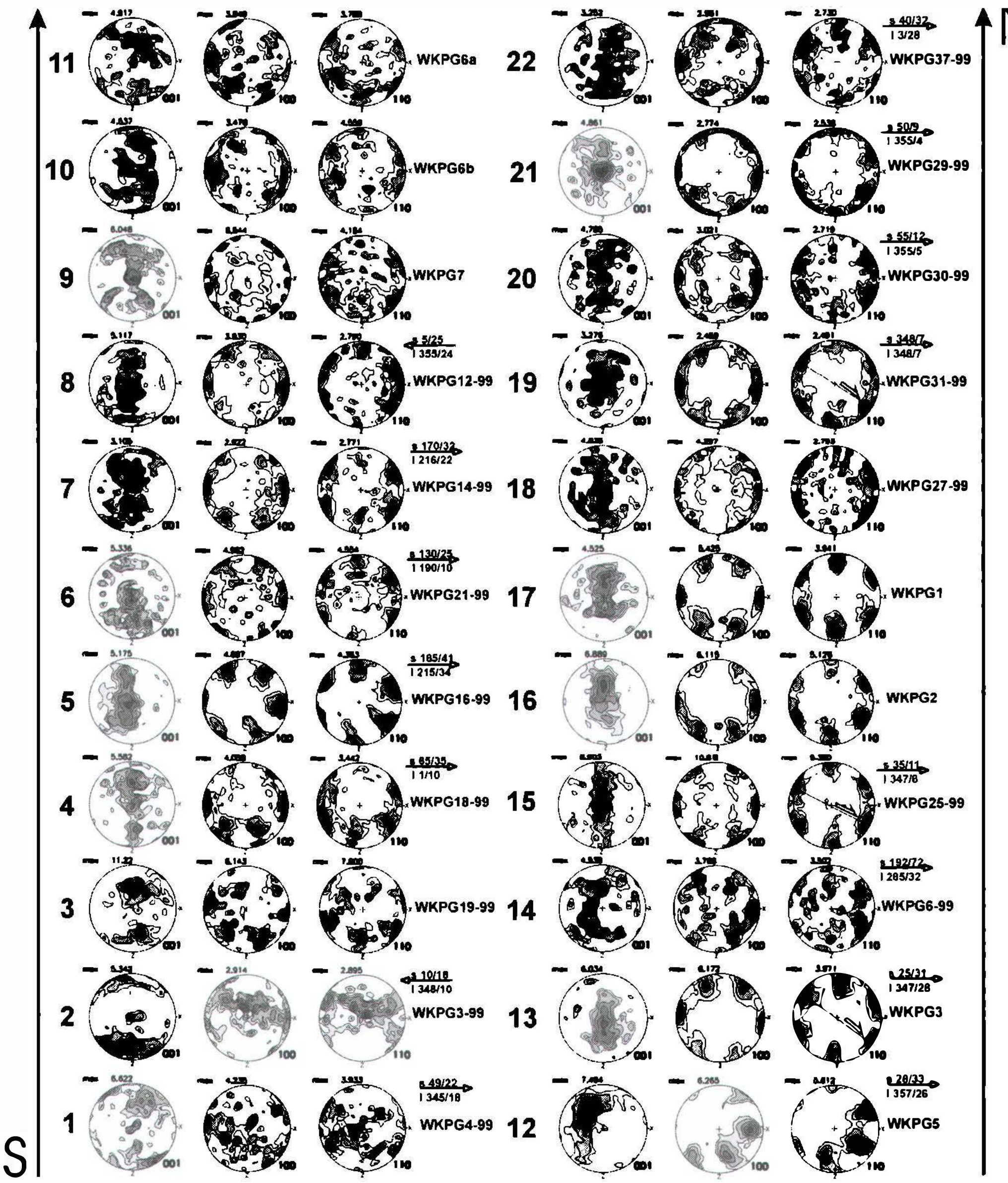


Fig. 19

Pole figures of quartz CPO from the Plattengneis, arranged along the S-N- section presented in Fig. BB; the sampling sites are displayed in Fig. BB; (001): c-axes; (110): a-axes; (100): poles to prisms; X marks the direction of the stretching lineation and the strike of the shear zone boundary; line through the dominating a-axis maxima and arrows in pole figures 13, 15, 19 indicate the orientation of the dominant gliding plane for prism-a-slip. Stereographic projections, lower hemisphere; logarithmic gradation of isolines; first isoline: uniform distribution; fifth isoline: 85% of maximum; the arrows at the top right of the pole figures indicate the dip direction of the stretching lineation; s: penetrative foliation; l: stretching lineation. Lack of axis symmetry in pole figure 12 results from cutting slighty oblique to the foliation and lineation. For explanation see text.

Location K4: Geopark Glashütten

The small, picturesque village of Glashütten, which was a booming centre for glass production ("Waldglas") in the 17th and 18th centuries, is today one of numerous tourist attractions in the area. The Geopark, situated in the centre of the village, has about 20 huge boulders (weighing up to 12 metric tons) on open-air display. These are hand-picked, often cut and polished, examples of typical rocks from the Koralpe, which include not only some rather spectacular eclogites from the main localities, but also "Plattengneis", marble, micaschist and pegmatite. The large polished surfaces allow an amazing insight into these rocks, even drawing the admiration of experienced scientists. A quartz-glass sculpture and a "geological mosaic" by artist Werner Schimpl add to the attraction and flair of the site.

4. SAUALPE EXCURSION

Location S1: Kupplerbrunn (N46°49′53 E14°37′22), Prickler Halt (N46°50′04 E14°37′43) Österreichische Karte 1:50.000, sheet 187 Bad Sankt Leonhard im Lavanttal

The granoblastic medium to coarse-grained eclogites are foliated and often banded on a dm-scale. Kyanite-bearing eclogites consisting of garnet + omphacite + kyanite + quartz + rutile + apatite ± phengite ± zoisite/clinozoisite ± amphibole ± dolomite ± zircon ± pyrite may be interlayered with kyanite-free compositional bands. Veins of various kinds are widespread in the eclogites and were formed during different stages of the metamorphic evolution. The earliest veins are oriented subparallel to the foliation. They are filled with quartz and varying amounts of kyanite, omphacite and zoisite, indicating the presence of a vein fluid during HP metamorphism. Late coarse-grained pegmatoid veins are oriented at high angles to the foliation and contain zoisite/clinozoisite, quartz, ± plagioclase, ± green amphibole ± rutile and zircon. One of these veins that crosscut an eclogite at Prickler Halt is the type locality for zoisite, named after the Austrian mineral collector Siegmund von Zois (1747-1819).

Bulk rock compositions for the Kupplerbrunn and Prickler Halt eclogites are quite variable with bulk-rock Mg-numbers ranging between 0.54 and 0.79. Fig. 4e shows that plagioclase-rich gabbroic cumulates recrystallized to Ky-rich eclogites, whereas Qtz-rich eclogites were derived from protoliths that were enriched in FeO, TiO_2 and incompatible elements relative to the plagioclase-rich cumulates.

Garnet is almandine and pyrope-rich, and frequently contains inclusions of rutile, quartz, zoisite, ± kyanite, apatite and zircon. Garnet may be zoned, usually concentrically (Fig. 21), with X_{Ca}, X_{Mn} and Fe/(Fe+Mg) decreasing from core to rim. Maximum pyrope contents in garnet rim domains vary from 30 to 57 mol% as a function of bulk-rock Mg-numbers between 0.54 and 0.79. Within a single sample, omphacite is unzoned and compositions vary only slightly, but there are distinct differences between samples. Most analyses are in the range X_{Jd} = 0.29 - 0.40. Calcic amphibole is a minor phase in most of the samples studied, where it occurs in a number of textural and compositional varieties, such as (1) inclusions in garnet and zircon, (2) a phase apparently in equilibrium with omphacite and garnet, (3) texturally late bleb-textured poikiloblastic grains, (4) strongly coloured grains at garnet/omphacite contacts and (5) vermicular intergrowths in symplectite replacing omphacite.

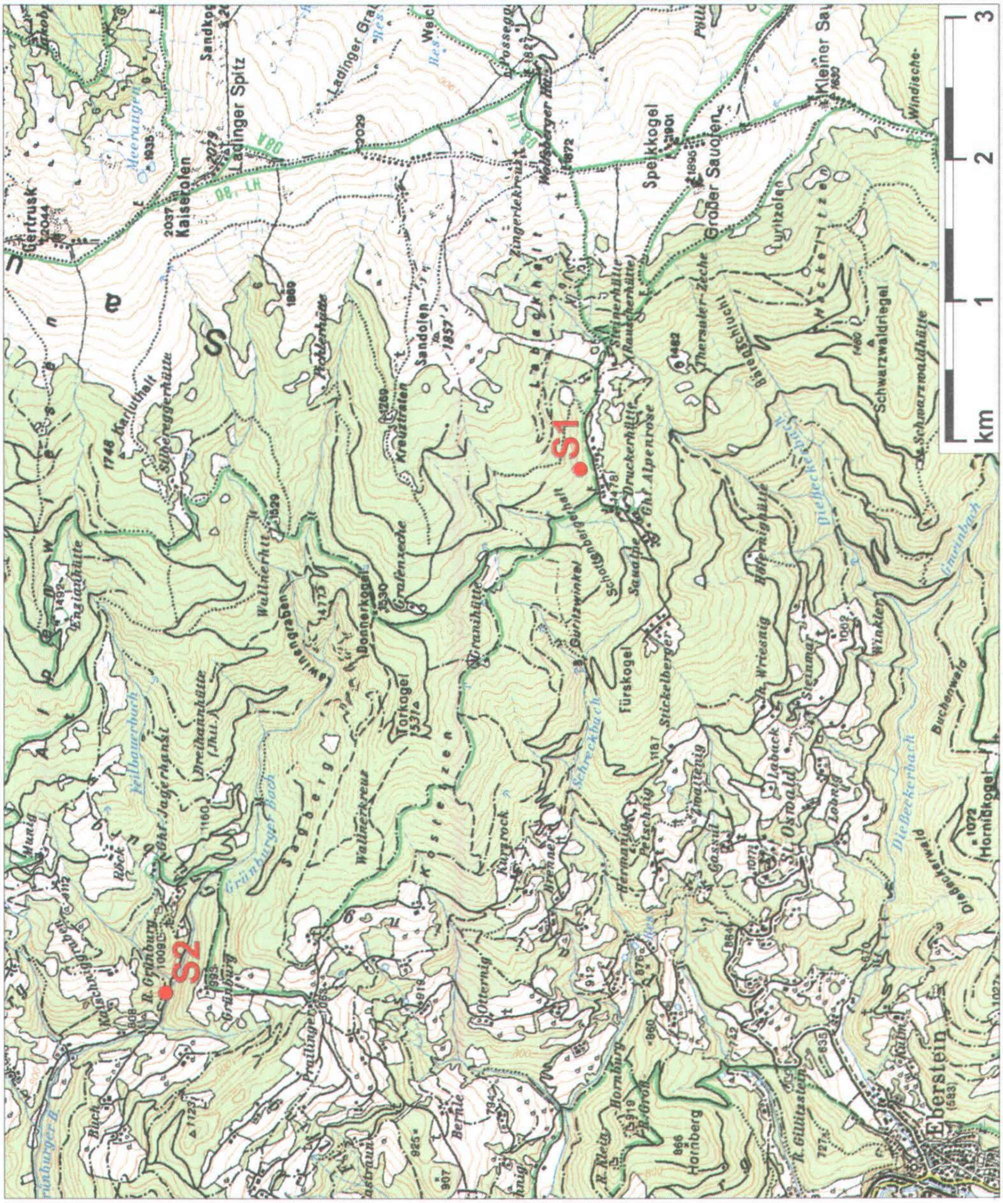


Fig. 20a

Locations Kupplerbrunn (S1) and Grünburg Graben (S2) visited on the Saualpe excursion.

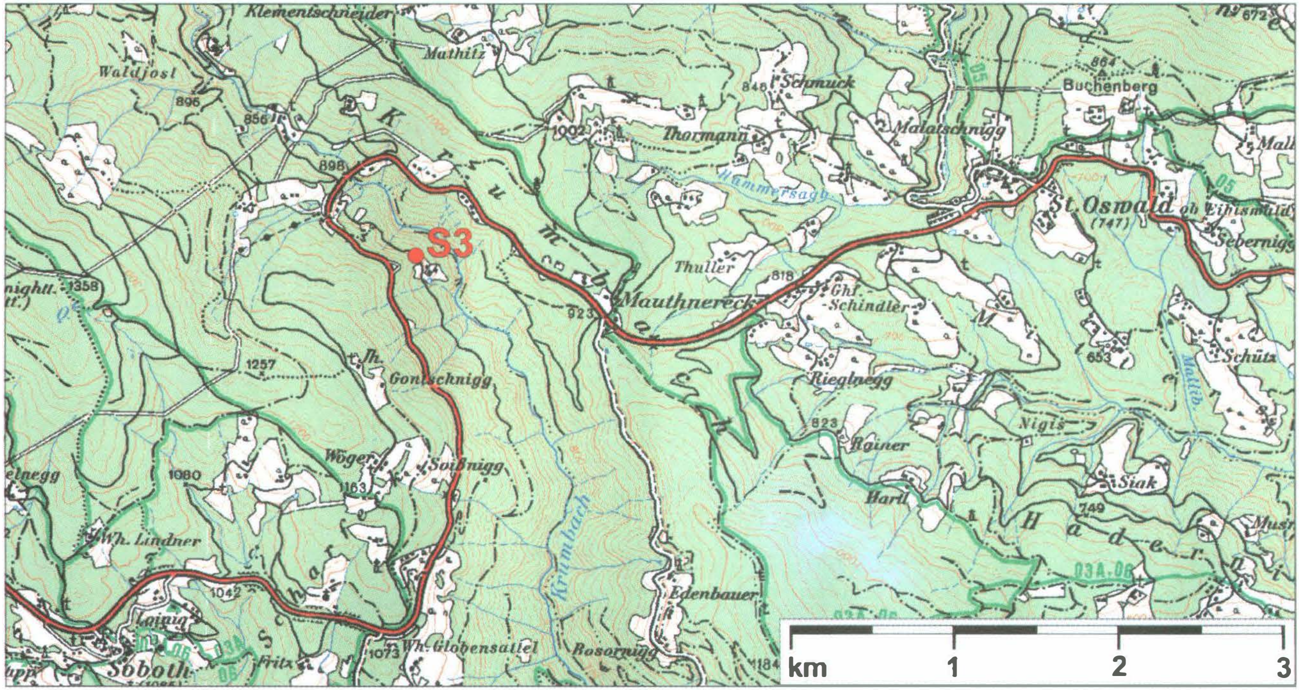


Fig. 20b

Location Krumbachgraben/Koralpe (S3) visited on the Saualpe excursion

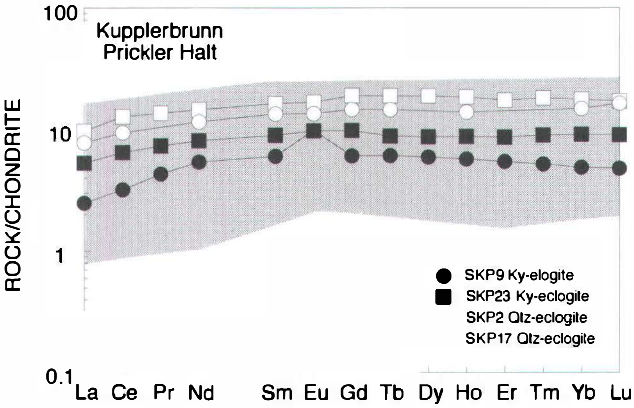


Fig. 4e
Chondrite-normalized (BOYNTON, 1984) rare earth element plot for two Ky-rich and two Qtz-rich eclogites from Kupplerbrunn and Prickler Halt, Saualpe.

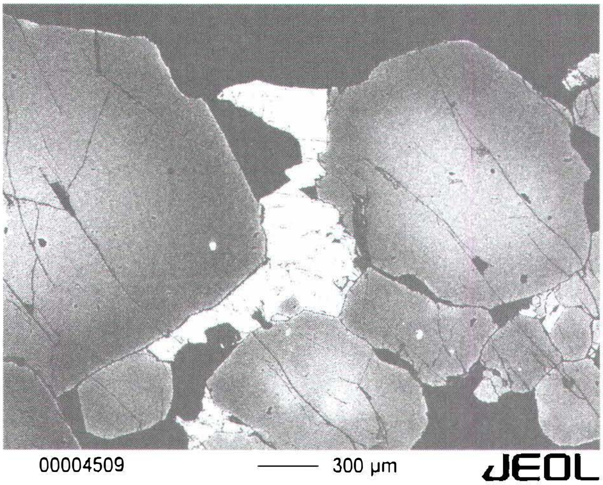


Fig. 21
BSE image of garnet in a Ky-rich eclogite from Kupplerbrunn, Saualpe. The bright core domain of the garnet shown on the upper right side has a composition of $Prp_{40.3}Alm_{38.2}Grs_{20.3}Sps_{0.9}Uv_{0.2}$, the dark rim domain has composition of $Prp_{44.6}Alm_{34.8}Grs_{19.9}Sps_{0.6}Uv_{0.2}$.

Some chemical differences between these textural types are illustrated in Fig. 22. In general, the primary amphiboles are magnesio-hornblendes that contain less tetrahedral Al and have lower A-site alkalies than the poikiloblastic grains. These bleb-textured amphiboles are edenitic, pargasitic or magnesio-hornblendes with less T-site alumina than other secondary amphiboles. This is compatible with their early formation still at high pressures. Secondary amphiboles in contact with garnet are highly aluminous subsilicic-alumino-pargasite, ferrian-alumino-pargasite, sodian pargasite and pargasitic hornblende. Where amphibole is present in symplectites after omphacite, it is magnesio-hornblende or actinolitic hornblende with distinctly lower Al^{VI} than all other amphiboles. Fe-poor zoisite with X_{Fe} from 0.02 to 0.04 is common in kyanite-rich eclogites, whereas quartz-rich eclogites may contain clinozoisite with X_{Fe} ranging from 0.11 to 0.13. Kyanite contains trace Cr (0.03 - 0.28 wt% Cr_2O_3) and Fe (0.18 - 0.39 wt% Fe_2O_3) as the main impurities. Phengite with 3.27 - 3.36 Si apfu is a minor phase and may be present in both eclogite-types.

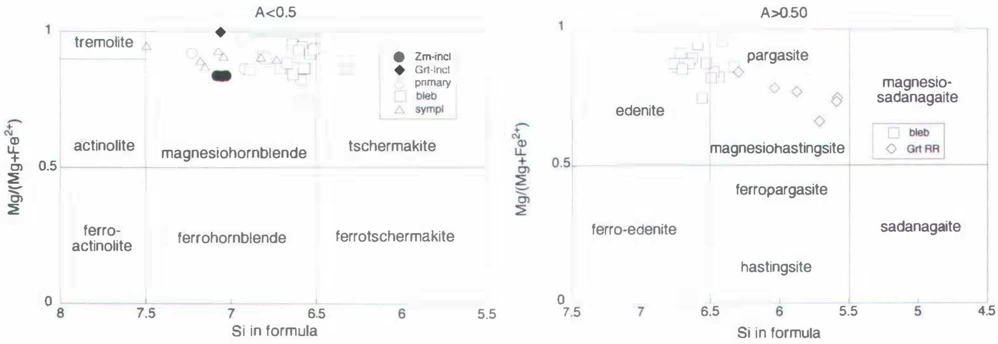


Fig. 22
Mg/(Mg+Fe²⁺) vs. Si diagrams for amphiboles from Kupplerbrunn and Prickler Halt (Saualpe) eclogites. The amphibole nomenclature is after LEAKE et al. (1997). See text for discussion.

Attempts to date the HP metamorphism from both Kupplerbrunn and Prickler Halt localities by the Sm-Nd method, using the famous Ky-eclogite, are faced with even more problems than those discussed for some Koralpe eclogites: (1) extremely low Nd concentrations (< 100 ppb) in Omp, Amp and Grt, for example Nd concentrations in garnet from four different samples range between 11 and 38 ppb (data from THÖNI & JAGOUTZ, 1992; THÖNI et al., data in prep.). (2) Nd isotope disequilibrium among HP minerals, as well as (3) post-HP metamorphic mineral reactions that may also perturb the isotopic systems, resulting in spurious "ages" (e.g., mostly too young Sm-Nd Grt-wr tie lines; THÖNI & JAGOUTZ, 1992).
The ε_{Nd} values for three whole rock samples, calculated for 260 Ma based on the Koralpe gabbro protolith age, are +7.3 (Prickler Halt), +8.1 and +9.0 (Kuppler Brunn); $^{87}Sr/^{86}Sr$ ratios are 0.70418 and 0.70316 (samples 88T35 and 86T09; THÖNI & JAGOUTZ, 1992). Rb-Sr dating of phengite separated from the massive eclogite resulted in a wr-phengite age of 102 ± 2 Ma, whereas wr-amphibole from the same sample (88T35) yielded a Rb-Sr age of 92.5 ± 1.6 Ma. Coarse-grained phengite from a late vein that crosscuts the eclogite-foliation discordantly gave ages of 84 ± 2.5 and 84.4 ± 2.1 Ma (THÖNI & JAGOUTZ, 1992).

A more recent multi-isotopic approach to dating the Kupplerbrunn eclogites resulted in better constrained age estimates. Some of these results are shown in Fig. 23 and discussed below (THÖNI et al., 2005, data in prep.). Sm-Nd mineral whole-rock regression (n = 5) yields an age of 91.2 ± 2.6 Ma for Qtz-rich eclogite SKP2 (ε_{Nd} = +8.2; MSWD = 4.9). Zircons from the same sample give a weighted mean $^{206}Pb/^{238}U$ SHRIMP age of 82.2 ± 3.8 Ma (n = 7; MSWD = 0.87) for the rims, whereas zircon cores show variable inheritance of radiogenic Pb (single spot ages up to 183 Ma). This is compatible with results from earlier studies on eclogite zircons from the Saualpe and Koralpe (HEEDE, 1997; PAQUETTE & GEBAUER, 1991). Lu-Hf isotope analysis of a meta-cumulate Ky-rich eclogite (sample 88T35) yields 88.4 ± 4.7 Ma for the garnet-omphacite pair. Inclusion of two whole rock analyses in the regression (n = 4) results in an age of 87.4 ± 11 Ma (ε_{Hf} = +15.2; MSWD = 4.0). These new data suggest that eclogite-facies conditions prevailed at Kupplerbrunn up to 90-88 Ma.

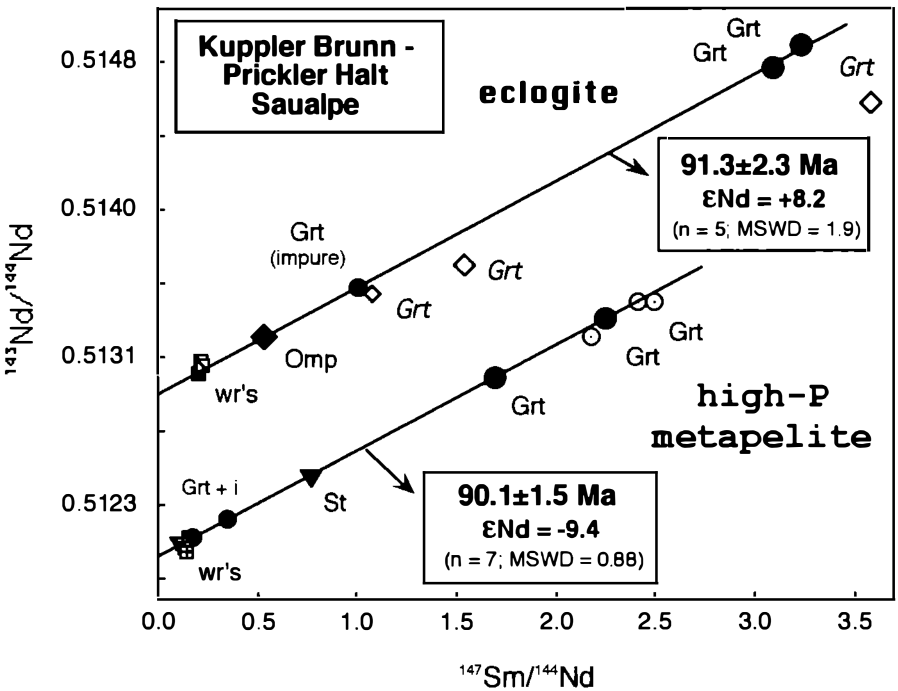


Fig. 23
Isochron plot of mineral and whole rock Sm-Nd data of quartz-eclogite SKP2 (THÖNI et al., data in prep.) and metapelitic host rocks of the Kupplerbrunn-Prickler Halt localities, Saualpe. In the upper part of the diagram data points of two handpicked Grt fractions, one impure garnet, Omp and the wr (solid symbols) of quartz-eclogite SKP2 define a regression age of 91.2 ± 2.6 Ma (ε_{Nd} = +8.2). Open diamonds (Grt) and squares (wr) are from Ky-eclogites with Nd isotope disequilibrium (THÖNI & JAGOUTZ, 1992, and unpubl. data). The lower part of the graph shows mineral and whole rock Sm-Nd data of metapelitic eclogite host rocks, which suffered coeval high-P metamorphism. Sample 89T22 (solid symbols) defines an isochron age of 90.1 ± 1.5 Ma, based on handpicked garnet, leached handpicked garnet, its leachate, impure garnet, staurolite, w. mica and the whole rock (n = 7; MSWD = 0.88). Open symbols are from other Kupplerbrunn-Prickler Halt metapelite samples (THÖNI & MILLER 1996; THÖNI 2002).

HEEDE (1997) showed that the Prickler Halt zoisite pegmatoid contains two zircon populations, (i) extremely U-rich (6800-21600 ppm U) metamict zircons and (ii) low-U (100-300 ppm U) unaltered colourless, pink or yellow zircons. Although most of the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ analyses of these zircons are analytically slightly discordant, they indicate ages of 92-94 Ma for the metamict group and 88-92 Ma for the U-poor zircons (HEEDE, 1997).
The HP metapelites (Pl-Ky-St-bearing garnet-mica schists and gneisses) that form the eclogite country rocks at Kupplerbrunn-Prickler Halt consistently yielded Grt-wr and/or mineral-mineral isochron Sm-Nd ages between 88.5 ± 1.7 and 90.9±0.7 Ma (THÖNI & MILLER, 1996) (Fig. 23), also suggesting that high PT conditions persisted at Kupplerbrunn up to 88 Ma B.P.

Location S2 (conditional): Grünburger Graben (N46°51´21 E14°33´30)
Österreichische Karte 1:50.000, sheet 186 Sankt Veit an der Glan

This outcrop is part of an eclogite lens with a length of about 1500 m and about 150 m wide, intercalated with country rock mica-schists and gneisses. Near the base of the outcrop a pegmatoid vein containing muscovite, plagioclase and quartz is seen to intrude this eclogite parallel to the foliation. The fine to medium-grained eclogites are of the Fe- and quartz-rich "metabasaltic" variety (Fig. 4f) and consist of garnet + omphacite + quartz + rutile + apatite ± amphibole ± phengite ± clinozoisite ± zircon ± pyrite. Garnet is slightly zoned with rim compositions of $Prp_{35-37}Alm_{39-40}Grs_{22-24}Sps_{0.5-0.6}$ and contains inclusions of Rt, Qtz, Czo, Ap and zircon. Omphacite is unzoned with 0.34-0.35 mol% jadeite and, together with clinozoisite, defines a foliation. Subcalcic magnesiohornblende is present as texturally late poikiloblastic grains overgrowing garnet, clinozoisite, quartz and rutile.

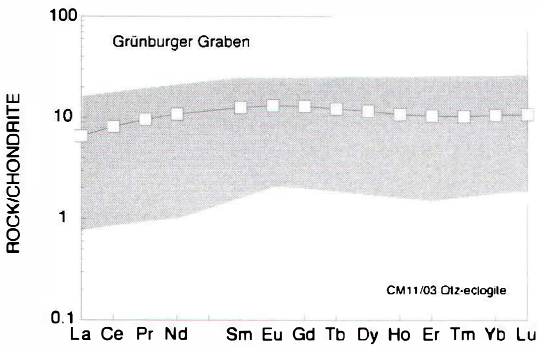


Fig. 4f
Chondrite-normalized (BOYNTON, 1984) rare earth element plot for a Qtz-rich eclogite from Grünburger Graben, Saualpe.

HEEDE (1997) attempted to date zircon (multigrain) separates from this eclogite, but without success due to their extremely low U contents (3.6-4.6 ppm) and Pb contamination problems. Sm-Nd studies are in progress (MILLER et al.). The Rb-Sr age of the muscovite from the pegmatoid is 81.1 ± 1.5 Ma, with an initial Sr isotope ratio of 0.71127 ± 8 (HEEDE 1997).

Location S3: Krumbach Graben - Koralpe (N46°42´29 E15°05´36)
Österreichische Karte 1:50.000, sheet 206 Eibiswald

A road cutting on the east-facing slope of the Krumbach Graben west of Mauthnereck provides a good exposure of a quartz-rich eclogite. The analysed whole rock sample plots in the basaltic field of the Al_2O_3-TiO_2 discrimination diagram (Fig. 2). Its trace element and LREE-depleted (Fig. 4d) signatures are similar to those of N-MORB. Primary phases observed in this quartz-rich eclogite are garnet, omphacite, clinozoisite, quartz, rutile, apatite, zircon and pyrite. Garnet is slightly zoned with core and rim compositions of $Prp_{35}Alm_{40}Grs_{24}Sps_1$ and $Prp_{39}Alm_{39.5}Grs_{21}Sps_{0.5}$ respectively, and may contain inclusions of quartz, rutile, apatite and zircon. Parallel oriented omphacite (X_{Jd} = 0.39) and clinozoisite (11-14 mol% pistacite) define an early foliation. Zircon was observed as inclusions in garnet, omphacite, clinozoisite and in the matrix. Grain size is highly variable, with longest dimensions ranging from approximately 20 to 160 µm. In cross section, zircon grains have ovoid or rounded shapes, irrespective of size.

One zircon grain contains inclusions of rutile and omphacite, suggesting zircon growth under eclogite-facies conditions (Fig. 5d). Growth of amphibole (magnesio-hornblende) seems to post-date all other primary phases, but it still appears to be part of the stable eclogite facies assemblage (Plate 2b). Post-eclogite alterations are restricted to narrow symplectite rims consisting of Na-poor clinopyroxene and plagioclase at omphacite grain boundaries.

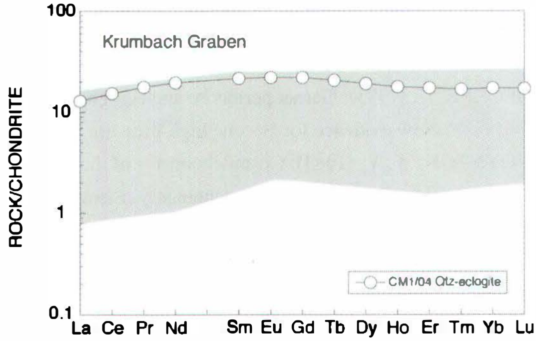


Fig. 4d
Chondrite-normalized (BOYNTON, 1984) rare earth element plot for quartz-rich eclogite, Krumbach, Koralpe.

Sm-Nd analysis of Grt and whole rock of an eclogite from this outcrop (sample DG92; GREGUREK, 1995, unpublished data) resulted in an age of 91.4 ± 6.7 Ma and an ε_{Nd} (calculated for 260 Ma) of +7.5.

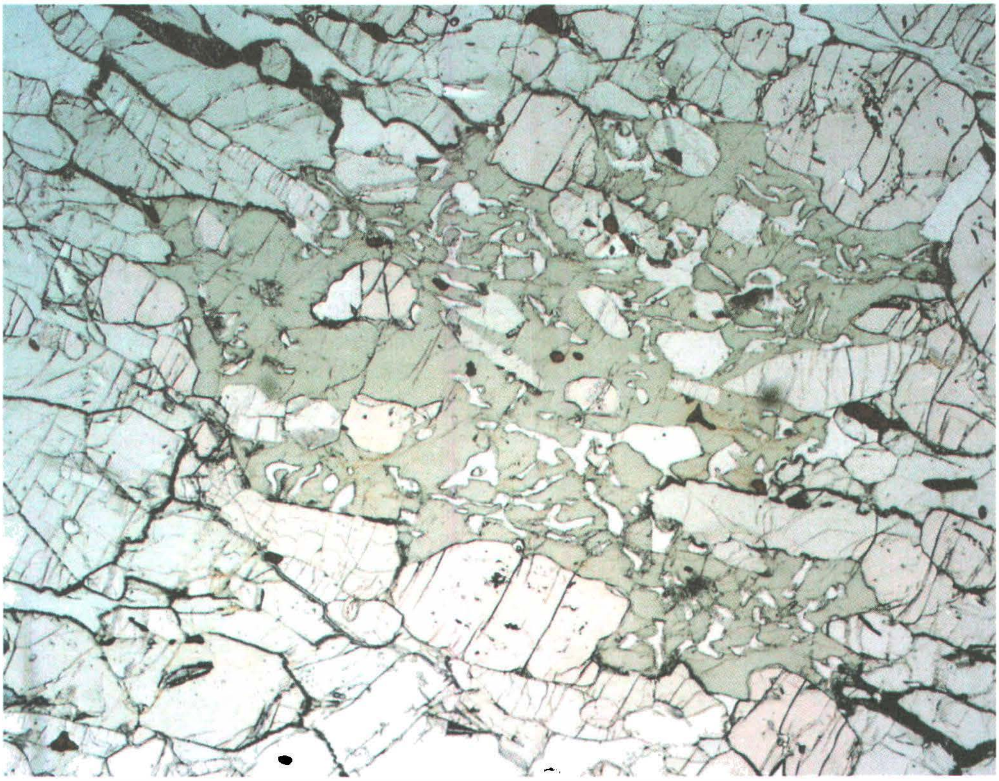


Plate 2b
Photomicrograph of a quartz-rich eclogite where a texturally late edenitic amphibole poikiloblast overgrows an earlier foliation defined by omphacite and clinozoisite. Krumbach, Koralpe.

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MANTLE XENOLITHS IN NEOGENE VOLCANIC ROCKS OF THE STYRIAN BASIN

by

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Volcanism in the Styrian Basin

The historical term "Styrian Volcanic Arc" for the volcanic province that extends from Pohorje in Slovenia, through SE Austria and into the Balaton area of Hungary (Fig. 1), was criticised by EMBEY-ISZTIN et al. (1989, 1990) because (i) it contradicts the modern concept of plate tectonics in that the alkali basaltic volcanoes are non-orogenic and unrelated to any subduction zone, (ii) geophysical evidence points to the presence of a mantle diapir below the Pannonian area and the alkali basalts and tuffs of Styria, Burgenland, Kisalföld and the Balaton regions are therefore most likely to have been generated by partial melting in the rising diapir, and (iii) the centre of the volcanic activity is in the Balaton area rather than Styria. It was therefore proposed that this term be replaced by the genetically neutral term ***Transdanubian Volcanic Region (TVR)***.

The volcanic rocks in the area comprise dacites, andesites, trachyandesites, trachytes, basalts, alkali basalts, basanites and nephelinites (HERITSCH, 1967). Lava compositions vary with both their spatial and their temporal distributions. The older Miocene (~ 17–15 Ma) volcanic activity is confined to the southern part of the volcanic region and is characterized by andesitic and trachytic lavas, whereas the younger Pliocene to Pleistocene (4–1 Ma) volcanics are of alkali-basaltic composition (HERITSCH, 1967; KOLLMANN, 1965). The main extension-related eruption provinces are in the Styrian basin and Burgenland (Eastern Austria), Balaton (Western Hungary), northern Hungary, southern Slovakia, and in the Eastern Translyvanian Basin of Romania (Fig. 1). As summarised by VASELLI et al., (1996a) the Plio-Pleistocene alkali basalt eruptions in this ***Carpatho-Pannonian Region (CPR)*** occurred subsequent to the subduction-related calc-alkaline volcanism that formed the Carpathian arc (SZABO et al., 1992). Both types of magmatic activity penetrated different tectonic microplates, which form a mosaic beneath the CPR (CSANTOS et al., 1992).

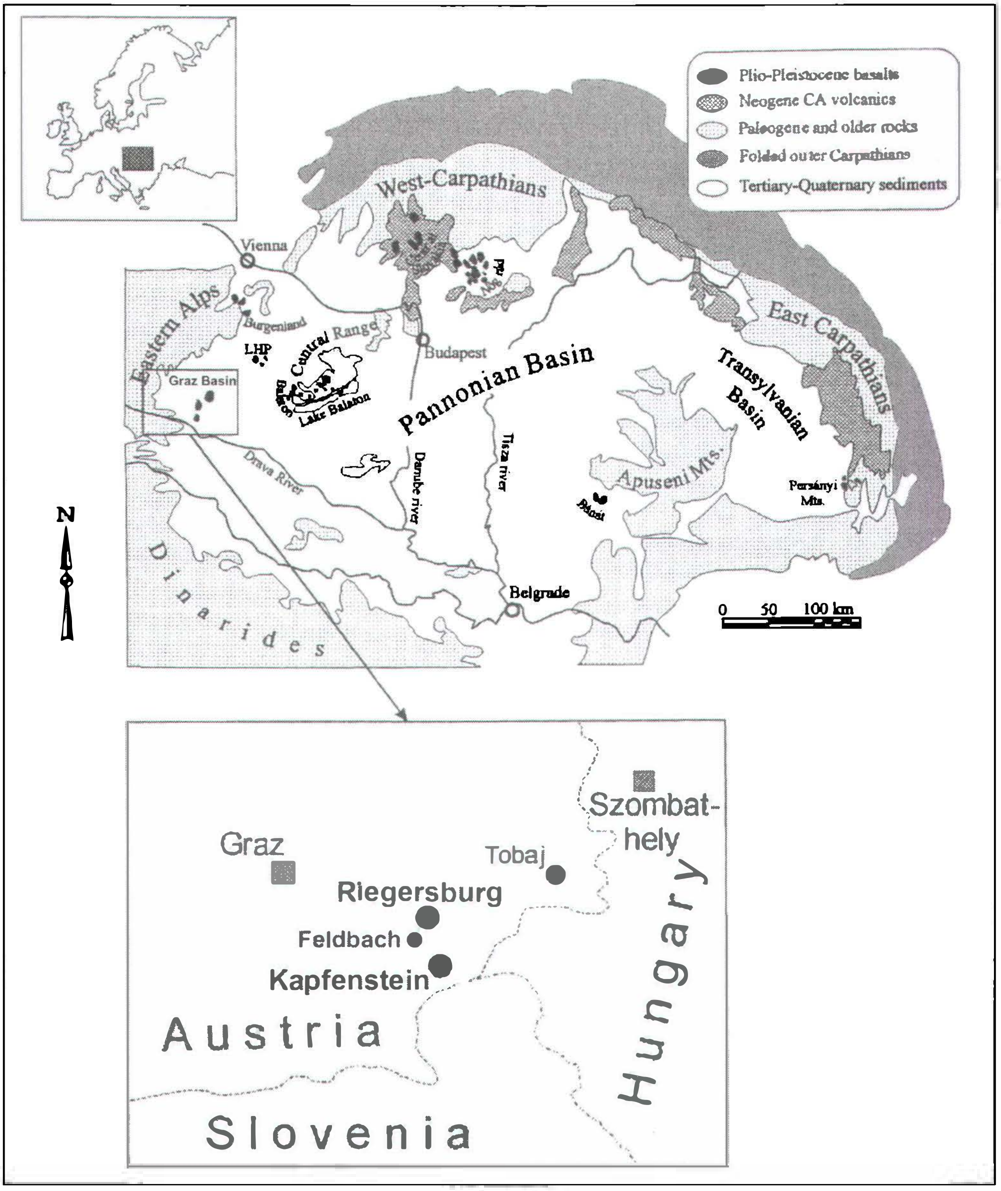

Fig. 1

Geological sketch map of the Pannonian Basin and the upper mantle xenolith localities of the Graz Basin, eastern Austria (adopted from DOBOSI et al., 1999).

Sedimentation ofthe Eastern Styrian Basin probably started in the Ottnangium and is documented since the Karpatium (Fig. 2). At the end of the Karpatium the first phase of volcanic activity produced acid to intermediate K-bearing magmas, commonly latitic, (e. g. Ilz-Walkersdorf, Gleichenberg-Mitterlabill-Perbersdorf, Weitendorf-Wundschuh). Radiometric age dating suggests that this phase goes back as far as the Lower Badenium and was followed by a second

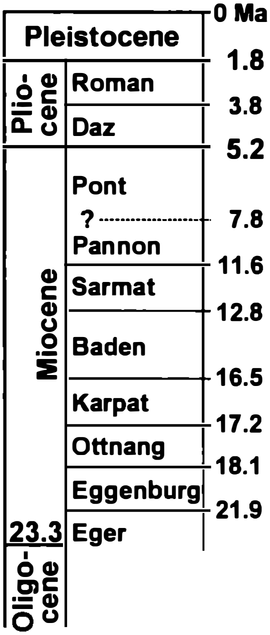

Fig. 2

A simplified geological timescale.

eruptive phase of Lower Pannonium age which has only been documented in Burgenland, at Pauliberg and Oberpullendorf (BALOGH et al., 1994). The sedimentary environment during this activity was mainly of limnic-fluvial character and only rarely marine, with deposits of a braided river system including vast flood plains and large areas of still water (according to the facies model of KOVAR-EDER & KRAINER, 1990).

The Plio-Pleistocene (4–1 Ma) volcanism is mainly basaltic and shows both effusive and explosive characteristics. The effusive deposits in Klöch and Hochstraden are interpreted as superficial lava sheets (WINKLER, 1913), while the basalt of the Steinberg (near Feldbach) is partly subvolcanic (MURBAN, 1939). In addition to these effusive manifestations of the volcanism in Eastern Styria there was also substantial explosive activity, documented by numerous tuff deposits. About 30 40 tuff volcanoes are known (KOLLMANN, 1965), most of them linked to explosion pipes. The diameter of these diatremes tapers off at depth, as documented by refraction-seismic studies in both the basaltic tuff area of Altenmarkt near Riegersburg and at the southern end of the basaltic tuff in Stadtbergen, near Fürstenfeld (KOLLMANN, 1965). Because of their strong resistance to weathering compared to the surrounding clastic sediments, which are generally unconsolidated, the volcaniclastics form prominent topographic highs (e. g. Riegersburg, Kapfensteiner Kogel, Kindsbergkogel & Seindl). Among these volcanoes are several tuff cones, which contain a wide variety of xenoliths of both crustal and upper mantle origin.

Location 1: Different types of pyroclastic rocks form the volcanic hills of the Riegersburg – Altenmarkt locality (FRITZ, 1994). The rock on which the Riegersburg castle is built (Fig. 3, photo a) shows many signs of a phreatomagmatic eruption mechanism (FRITZ, 1996). The low vesicularity of the juvenile components, the high frequency and great number of eruptions are just as characteristic of phreatomagmatic eruptions as the low-angle cross-stratification which can be detected in some places.

In the volcanic areas of Altenmarkt, near Riegersburg, (see Table 1 for representative analysis) clear layers of (ash) lapilli tuffs, the formation of which can be largely attributed to fall out deposits, are exposed in an old quarry, (Fig. 3). In some areas bomb sag structures can be found, indicating "wet" conditions of formation. Well layered fine grained sediments provide evidence of the presence of a maar lake at the end of the volcanic activities in Altenmarkt.

The mantle xenoliths embedded in the host basalt of this area are usually rather small (up to a few centimetres), some of them nicely preserved in the building stones used for the pavements, walls and doorways of the castle. In some cases gabbroid inclusions in basaltic bombs are documented (Photo b). However, most of the xenoliths found in this locality are of crustal origin, very prominently exposed along the footpath up to the Riegersburg.

Photo a

Riegersburg castle with a drawing of the volcanic outcrop (by contemporary styrian artist Josef Taucher).

	Kapfenstein					Riegersburg
	Websterite	Harzburgite	Lherzolite	Hbl-Lherzolite	Basanite	Basanite
SiO_2	47.49	41.92	42.78	43.21	45.41	46.35
TiO_2	0.47	0.008	0.03	0.08	1.95	1.82
Al_2O_3	12.85	0.96	1.55	2.74	14.39	14.04
Cr_2O_3	0.184	0.183	0.303	0.396	0.038	
FeO_t	7.49	8.57	8.09	9.57	9.7	10.85
MnO	0.165	0.125	0.133	0.164	0.197	0.17
MgO	19.9	46.26	43.28	39.8	8.28	8.3
CaO	9.93	0.59	1.75	2.01	9.44	9.67
Na_2O	0.961	0.081	0.127	0.469	4.14	3.2
K_2O	0.005	0.005	0.017	0.029	2.18	2.27
Total	99.44	98.7	98.06	98.46	95.73	96.67
Mg/(Mg+Fe)	82.6	90.6	90.5	88.1	60.3	43.34
Co	53.3	125.	113.	109.	36.5	NA
Ni	560.	2750.	2270.	2010.	190.	NA
Rb	0.24	-	-	-	82.7	NA
Sr	18.6	-	-	-	1100.	NA
Ba	9.	-	-	-	924.	NA
La	0.44	0.19	0.25	0.78	68.5	NA
Ce	1.77	-	-	2.5	124.5	NA
Sm	1.15	0.033	0.088	0.28	8.8	NA
Eu	0.45	0.017	0.037	0.11	2.79	NA
Tb	0.4	-	-	-	1.07	NA
Dy	3.	-	-	-	5.71	NA
Yb	1.83	0.09	0.16	0.25	2.37	NA
Lu	0.29	0.015	-	0.036	0.33	NA

Table 1

Major (wt.%) and trace element (ppm) contents of host basanite and ultramafic xenoliths from Kapfenstein, Austria.

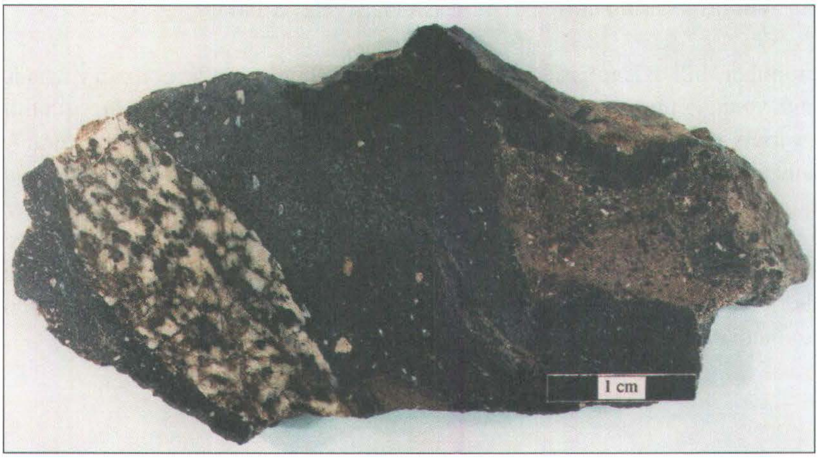

Photo b
Gabbro xenolith in a basaltic tuff.

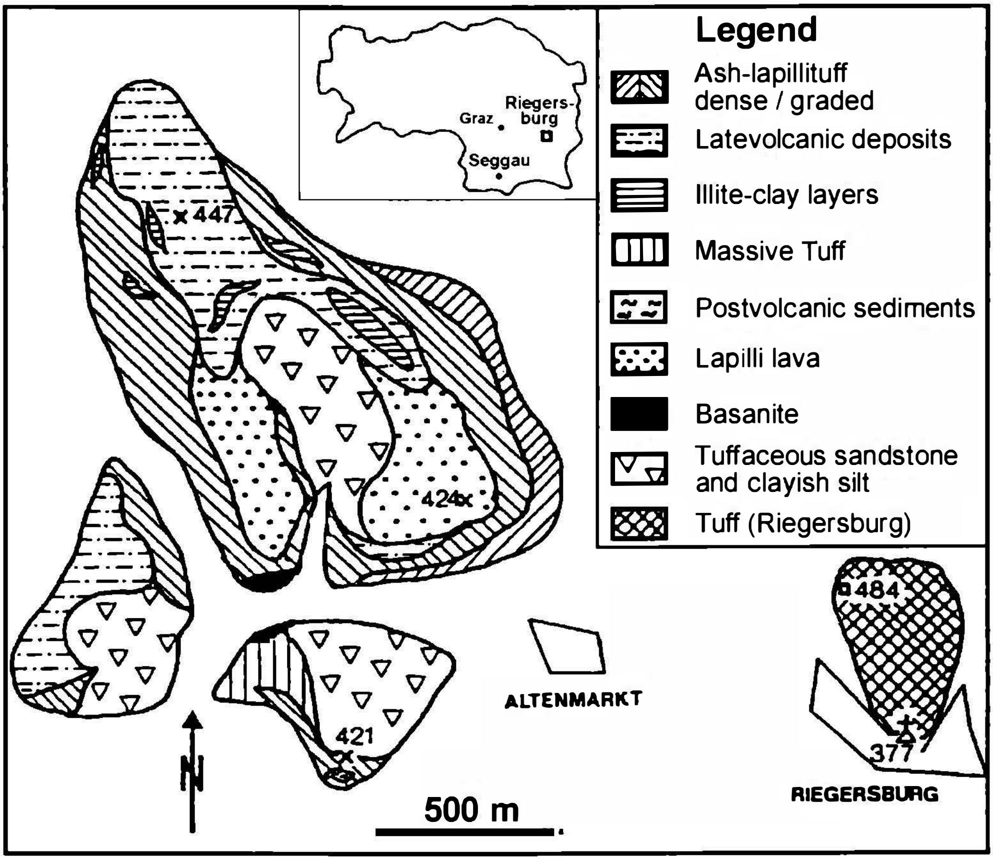

Fig. 3
Simplified geological map from Altenmarkt near Riegersburg.

Ultramafic mantle xenoliths from Kapfenstein, Eastern Styria, Austria

Location 2: The prominent hill of Kapfenstein, adorned with yet another castle, is also a volcanic edifice of the second, younger phase of volcanism in the Styrian basin (Fig.1, photo c), with tuff cones and a wide variety of xenoliths of both crustal and upper mantle origin. A considerable number of ultramafic mantle xenoliths of variable composition (see below) have been found and investigated from this site. They occur embedded in mainly porphyroclastic sediments that also contain a high percentage of crustal xenoliths, including large rounded pebbles from river beds. The various features of the volcano-sedimentary environment are described and are visible in exposures along the "Geotrail" Mantle xenoliths can be found at a few locations along the trail and in exposures immediately beneath the castle.

Photo c
Kapfenstein castle (seen from the south).

Kapfenstein was recognized early as a locality for mantle xenoliths and has subsequently became a classical one (SIGMUND, 1899, SCHADLER, 1913, SCHOCKLITSCH, 1933). Analytical data on xenoliths from Kapfenstein have been reported by SCHADLER (1913), ROSS et al, (1954); KURAT (1971), KURAT et al., (1976, 1977a, 1980, 1991), VASELLI et al., (1996a), DOBOSI et al., (1999) and SCHNEIDER, (2004). Based on analytical data, KURAT (1971) ascertained the upper mantle origin of these rocks. In addition, KURAT et al., (1977b, 1980, 1991), VASELLI et al. (1996a) reported extensive geochemical data of these xenoliths with the objective of characterizing the upper mantle below Kapfenstein and to shed light on the genesis of these rocks.

Petrographic descriptions of the xenoliths and the host rocks (from KURAT et al., 1980)

Host basanite: This is a vesicular vitrophyric rock with abundant phenocrysts of augite and plagioclase; common are xenoliths of olivine, orthopyroxene, clonopyroxene, and spinel which obviously have been derived from peridotite inclusions; interstitial glass is very alkali-rich and bears variable amounts of small plagioclase laths and titanian magnetite.

Ultramafic xenoliths: Rocks are almost exclusively members of the spinel-lherzolite-harzburgite-dunite suite with spinel-lherzolite being by far the most abundant rock type. Some of the characteristic ultramafic xenoliths are described below:

Garnet-spinel-websterite: This rock consists of clinopyroxene (60 vol.%), orthopyroxene (30 vol.%), 5–10% spinel and minor amounts of garnet and opaques. Texture is granoblastic and clinopyroxenes show extensive exsolutions of orthopyroxene, spinel and garnet. All the garnet present has apparently exsolved from clinopyroxene.

Hornblende-spinel lherzolite: This is a typical equigranular granoblastic rock with dispersed greenish-brown titanium pargasites. Close to the hornblendite contact there are large sheets of phlogopite and a zone of large clinopyroxene crystals.

Hornblendite: consists almost exclusively of coarse grained (ca. 1 cm) titanium pargasite which has a tendency to form equilibrium triple points. Sulfides (now oxidized) are generally present as droplike inclusions within large amphibole crystals. Olivine (round inclusions in amphibole) and phlogopite (intergranular) are rare and irregularly distributed.
Amphibole lherzolite: medium grained; typical equigranular granoblastic; green spinel; clinopyroxenes have sometimes orthopyroxene exsolution lamellae; brown titanium pargasite is located around spinel grains. The overall mineral chemistries are indistinguishable from normal amphibole-free lherzolites. The amphibole has low K-content suggesting that it was formed late by H_2O-metasomatism.
Coarse grained lherzolite: This is part of the normal dunite-lherzolite series. Spinels are brown and both clino- and orthopyroxenes have exsolution lamellae. The rock is slightly deformed and some small scale fine-grained recrystallization have developed at grain boundaries.
Coarse-grained harzburgite: is part of the normal dunite-lherzolite series with dark brownish-red spinels and ganoblastic texture.

Modal mineral composition

Based on electron microprobe analyses of minerals and bulk analyses of rocks the modal contents of olivine, orthopyroxene, clinopyroxene, amphibole and spinel in the Kapfenstein xenoliths were calculated (KURAT et al., 1980). The harzburgite xenolith consists of 83.4 vol.% olivine, 13.7 vol.% orthopyroxene, 2.2 vol.% clinopyroxene and 0.6 vol.% spinel; whereas the different types of lherzolites (described above) contain 57.2 – 76.4 vol.% olivine; 14.4 – 30.2 vol.% orthopyroxene, 7.9 – 14.2 vol.% clinopyroxene; 1.2 – 4.2 vol. % spinel and in the amphibole-bearing lherzolites, 0.8 – 6.6 vol.% amphibole.

Chemical composition of the host rock and xenoliths

Basanite: The Kapfenstein basanite is very similar in composition to several nepheline basanite lavas from the Styrian volcanic arc. Major and trace element contents are presented in Table 1 (taken from KURAT et al., 1980). The La/Yb ratio for the Kapfenstein basanite is very high (Fig. 4). This is due to stronger enrichment of light rare earth elements (LREE) relative to the heavy rare earth elements (HREE). Since the Mg/(Mg+Fe) ratio of the Kapfenstein basanite (0.63) and its Ni and Co content are high, the strong LREE enrichment cannot be attributed to fractional crystallization but rather indicate a primitive liquid derived by a small degree of partial melting of the upper mantle rocks (KURAT et al., 1980). The high degree of REE fractionation clearly places the site of melt generation into the deeper parts of the upper mantle where garnet peridotites are stable (KAY & GAST, 1973).

	Kapfenstein	Gerce	Szentbekalla	Szigliget	Bondorohegy
Total sample/N/	38	112	138	113	85
Protogranular & protogranular-porphyritoclastic	100	10	67	31	31
Porphyroclastic	-	81	-	-	-
Equigranular	-	5	14	65	25
Granoblastic tabular	-	-	-	-	37
Poikilitic	-	4	19	4	7

Table 2

Percentage abundance of xenolith textural types of the Transdanubian Volcanic Region (after KURAT et al., 1991).

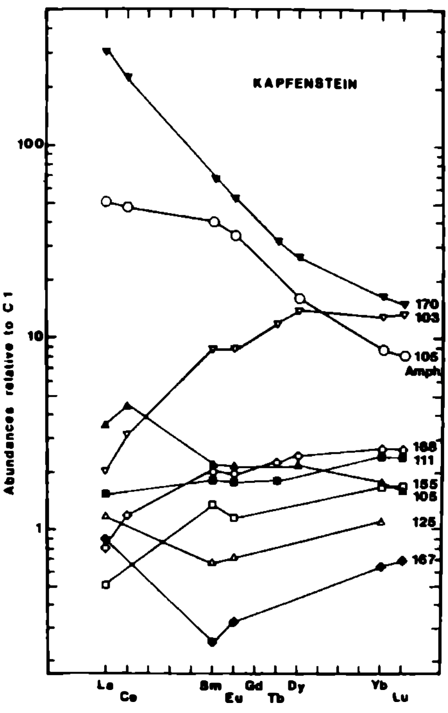

Fig. 4

REE pattern (normalized to C1) of samples from Kapfenstein, Austria (from KURAT et al., 1980). 170: host basanite; 103: websterite; 168, 111, 155, 105 and 125: lherzolites; 167: harzburgite.

Spinel-lherzolite-harzburgite main series: The major element composition of spinel lherzolite and harzburgite xenoliths from all over the world is similar (MAALØE & AOKI, 1971) and varies in between narrow limits. Comparison of the lherzolite suite from Kapfenstein with data for xenoliths from other localities reveals some remarkable features of the Kapfenstein samples:

i) Most Kapfenstein samples have extremely low K contents (ca. 10 ppm). Based on the low concentration of K in the xenoliths even minor contaminations of the Kapfenstein xenoliths by the host basanite is improbable.

ii) Spinel lherzolite has the lowest Mg/(Mg+Fe) ratio and the highest Al and Ca contents of the Kapfenstein main lherzolite series. Its CaO content (3.04 %) is among the highest reported so far from lherzolites (KURAT et al., 1980). Except for a depletion of highly incompatible elements, this xenolith closely approaches the composition of postulated primordial mantle material (RINGWOOD, 1975; PALME et al., 1978).

Textures of xenoliths in the TVR

It has been widely recognized that textures of peridotite xenoliths in alkali basalts, lamprophyres, and kimberlites directly reflect the structural state of the upper mantle as well as ancient tectonic events and deformations (e.g. WITT & SECK, 1987 among others). Protogranular rocks are essentially undeformed, porphyroblastic, and equigranular; fluidal and disrupted textures represent progressively deformed states of the upper mantle (MERCIER & NICOLAS, 1975; HARTE, 1977). If one considers the geographic distribution and abundances of texture types across the TVR (Table 2) it becomes clear that this distribution is not random and shows characteristics similar to those noticed in the Massif Central by COISY (1977). In the external region of the TVR (below Kapfenstein) the upper mantle is essentially undeformed or only slightly deformed (dominance of protogranular textures), whereas in the internal region (Balaton, Hungary) both deformed (equigranular) and undeformed (protogranular) xenoliths occur. Porphyroclastic textures predominate in areas situated between the external and internal regions. Thus, the textures of upper mantle xenoliths from inside and outside the TVR seem to support the diapir model of EMBEY-ISZTIN et al. (1989, 1990).

Mineral chemistry of Kapfenstein ultramafic Xenoliths

The chemical variability of the rock-forming minerals corresponds to that observed in peridotite xenoliths from many other localities. Thus, the composition of olivine varies between Fo 89-92.5, NiO between 0.3-0.4 wt.%, CaO 0.03-0.08 wt.%. Most orthopyroxenes of Kapfenstein xenoliths have CaO contents between 0.6-0.9 wt.%. The composition of spinels exhibits the greatest chemical range (Cr-number 6-59; mg-number 57-78). Amphiboles have generally pargasitic compositions and appear to be equilibrated with the coexisting phases except in some samples where amphibole compositions vary from grain to grain and with distance from the hornblendite vein.

In Figs 5, 6 & 7 some mineral chemical data for olivines, spinels, and clinopyroxenes respectively from Kapfenstein are compared with those from other TVR localities. The frequency distribution of Fo-contents (Fig. 5) shows a regular unimodal pattern with a pronounced peak in the case of Kapfenstein xenoliths but a flat distribution pattern for the rocks of other TVR occurrences. The mg-cr diagrams (Fig. 6) show that the compositional variability of spinels falls within the limits for xenolith spinels of world-wide occurrences as given by IRVINE (1967), however, the higher proportion of medium and high Cr spinels in the Hungarian xenoliths is evident. In contrast, the Kapfenstein peridotite xenoliths show a unimodal distribution with a predominance of low Cr spinels. In the Cr_2O_3-Al_2O_3 plot for clinopyroxenes (Fig. 7) the majority of the Kapfenstein xenoliths clusters between the lines representing $Al_2O_3 : Cr_2O_3$ ratios between 5 and 10, whereas the respective values are between 2 and 10 for xenoliths of other TVR localities. All these data indicate that the Kapfenstein xenoliths are much less fractionated than all other TVR xenoliths. Apparently, the undeformed xenoliths from Kapfenstein are mainly primitive and unfractionated.

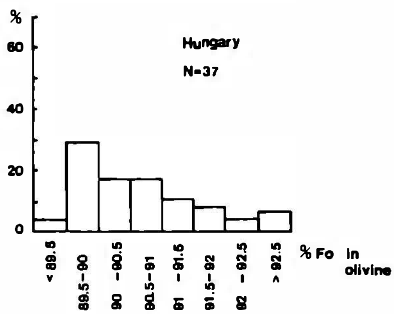

Fig. 5

Frequency distribution of molecular Fo-contents of xenolithic olivine from Kapfenstein and from Hungarian TVR localities (from KURAT et al., 1991).

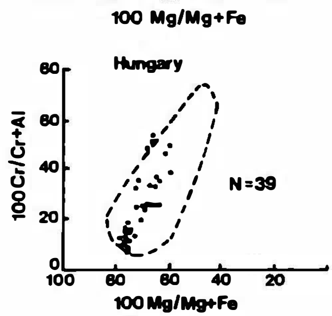

Fig. 6

Cr-number vs. mg-number in spinels from Kapfenstein and from other TVR localities (from KURAT et al., 1991).

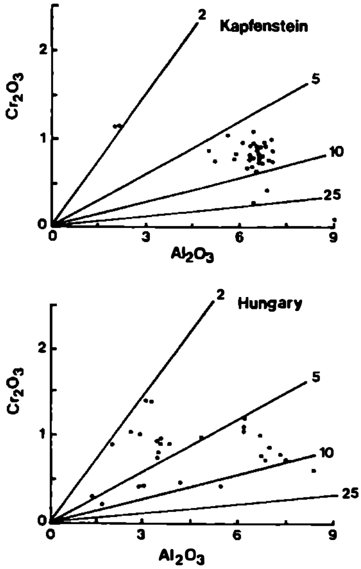

Fig. 7

Weight percent Cr_2O_3 vs. Al_2O_3 in clinopyroxenes from Kapfenstein and other TVR localities. Straight lines indicate different Al_2O_3/Cr_2O_3 ratios (from KURAT et al., 1991).

Crystallization temperature and pressure of the ultramafic xenoliths in the TVR

The frequency distribution of equilibrium temperatures (Fig. 8) also exhibits striking differences. Kapfenstein xenoliths show a very regular pattern and a maximum at the interval of 1000 – 1050°C using WELLS (1977) geothermometer. In contrast, the pattern is flat for the other samples. The P-T equilibrium (Fig. 9) conditions (VASELLI et al., 1996a) as derived by the single-pyroxene thermobarometry of MERCIER (1980) shows that the Hungarian xenoliths differ from the Kapfenstein xenoliths by a wider range in both P and T. While most equilibrium conditions for Kapfenstein xenoliths cluster between 15 and 20 kb at temperatures mostly about 150°C above the geotherm, those for the Hungarian xenoliths spread over a much wider P-T range.

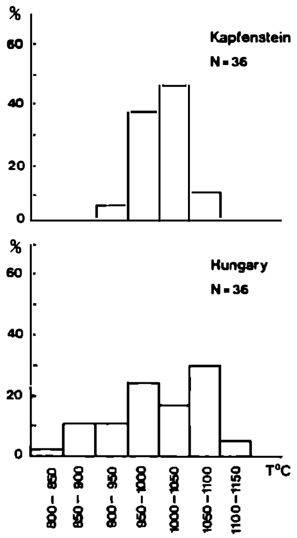

Fig. 8

Frequency distribution of equilibrium temperatures for Kapfenstein and for Hungarian TVR peridotite xenoliths (from KURAT et al., 1991).

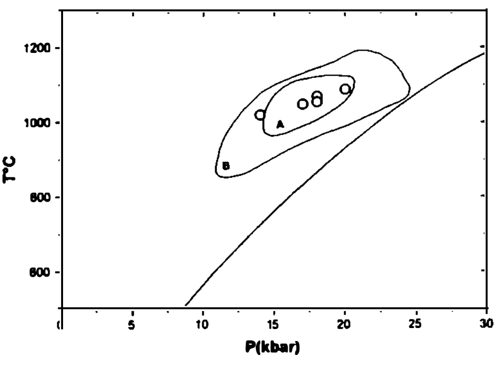

Fig. 9

Equilibrium P-T conditions for spinel-lherzolite xenoliths from Kapfenstein. Line indicates the oceanic geotherm of CLARKE & RINGWOOD (1964). A and B fields indicate ultramafic xenoliths from Kapfenstein and Central Hungary, respectively (from KURAT et al., 1991 and VASELLI et al., 1996a).

Petrogenesis

Petrological analyses of several ultramafic xenoliths from Kapfenstein, Austria, suggest that the upper mantle below Kapfenstein has been sampled by the basanite lava ca 50-80 km depth (KURAT et al., 1980). In spite of the large ca.30 km sampling profile, the upper mantle below Kapfenstein appears to be of rather monotonous composition with lherzolite being by far the most common rock type. Furthermore, these lherzolites generally show little variation in mineral composition which implies little variation in bulk composition for a large proportion of lherzolite samples. The overall range of modal composition reaches from lherzolite to dunite and is characterized by continuously changing mineral compositions. The most apparent variables are the Fe/Mg ratio of the silicates and the Cr content of spinel. The Cr content of spinels tends to systematically increase with decreasing Fe/Mg ratio of the silicates. Within these suite of rocks ranging from high $(Fe/Mg)_{ol}$ and low $(Cr/Al)_{sp}$ to low $(Fe/Mg)_{ol}$ and high $(Cr/Al)_{sp}$, bulk major, minor and trace element contents vary similarly in a regular manner. According to KURAT et al., (1980) this rock suite represents a residual sequence formed by different degrees of partial melting in the upper mantle ranging from a "primitive" lherzolite to a highly depleted harzburgite. Only very few samples bear evidence for local inhomogeneities as well as evidence for mobilization processes taking place within the upper mantle:

i) the hornblendite represents a wet alkali-basaltic mobilisate which crystallized within the upper mantle. This basaltic mobilisate not only formed the hornblendite but also caused

ii) a basalt metasomatism of a normal lherzolite which led to formation of the amphibolite lherzolite.

iii) two amphibole-lherzolites give evidence for H_2O metasomatism taking place within the upper mantle. The overall bulk and mineral compositions of these rocks fit perfectly the normal lherzolite-dunite sequence. Amphibole in these samples has been formed by reaction of spinel with clinopyroxene and water. No contamination of these samples by larger amounts of incompatible elements is detectable. Thus, addition of solely water to normal lherzolite, causing formation of amphibole characteristically poor in K, is responsible for the formation of these rocks.

iv) the garnet-spinel websterite sample provides evidence for the formation and trapping of tholeiitic liquids within the upper mantle below Kapfenstein.

Investigations of trace element distributions between different minerals not only revealed that the lherzolite-dunite series is indeed a depletion series but also showed that several trace element distribution coefficients are strongly dependent on equilibration temperature. The bulk composition of Kapfenstein xenoliths varies from depleted mantle harzburgites to scarcely depleted spinel lherzolites, and geochemically and isotopically they are rather heterogeneous. Geochemical and textural similarities to xenoliths from the Persani Mts (Eastern Transylvanian Basin, Romania) suggest similar deformation, depletion and enrichment processes in the mantle underlying these two areas. The Styrian Basin is on the westernmost edge of the diapiric upwelling which geophysical investigations indicate is centered in the Balaton region of the TVR.

Thus it is not surprising that the deformation and geochemical signatures of the Styrian Basin lithospheric mantle resemble those found in the easternmost edge at Persani Mts. (VASELLI et al., 1996a).

A metasomatic process that has taken place in the upper mantle beneath Southeastern Austria has been discussed by DOBOSI et al., (1999). Based on a LA-ICP-MS study of the different mineral phases of the ultramafic xenoliths, these authors derived a non-equilibrium trace element distribution between clinopyroxenes and concluded that a metasomatic event took place shortly before the rocks were delivered to the Earth's surface. Thus, metasomatism and volcanic activity seem to be related and a consequence of the rising diapir underneath the Pannonian Basin. Several metasomatic events, probably related to fluids dominated by CO_2, water, or both were taking place. However, the intensity of that activity was generally low, as was the tectonic activity in the border zone of the Pannonian Basin.

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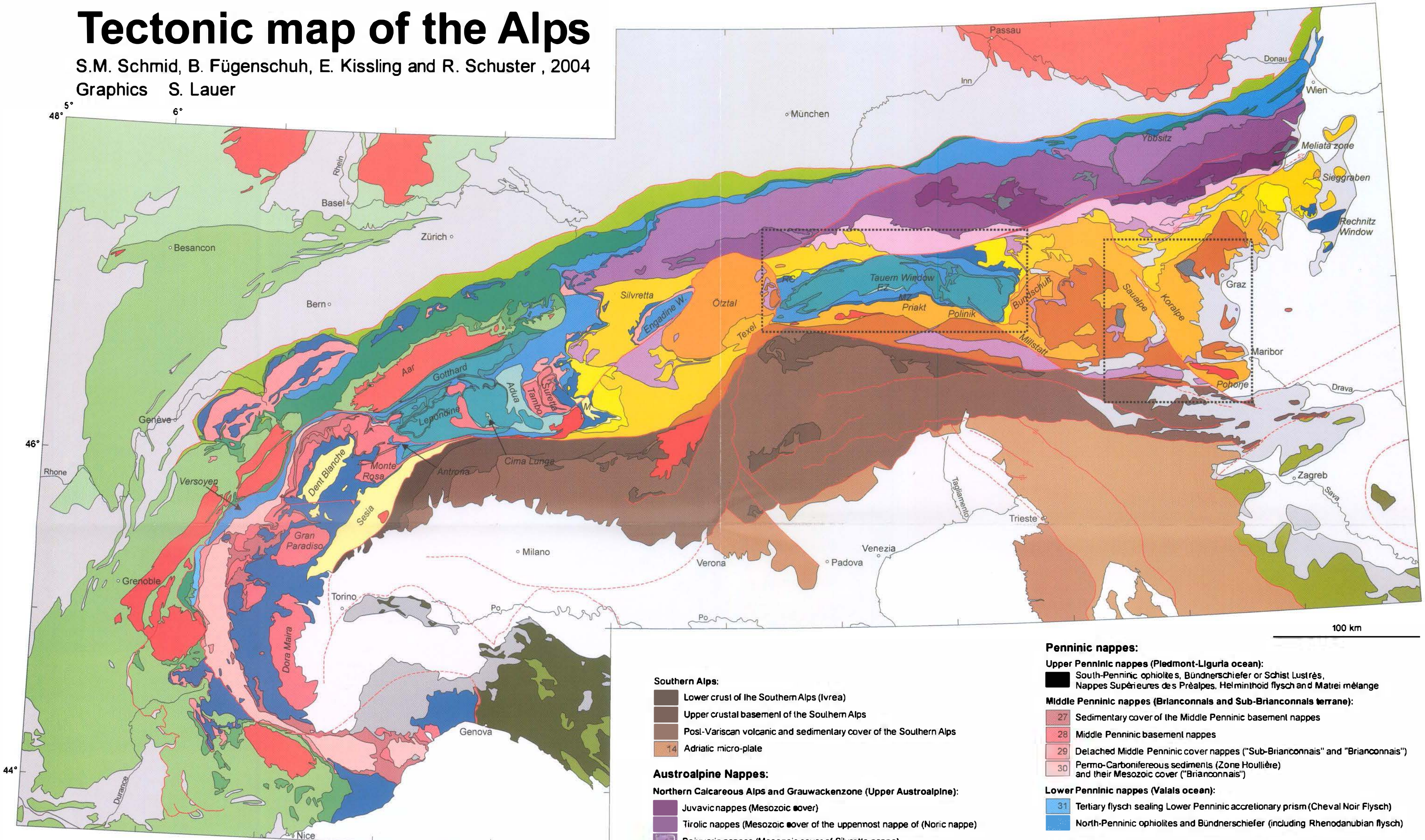
Tectonic map of the Alps

S.M. Schmid, B. Fügenschuh, E. Kissling and R. Schuster , 2004
Graphics S. Lauer



Southern Alps:
- Lower crust of the Southern Alps (Ivrea)
- Upper crustal basement of the Southern Alps
- Post-Variscan volcanic and sedimentary cover of the Southern Alps
- 14 Adriatic micro-plate

Austroalpine Nappes:

Northern Calcareous Alps and Grauwackenzone (Upper Austroalpine):
- Juvavic nappes (Mesozoic cover)
- Tirolic nappes (Mesozoic cover of the uppermost nappe of (Noric nappe)
- 17 Bajuvaric nappes (Mesozoic cover of Silvretta nappe)
- 18 Greywackyzone

Upper Austroalpine basement nappes:
- 19 Mesozoic cover of the Austroalpine basement nappes
- 20 Drauzug-Gurktal nappe system (e.g. Tonale series, Steinach nappe, Basement of Drauzug, Gurktal nappe, Graz Paleozoic)
- 21 Ötztal-Bundschuh nappe system (Ötztal and Bundschuh nappes)
- 22 Koralpe-Wölz nappe system (Schneeberg, Millstatt, Wölz, Saualpe-Koralpe Complex)
- 23 Silvretta-Seckau nappe system (Campo-Sesvenna-Silvretta nappes, Schladming, Seckau Complex)

Lower Austroalpine nappes:
- 24 Lower Austroalpine nappes (e.g. Ela, Err-Bernina, Radstätter Tauern, Semmering, Wechsel nappes)
- 25 Nappes derived from the Margna-Sesia fragment (Margna-Sella, Sesia-Dent Blanche nappes)

Penninic nappes:

Upper Penninic nappes (Piedmont-Liguria ocean):
- South-Penninic ophiolites, Bündnerschiefer or Schist Lustrés, Nappes Supérieures des Préalpes, Helminthoid flysch and Matrei mélange

Middle Penninic nappes (Brianconnais and Sub-Brianconnais terrane):
- 27 Sedimentary cover of the Middle Penninic basement nappes
- 28 Middle Penninic basement nappes
- 29 Detached Middle Penninic cover nappes ("Sub-Brianconnais" and "Brianconnais")
- 30 Permo-Carboniferous sediments (Zone Houillère) and their Mesozoic cover ("Brianconnais")

Lower Penninic nappes (Valais ocean):
- 31 Tertiary flysch sealing Lower Penninic accretionary prism (Cheval Noir Flysch)
- North-Penninic ophiolites and Bündnerschiefer (including Rhenodanubian flysch)

Sub-Penninic nappes (distal European margin):
- Mesozoic cover of Sub-Penninic basement nappes (including cover of "Gotthard Massif")
- Non-eclogitic Sub-Penninic basement nappes (including "Gotthard massif")
- 35 Eclogitic Sub-Penninic basement nappes

Northern Alpine foreland and Helvetic nappes:
- Helvetic and Ultrahelvetic nappes (including Combeynol and Tavetsch "Massifs")
- Helvetic flysch
- 38 Subalpine molasse
- 39 Deformed autochthonous and para-autochthonous pre-Teriary cover of the northern Alpine foreland, including the Jura Mountains
- 40 Undeformed pre-Tertiary cover of the Northern Alpine foreland
- 41 External massifs of the Alps and Variscan basement of the undeformed Northern Alpine foreland

Various units:
- 1 Plio-Pleistocene (Po-plain, Pannonian basin)
- 2 Tertiary cover in general (Molasse, Rhine Graben, intramontane basins)
- 3 Oligo-Miocene post-tectonic cover (unconformable on Ligurian Alps and Apennine)
- Gosau beds (Late Cretaceous to Paleogene post-tectonic cover of Austroalpine nappes)
- Periadriatic Intrusions

Dinarides:
- Tizaunit
- 7 Internal Dinarides (including Dinaridic ophiolite zones)
- 8 External Dinarides

Apennine:
- Ligurian nappes
- 10 Tuscan nappes