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Middle and Upper Austroalpine units of Gurktal Mountains/Nock region

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Abstract

Petrological and structural investigations were carried out on samples of Middle and Upper Austroalpine units at the western edge of the Gurktal nappe complex, Eastern Alps (Nock mountains). Based on thermobarometric calculations applying to garnet-plagioclase-muscovite-biotite paragenesis the Alpine metamorphic conditions in the Middle Austroalpine crystalline basement (Radenthein and Bundschuh nappes) can be estimated at c. 600°C and 10-11 kbar within upper epidote-amphibolite facies conditions. Moreover, the presence of an earlier stage with even higher pressure conditions is likely. Pre-Alpine (probably Variscan) relict mineral parageneses are not preserved in all investigated Middle Austroalpine rocks. Calcite-dolomite thermometry in the Upper Austroalpine (Murau nappe) yielded temperatures of c. 460-500°C which are interpreted to represent Alpine metamorphic conditions in contrast to temperatures of 550-600°C from garnet-biotite thermometry which are assumed to indicate pre-Alpine metamorphic conditions. Garnet-biotite parageneses were later strongly overprinted by retrogression within greenschist facies conditions. The break in metamorphic P-T conditions between Middle Austroalpine units and the Murau nappe is considered to result from Late Cretaceous low-angle normal faulting that juxtaposed these two units along a ductile shear zone with top-to-the-ESE displacement.

Introduction

Crustal-scale nappe assembly within collisional orogens regularly leads to burial and metamorphic overprint of crustal pieces (e.g., England and Thompson, 1984). Subsequent extensional processes result in exhumation of previously buried crustal pieces. Vertical motion in relation to the Earth's surface can be, therefore, monitored by changing metamorphic pressure conditions. Furthermore, varying metamorphic pressure-temperature conditions can be used to discriminate tectonic bodies, e.g. nappes and extensional allochthons.

This paper is dealing with the structural and metamorphic relationships between the Middle and Upper Austroalpine nappe units along the western margin of the Gurktal nappe complex (Upper Austroalpine units) in the Eastern Alps (Fig. 1) with strongly contrasting metamorphic pressure-temperature conditions of the penetrative Cretaceous overprint (e.g., Frank, 1987;

Schimana, 1986). New structural, textural and petrological data are used to constrain the Cretaceous tectonic processes of that region where previous data suggest Late Cretaceous extension (e.g., Ratschbacher et al., 1990).

Geological setting

The Austroalpine units within the Eastern Alps form a coherent plate composed of a number of nappes that were assembled during Late Cretaceous nappe stacking under ductile strain and a wide spectrum of metamorphic pressure-temperature conditions (e.g., Frank, 1987; Tollmann, 1987, Ratschbacher and Neubauer, 1989). Available data show that penetrative internal deformation occurred during the Cretaceous (e.g., Frank et al., 1987; Dallmeyer et al., 1996), partly associated with high pressure metamorphic conditions up to eclogite facies (e.g., c. 18 kbar; Miller, 1990; Ehlers et al., 1994). Major portions of these units are interpreted to represent lower plate sequences emplaced during Cretaceous subduction of Austroalpine continental crust beneath Meliata-like oceanic tectonic elements (Neubauer, 1994; Dallmeyer et al., 1996, 1998). Late Cretaceous exhumation led to crustal thinning and cooling of previously overthickened crust (Ratschbacher et al., 1989; Neubauer et al., 1995; Dallmeyer et al., 1998). Subsequent Tertiary piggy-back emplacement of these units onto Penninic units did not lead to major internal deformation of Austroalpine units.

East of the Penninic Tauern window all major Austroalpine units are exposed in the classical Bundschuh area where Holdhaus (1921), based on fossil discoveries, argued for an intra-Austroalpine nappe structure (Fig. 1b). Here, the Austroalpine units comprise from footwall to hangingwall (Tollmann, 1975; 1977; Schimana, 1986; Neubauer, 1987; Neubauer and Pistotnik, 1984; von Gosen, 1989): (1) the Radenthein micaschist complex (RMC), a basement complex constituting the Radenthein nappe; (2) the Bundschuh nappe including the Bundschuh complex (BC), a gneissic, pre-Permian basement unit, and a Permian to Mesozoic cover sequence (Stangalm group); Radenthein and Bundschuh nappes are classically interpreted to represent the Middle Austroalpine units; (3) the Murau nappe with a phyllitic Paleozoic basement; and (4) the Stolzalpe nappe also with a phyllitic Paleozoic basement, and Late Carboniferous to Triassic cover sequences. Murau and Stolzalpe nappes are part of the Gurktal nappe complex (Upper Austroalpine nappe complex).

The superposition of the Gurktal nappe complex over Middle Austroalpine units is interpreted to result from Cretaceous nappe stacking within ductile deformational conditions (Tollmann, 1977; Neubauer, 1980, 1987; Ratschbacher and Neubauer, 1989; von Gosen, 1989) although there is a wide disagreement on the nature and extent of displacement (e.g., Clar, 1965; Tollmann, 1975; Frank, 1987; Frimmel, 1986a, b; 1988). Based on scarce shear sense criteria a top to the W (WNW) displacement of hangingwall units was proposed (Neubauer, 1987; Ratschbacher and Neubauer, 1989; Ratschbacher et al., 1989; von Gosen, 1989). Furthermore, many structural data favour an overprint by a second ductile phase with a general top to the ESE displacement (Neubauer, 1987) that was interpreted to represent subsequent Late Cretaceous east-directed motion due to extension (Ratschbacher et al., 1989, 1990; Stock, 1992; Antonitsch and Neubauer, 1992). The second event was also interpreted to be responsible for a break in Cretaceous peak metamorphic conditions between the Middle Austroalpine units/Murau nappe and the overlying Stolzalpe nappe (Neubauer, 1980; Ratschbacher et al., 1990).

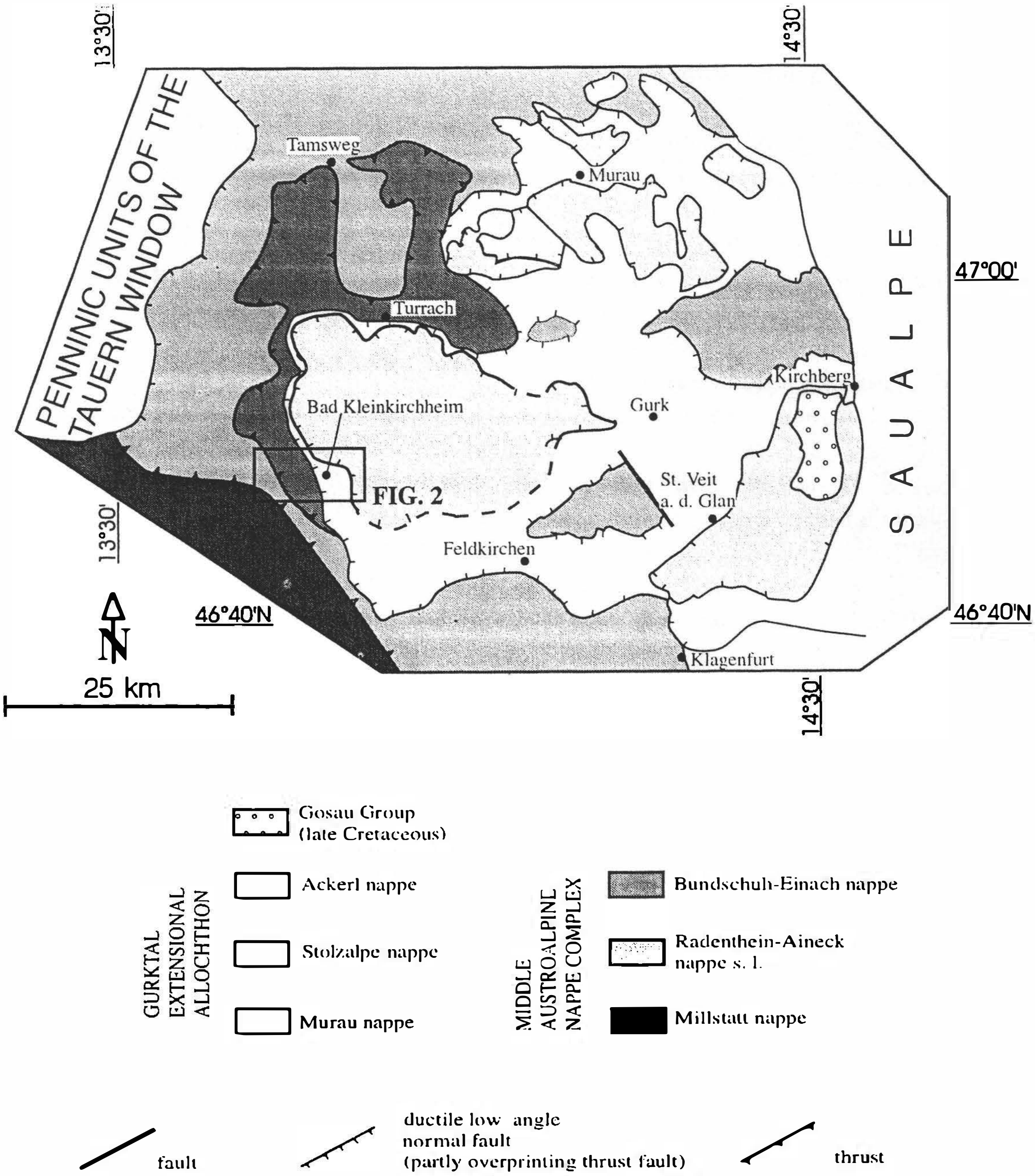

Fig. 1. Simplified geological map showing general geological relationships of the Gurktal nappe complex/Gurktal extensional allochthon to underlying units.

Stolzalpe nappe

The Stolzalpe nappe comprises a low-grade metamorphic, Variscan basement and a very low-grade metamorphic Late Carboniferous to Triassic cover succession (for detailed reviews, see Krainer 1989a, b)Neubauer, 1992; Neubauer and Sassi, 1993). The stratigraphy of the basement is nearly exclusively based on conodonts which were found in thin dolomite interlayers within the otherwise clastic and volcanic sequences. Models to the paleogeographic evolution are shown in Figures 2 and 3. As a rule, thick mafic volcanic sequences occur at the base. This are divided into a late Middle to Late Ordovician Magdalensberg Formation, Nock

Formation, and the likely Late Ordovician Kaserer Formation, and into the Silurian Eisenhutschiefer Formation. The Nock Fm. exhibits calc-alkaline geochemical affinities, other mafic volcanic formations display mildly alkaline geochemical characteristics (Giese, 1988; Loeschke, 1989).

A slaty facies with cherts and allodapic limestones persists through the Wenlockian to the boundary of Lochkovian/Pragian (Magdalensberg facies). This facies is contrasted by thick sandstones, quartzwackes and quartzarenites (Pranker facies) covering the same time span. A $^{40}Ar/^{39}Ar$ age of detrital white mica yielded a Cadomian age (ca. 560 Ma). The Auen facies with dolomite and pelagic limestone of Late Wenlockian to Pragian form a third facies realm. Similar carbonates spread from the Pragian/Zlichovian onwards over all other facies realms and persist up to the Early Carboniferous. Locally, cherts were found at the Tournaisean/Visean boundary. These are overlain by synorogenic grawwackes.

The cover sequence of the Stolzalpe nappe occurs along western and eastern margins of the Gurktal nappe complex. At the western margins, the succession starts with the Late Carboniferous Stangnock Formation with conglomerate, sandstone and anthracite. The sequence was deposited by a river system under a humid climate. The overlying Permian Werchzirm Formation with redbeds and some acidic tuffs in basal portions monitors a gradual transition into semi-arid climatic conditions.

The Pfannock sequence at the westernmost sectors of the Gurktal nappe complex is partly overturned and is interpreted to represent a detached portion of the Stolzalpe nappe. There, the cover sequence is deposited on the Pfannock gneiss, a Silurian or Devonian acidic orthogneiss. The cover sequence on top of it range from Permian to Late Triassic. It includes the Permian Bock Breccia, the Skythian Werfen Fm., the Anisian Pfannock Fm., the Anisian-Ladinian Wetterstein Dolomite, and the Late Triassic Hauptdolomite and Kössen Formations. A detrital white mica age of (317.6 ± 0.6 Ma) from the Pfannock Fm. constrain a Variscan source region of this succession.

The Krappfeld Gosau is laid down on tilted and partly eroded Triassic cover sequences along eastern margins of the Gurktal nappe complex. It comprises a Late Santonian to lower Late Maastrichtian sequence (Neumann, 1989)with basal reef limestone and later marls and olistolitic beds (Thiedig, 1975). The Gosau is interpreted to represent a collapse basin on top of exhuming overthickenned continental crust.

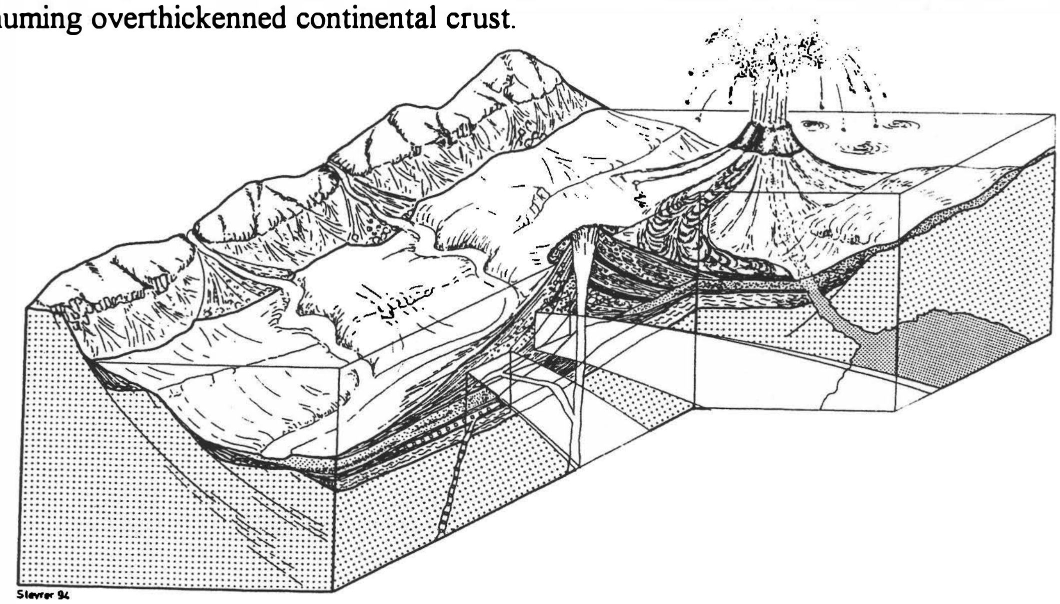

Fig. 2. Sketch showing Silurian paleogeography of the Stolzalpe nappe (from Antonitsch-Genser et al., in prep.).

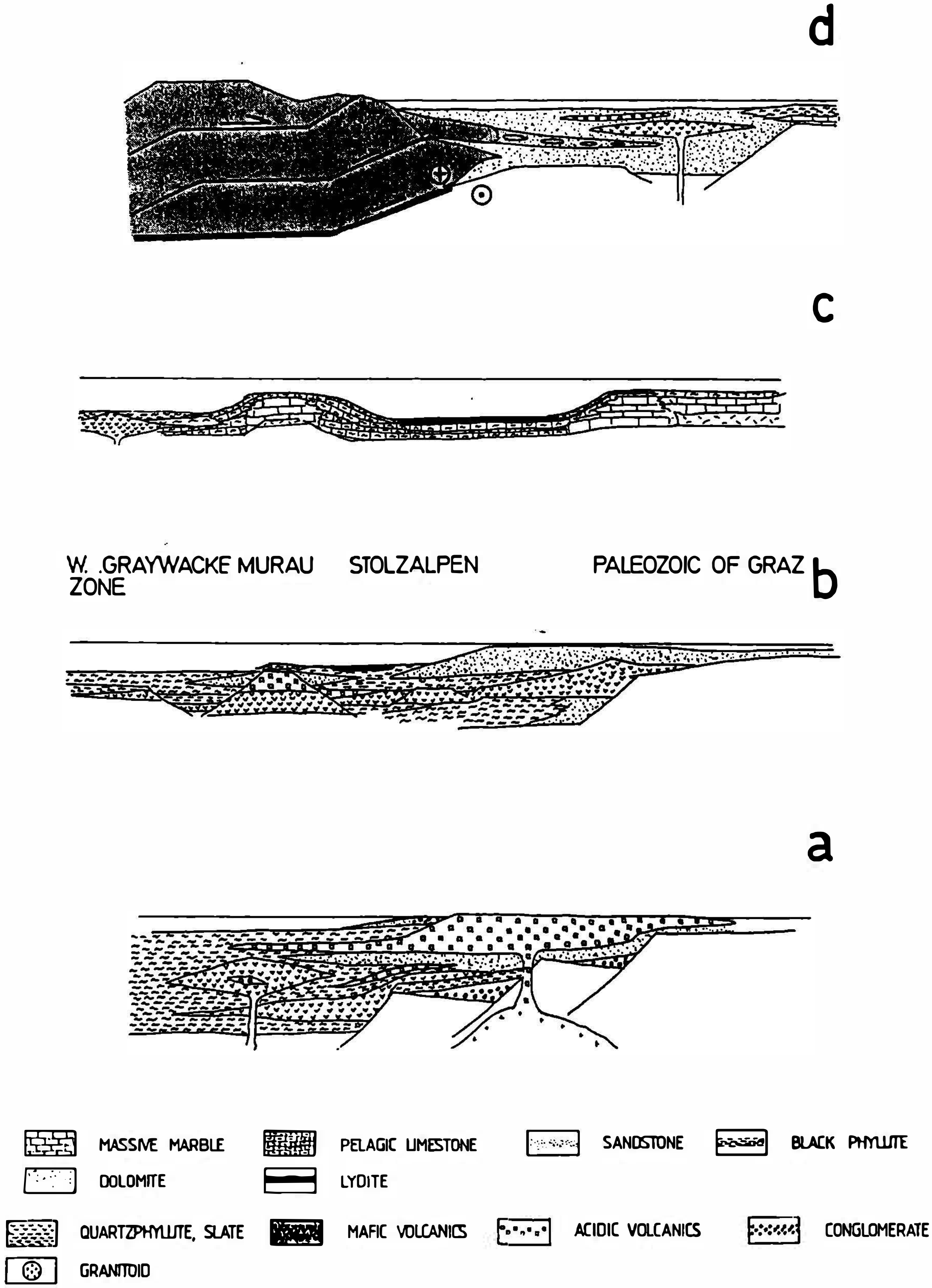

Fig. 3. Evolution of Upper Austroalpine units including sequences exposed within the Stolzalpe nappe during the Paleozoic. a - Late Ordovician; b - Late Silurian to Lower Devonian; c - Late Devonian to Early Carboniferous; d - late Early Carboniferous.

New Ar-Ar ages

New $^{40}Ar/^{39}Ar$ ages measured from 2-5 white mica grains have been prepared at the Salzburg Ar-Ar Laboratory. These new ages include (Fig. 4): 1) A plateau age of 89.0 ± 0.6 Ma from metamorphic sericite (sample FN-G-3) from a Skythian quartzite at the stratigraphic base of the Stangalm Mesozoic sequence. It is interpreted to represent the age of cooling through appropriate Ar retention temperatures (ca. 350-400°C) during exhumation of this sequence. 2) A disturbed Cretaceous-age pattern from a further sample (FN-G-1) from hangingwall portions from the Skythian Quartzite. 3) Detrital white mica from the Pfannock Formation (FN-G-14) at the northern slope of Pfannock yielded a plateau-type Variscan age (317.6 ± 0.6 Ma). This age is interpreted to constrain the cooling through ca. 350-400°C in the source region in the hinterland.

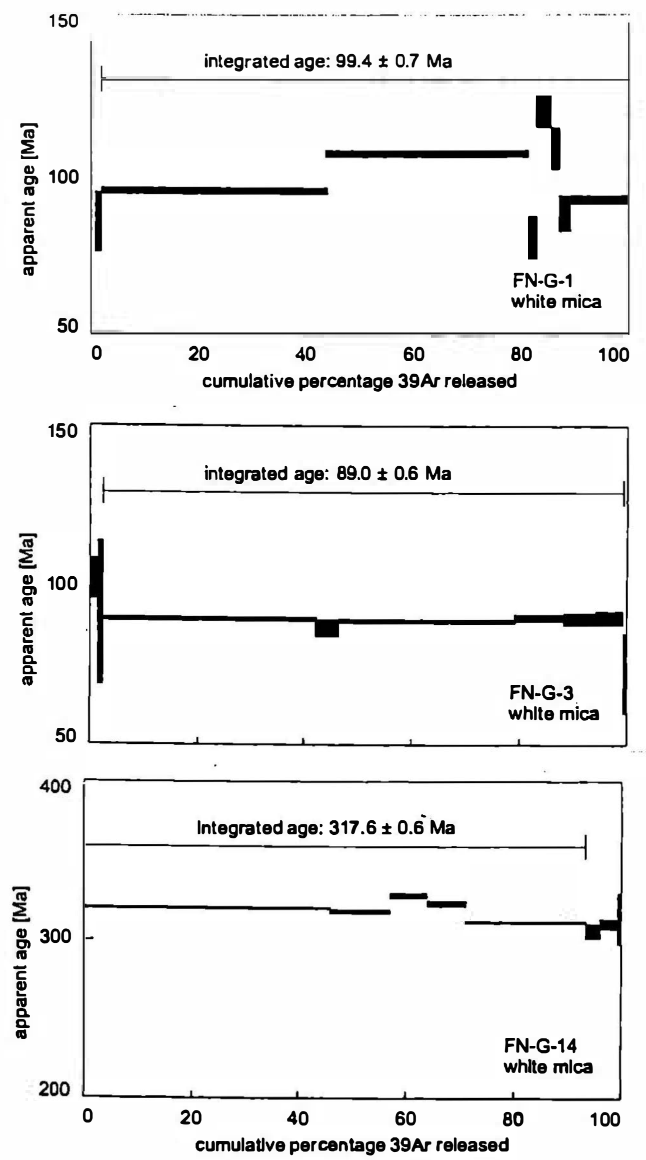

Fig. 5: $^{40}Ar/^{39}Ar$ ages from the basal, Skythian Quartzite (samples FN-G-1, FN-G-3) and detrital white mica from the Pfannock Formation (sample FN-G-14).

Structural investigations

Two sets of structures have been observed in all tectonic units (along the Radenthein - Patergassen section; Fig. 5): (1) penetrative ductile structures that formed within peak and/or retrogressive metamorphic conditions; and (2) late-stage brittle structures that overprinted the earlier ones.

Lithologies of the upper portions of the Radenthein Micaschist Complex show a flat-lying, NE-dipping, penetrative foliation and an associated ESE-plunging stretching lineation (Fig. 2). These rocks generally are well-recrystallized and do not show retrogression.

Paragneisses and micaschists of the Bundschuh nappe as well as marbles of the Stangalm group also include a gently NE-dipping penetrative foliation and an associated E- to ESE-plunging stretching lineation. The foliation of the Murau and Stolzalpe nappes gently dips N to NE, while the associated stretching lineation trends mostly E (Fig. 6). The foliation of phyllitic rocks within the Murau nappe is penetrative, closely spaced, and comprises fine ribbon quartz and sericitic layers. Shear bands are common within phyllitic lithologies and indicate E- to ESE-directed shear. The penetrative foliation is refolded into open, upright NNE-plunging folds that also contain a widely spaced axial surface foliation. Subvertical N-trending tension gashes are common within the Murau nappe. They indicate approximately E-W oriented, (sub)horizontal extension. Both, open upright folds and steep tension gashes also occur within the Bundschuh nappe.

Mesoscale faults and striae are common both in upper portions of the Bundschuh nappe and in the Murau nappe (Fig. 7). In general, these are dominated by a conjugate set of ENE respectively NW-dipping normal faults. Resulting paleostress orientation patterns indicate a subvertical orientation of σ_1 and a subhorizontal WNW trending σ_3 direction due to WNW-ESE stretching of rocks (Fig. 7).

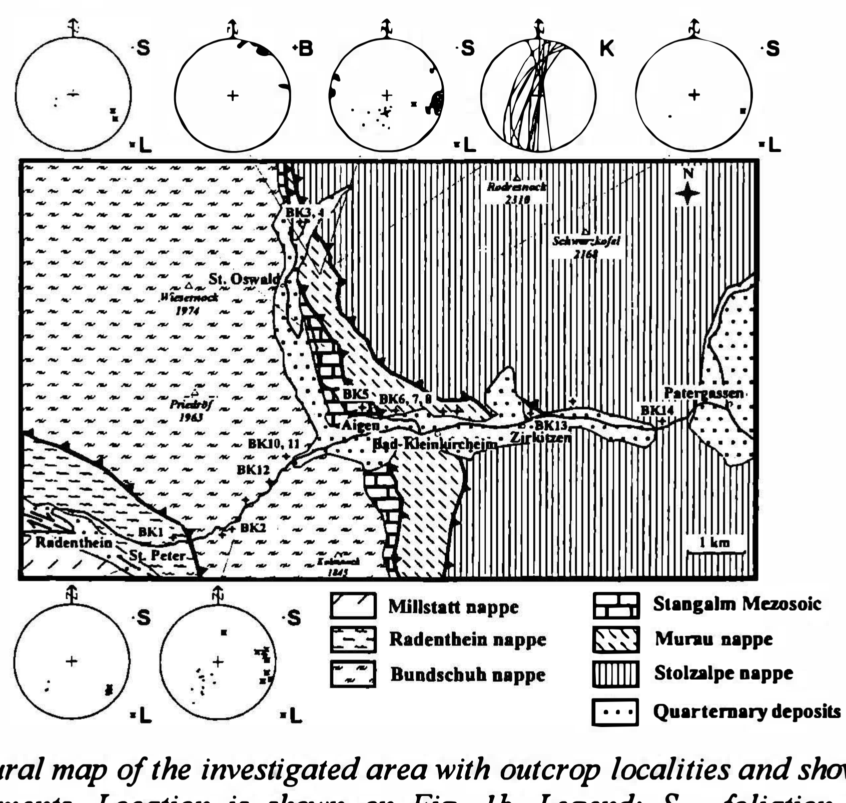

Fig. 6. Simplified structural map of the investigated area with outcrop localities and showing the main structural elements. Location is shown on Fig. 1b. Legend: S - foliation, L - stretching lineation, B - fold axis, K- tension gash. Lambert projection, lower hemisphere.

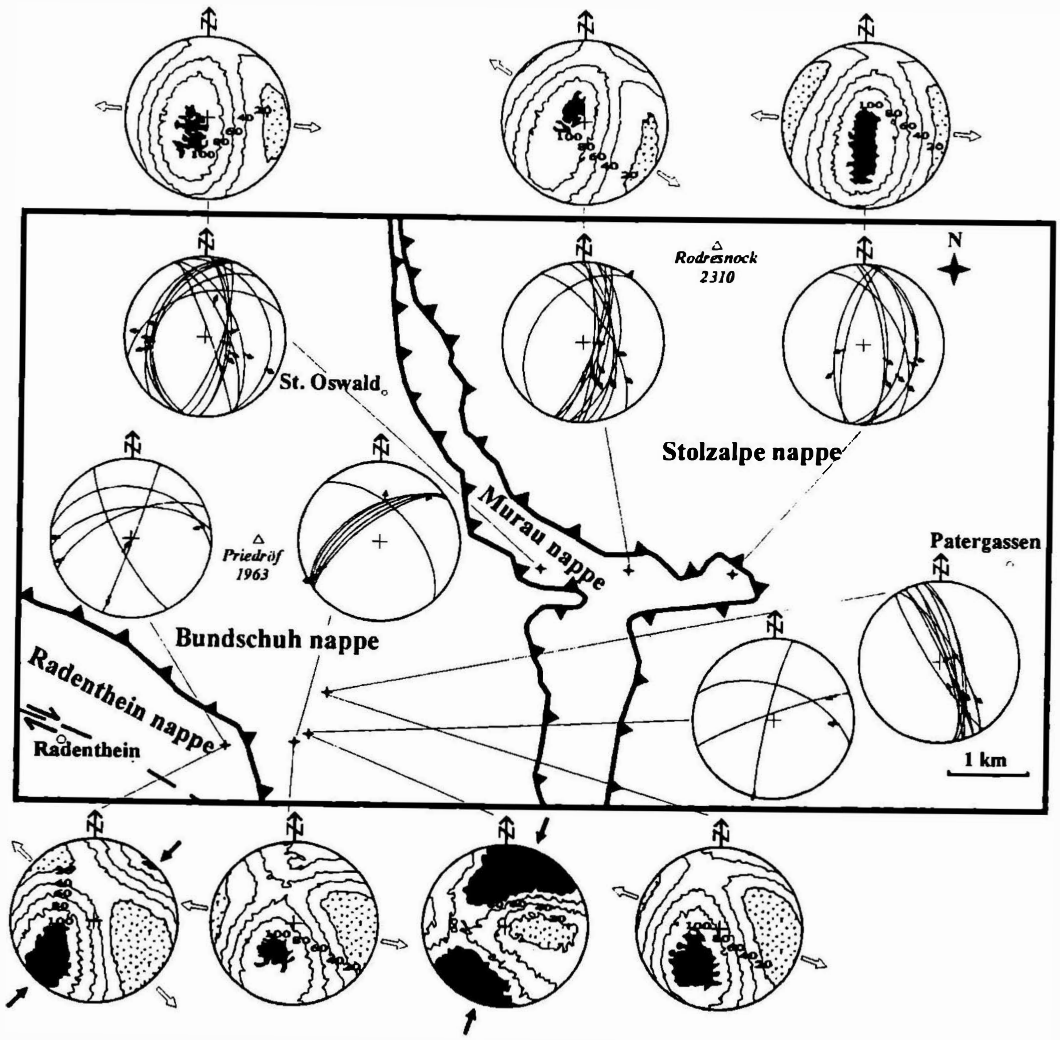

Fig. 7. Orientations of faults and striae and deduced paleostress orientations. Lambert projection, lower hemisphere. Legend of paleostress projections: Black - possible maximum principal stress orientation; stippled - possible minimum principal stress orientation.

Microfabrics and textures

Quartz c-axis patterns of some lithologies from the Radenthein micaschist complex usually display a small circle distribution around the Y direction (Fig. 8). Rotated σ-porphyroclasts of garnet and intrafolial folds show top-to-the W transport. The orientation of tensional fractures between garnet fragments indicates ca. ESE-WNW orientated stretching. Crenulation of the foliation can be observed, too.

Rocks of the Bundschuh Complex are well-recrystallized and annealed, and do not contain a preferred orientation of quartz c-axes (Fig. 8). Well-developed shear indicators are missing here.

In the Murau nappe, sample BK3 a very well-developed quartz mylonite, shows a prominent preferred quartz c-axis orientation. Shear bands and S-C fabrics, indicating top to the ESE shear, are common within this type of mylonite. For other studied rocks (samples BK6, 8, and 14 from Murau and Stolzalpe nappes) no preferred quartz c-axis orientation could be observed (Fig. 8). Shear bands and asymmetrical pressure shadows around garnets are also characteristic for the Murau nappe. Occasionally, normal slip crenulation and asymmetrical foliation boudinage occur as well. These indicate mostly top-to-the E to ESE transport. Boudinaged white mica indicates E-W stretching, too.

Grain boundaries of quartz layers and lenses of rocks exposed within the Murau nappe are dentate to lobate in most cases, recording that deformation occurred after the thermal peak of the metamorphism. Elongated grains, undulose extinction, deformation lamellae and mortar texture also record strong deformation after peak metamorphic conditions. However, well-equilibrated grain boundaries are also present in some samples. These are interpreted to represent remnants of an earlier stage and suggest strain partitioning within the Murau nappe during the last deformation stage. Feldspar and garnets often appear as rigid porphyroclast (0.2-0.7 mm) with pressure shadows in rocks of the Murau nappe, but also small (0.01-0.1 mm) well-recrystallized grains, often with strain-free optical properties can be observed.

These relationships suggest that rocks of Bundschuh nappe are mostly annealed. In contrast, quartz of rocks from the Murau nappe is heavily deformed under low temperature

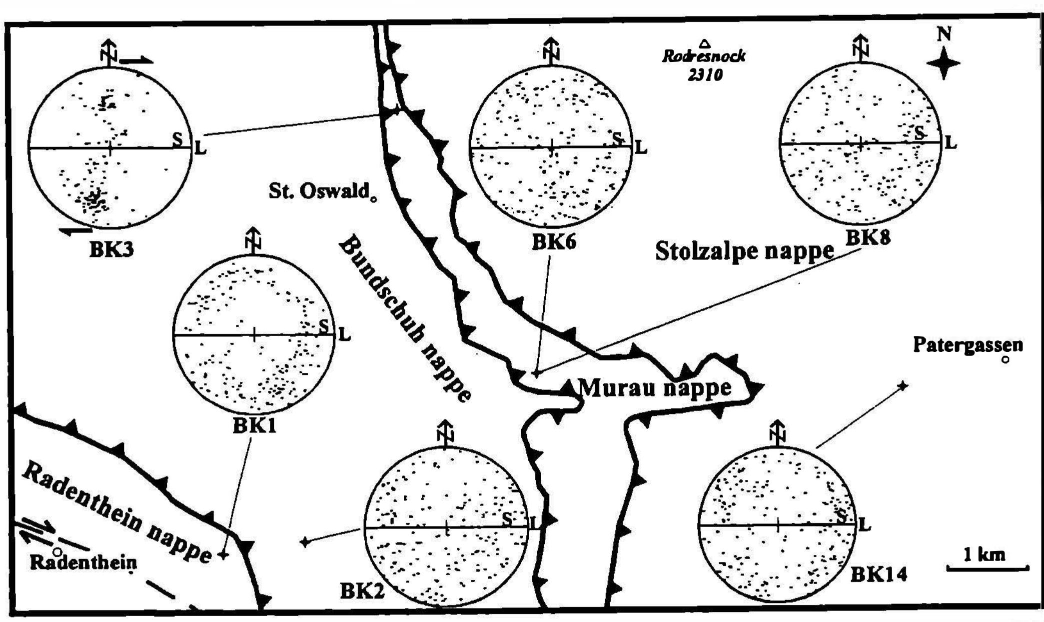

Fig. 8: Quartz c-axis patterns from the Radenthein - Pattergassen section.

Petrological investigations

Metamorphic conditions were determined on the basis of equilibrium mineral parageneses in each tectonostratigraphic unit, concentrating - first of all - on the Middle Austroalpine crystalline basement (Radenthein and Bundschuh nappes). Garnet is a characteristic metamorphic mineral in these rocks and therefore numerous profiles were measured from several locations and tectonic units. Representative garnet profiles are shown in Fig. 10. We applied Tweeq (Berman, 1991) (Fig. 9) and Thermocalc programs (Powell and Holland, 1988) for the calculation of P-T conditions, using also the calibrations of KLEEMANN and REINHARDT (1994), HOISCH (1991) and HODGES and CROWLEY (1985), respectively, on mineral assemblages which are in textural equilibrium. The solid solution models used for Tweeq where from Berman (1990) for garnet, from Furmann and Lindsley (1988) for feldspar, from Chatterjee and Froese (1975) for mica, and from McMullin et al. (1991) for biotite. As examples, results of P-T estimates using the calibrations of KLEEMANN and REINHARDT (1994), HOISCH (1991) and HODGES and CROWLEY (1985) for chemical compositions presented in Table 1.

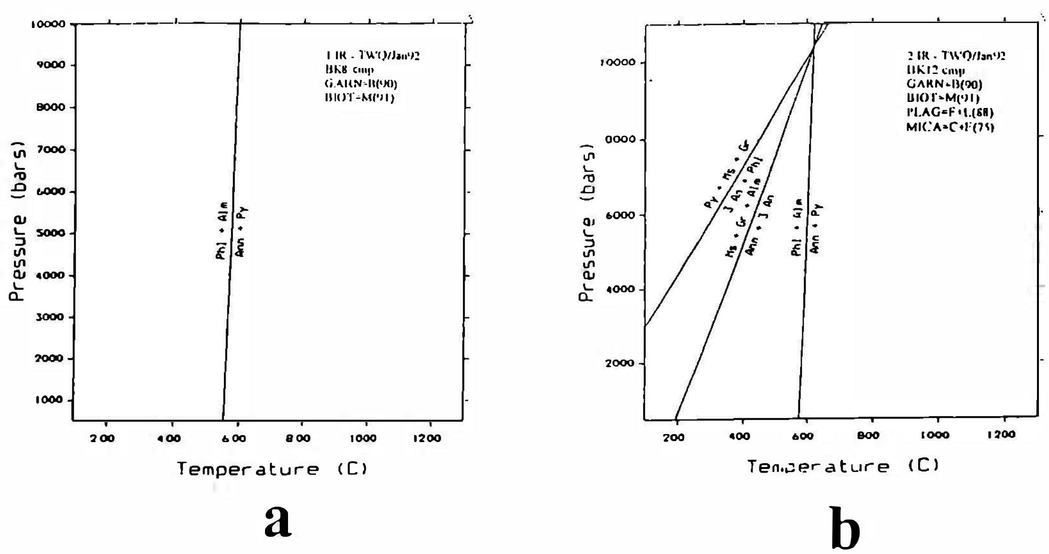

Fig. 9. Representative examples of thermobarometric results with the Tweeq program. a - BK8: Garnet-biotite thermometry, b - BK12: garnet-biotite-muscovite-plagioclase thermobarometry.

Tab. 1. Overview on P-T estimates of samples collected from Radenthein and Bundschuh nappes. The P-T estimates using geothermometers and geobarometers of KLEEMANN and REINHARDT (1994), HOISCH (1990) and HODGES and CROWLEY are listed for representative mineral compositions.

Sample	BK1	BK2	BK10	BK11	BK12
Tweequ	600 °C, 11 kbar	600 °C, 9.8 kbar	600 °C, 10.3 kbar	580 °C, 9.7 kbar	630 °C, 10.3 kbar
Thermocalc	627 ± 117 °C 11.2 ± 2.6 kbar	632 ± 27 °C 10.2 ± 1.1 kbar	675 ± 43 °C 12.1 ± 1.6 kbar	631 ± 28 °C 12.7 ± 1.0	642 ± 27 °C 10.6 ± 1.1 kbar
garnet-biotite Kleemann and Reinhardt, 1994	604 °C	597 °C	593 °C	578 °C	607 °C
Hoisch, 1990		10.6-10.7 kbar	11.1 kbar	10.3 kbar	11.5 kbar
Hodges & Crowley, 1985		10.3 kbar	10.5 kbar	9.8 kbar	10.7 kbar

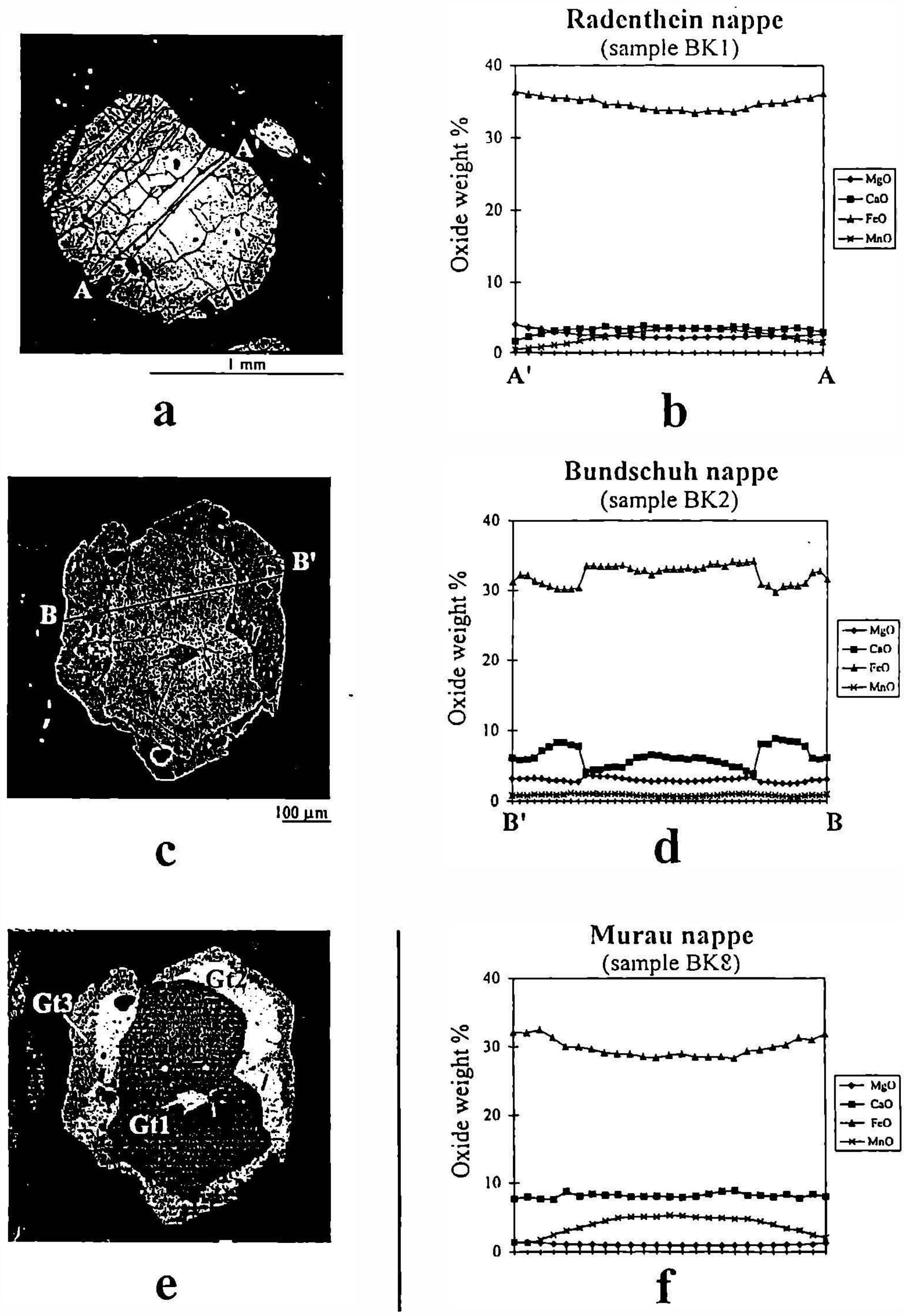

Fig. 7. Representative chemical composition of granet from the Radenthein, Bundschuh and Murau nappes. a - Back-scattered electron image of garnet in BK1 (Radenthein nappe). No core-rim structure is developed. b - Element distribution in BK1. Length of section line is shown in Fig. 7a. c - Back-scattered electron image of garnet in BK2 (Bundschuh nappe). Note the characteristic core-rim structure. d - Element distribution in BK2. Section line is shown in Fig. 7c. e - relative intensity distribution for Ca-K_α X-ray line in the same grain. Note the three garnet generations. f - Element distribution in BK8. Length of section line is ca. 4.5 mm, analyzed grain is not shown. Murau nappe.

Discussion of the Cretaceous tectonic evolution

Geochronological data constraining the age of the metamorphic event(s) of investigated tectonic units were publishe by Frimmel, 1986a, Schimana, 1986, and Hawkesworth, 1976. The minimum age of metamorphism in the Radenthein nappe is about 88-84 Ma according to Rb/Sr small scale whole rock and mineral isochrons. K/Ar data record an Alpine age in the Radenthein and Bundschuh (Priedröf) nappes mostly in the range of 70-110 Ma. The muscovite K/Ar age from Stangalm Mesozoic cover rocks is about 70 Ma (Schimana, 1986). Bundschuh gneiss samples from sites W of Turrach (Fig. 1b) Nappe have given ages of 363 to 403 Ma (Rb/Sr whole rock isochrons) which were interpreted as mixed Caledonian-Variscan protolith ages (Frimmel, 1986a, b). Rb/Sr muscovite ages also indicate an early Variscan event (350-354 Ma) within these rocks. In orthogneisses deformed intensively during the Cretaceous metamorphism Rb/Sr mineral ages (muscovite, feldspar) are variably resetted to 119 to 91 Ma (Frimmel, 1986a, b). According to these data, the Radenthein and Bundschuh tectonic units were strongly affected by Cretaceous metamorphism, while pre-Alpine metamorphism is restricted to the Bundschuh basement.

The results of the thermobarometric calculations with the two different programs (Tweeq and Thermocalc) are roughly in agreement. Based on these data, the Alpine metamorphic conditions are estimated in the Middle Austroalpine crystalline basement (Radenthein and Bundschuh nappes) to be around 600°C and 10-11 kbar. These values mean upper epidote-amphibolite facies conditions within the stability field of kyanite, although it was not observed in the investigated rocks (because of the Al-poor bulk composition). However, kyanite and staurolite are found in the surrounding area in the Radenthein nappe (kyanite-garnet micaschist with the local name "Radentheinit"; e.g., Schimana, 1986). The estimated pressure suggests that these rocks were at a depth of ca. 35 km during the Cretaceous metamorphic event. This depth nearly corresponds to the base of continental crust with a normal thickness.

Among the Middle Austroalpine units two types can be identified (see also Schimana, 1986): The Radenthein nappe was affected by one (Alpine) metamorphism only, while in the Bundschuh nappe two regional (Alpine and a pre-Alpine, probably Variscan) metamorphic events are recorded. Moreover, chemical zonation (with an inner and outer garnet-rim) suggests two stages within the Alpine metamorphism. The very CaO-rich inner zone of the Alpine rim in the garnets may indicate earlier, higher pressure metamorphic conditions than the outer, Ca-poorer, zone. The albite-rich core of the zoned plagioclases may be correlated with the above mentioned inner zone; because of the absence of minerals in equilibrium, P-T conditions could not be calculated, however.

The Variscan metamorphic conditions are less clear in the investigated rocks, because pre-Alpine relict minerals apart from the Fe-rich cores of the garnets were not preserved. The element distribution in the almandine-rich cores indicates a progressive metamorphism at least in the case of sample BK2. The homogeneous element distibution in garnet-cores of sample BK10 may indicate a complete rehomogenization during the pre-Alpine metamorphic event. This would mean that garnets grew before the thermal peak of the pre-Alpine metamorphism which had to reach temperatures of at least 650°C. The pseudomorphs containing paragonite are probably after staurolite, which is also wide-spread and well-preserved in surrounding and northwestern areas in the Bundschuh nappe (e.g., Schimana, 1986). This suggests at least upper epidote-amphibolite facies conditions for the pre-Alpine metamorphism.

Common mineral assemblages (quartz, muscovite, chlorite, albite ± garnet, biotite, epidote, clinozoisite, calcite, dolomite) in the Gurktaler phyllite (Murau nappe, samples BK3, 4, 6, 7, 8 and 13) and in the meta-arkose (Stolzalpe nappe, BK14) suggest greenschist facies metamorphic conditions within the Upper Austroalpine units. Von Gosen et al. (1987) found, based on illite crystallinity studies, very low grade to low grade metamorphic conditions within the Stolzalpe nappe exposed immediately to the north of the study area. Conodont color alteration and conodont surface recrystallization studies indicate similar conditions (Neubauer and Friedl, 1997), in agreement with the presence of anthracite in Late Carboniferous cover sequences (Rantitsch and Russegger, in prep.). A reasonable estimate for temperature conditions within the Stolzalpe nappe is, therefore, ca. 325 ± 50°C (Frey, 1987; Kisch, 1987).

Metamorphic conditions within the Murau nappe were calculated with the calcite-dolomite thermometer (Anovitz and Essene, 1987; Dachs, 1990) which gives ca. 460-500°C (BK13) and with garnet-biotite equilibria (BK8) yielding ca. 550-600°C. Calcite-dolomite microfabrics are obviously associated with extensional deformation, indicating re-equilibration of calcite-dolomite mineral assemblages. The age of the metamorphism in the Murau nappe is rather uncertain, no geochronological data are available in the investigated area yet. We consider a pre-Alpine age of peak conditions of metamorphism recorded by garnet-biotite equilibria because these are constrained within garnet porphyroclast (first stage of textural evolution) which are overprinted by a second-stage tectonothermal event within greenschist facies conditions. The second stage including the calcite-dolomite equilibria is considered to represent the Alpine metamorphic overprint. Similar polyphase fabrics were also reported from other regions of the Murau nappe (von Gosen, 1989, and references cited therein).

A break in metamorphic isogrades obviously coincides with the lower low angle normal fault boundary of the Gurktal nappe complex. It appears, furthermore, that the entire Murau nappe along the western margins of the Gurktal nappe complex is thinned out extremely (to minimum several tens of metres) along the east-directed ductile low angle normal fault. Further local evidence of east-directed motion has already been provided by Neubauer (1987), Ratschbacher and Neubauer (1989), Stock (1989; 1992), and Ratschbacher et al. (1990) always recorded from basal sectors of the Gurktal nappe complex. Therefore, the entire Gurktal nappe complex represents an extensional allochthon. Middle Austroalpine footwall units are entirely annealed and recrystallized within a distance of several hundreds of metres in the footwall of the basal tectonic contact of the Gurktal nappe complex.

In summary, the data presented above suggest the following Cretaceous tectonic history of Austroalpine units along western margins of the Gurktal nappe complex: Middle Austroalpine continental units were buried during Cretaceous contraction to depths close to the base of continental crust (35 km). In contrast, the Murau and Stolzalpe nappes remained at middle to upper crustal levels (Fig. 10a). The direction of nappe stacking is not evidenced from our data except some weak indications of westward rotation recorded in garnets of the Radenthein nappe. Later on, a crustal-scale, east-directed, ductile low angle normal fault developed at the upper margin of the Bundschuh nappe probably reactivating older thrust surfaces. A late stage brittle normal fault has already been described by Clar (1965) along this contact. Mineral cooling ages of 84-80 Ma from Bundschuh and Radenthein nappes (Hawkesworth, 1976; Schimana, 1986; Frimmel, 1986a, b) are contemporaneous with sediment deposition within the Late Cretaceous (Krappfeld) Gosau basin (van Hinte, 1963; Thiedig, 1975) on top of the Stolzalpe nappe along the eastern margin of the present exposure of the Gurktal nappe complex (Fig. 1b).

The tectonic scenario derived from these investigations in the Gurktal nappe complex is similar to that described from other regions of the Austroalpine nappe complex exposed east and west of the Tauern window, where east-directed Late Cretaceous syn-Gosau normal faulting is recorded (e.g., Neubauer and Genser, 1990; Ratschbacher et al., 1991; Froitzheim et al., 1994, 1997; Neubauer et al., 1995; Handy, 1996).

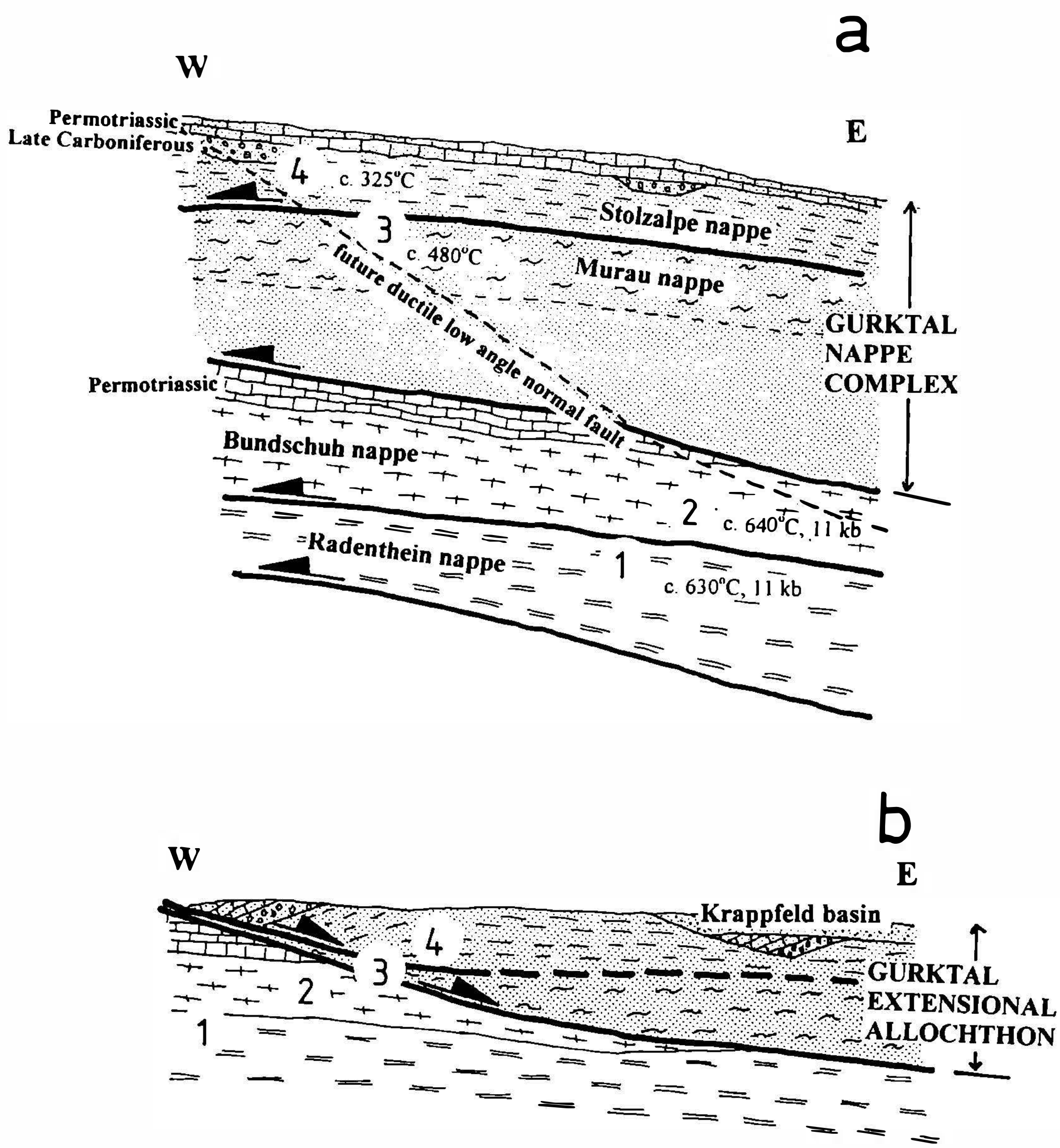

Fig. 5. Models of the tectonic evolution along the western margin of the Gurktal nappe complex. A - Nappe stacking at the stage of maximum peak metamorphic conditions in the Bundschuh and Radenthein nappes. B - Stage after extension by east-directed, ductile, low-angle normal faulting. 1 - 4 represent suggested locations with Cretaceous peak metamorphic conditions (A) and post-extensional locations (B) within all four investigated structural units.

References

Angelier, J. and Mechler, P. (1977): Sur une méthode graphique de recherche des contraintes principales également utilisable en tectonique et en séismologie: la methode des dièdres droits. Bull. Soc. Géol. France, VII, 19, 1309-1318; Paris.

Anovitz, L.M. and Essene, E.J. (1987): Phase equilibria in the system $CaCO_3$-$MgCO_3$-$FeCO_3$. J. Petr., 28, 389-414.

Antonitsch, W. and Neubauer, F. (1992): Altpaläozoischer alkalischer Riftvulkanismus und kretazische Imbrikation in der westlichen Gurktaler Decke, Ostalpen. Frankf. Geowiss. Abh., A11, 15-18.

Berman, R.G. (1990): Mixing properties of Ca-Mg-Fe-Mn garnets. Am. Miner. 75, 328-344.

Berman, R.G. (1991): Thermobarometry using multi-equilibrium calculations: A new technique with petrological applications. Can. Mineral., 29, 833-855.

Chatterjee, N.D. and Froese, E. (1975): A thermodynamic study of the pseudo-binary join muscovite-paragonite in the system $KAlSi_3O_8$-$NaAlSi_3O_8$-Al_2O_3-SiO_2-H_2O: new phase equilibria data, some calculated phase relations, ad their petrological applications. Contrib. Mineral. Petrol., 88, 1-13.

Choukroune, P., Gapais, D. and Merle, O. (1987): Shear criteria and structural symmetry. J. Struct. Geol., 9: 525-530.

Clar, E. (1965): Zum Bewegungsbild des Gebirgsbaues der Ostalpen. Z. Deutsch. Geol. Ges. 116, 267-291.

Dachs, E. (1990): Geothermobarometry in metasediments of the southern Grossvenediger area (Tauern Window, Austria). J. Met. Geol., 8, 217-230.

Dallmeyer, R. D., Neubauer, F., Handler, R., Fritz, H., Müller, W., Pana, D. and Putis, M. (1996): Tectonothermal evolution of the internal Alps and Carpathians: Evidence from $^{40}Ar/^{39}Ar$ mineral and whole-rock data. Eclogae geol. Helv. 89, 203-227.

Dallmeyer, R.D., Handler, R., Neubauer, F. and Fritz, H. (1998): Sequence of thrusting within a thick-skinned tectonic wedge: evidence from $^{40}Ar/^{39}Ar$ and Rb-Sr ages from the Austroalpine nappe complex of the Eastern Alps. J. Geol., 106, 71-86.

Ehlers, K., Stüwe, K., Powell, R., Sandiford, M. and Frank, W. (1994): Thermmetrically inferred cooling rates from the Plattengneis, Koralm region, Eastern Alps. Earth Planet. Sci. Lett., 125, 307-321.

England, P.C. and Thompson, A.B. (1984): Pressure-temperature-time paths of regional metamorphism. Part I: Heat transfer during the evolution of regions of thickened contiental crust. J. Petrol., 25, 894-928.

Frank, W. (1987): Evolution of the Austroalpine elements in the Cretaceous. In: Flügel, H.W., and Faupl, P., eds., Geodynamics of the Eastern Alps. Deuticke, Wien, p. 379-406.

Frey, M. (1987): Very low-grade metamorphism of clastic sedimentary rocks. In: Frey, M., ed., Low temperature metamorphism. Chapman and Hall, New York, pp. 9-58.

Frimmel, H. (1986a): Petrographie, Gefügemerkmale und geochronologische Daten von Kristallingeröllen aus dem Oberkarbon der Gurktaler Decke im Vergleich zum benachbarten Altkristallin. Mitt. Ges. Geol. Bergbaustud. Österr., 32, 39-65.

Frimmel, H. (1986b): Isotopengeologische Hinweise für die paläogeographische Nachbarschaft von Gurktaler Decke (Oberostalpin) und dem Altkristallin östlich der Hohen Tauern (Österreich). Schweiz. Mineral. Petrogr. Mitt., 66, 193-208.

Frimmel, H. (1988): Metagranitoide am Westrand der Gurktaler Decke (Oberostalpin) - Genese und paläotektonische Interpretation. Jb. Geol. Bundesanst., 131, 575-592.

Froitzheim, N., Schmid, S.M. and Conti, P. (1994): Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. Eclogae Geol. Helv., 87, 559-612.

Froitzheim, N. Schmid, S.M. and Frey, M. (1996): Mesozoic paleogeography and the timing of eclogite-facies metamorphism in the Alps: A working hypothesis. Ecl. Geol. Helv., 89, 81-110.

Froitzheim, N., Conti, P. and van Daalen, M. (1997): Late Cretaceous, synorogenic, low-angle normal faulting along the Schlinig fault (Switzerland, Italy, Austria) and ist significance for the tectonics of the Eastern Alps. Tectonophysics, 280, 267-293.

Fuhrman, M.L. and Lindsley, D.H. (1988): Ternary feldspar modeling and thermometry. Am. Mineral., 73, 201-215.

Giese, U., 1987. Altpaläozoischer Vulkanismus am NW-Rand der Gurktaler Decke. –

Geologie, Petrologie, Geochemie - Unpubl. PHD-thesis, University of Tübingen, p.227.

Giese, U., 1988. Lower Paleozoic volcanic evolution at the northwestern border of the Gurktal nappe Upper Austroalpine eastern Alps. Schweiz. Mineral. Petrogr. Mitt. 68: 381-396.

Gosen, W. von (1982): Geologie und Tektonik am Nordostrand der Gurktaler Decke (Steiermark/Kärnten - Österreich). Mitt. Geol.-Paläont. Inst. Univ. Hamburg, 53, 33-149.

Gosen, W. von (1989): Gefügeentwicklungen, Metamorphosen und Bewegungen der ostalpinen Baueeinheiten zwischen Nockgebiet und Karawanken (Österreich). Geotekt. Forsch., 72, 1-247

Gosen, W. von, Pistotnik, J. and Schramm, J.M. (1987): Schwache Metamorphose in Gesteinsserien des Nockgebietes und im Postvariszikum des Karawankenvorlandes (Ostalpen, Kärnten). Jb. Geol. Bundesanst., 130, 31-36.

Handy, M.R. (1996): The transition from passive to active margin tectonics: a case study from the zone of Samedan (Eastern Switzerland). Geol. Rundsch, 85, 832-851.

Hawkesworth, C.J. (1976): Rb/Sr Geochronology in the Eastern Alps. Contrib. Min. Petr., 54, 225-244.

Hodges, K.V. and Crowley, P.D. (1985): Error estimates and empirical geobarometry for pelitic systems. Am. Mineral., 72, 671-680.

Hoisch, T.D. (1991): Equilibria within the mineral assemblage quartz-muscovite-biotite-garnet-plagioclase and implications for the mixing properties of octohedrally coordinated cations in muscovite and biotite. Contrib. Mineral. Petrol., 108, 43-54.

Holdhaus, K. (1921): Über die Auffindung von Trias im Königstuhlgebietes in Kärnten. Anz. Akad. Wiss. Wien, math.-naturwiss. Kl., 58, 19-21.

Kisch, H.J. (1987): Correlation between indicators of very low-grade metamorphism. In: Frey, M., ed., Low temperature metamorphism. Chapman and Hall, New York, p. 227-300.

Kleemann, U. and Reinhardt, J. (1994): Garnet-biotite thermometry revisited: the effect of Al^{VI} and Ti in biotite. Eur. J. Mineral., 6, 925-941.

Krainer, K., 1984. Sedimentologische Untersuchungen an permischen und untertiradischen Sedimenten des Stangalm-Mesozoikums (Kärnten/Österreich). Jahrb. Geol. Bundesanst., 127: 159.179.

Krainer, K., 1989a. Molassesedimentation im Oberkarbon der Ostalpen am Beispiel der Stangnock Formation am NW-Rand der Gurktaler Decke (Österreich). Zentralbl. Geol. Paläont. Teil 1, 1988, H. 7/8: 807-820.

Krainer, K., 1989b. Die fazielle Entwicklung der Oberkarbonsedimente (Stangnock Fomation) am NW-Rand der Gurktaler Decke. Carinthia II, 179/99:563-601.

Loeschke, J., 1989. Lower Paleozoic volcanism of thc Eastem Alps and its geodynamic implications. Geol. Rdsch., 78: 599-616.

McMullin, D.W.A., Berman, R.G. and Greenwood, H.J. (1991): Calibartion of the SGAM thermobarometer for pelitic rocks using data from phase-equilibrium experiments and natural assemblages. Can. Miner., 29, 889-908.

Miller, C. (1990): Petrology of the type locality eclogites from the Koralpe and Saualpe (Eastern Alps), Austria. Schweiz. Mineral. Petrogr. Mitt., 70, 287-300.

Neubauer, F. (1980): Zur tektonischen Stellung des Ackerlkristallins (Nordrand der Gurktaler Decke). Mitt. Österr. Geol. Ges., 73, 39-53.

Neubauer, F. (1987): The Gurktal Thrust System within the Austroalpine region - some structural and geometrical aspects. In: Flügel, H.W. and Faupl, P., eds., Geodynamics of the Eastern Alps. Deuticke, Wien, p. 226-236.

Neubauer, F., ed., (1992): ALCAPA Field Guide - The eastern Central Alps of Austria. 245 p., IGP/KFU Graz.

Neubauer, F. (1994): Kontinentalkollision in den Ostalpen. Geowissenschaften, 12, 136-140.

Neubauer, F. and Friedl. G. (1997): Conodont preservation within the Gurktal nappe complex, Eastern Alps. Zentralbl. Geol. Paläont. Teil II, 1997, 277-289.

Neubauer, F. and Pistotnik. J. (1984): Das Altpaläozoikum und Unterkarbon des Gurktaler Deckensystems (Ostalpen) und ihre paläogeographischen Beziehungen. Geol. Rundsch., 73, 149-174.

Neubauer, F. and Sassi, F.P., 1993: The quartzphyllite and related units of the Austro-Alpine domain. - In: Raumer, J.von and Neubauer, F., eds., Pre-Mesozoic Geology in the Alps. Berlin (Springer), 423-439.

Neubauer, F., Dallmeyer, R.D., Dunkl, I. and Schirnik, D. (1995): Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics, 242, 79-98.

Neumann, H.H., 1989. Die Oberkreide des Krappfeldes. In: T. Appold and F. Thiedig (Editors), Arbeitstagung der Geol. Bundesanst., 1989. Geol. Bundesanst., Wien, pp. 70-79.

Powell, R. and Holland, T.J.B. (1988): An internally consistent thermodynamic dataset with uncertanities and correlations. III. Application methods, worked examples and a computer program. J. metamorphic Geol., 6, 173-204.

Rantitsch, G. and Russegger, B. (1998): Thrust-related very low grade metamorphism within the Gurktal nappe complex (Eastern Alps). (submitted).

Ratschbacher, L. and Neubauer, F. (1989): West-directed decollement of Austro-Alpine cover nappes in the eastern Alps: geometrical and rheological considerations. Geol. Soc. Spec. Publ., 45, 243-262.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S. M. and Neugebauer, J. (1989): Extension in compressional orogenic belts: The eastern Alps. Geology, 17, 404-407.

Ratschbacher, L., Schmid, S.M., Frisch, W. and Neubauer, F. (1990): Reply on the Comment of S.R. Wallis to "Extension in compressional orogenic belts: the eastern Alps. Geology, 18, 675-676.

Schimana, R. (1986): Neue Ergebnisse zur Entwicklungsgeschichte des Kristallins um Radenthein (Kärnten, Österreich). Mitt. Ges. Geol. Bergbaustud. Österr., 33, 221-232.

Simpson, C. and Schmid, S.M. (1983): An evaluation of criteria to deduce the sense of movement in sheared rocks. Geol. Soc. Amer. Bull., 94, 1281-1288.

Stock, P. (1989): Zur antithetischen Rotation der Schieferung in Scherbandgefügen - ein kinematisches Deformationsmodell mit Beispielen aus der südlichen Gurktaler Decke (Ostalpen): Frankfurter Geowiss. Arb., A7, 1-155.

Stock, P. (1992): A strain model for antithetic fabric rotation in shear band structures. J. Struct. Geol., 14, 1267-1275.

Thiedig, F. (1975): Submarine Brekzien als Folge von Felsstürzen in der Turbidit-Fazies der Oberkreide des Krappfeldes in Kärnten (Österreich). Mitt. Geol.-Paläont. Inst. Univ. Hamburg, 44, 495-516.

Tollmann, A. (1975): Die Bedeutung des Stangalm-Mesozoikums in Kärnten für die Neugliederung des Oberostalpins in den Ostalpen. N. Jb. Geol. Paläont. Mh., 150, 19-43.

Tollmann, A. (1977): Geologie von Österreich. Band 1. Die Zentralalpen. XVI + 710 p., Vienna (Deuticke).

Tollmann, A. (1987): The Alpidic Evolution of the Eastern Alps. In: Flügel, H.W. and Faupl, P., eds., Geodynamics of the Eastern Alps. Deuticke, Wien, p. 361-378.

Van Hinte, J.E. (1963): Zur Stratigraphie und Mikropaläontologie der Oberkreide und des Eozäns des Krappfeldes (Kärnten). Jb. Geol. Bundesanst. Sdbd., 8, 1-147.