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Deformation phases and age data of the Austro-Alpine – Penninic plate boundary, Eastern Tauern Window

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Introduction

One of the main questions regarding the tectonic evolution of the Eastern Alps is the relation between nappe stacking and metamorphism in the Austro-Alpine unit to the subduction of the Penninic units beneath, as new data challenge important assumptions of present (plate)tectonic models (Hawkesworth et al. 1975, Frisch 1979, Tollmann, 1987, Frank 1987, Behrmann 1990). These models relate the early to middle Cretaceous nappe stacking and Barrovian type metamorphism in the Austro-Alpine unit to the subduction of the South Penninic ocean beneath or to the final collision with the Middle Penninic basement complex, exposed in the Tauern Window. Recognition of a Cretaceous high-P metamorphism (Thöni and Jagoutz 1992) in the Austro-Alpine unit in the last years points to a Cretaceous subduction of the AA and hence a lower plate position for this unit during that time span, rather. The two mega-units also show very different timings of the metamorphic evolution, but very similar metamorphic paths (eclogite facies followed by amphibolite facies). In the Austro-Alpine, the temperature peak occurred in the early Late Cretaceous, cooling below *c.* 300°C was completed in the late Cretaceous, already (Fig. 1). In the Penninic units, the thermal peak falls into the late Palaeogene, cooling into the Miocene (Frank et al 1987) (Fig. 2).

The following is a presentation and discussion of mainly structural and thermochronological data from the Eastern Tauern window, where in the area of the Malta and Lieser valleys, a continuous profile from the deepest tectonic units of the eastern Tauern window up to the Middle Austro-Alpine units is exposed (Fig. 3). It is situated ideally, therefore, to study the relationships between the two mega-units. The area of the eastern TW includes three tectonic mega-units, the Austro-Alpine upper plate, the Glockner Nappe and the basement units of the Venediger Nappe (Fig. 3). The Austro-Alpine unit consists of three individual nappes in the area, that were stacked during the Cretaceous and subsequently thrusted onto the Penninic unit. The Penninic unit comprises the remnants of the South Penninic oceanic crust, the Glockner Nappe, and Middle Penninic units comprising a basement complex and an overlying Permo-Mesozoic cover unit. Between the Glockner Nappe and the parautochthonous basement are several nappes that were derived from the Middle Penninic continental complex (Kurz et al. 1998).

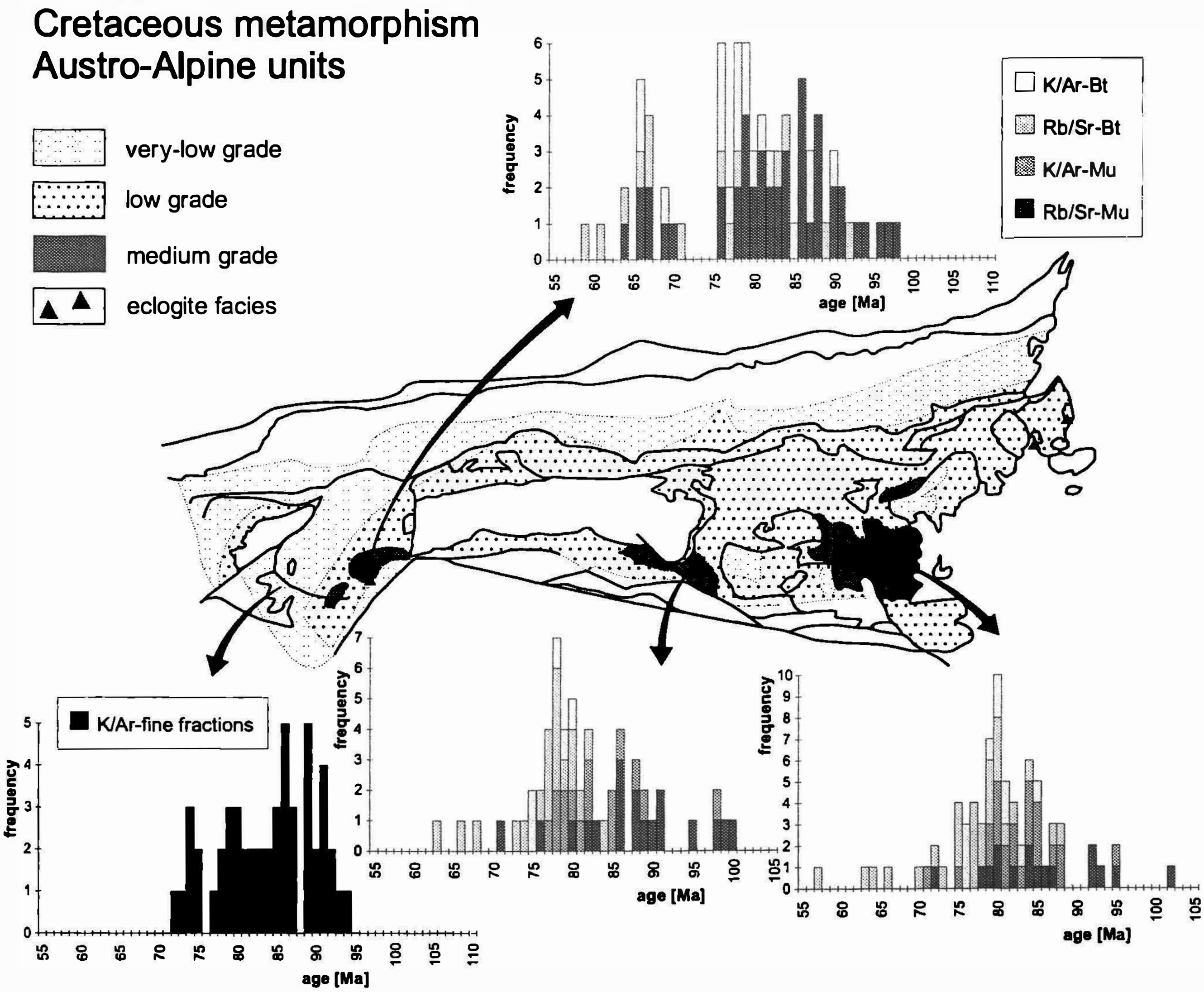
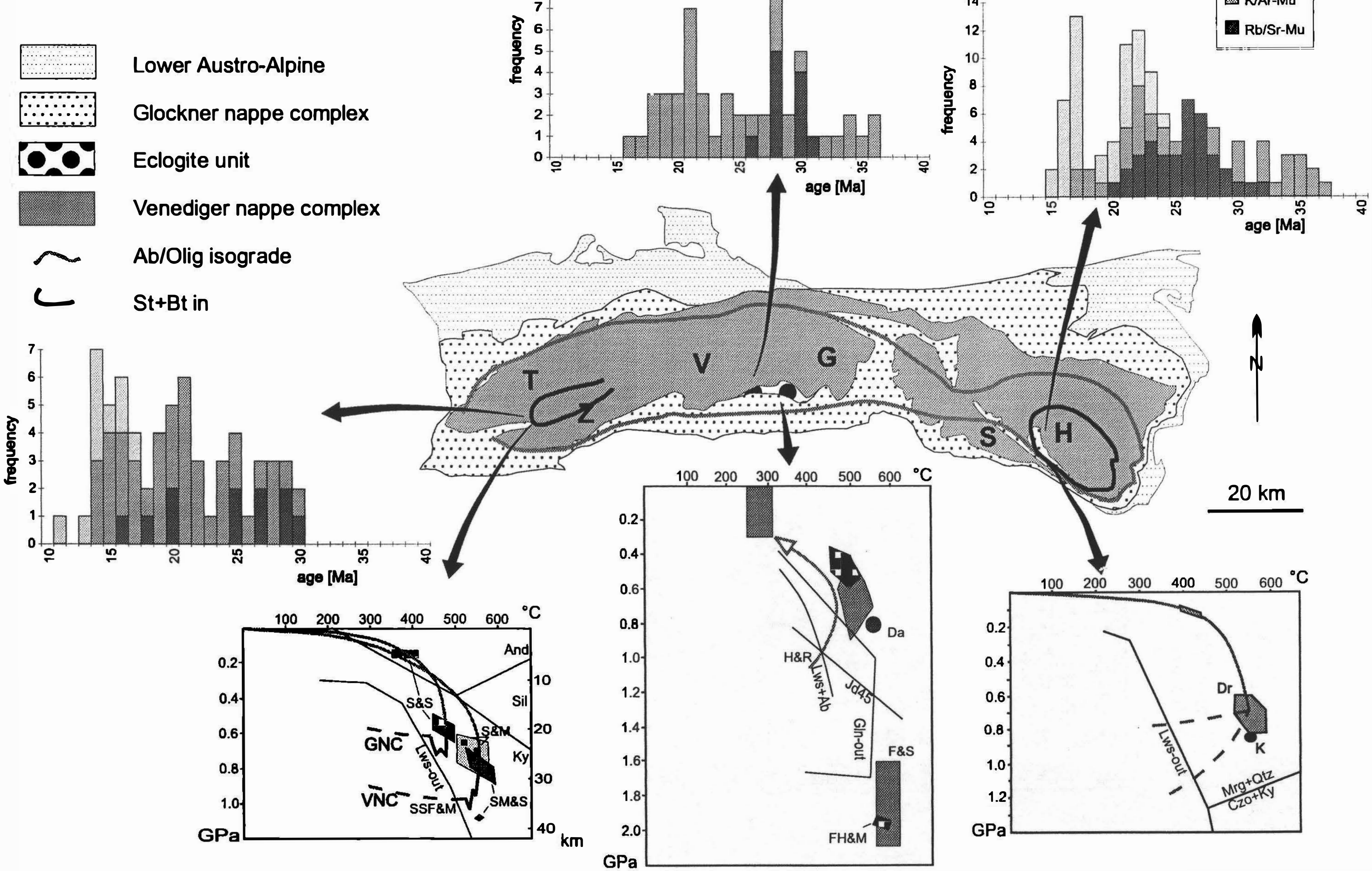


Fig. 1: Map of the Cretaceous metamorphism in the Austro-Alpine unit with radiometric age data from various systems (from Genser et al. 1996; see references therein).

Fig. 2: Alpine metamorphism in the Tauern window with p-T paths and radiometric age data (from Genser et al. 1996; see references therein).

Alpine metamorphism Tauern Window



Penninic unit

From bottom to top we can distinguish the following tectonic units (Fig. 3), which can be correlated over the entire Tauern window (Kurz et al. 1998).:

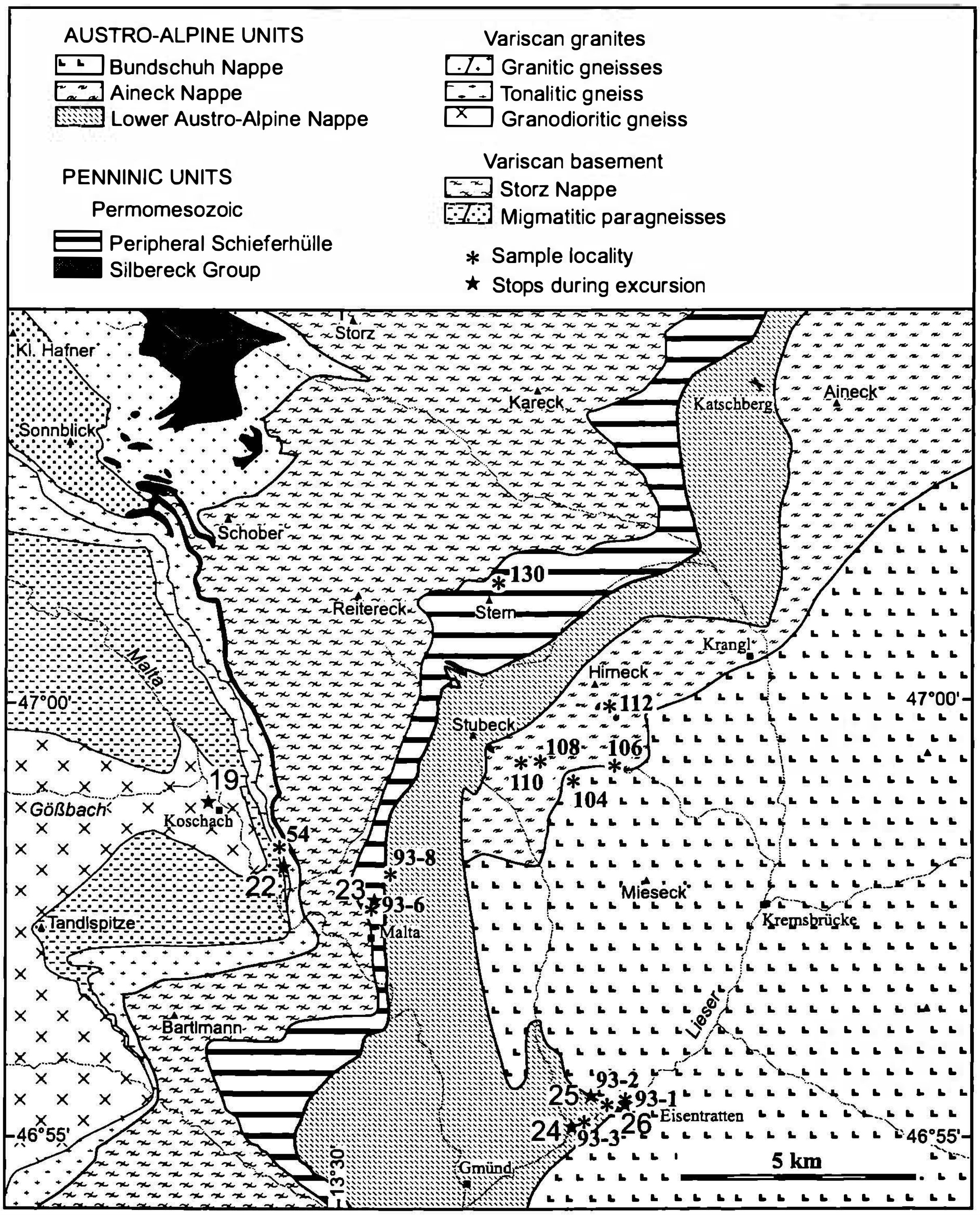


Fig. 3: Geological map of the area of the eastern Tauern window, Lieser and Malta valleys.

1. Parautochtonous basement consisting of a pre-Permian basement complex intruded by Variscan granitoids, the Zentralgneis (Central gneisses). On top is a primary Permo-Mesozoic cover sequence, the Silbereck Group in this area.
2. The Eclogite zone, that occurs only in the middle part of the Tauern window.
3. Nappes that consist of basement and cover parts that were derived from continental margin sequences of the Middle Penninic terrane.
4. The Glockner nappe, comprising ophiolites and mainly volcano-sedimentary sequences of the South Penninic oceanic basin.
5. The Matrei and the Nordrahmen units, melange units deposited during the active margin stage.

In detail, the basement essentially consists of migmatitic paragneisses and minor micaschists and amphibolites (e.g., Frisch et al. 1993). The Variscan granitoids represent intrusions ranging from tonalites to granites, with the main members (Holub and Marschallinger 1989, Marschallinger and Holub 1991, Finger et al. 1993): a high-K, calc-alkaline I-type series with syenite, Malta tonalite, Hochalm porphyrygranite, Kölnbrein leucogranite, and two-mica granite and the Na-rich Göß granodiorites to granites. These Variscan granites occur in several cores, divided by metasedimentary basement units. In the eastern Tauern Window (TW), these are the Göß, Hochalm, Hölltor, Sieglitz and Sonnblick cores.

These basement units are overlain by the post-Variscan, Permo-Mesozoic sedimentary sequence of the Silbereck Group. It comprises basal quartzites, overlain by marbles, cargneuls, dolomites and finally calcschists, phyllites to micaschists and minor greenschists.

Thrusted onto this parautochthonous unit are the Mureck and the Storz Nappe that comprises mainly Variscan metamorphic paragneisses, amphibolites and micaschists (Vavra 1989, Vavra and Frisch 1989, Frisch et al. 1993) and minor granites that intruded during the Variscan (Vavra and Hansen 1991).

The overlying Murtörl unit consists of black albite-phyllites, chloritoid-bearing chlorite-micaschists and graphitic quartzites that are probably of post-Variscan age (because of missing intrusions) and the primary cover of the Storz Group (Kurz et al 1998).

The Schrovin Nappe comprises orthogneisses and mainly Permo-Mesozoic sediments, quartzites, calcite and dolomite marbles and calcschists. It must be derived from a continental shelf sequence, too.

The Glockner Nappe is delineated by some ophiolitic remnants (serpentinites, MOR-basalts) at its base (Höck and Miller 1987). It mainly consists of the so called Bündner schists, calcschists, grading into marbles and phyllites, and greenschists, deposits of a deep oceanic basin. In this area, the relationship of the basement rocks of the Storz Nappe to the overlying sequence of black phyllites, a Permotriassic shelf sequence and the deep-sea sediments of the Glockner facies is obscured by the strong tectonic overprint, expressed in the parallelism of all the lithological boundaries and also in the strong thinning of the units. All the post-Variscan series are therefore often subsumed in the Peripheral Schieferhülle.

Detailed descriptions of the rock successions and lithologies can be found in the papers by Exner (1971, 1980b, 1982, 1983, 1984, 1989).

The oldest brittle to semiductile deformation structures in the Penninic units are overprinted by the main, ductile deformation. Indications of earlier deformations under cooler conditions are imbrications of different rock units and parallel trails of graphitic material, preserved in porphyroblasts (mainly albite), pointing to pressure solution as an early deformation mechanism.

The earliest kinematically interpretable deformation structures are a mylonitic foliation parallel to the lithological boundaries with only few intrafolial isoclinal folds (transposition) and a related N-S trending stretching lineation (Fig. 4). Kinematic indicators, as asymmetric porphyroclasts in granitoids and asymmetric quartz textures, the latter preserved in Triassic quartzites of the Peripheral Schieferhülle, indicate tectonic transport top to the N (Figs. 4, 5).

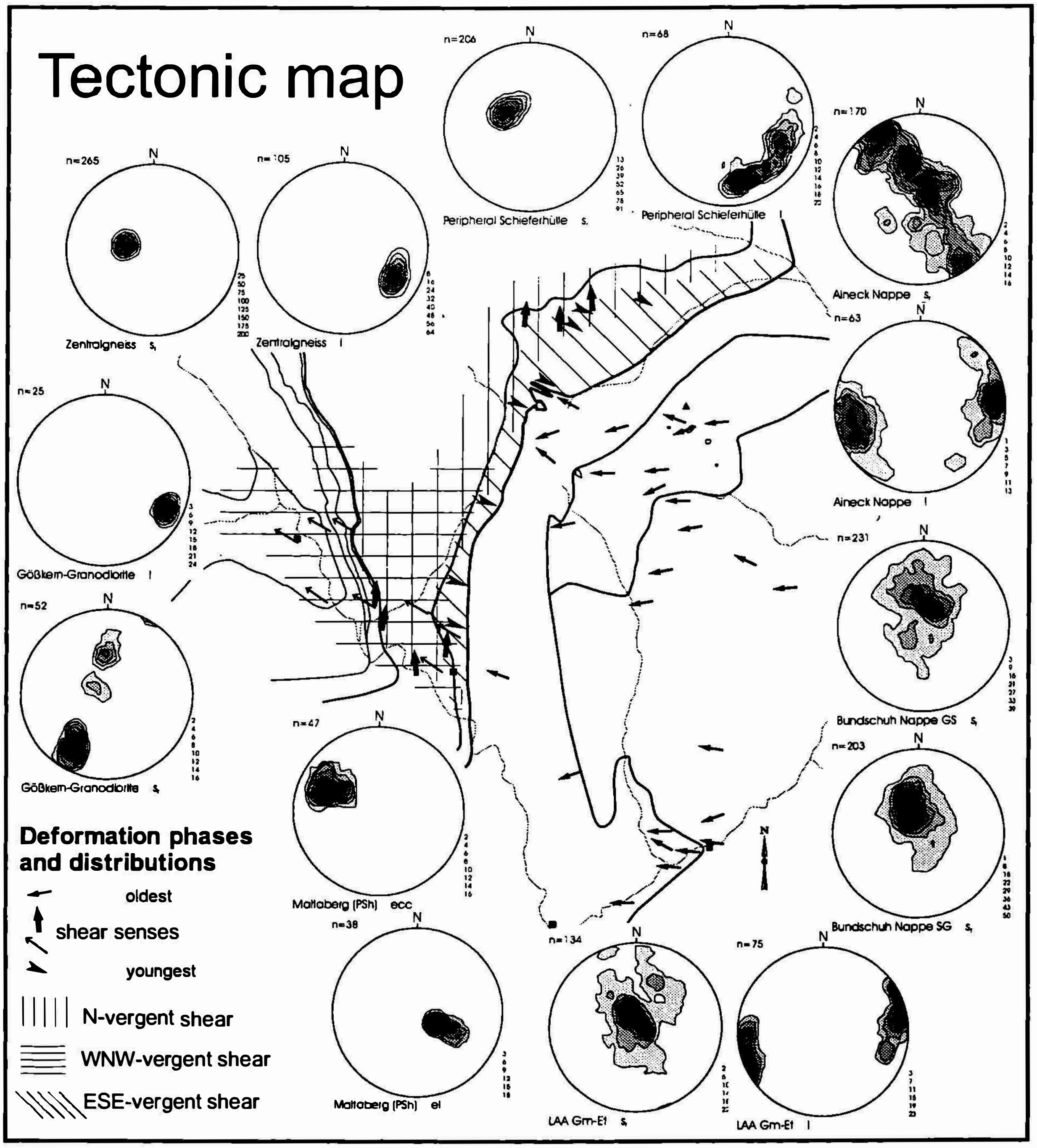


Fig. 4: Tectonic map showing the spread of deformation structures, shear senses, and plots (equal area, lower hemisphere) of foliations and lineations. s_f and l are the penetrative foliations and stretching lineations, ecc and el extensional crenulation cleavage and related extensional lineation, respectively.

This N-S trending stretching lineation can be traced from the Peripheral Schieferhülle down to the base of the Silbereck-Fm., affecting the uppermost part of the basement, sometimes (Fig. 4). A mylonitic foliation with N-S trending stretching lineations can be found throughout the Storz nappe, especially well developed in granitic rocks and amphibolites. In paragneisses and micaschists an older (pre-Alpine?) foliation is folded isoclinally and transposed by this foliation. The structures related to this deformation are best preserved in Triassic rocks of the Peripheral Schieferhülle in northern parts of the investigated area (around Stern). Quartzites, dolomites and intercalated calcite marbles display a strong mylonitic foliation with a pronounced N-S trending stretching lineation. Earlier planar structures, as graphitic trails, are folded isoclinally, but also the mylonitic foliation can show a progressive isoclinal refolding with fold axes parallel to the stretching lineation. During this deformation quartz, calcite, and dolomite recrystallised dynamically. In the Peripheral Schieferhülle this deformation occurred until peak metamorphic conditions were reached, as dolomite was deformed by crystal-plastic mechanisms. Dolomite marbles and quartzites kept their synkinematic deformation features, only calcite shows evidence for a subsequent static recrystallization.

In deeper Penninic units, this deformation preceded the temperature peak, but occurred at higher pressure conditions than those of the metamorphic peak. This deformation started within the stability field of albite, even at tectonic levels that later on reached the oligoclase field during metamorphic peak conditions. Granitic gneisses affected by this deformation display the growth of white mica, with celadonite-rich cores and celadonite-poor rims, pointing to a pressure decrease during this deformation.

The next deformation phase affects almost all of the Penninic units in the investigated area and represents the main deformation phase in the mass of the Variscan granitoids. Only parts of the deeper Peripheral Schieferhülle and also parts of the deeper basement complex remain spared. It develops a mylonitic foliation with a very consistent WNW-ESE trending stretching lineation (Fig. 4). Numerous sense-of-shear criteria, as asymmetric porphyroclasts (δ- and σ-clasts), shear bands, C/S structures and quartz textures (Fig. 5) unequivocally prove shear of top-to-the WNW.

In the higher Penninic parts, especially in the Storz-Nappe, this deformation is expressed in discrete, W-dipping shear bands with WNW-ESE trending striations, without obliterating the penetrative N-S trending stretching lineation. But quartz textures, mainly oblique cross to single girdle c-axes distributions, indicating WNW-directed shearing, prove a penetrative deformation during this phase in these parts, too. In deeper parts, this deformation phase is the first penetrative event, except in country rocks of the Variscan granitoids that display pre-Alpine deformation structures (sometimes even several phases of superposed folding sealed by Variscan intrusions). Along the northern side of the Malta valley the foliation dips to the E to SE, the stretching lineations to the ESE, in the deepest exposed levels the stretching lineation keeps this very consistent plunge to the ESE, but the foliations display a great circle distribution around this lineation (Fig. 4). Across the Malta valley the foliations in the granodiorites of the Gößß core dip gently to the ESE on the northern side of the valley, steeply to the NNE in the middle (Koschach) and moderately to the S on the southern side. In the central part no foliation can be defined, the rocks display apparently uniaxial extension. In the area of steep foliations pronounced stretching lineations also point to deformation in the constrictional field, but some shear criteria, as asymmetric porphyroclasts, asymmetric quartz textures (Fig. 5), and asymmetric distributions of extensional and compressional quadrants of aplitic veins point to general non-coaxial deformation with a right-lateral sense of shear. In the granitoids of the Göß core, discordant aplitic and pegmatitic veins show a strong deformation too, although not very obvious macroscopically. It is expressed in a strong recrystallization of feldspars and quartz, mostly occurring in elongated aggregates, and strong lattice preferred orientations of quartz (Fig. 5).

During this deformation all major rock forming minerals recrystallised dynamically. It continued until peak metamorphic conditions were reached in deeper tectonic levels. Feldspars recrystallised dynamically, with inversely zoned recrystallised grains of oligoclase, pointing to deformation at at least uppermost greenschist facies conditions.

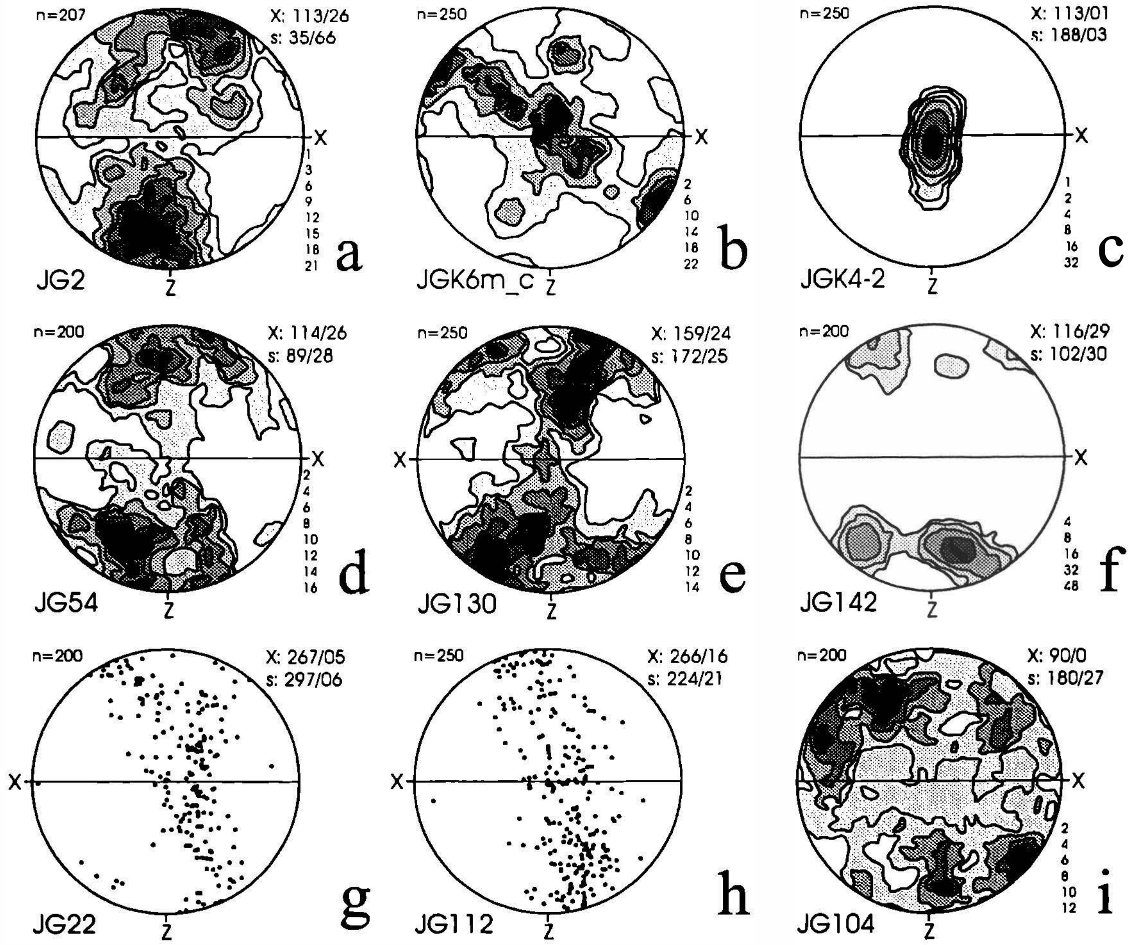


Fig. 5: Quartz-c-axes textures. Equal area, lower hemisphere diagrams, gradation of isolines are given at the right. For location see Fig. 3.
(a) Granodiorite of the Gößcore, Koschach quarry; (b) discordant aplite in granodiorite of Göß core, Koschach quarry; (c) late-stage, discordant shear zone in granodiorite of Göß core, Koschach quarry; (d) tonalite gneiss from the Hochalm core, Rödern; (e) Triassic quartzite from the Schrovin nappe, Stern area; (f) quartzite from Peripheral Schieferhülle, Maltaberg; (g) quartzite from the Lower Austro-Alpine unit, Lieser valley between Gmünd and Eisentratten; (h) Triassic (?) quartzite from the Aineck Nappe, Hirneck; (i) quartzite from the base of the Bundschuh Nappe, Krangl Alm.

The last main deformation event led to the exhumation of the Penninic unit. The main shearing was concentrated within a low-angle fault zone in the top of the Glockner Nappe, displacing the AA nappe stack to the ESE (Genser and Neubauer 1989, Elsner 1991). Structures range from mylonitic shear zones with penetrative deformation, especially in calcschists, to the development of a discrete extensional crenulation cleavage (Fig. 4), often as multiple sets. Other structures are extension veins and boudinage of competent rock layers. Numerous shear criteria prove shearing top-to-the-ESE. This deformation started at elevated temperatures (crystal-plastic deformation of quartz), but continued until cool, brittle conditions under the same kinematic frame (Kurz et al. 1994). In deeper parts, flat-lying, conjugate shear zones are related to this event. Prominent examples are fine grained, cm-thick shear zones in granitoids of the Göß core, that cross-cut the main foliation. In these shear zones, feldspars, quartz, and biotite recrystallised dynamically, quartz-c-axes textures show a maximum parallel to the Y-axis (Fig. 5). Deformation here also started near peak metamorphic conditions, but can then be followed to cool, brittle conditions within the same kinematic frame.

Austro-Alpine unit

In the area of investigation (Fig. 3), the Austro-Alpine (AA) unit can be divided into three nappes: from the top to the bottom, the (1) Bundschuh Nappe, the (2) Aineck Nappe, and (3) the LAA Nappe (Theiner 1987). These nappes are distinguished by distinct pre-Alpine and Alpine metamorphic conditions (Fig. 7).

The Bundschuh Nappe comprises mainly paragneisses, micaschists and granitic gneisses and shows a two-stage metamorphic evolution. The Bundschuh Nappe shows widespread Variscan amphibolite facies metamorphism, with garnet and staurolite (Exner 1980a). The Alpine metamorphism reached lower amphibolite facies conditions, leading to the growth of a second, Alpine garnet generation, often as rims around pre-Alpine garnet cores (Schimana 1986, Theiner 1987) (Fig. 6). Thermobarometry on the Alpine paragenesis yielded *c.* 600°C and 10 kbar for the Alpine metamorphic peak.

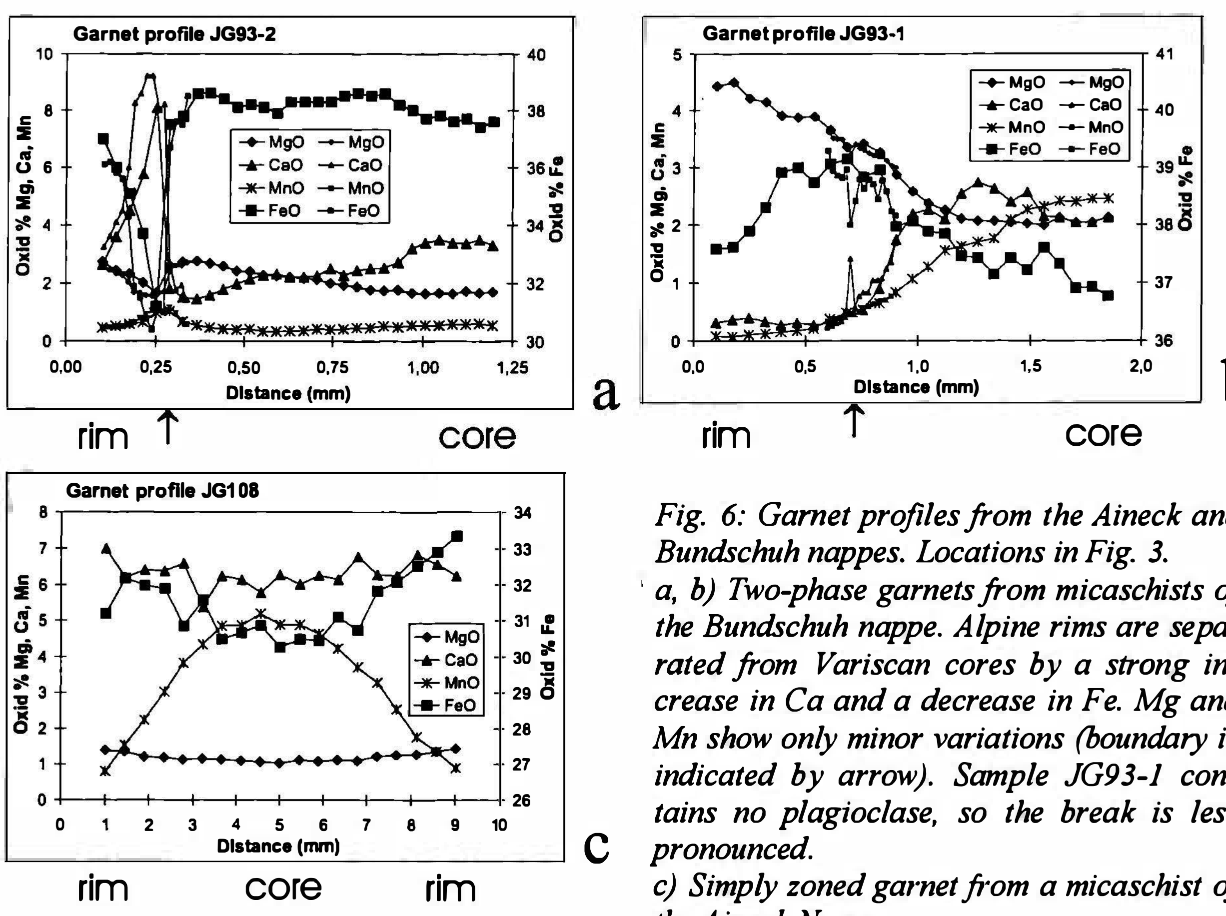


Fig. 6: Garnet profiles from the Aineck and Bundschuh nappes. Locations in Fig. 3.
a, b) Two-phase garnets from micaschists of the Bundschuh nappe. Alpine rims are separated from Variscan cores by a strong increase in Ca and a decrease in Fe. Mg and Mn show only minor variations (boundary is indicated by arrow). Sample JG93-1 contains no plagioclase, so the break is less pronounced.
c) Simply zoned garnet from a micaschist of the Aineck Nappe.

The underlying Aineck Nappe includes garnet-micaschists, paragneisses, and amphibolites and shows only one peak metamorphic assemblage of upper greenschist facies conditions. Garnets typically show continuous zonations and the same suite of inclusion minerals from the core to the rim (Theiner 1987) (Fig. 6). Thermobarometry gave conditions for the metamorphic peak of approximately 540°C and 9 kbar. The Radenthein unit that underlies the Bundschuh Nappe in the south, displays also only a single stage metamorphism, but shows somewhat higher temperatures (amphibolite facies conditions) (Schimana 1986).

The LAA Nappe along the eastern margin of the Tauern window is only a remnant of the prominent development at the north-eastern corner in the Radstädter Tauern. There, the Lower Austro-Alpine unit consists of several nappes, build up of pre-Alpine basement slices (para- and orthogneisses, often retrogressed) and thick Permo-Mesozoic cover units of a terrestric to shallow marine evolution (e.g., Tollmann 1977, Becker 1993). In this area, the only remaining nappe displays an inverted tectonic and metamorphic position with pre-Alpine relics of upper greenschist facies minerals, as e.g. garnet, in tectonic higher parts, and only lower greenschist facies conditions in deeper parts. This setting is also evidenced by a remnant Permo-Mesozoic cover sequence at the base of the unit, that is inverted too (Exner 1971, 1982).

The main deformation event in the Bundschuh Nappe, related to thrusting, occurred prior to the metamorphic peak. This deformation is characterised by an E–W-trending stretching lineation and the transposition of a pre-Alpine planar fabric (Fig. 4). Pre-Alpine garnets are broken and pulled apart, the individual pieces overgrown by a rim of Alpine garnet. Micas show only weak alignments in the Alpine foliation, quartz has recrystallised statically as well (random lattice preferred orientations, Fig. 5). The main deformation must have taken place in the ductile domain, however, i.e. at least within greenschist facies conditions. The thermal peak must have outlasted the thrust-related deformation, however, and annealed earlier deformation fabrics.

In the Aineck Nappe, the main deformation, again with an E–W-trending stretching lineation (Fig. 4), is pre- to syn-metamorphic. Micas are aligned in the foliation, garnets show helicitic inclusion trails and quartz various degrees of lattice preferred orientations (Fig. 5). The main foliation is folded into upright folds around NE–SW-trending axes, with white mica of the first generation folded around fold hinges. This fabric is overprinted by a static recrystallization under lower greenschist facies conditions, with the growth of white mica, chlorite, albite, and rare stilpnomelane randomly across the older fabric. The main deformation must thus have occurred under upper greenschist facies conditions, followed by a phase of cooling and folding of the main foliation. The static overprint happened under lower greenschist facies conditions, most likely driven by fluid infiltration.

The nappe contact between the Bundschuh Nappe and the Aineck Nappe is cut by the basal thrust that carried the two units on top of the LAA Nappe (Fig. 3). Thrusting must thus post-date the internal imbrication within the MAA units.

The LAA Nappe shows the same E–W-trending stretching lineation as the Bundschuh Nappe and the Aineck Nappe (Fig. 4), but the main deformation occurred under lower greenschist facies conditions. Quartz was deformed by low-temperature plasticity and shows lattice preferred orientations typical for cool deformation conditions (Fig. 5). Pre-Alpine garnets are mostly chloritised and deformed into elongated ellipsoids. White micas are frequently rotated into the main Alpine foliation, but also occur in microlithons, tracing an older foliation.

Ar/Ar data

Single grain $^{40}Ar/^{39}Ar$ laser probe (step-wise heating) dating was carried out on white mica, biotite, and amphibole across the Penninic–Austro-Alpine suture at the eastern margin of the Tauern Window in order to constrain the timing of the main Alpine deformation events that led to the juxtaposition of the regarded units. Selected age data for white mica are presented in Fig. 7.

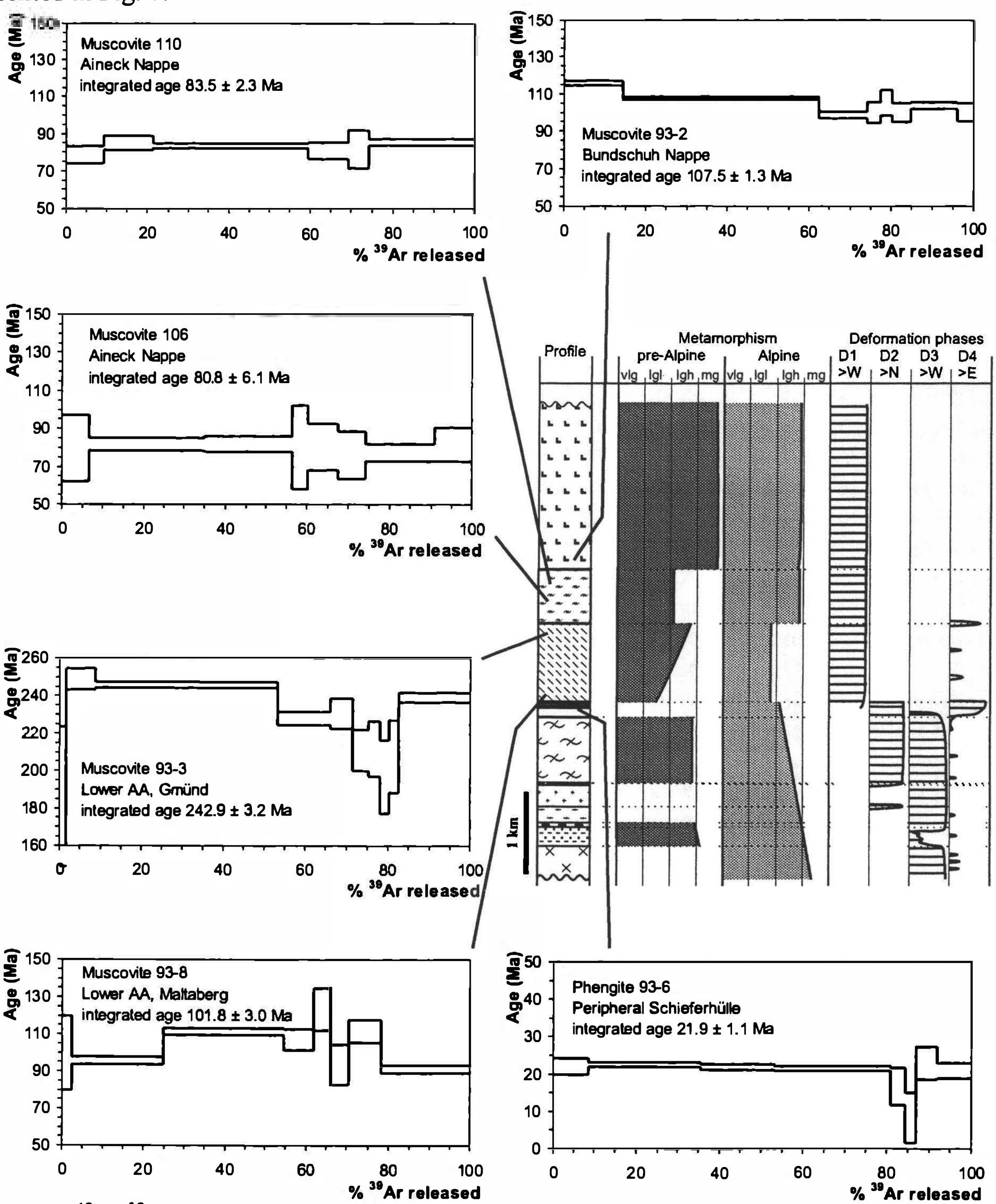


Fig. 7: $^{40}Ar/^{39}Ar$ age diagrams of single grains of white mica and profile of the tectonic units at the eastern margin of the Tauern window. Distributions of pre-Alpine and Alpine metamorphic conditions (vlg: very low grade, lgl, lgh: low grade, mg: medium grade) and parts affected by the main deformation phases are given. For location of samples see also Fig. 3.

The Bundschuh Nappe, mainly deformed prior to the metamorphic peak of lower amphibolite facies conditions, yielded an integrated age of 107.5 ± 1.3 Ma for muscovite, giving a minimum age for the main deformation. The next deeper unit (Aineck Nappe), deformed close to the metamorphic peak of slightly lower temperatures, gave an integrated age of 83.5 ± 2.3 Ma for white mica of the peak metamorphic assemblage. White mica of a second generation, grown due to a static, fluid-driven metamorphic overprint, gave ages of 80.8 ± 6.1 Ma. The static metamorphic overprint of lower greenschist facies conditions in the Aineck Nappe should be constrained in time by the age of the second generation of muscovite, as the temperature of this event is below or at about the closure temperature of muscovite. The cooling age of Mu I (110) of *c*. 85 Ma gives a lower age limit for the penetrative deformation in the Aineck Nappe, related to the W-directed nappe stacking process. From these data a short time interval between cooling from the metamorphic peak (Mu I, sample 110) and the static metamorphic overprint (Mu II, sample 106) can be deduced, as the ages are the same within the 2σ-error limits. A common cause for cooling from the peak metamorphic conditions, for shortening, expressed in the folding of the penetrative foliation at already cooler conditions, and for the subsequent static metamorphic overprint by fluid infiltration can be the thrusting of the Aineck Nappe onto a cool, fluid-rich unit. This could be the LAA unit, derived from the continental margin, on the one hand and the oceanic South Penninic unit on the other hand. The LAA contains mainly low-grade metamorphic pre-Alpine basement rocks and a Mesozoic, carbonate shelf cover sequence that should be rather depleted in fluids in comparison with the shaly-marly deep sea sequence of the South Penninic unit. Also the retrogressive overprint of the LAA with chloritization of garnet needs external fluid sources. These fluids, infiltrating the base of the MAA, are therefore most likely derived from the South Penninic unit, and give a possible age constraint on the subduction of the South Penninic ocean beneath the AA continental margin.

The deepest, Lower AA Nappe, yielded Variscan white mica ages (242.9 ± 2.2 and 239.6 ± 1.1 Ma) from tectonically high levels and strongly disturbed ages of *c*. 100 Ma from the base. Alpine metamorphic conditions were obviously too low to reset the Ar-system of white mica completely, consistent with the observed deformation conditions and metamorphic assemblages. From the presented data no direct time constraint on the deformation of this unit can be given, but if no marked inverted thermal gradient existed during deformation, the Alpine deformation must be younger than the 85 Ma of Mu I of the overlying Aineck Nappe (sample 110). Thermal models indicate that in shallow to medium crustal levels, that are appropriate for the burial of the LAA in this area, no inverted thermal gradients occur at reasonable thrusting rates (Genser et al. 1996). Additionally, the age sequence with cooling of the higher nappe well before cooling of deeper levels indicates that no inverted geothermal gradient existed during nappe stacking within the exposed crustal levels. The observed inverted metamorphic gradient in the AA edifice must therefore be attributed to the late to post-metamorphic transport of those nappes over deeper ones.

For the LAA Nappe in this area, no pressure data are available that could constrain its burial depths. Its position at the base of the AA nappe complex, however, points to burial depths that are in the same order as for the overlying units. This would imply reduced geothermal gradients during underthrusting of the LAA, a scenario that could be met in an oceanic subduction zone environment. Beginning subduction of the SP oceanic lithosphere, together with the leading edge of the AA continental margin that is deformed into the LAA nappe complex, and fluid infiltration of the base of the MAA, fit into this scenario (Peacock 1993). Tectonic inversion of the continental margin, as presently exposed, at the beginning of oceanic subduction conforms, too. We thus correlate the underthrusting of the LAA with the beginning of subduction of the SP ocean rather than with the end, as proposed by Slapansky and Frank (1987), who connected it with the collision of the AA and the MP units. It is constrained in time by the second generation of muscovite in the Aineck Nappe at about 80-85 Ma.

A white mica from tectonically high parts of the Penninic unit, showing a normal metamorphic gradient of greenschist facies conditions, yielded an age of 21.9 ± 1.1 Ma. The flat age spectra record the cooling of the Peripheral Schieferhülle through *c*. 375° C. The second penetrative deformation event in the Penninic units, the WNW-directed shearing that occurred on the heating path and at thermal peak conditions, that were higher than the closure temperature of phengite, must thus precede these ages. This deformation event should thus be Late Oligocene (Harland et al. 1990) in age. The cooling age of 22 Ma gives the onset or an upper age constraint for the ESE-directed shearing, as structural features (e.g. low-temperature plasticity of quartz, calcite twinning) indicate that this deformation started at lower greenschist facies conditions at these tectonic levels, hence at or below the closure temperature of this system. The resulting differential uplift of the Penninic unit should continue to *c*. 16.5 Ma, the cooling ages of biotite (Rb/Sr) across the centre of the Hochalm Dome (Cliff et al. 1985).

Discussion

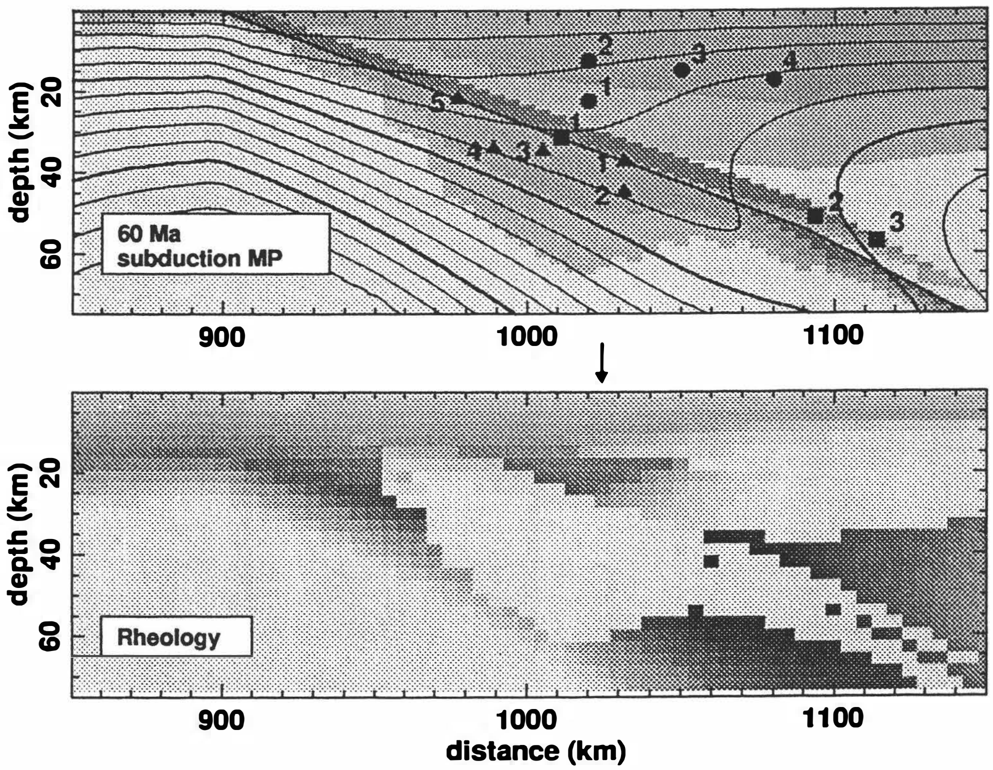
Structural, metamorphic and age data demonstrate distinct Alpine evolutions for the Austro-Alpine and Penninic units. Thrusting in the Austro-Alpine units is generally towards the W, following by folding around E-W to NE-SW trending axes. This thrusting occurred over an extended time-span. The Alpine thrusting in the highest unit (pre-metamorphic) and the subsequent cooling from the highest greenschist to lower amphibolite facies to about 350-400 °C predates 100 Ma. In the next lower unit, thrusting could have persisted until ca. 85 Ma. Nappe stacking must have propagated from the hangingwall to the footwall, therefore, incorporating successively more external and deeper units.

The attainment of higher peak temperatures in higher nappes of the Austro-Alpine unit and the subsequent thrusting onto progressively cooler units of the same mega-unit points to a continuous accretion of parts of the footwall to the hangingwall in the stacking process. Thus thrusting could be explained by an intra-Austro-Alpine subduction. This progressive accretion can also explain the observed inverted metamorphic gradient, without need to invoke inverted temperature gradients.

The beginning of subduction of the oceanic Penninic lithosphere could be dated by the second generation of white mica at the base of the Austro-Alpine unit, that grew due to fluid infiltration. The ages of 80 – 85 Ma indicate a possible interference between intra-Austro-Alpine thrusting and commencing subduction ofthe Penninic ocean beneath.

In the Penninic units, three distinct deformation stages can be distinguished, that can be found in a very consistent manner over the entire Tauern window (Kurz et al. 1997). The oldest deformation is a shearing top-to-the N to NE, and is found especially the South Penninic Glockner nappe and the underlying gneiss nappes. This event is followed by a shearing top-to-the WNW, that affected most of the units, particularly the deeper parautochthonous Zentralgneis unit. The main deformation in the higher Penninic parts, related to their subduction and intra-Penninic stacking is pre- to syn-metamorphic. Hence the oldest ages from that unit of about 30 – 32 Ma, already cooling ages, give a minimum age for N-directed shearing, the oldest, ductile deformation. The ages of about 22 Ma place a lower age limit on the WNW-directed shearing, occurring at about peak metamorphic conditions, and an upper age constraint on the subsequent ESE-directed, extensional shearing. K/Ar ages from 22 to 17 Ma for white mica are common along the central dome of the eastern Tauern window, biotite

Rb/Sr ages are very uniform at about 15.5 - 17 Ma (Cliff et al. 1985). This ages point to rapid exhumation of the Penninic units from depths of 25 to 20 km to near to the surface in this time span (Cliff et al. 1985). This rapid exhumation was enabled by the tectonic unroofing of the Tauern window along the low-angle normal faults along the Penninic–Austro-Alpine interface. Laterally, the window is bound by sinistral strike-slip faults, indicating that extension subparallel to the orogen took place in a wrench regime (Genser and Neubauer 1989, Kurz and Neubauer 1996).



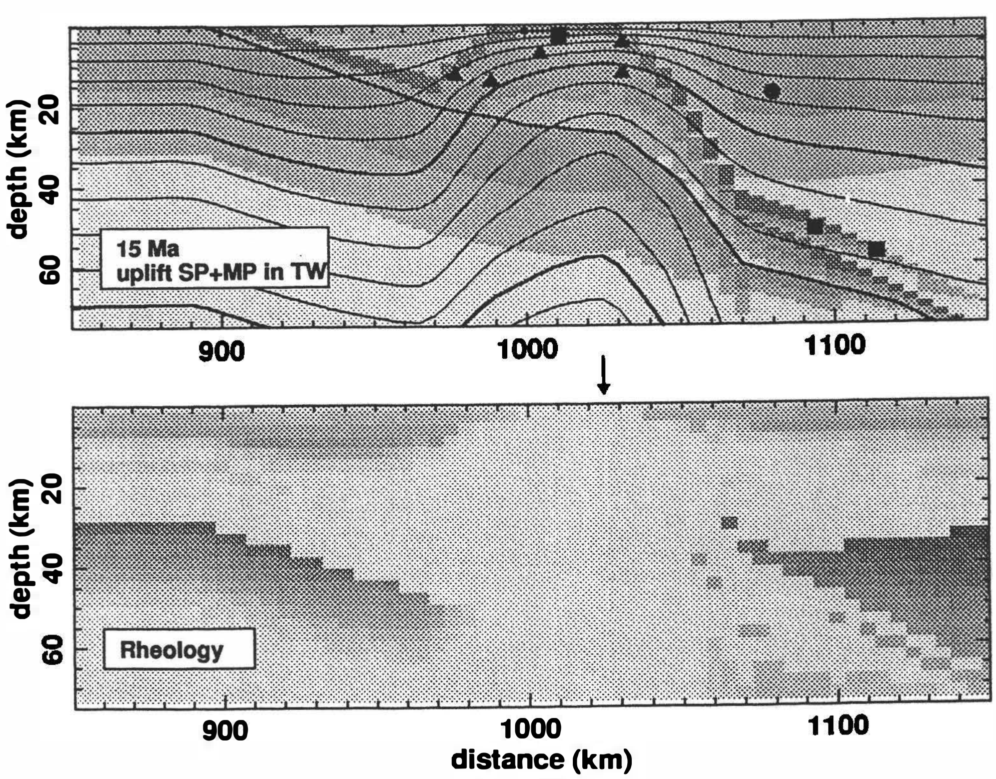
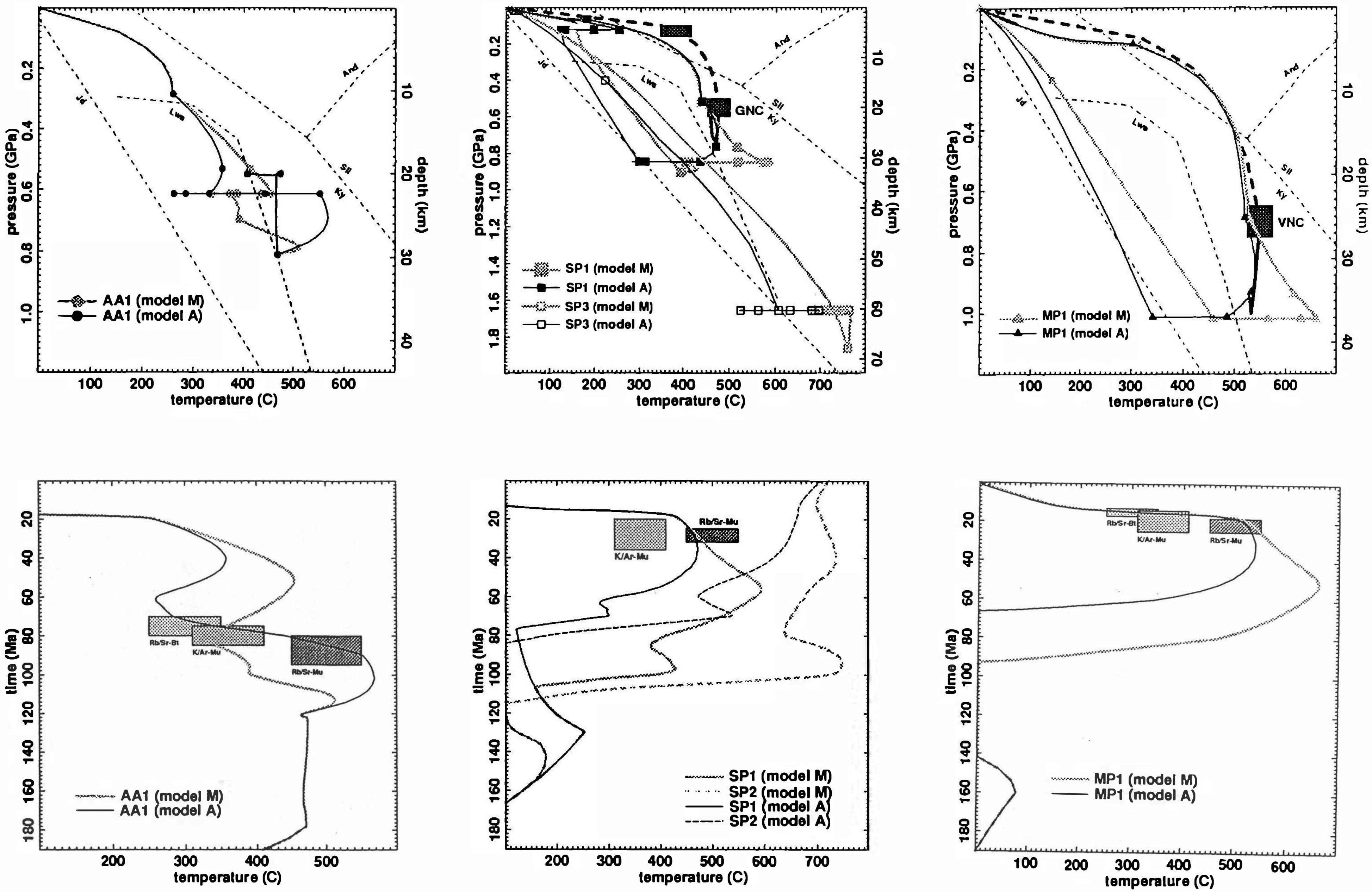


Fig. 8: Thermo-rheological models for subduction of Penninic and subsequent Helvetic-European units beneath the Austro-Alpine upper plate. Thermal modelling was carried out with a 2-D finite difference scheme. From Genser et al. (1996).
(a) Situation after subduction of the South Penninic (90-70 Ma) and subsequent Middle Penninic (70-60 Ma) beneath the Austro-Alpine unit.
(b) Situation after consecutive subduction of North Penninic basin and the southern margin of the European foreland (Helvetic) from 50 to 20 Ma and the rapid uplift of the Penninic units in the Tauern window by extensional unroofing from 20 to 15 Ma.

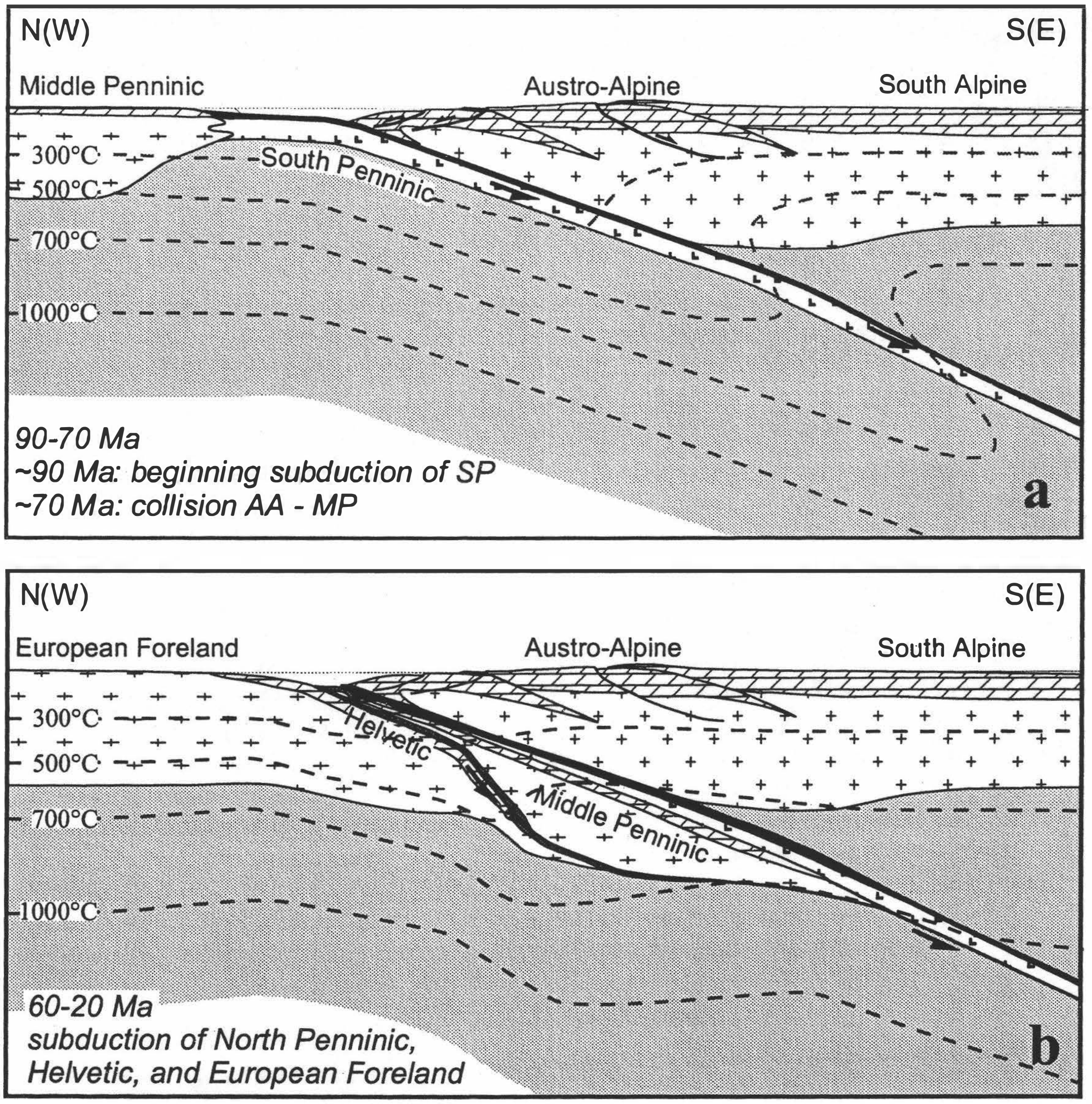
Thermal modelling of the metamorphism in and around the Tauern window by Genser et al. (1996) also substantiate an independent Alpine evolution of the Penninic and Austro-Alpine units, respectively. A model, where subduction of the South Penninic ocean commenced after the main nappe stacking in the Austro-Alpine unit (Fig. 8), give P-T-t paths, that are in accordance with petrological and thermochronological data (Fig. 9). Models that relate compression and metamorphism in the Austro-Alpine to subduction of the South Penninic ocean and its subsequent collision with the Middle Penninic continental block (model M of Fig. 9) are grossly inconsistent with these constraining data. A sketch of our preferred model of the relative and absolute timing of the major events is given in Fig. 10.

Fig. 9: Modelled P-T and T-t paths for points (for location see Fig. 8) within the AA, South and Middle Penninic units. The preferred model (model A, shown in Fig. 8) gives paths, that closely correspond to observed metamorphic paths and cooling ages. Model M, with early subduction of Penninic units during nappe stacking in the AA unit, is grossly inconsistent.

Fig. 10: Thermo-tectonic model for the subduction of the Penninic and Helvetic units beneath the Austro-Alpine hangingwall plate (from Genser et al. 1996).



pressure (GPa)
depth (km)
temperature (C)
Jd
Lws
And
Sil
Ky
AA1 (model M)
AA1 (model A)
GNC
SP1 (model M)
SP1 (model A)
SP3 (model M)
SP3 (model A)
VNC
MP1 (model M)
MP1 (model A)
time (Ma)
Rb/Sr-Bt
K/Ar-Mu
Rb/Sr-Mu
SP1 (model M)
SP2 (model M)
SP1 (model A)
SP2 (model A)


N(W)
S(E)
Middle Penninic
Austro-Alpine
South Alpine
300°C
500°C
700°C
1000°C
South Penninic
90-70 Ma
~90 Ma: beginning subduction of SP
~70 Ma: collision AA - MP
a
N(W)
S(E)
European Foreland
Austro-Alpine
South Alpine
300°C
500°C
700°C
1000°C
Helvetic
Middle Penninic
60-20 Ma
subduction of North Penninic,
Helvetic, and European Foreland
b

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