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# Tectonometamorphic evolution of the Koralm Complex (Eastern Alps): constraints from microstructures and textures of the 'Plattengneis' shear zone

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## Abstract

Lattice preferred orientations (LPO) of quartz have been investigated along a south–north oriented section across the Plattengneis of the Koralm Complex (Eastern Alps). The Plattengneis forms an important shear zone within the Austroalpine nappe complex of the Eastern Alps, which has developed during the Cretaceous evolution of the Alpine orogen. The quartz *c*-axes form small circle distributions in the southernmost parts of the Koralm Complex, which represent the uppermost structural level of the Plattengneis. 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 the tendency to be distributed along a single girdle, with three corresponding maxima of *a*-axes near the margin of the pole figure, can be observed in the central and northern parts. Such LPO are characteristic for both high grade metamorphic conditions and high finite strain. The microstructures display that the deformation within the Plattengneis shear zone was synmetamorphic. A continuous increase of peak temperatures (and pressure) 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 to approximately 650 °C from the central parts to the North. The related pressures increase from 8 to 16 kbar, and then decrease to 10 kbar. The LPO 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. The temperature and pressure evolution may indicate that the central parts of the Koralm Complex have been exhumed by larger amounts than the northern and southern parts. This is also documented by the LPO evolution. Therefore, we assume that the Plattengneis shear zone formed during the exhumation of the Koralm Complex, and is related to the exhumation of high-pressure units in the footwall of this shear zone. Accordingly, the kinematics of the Plattengneis shear zone is rather extensional than thrust-related. The implications for the structural evolution of the Eastern Alps are shortly discussed.

*Keywords*: Plattengneis shear zone; Lattice preferred orientations (LPO); Microstructure; Exhumation; Koralm Complex; Eastern Alps

## 1. Introduction

The Plattengneis (or so-called 'Stainzer Plattengneis') forms an important shear zone within the Austroalpine nappe complex of the Eastern Alps (Fig. 1). This major shear zone has been interpreted to have developed during the Early Cretaceous collisional event within the Austroalpine unit (Frank, 1987; Krohe, 1987; Stüwe and Powell, 1995). Thus, the Plattengneis was the subject of many structural and microstructural investigations for several years (e.g. Frank et al., 1983; Flöttmann et al., 1986; Krohe, 1987). In particular the Plattengneis has been investigated in order to obtain information about the evolution of microfabrics and the development of lattice preferred orientations (LPO; textures) in high-grade, amphibolite facies crustal shear zones (De Roo, 1983; Frank et al., 1983; Simpson and Schmid, 1983; Flöttmann et al., 1986; Schmid and Casey, 1986; Krohe, 1987; Kurz and Unzog, 1999; Brosch et al., 2000). However, these investigations were often restricted both to single outcrops and from a methodological point of view. Therefore, we will discuss the evolution of the Plattengneis shear zone along a S–N section across the Koralm Complex in order to get information on the homogeneity of deformation and on the strain geometry, based on the relationships beween the microstructures, LPO, and the metamorphic field gradient (Tenczer and Stüwe, 2001,

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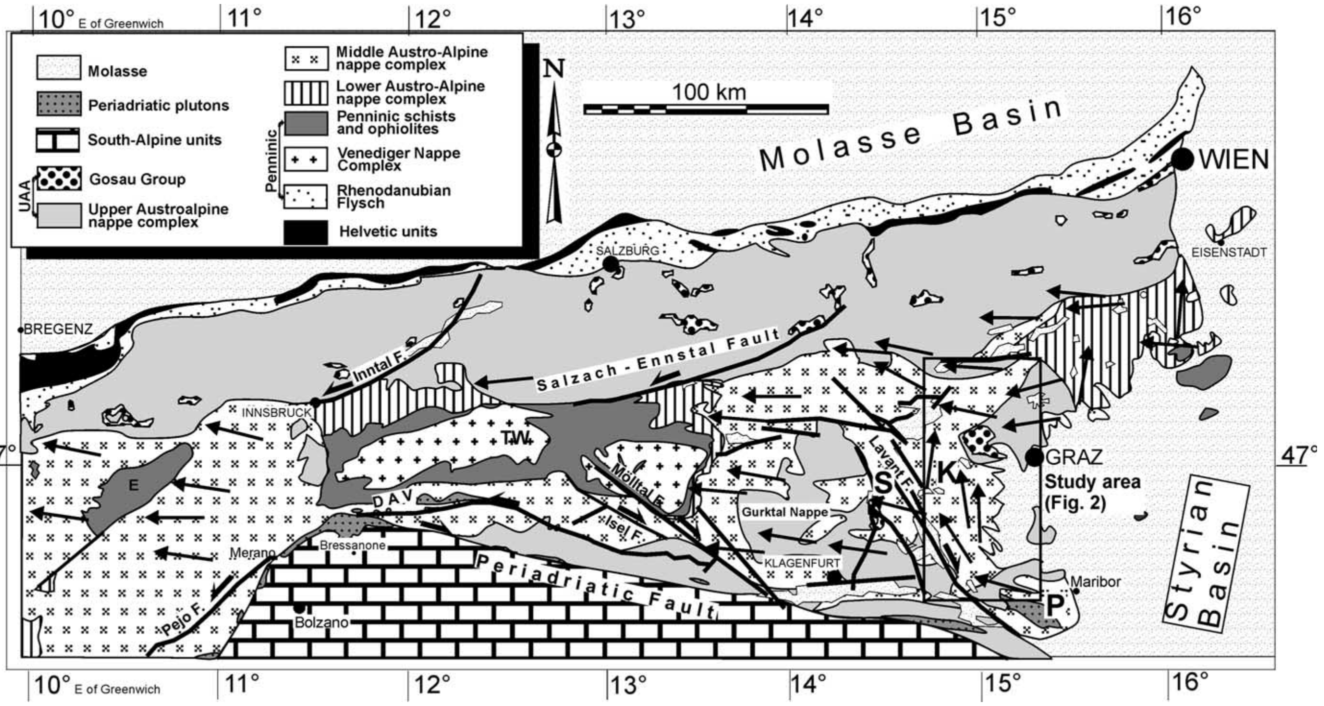


Fig. 1. Simplified tectonic map of the Eastern Alps (modified after Janoschek and Matura, 1980; Neubauer and Höck, 2000); the area of detailed investigation is marked. Arrows indicate direction of nappe emplacement within the Austroalpine nappe complex (compiled data from Ratschbacher, 1986; Krohe, 1987; Ratschbacher and Neubauer, 1989; Neubauer et al., 1992, 2000; Linzer et al., 1995); DAV: Defereggen–Antholz–Vals Fault; E: Lower Engadine Window; K: Koralpe; P: Pohorje mountains; S: Saualpe; TW: Tauern Window; UAA: Upper Austroalpine.

2002). Referring to this microstructural evolution we will discuss the development of this shear zone during the Alpine orogeny in the Cretaceous, and its implications for the tectonic evolution of the Eastern Alps.

## 2. Geological setting of the Koralm Complex

The Koralm Complex (Figs. 1 and 2) forms part of the Middle Austroalpine nappe complex, which has been incorporated into the Austroalpine nappe stack during the Early Cretaceous (Frank et al., 1983; Frank, 1987; Krohe, 1987; Neubauer et al., 1992, 2000). Several regionally important shear zones formed during this collisional event. The Plattengneis has been interpreted to represent one of these major shear zones. The Koralm Complex is part of the Koriden Unit within the Middle-Austroalpine nappe complex, mainly exposed within the Koralpe, the Saualpe, and the Pohorje Mountains (Frank et al., 1992) (Fig. 2). The Koriden Unit comprises an eclogite-bearing basement complex (the so-called 'Gneiss Group') and the overlying 'Micaschist Group' (e.g. Heritsch, 1980). It is overlain by the ophiolitic Plankogel Complex (Gregurek et al., 1997) (Figs. 2 and 3). To the north, the Koriden Unit is bordered by the Muriden Unit (Figs. 2 and 3) (Becker, 1981; Flügel and Neubauer, 1984), which is mainly exposed within the Gleinalm Dome (Fig. 3). The Muriden Unit comprises the Micaschist–Marble Complex as the uppermost unit, the Speik Complex, and the Core Complex at the base. The Speik Complex comprises garnet amphibolite, banded amphibolite, augengneiss, serpentinite, and metasedimentary rocks, forming a pre-Alpine metaophiolithic sequence (Neubauer et al., 1989). The Core Complex is made up of biotite–plagioclase paragneiss, plagioclase orthogneiss, and amphibolite.

The Koralm Complex consists of a sequence of kyanite-bearing paragneiss, and paragneiss with pseudomorphs after andalusite, enclosing up to kilometer-sized lenses of eclogite and eclogite–amphibolite. Relics of metagabbro as well as marble, manganese quartzite, calcsilicate rocks, and pegmatite are locally intercalated (Weissenbach, 1975; Raith, 1988) (Fig. 2).

The Koralm Complex is characterized by a poly-metamorphic history with signatures of pre-Alpine events (Frank et al., 1983; Frank, 1987), and reached amphibolite to eclogite facies conditions during the Cretaceous (Eo-Alpine event) (Morauf, 1980, 1982; Miller and Frank, 1983; Miller, 1990; Thöni and Jagoutz, 1992, 1993; Ehlers et al., 1994, 1995; Stüwe and Powell, 1995; Miller and Thöni, 1997). The pressure peak (approximately 18 kbar) was reached during eclogite facies metamorphism, which has been dated around 100 Ma (Thöni and Jagoutz, 1992, 1993; Thöni and Miller, 1996; Miller and Thöni, 1997). The temperature peak was reached during subsequent amphibolite facies metamorphism, dated around 90 Ma (Thöni and Miller, 1996; Miller and Thöni, 1997). However, Manby

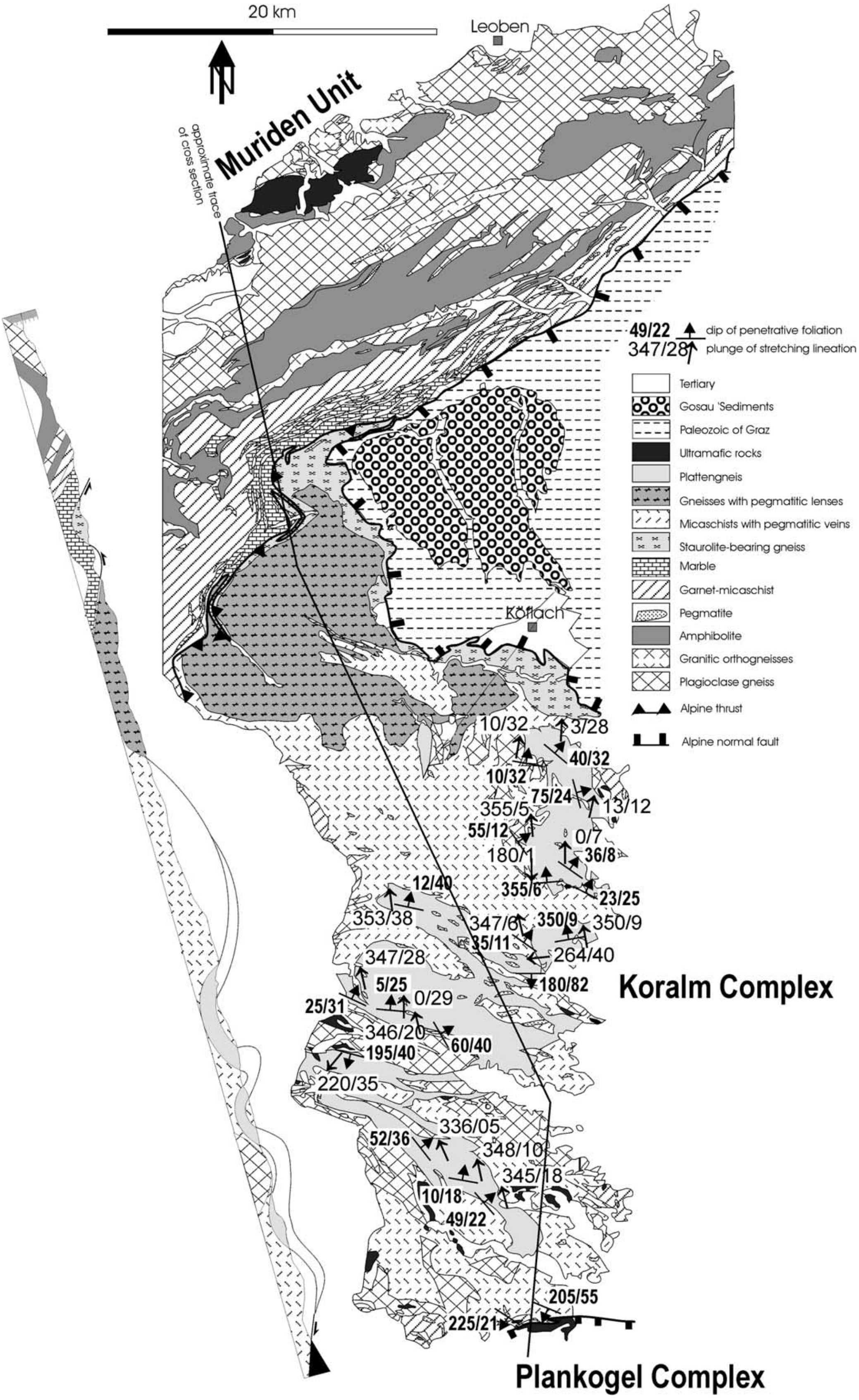


Fig. 2. Geological map of the Koralm area, with structural data from Plattengneis exposures, and cross-section.

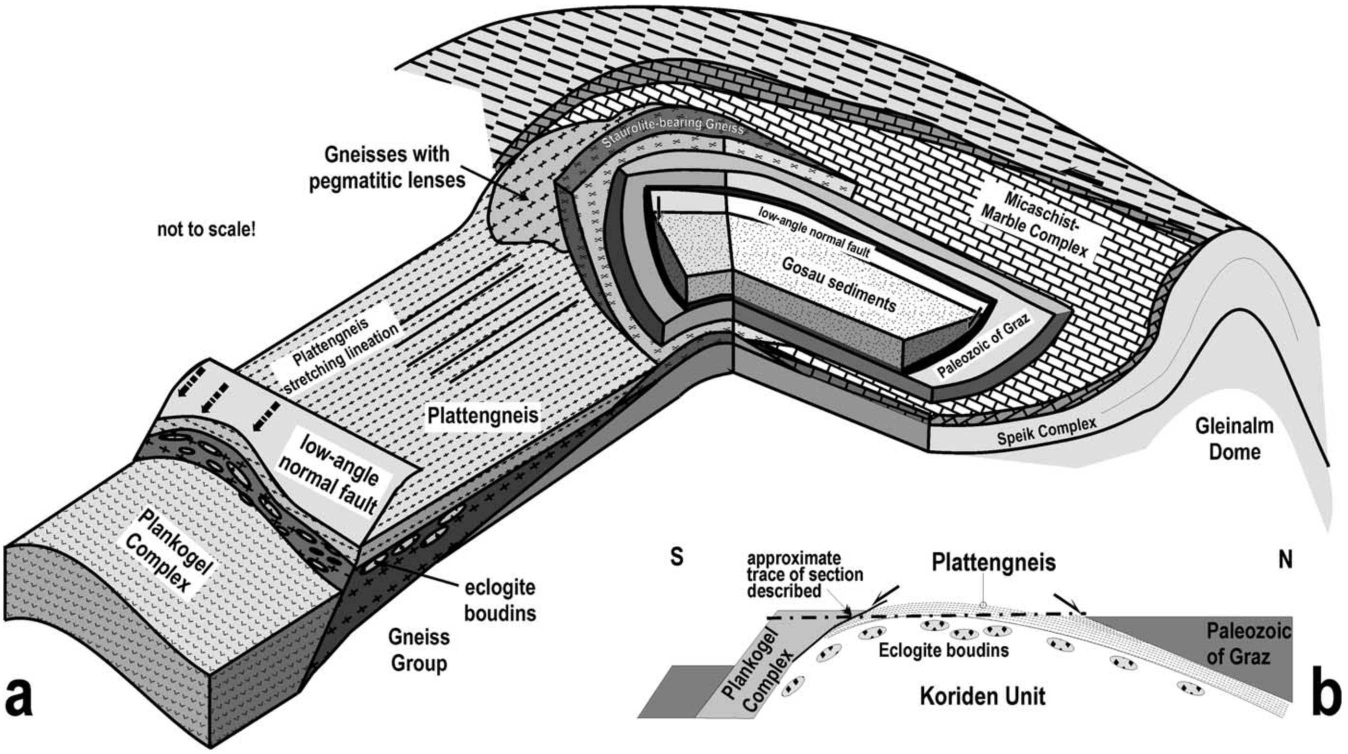


Fig. 3. (a) Model showing the structural relationships between the Koralm Complex and the surrounding tectonic units of the central Eastern Alps. (b) Sketch showing the relationships between the Koralm Complex, the Plankogel Complex, and the Paleozoic of Graz along a SSW–NNE section; subsequent regional folding, as displayed in Fig. 2, has been neglected.

and Thiedig (1988) and Manby et al. (1990) argued for late Precambrian eclogite facies metamorphism based on Sm–Nd garnet–whole rock ages of 693 Ma. The geochronological studies of the Koralm Complex have not yet resulted in a conclusive picture of the metamorphic evolution, and some data are still contradictory. A Permian age of the gabbroic eclogite protoliths has been suggested by Thöni and Jagoutz (1992, 1993), Thöni and Miller (1996), and Miller and Thöni (1997); the protolith has been metamorphosed at eclogite facies conditions (18–20 kbar, 600–620 °C) during the Alpine event at approximately 100 Ma. However, a pegmatite within eclogite amphibolites yielded Permian Rb–Sr white mica ages (Göd, 1989; Thöni and Miller, 2000). On the other hand, many other pegmatites that were not dated radiometrically crosscut an eclogite facies penetrative foliation (Neubauer, 1991; Kurz et al., 1999). Muscovites from pegmatites in paragneissic country rocks yielded Rb–Sr ages between 267 and 244 Ma (Frank et al., 1981; Morauf, 1981). Rb–Sr thin slab isochrons from the Plattengneis also gave intra-Permian ages (Frank et al., 1981, 1983). Garnet–whole rock Sm–Nd ages from metapelites, the common host rocks of the gabbros and eclogites, range from approximately 89 to 85 Ma (Miller and Thöni, 1997). In general, the eclogites and eclogite amphibolites are structurally situated below the Plattengneis.

The Plattengneis forms a ductile shear zone and is restricted to the uppermost sections of the Koralm Complex. The thickness of the Plattengneis reaches up to 500 m. The mylonites of the Plattengneis are connected to their host rocks by transitional zones with prevailing lenticular and augen structures (Brosch et al., 2000). The mylonitic gneiss shows a distinct planar fabric (penetrative foliation). Macroscopically, it is characterized by a nearly perfect tabular fissility parallel to the penetrative folition, and a very prominent stretching lineation which is generally trending N–S (Figs. 2 and 3).

An essential part of the Plattengneis derived from metapelitic protoliths (paragneisses). Locally, the Plattengneis is intruded and crosscut by pegmatitic dykes and veins. Most of these veins are transposed parallel to the penetrative foliation and are transformed into a pegmatitic type of Plattengneis. From top to bottom, the Plattengneis shear zone develops continuously from an undeformed protolith, to a protomylonite, and finally to the mylonites of the Plattengneis. In the northern part of the Koralm Complex this protolith is formed by the so-called 'Hirschegger Gneis' (Becker, 1976) (part of the 'Gneisses with pegmatitic lenses' in Fig. 2).

## 3. Methods

We discuss the evolution of microstructures and LPO within the Plattengneis of the Koralm Complex. We investigated several outcrops in order to get information on the lateral and vertical variations of LPO. X-ray texture analyses of quartz were carried out with a Siemens D500 X-ray goniometer at the University of Graz (Austria) in reflexion mode. Because of the apparative and methodical limitations the sample size is restricted to $2.5 \times 1.5$ cm. The X-ray beam is reflected from an area of about $5 \times 5$ mm. In order to avoid additional complications due to additional mineral phases either samples with high contents of quartz (>75 vol%), or quartz ribbons have been used for the measurements and the evaluation of LPO. Samples have been taken from exposures, which do not show structures of later deformational overprint.

The pole figures were calculated with the program TexAT v. 2.2c/ODF AT v.1.1a provided by Siemens Co., which is based on the 'Harmonic Method' (Bunge, 1981, 1985; Bunge and Esling, 1985), and with the program MENTEX ('Vector Method'; Schaeben et al., 1985; Schaeben, 1994). Both program packages include corrections for background and beam defocussing. Furthermore, neutron texture analyses have been carried out with the goniometer SKAT at the pulsed neutron reactor IBR2 at the Joint Institute for Neutron Research (JINR) in Dubna (Russia), which allows the measurement of samples of about 27 $\mathrm{cm}^3$. These analyses are based on the time of flight (TOF) of neutrons within a neutron beam, which is directly related to their wavelength (Ullemeyer et al., 1998) and, therefore, d-spacing.

## 4. Mapscale and mesoscale structures

In the southern part of the Koralm Complex and the Plankogel Complex the penetrative foliation dips to the South, the northern part of the Koralm Complex (area south of Köflach) is generally characterized by a north-dipping foliation (Figs. 2 and 3). In the central part the penetrative foliation has a subhorizontal orientation. Thus, the Koralm Complex forms a dome structure with an approximately E–W-trending axis (Fig. 3b). A section from the South towards the central parts, therefore, exposes continuously deeper structural levels both of the Koralm Complex, and in particular the Plattengneis shear zone. The opposite evolution can be traced from the central parts towards the North. Locally, small scale folds and a crenulation of the penetrative mylonitic foliation are observed; the axes of these folds generally dip gently to the East. In the area of investigation, the penetrative foliation of the Plattengneis gently dips N to NE. This foliation is isoclinally folded; the related fold axes are parallel to the stretching lineation, which gently dips N. In several layers near its base, boudins of eclogite are incorporated into the Plattengneis shear zone. The boudins are elongated in a N–S direction and range from 100 to 0.1 m in thickness. Subsequently the penetrative foliation has been gently folded around subhorizontal, E–W oriented axes, which resulted in the development of kilometer-scale syn- and anticlines (Fig. 2).

In the following, the evolution of microstructures and textures of the Plattengneis will be described in a direction from South to North, and therefore, from structurally higher to deeper levels of the Koralm Complex.

## 5. Microstructures

Quartz typically forms layers and lenses in the Plattengneis (Fig. 4a). Within these lenses the quartz grains are characterized by uniform size in the range from 0.1 to 0.2 mm. In the matrix, however, the occurrence of additional mineral phases, especially plagioclase, white mica and biotite, resulted in an irregular grain size distribution within several domains. Within layers and lenses, the quartz grains show an equant shape. The grains are characterized by serrate and lobate grain boundaries typical for high temperature deformation (equigranular–interlobate fabric after Passchier and Trouw, 1996). The main mechanism of dynamic recrystallization is grain boundary migration recrystallization. Subgrains commonly occur. In many cases the subgrains show undulatory extinction. Most of the traces of subgrain boundaries are oriented parallel to the traces of the *c*-axes and are likely to be parallel to the prism planes. Some domains are characterized by uniformly sized quartz grains bordered by straight grain boundaries. These fabrics may document partial annealing.

In places, monomineralic quartz veins of centimeter to decimeter thickness can be observed within the Plattengneis host rocks (Fig. 4b). These veins are parallel to the penetrative foliation, and have a grain size of up to 2 mm. The quartz grains show strong undulatory extinction, development of subgrains, and highly lobate grain boundaries. The only difference between the quartz microstructures of layers and lenses within the host rock and the quartz veins is the grain size, which is up to 10 times larger in diameter within the veins.

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. 4c). 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) (Passchier and Trouw, 1996). The porphyroclasts are sometimes surrounded by asymmetrically arranged strain shadows. These kinematic indicators document a top-to-the-N sense of shear. The strain shadows are either filled with dynamically recrystallized feldspars, or with quartz grains.

In paragneisses, garnet is partly boudinaged (Fig. 4d), 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

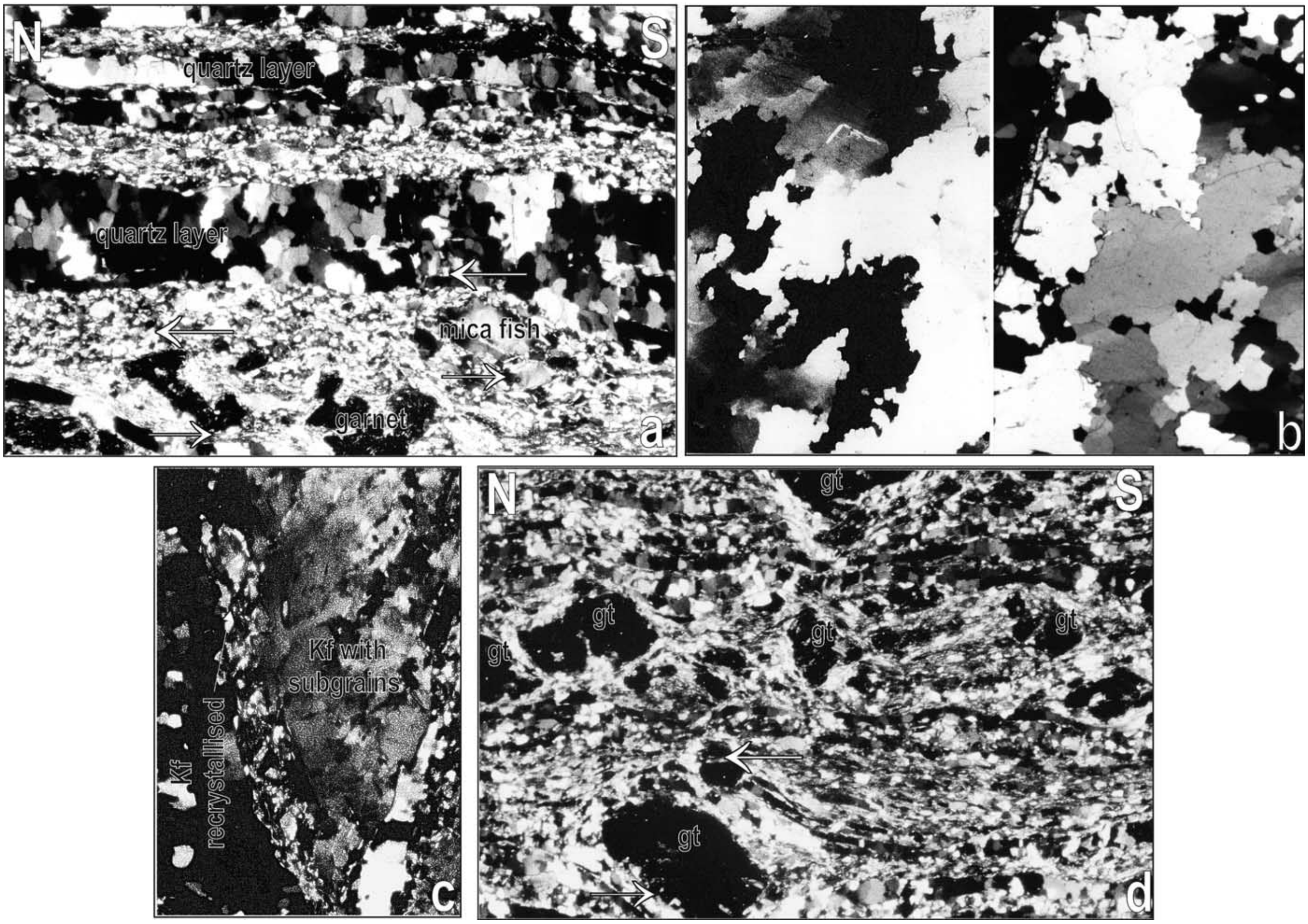


Fig. 4. Representative microstructures from the Plattengneis. (a) Typical quartz layers parallel to the penetrative foliation showing HT microstructures (for explanation see text). (b) Quartz microstructures from transposed quartz vein; the quartz grains show typical lobate grain boundaries. (c) K-feldspar (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-the-N sense of shear, and are filled with biotite; quartz within layers shows uniform grain size and partially straight grain boundaries. (a)–(d): crossed polarized Nicols. (a), (b), (d): long axis of photograph about 4 mm; (c): long axis of photograph about 2 mm.

asymmetrically arranged around garnet cores. These fabrics also indicate a top-to-the-N sense of shear (Fig. 4d).

## 6. Quartz lattice preferred orientations

Plattengneis samples for texture analyses have been taken along a S–N oriented traverse across the Koralm Complex (Fig. 5), perpendicular to the trend of the penetrative foliation and the lithostratigraphic boundaries within this unit. The section crosses the Plankogel Complex and the uppermost parts of the Plattengneis in the South, and continuously deeper parts of the Plattengneis towards the central parts. Towards the north shallower structural levels are crosscut again. This provides information on the vertical variations of the textural evolution of the Plattengneis. We will discuss the basic features and the general trend of LPO evolution along this traverse, and the relations to the metamorphic field gradient (Tenczer and Stüwe, 2001, 2002). The methods of geothermobarometric calculations in the area of investigation will be described by Tenczer and Stüwe (2002). The pole figures in Fig. 6 are arranged in a S–N direction.

Generally, a continuous change from small circle distributions in the southernmost parts, to crossed girdles in the central parts, and single maxima centered in the *Y*-axis of the finite strain ellipsoid in the central and northern parts can be observed. The terminology of crossed girdles follows Lister (1977) and Lister and Hobbs (1980).

In the southern part of the study area, symmetrical or slightly asymmetrical small circle distributions of quartz *c*-axes [001] are developed (Fig. 6) (pole figures 1 and 2). Along the small circles two clusters that are asymmetrically arranged near the *Z*-axis can be recognized. The *a*-axes [110] and the poles to the prism planes [100] are distributed along two small circles with a large opening angle, oblique to the *X*–*Y* plane of the finite strain ellipsoid. These textures are asymmetric with respect to the penetrative foliation,

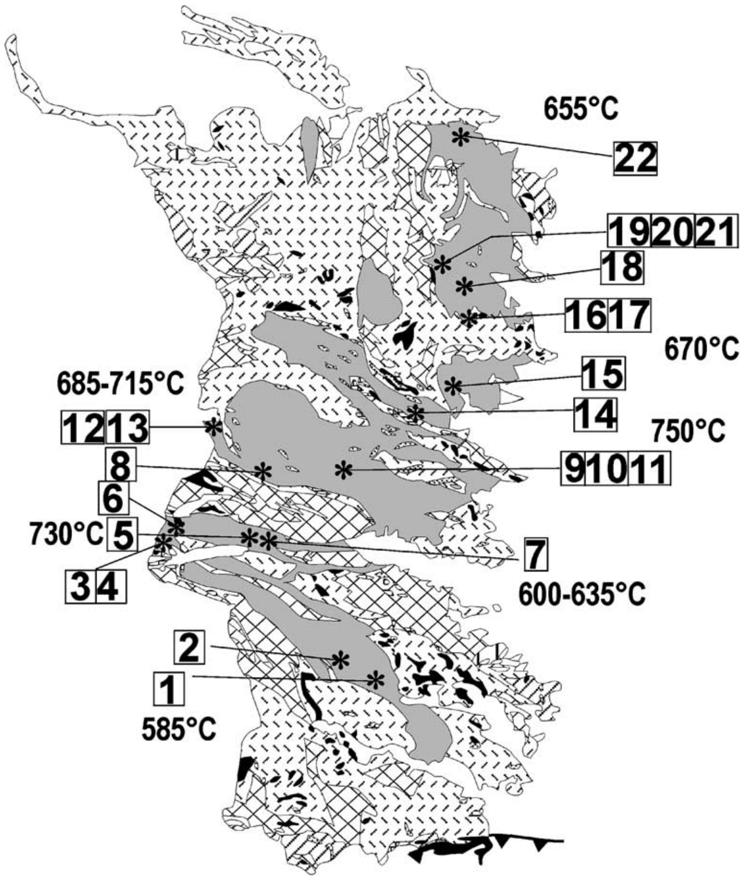


Fig. 5. Geological map of the Koralm area including the sampling sites for texture measurements; numbering corresponds to the pole-figure-numbers in Fig. 6. For legend see Fig. 2.

indicating non-coaxial deformation (e.g. simple shear). This asymmetry indicates a top-to-the-N sense of shear. Geothermometric calculations in this sampling area gave peak temperatures in the range of approximately 585 °C (Tenczer and Stüwe, 2001) (Fig. 5).

Pole figure 3 (Fig. 6) shows two strong maxima between the *Y*- and the *Z*-axes of the finite strain ellipsoid, and only minor remnants of a type I crossed girdle. The corresponding *a*-axes [110] and prism poles [100] show three well defined maxima distributed along a great circle normal to the corresponding *c*-axes maximum, 120° away from each other. Towards the North, the quartz *c*-axis distributions continuously grade into either single girdle distributions or type I crossed girdles (pole figures 4–11) (Fig. 6). The fabric of pole figure 10 is interpreted to represent a type II crossed girdle. The peak temperatures in this sampling area range from approximately 600 to 635 °C according to Tenczer and Stüwe (2001) (Fig. 5).

Further to the North, the LPO are characterized by a strong maximum of *c*-axes [001] in the *Y*-axis of the finite strain ellipsoid (pole figures 12–22), with a slight tendency towards the formation of a single girdle (pole figures 12, 15 and 18) (Fig. 6); the lack of axis symmetry in pole figure 12 results from cutting slighty oblique to the foliation and lineation; pole figure 14 shows the remnants of a type I crossed girdle distribution. The corresponding poles to the primary prisms (*a*-axes) [110] form three maxima at the periphery of the pole figure. In general, these maxima are symmetrically arranged with respect to the penetrative foliation. In pole figure 13 they are distributed slightly asymmetrically about the macroscopic fabric axes. One maximum is centered about 5° from *Z* in the NE and SW sectors of the pole figure. However, the strongest maximum can be observed in the SE/NW sector of the pole figure, which indicates the macroscopic shearing direction with a top-to-the-N sense of shear, and the orientation of preferred slip, respectively (pole figures 13, 15 and 19 in Fig. 6). Accordingly, the poles to the secondary prism planes [100] form three maxima at the periphery of the pole figure, too. Geothermometric calculations indicate peak temperatures in the range from approximately 685 to 750 °C in the central parts of the Koralm Complex, and from 655 to 670 °C in the northern parts (Fig. 5).

This textural evolution is independent of the protolith of the Plattengneis. It can be observed both within metapelitic Plattengneis rocks, meta-pegmatitic mylonites, and within quartz veins, which have been transposed parallel to the penetrative mylonitic foliation. Although the veins display a quartz grain size up to 10 times larger in diameter than within the Plattengneis mylonites (see Fig. 4a and b), they

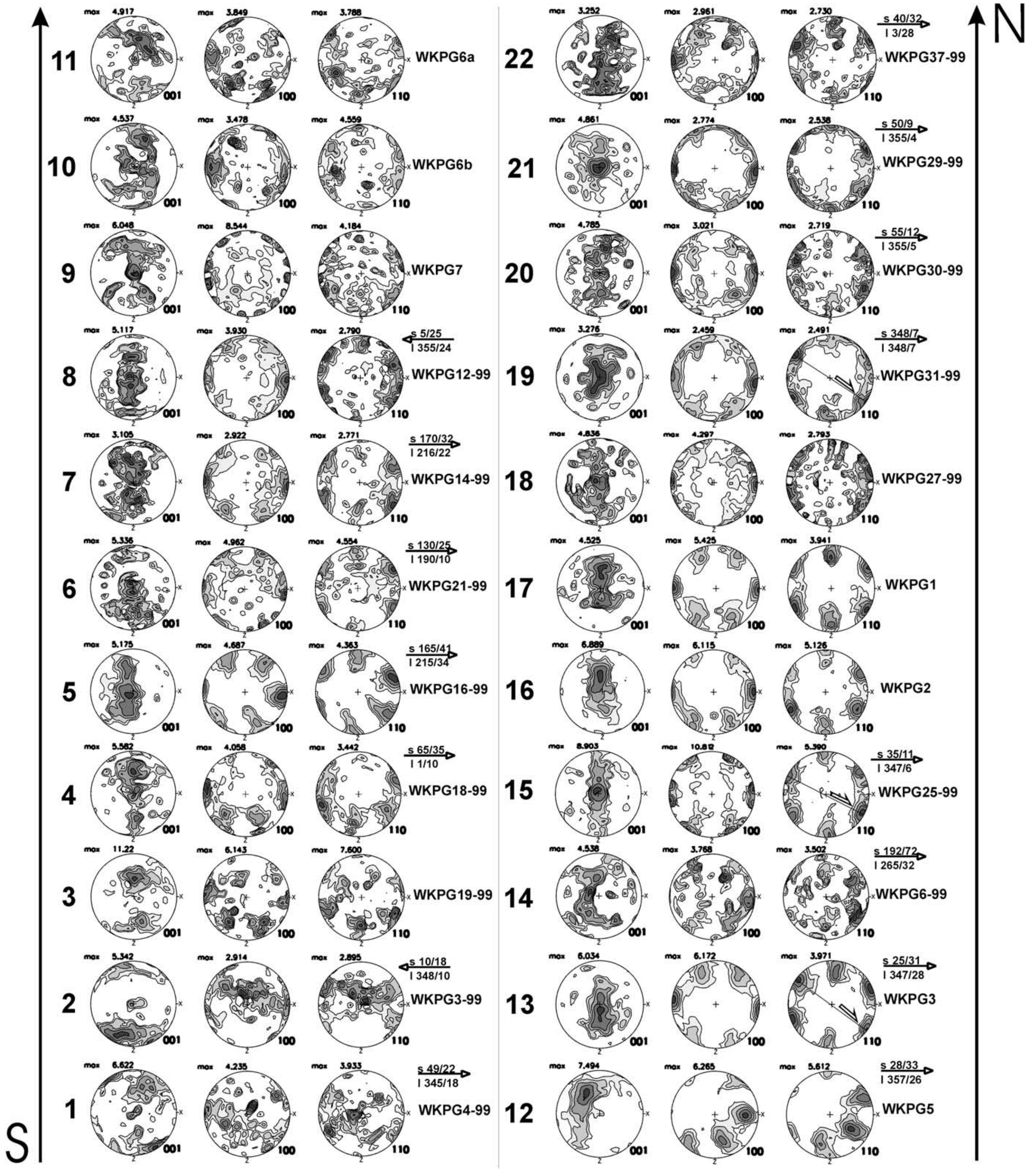


Fig. 6. Pole figures of quartz LPO from the Plattengneis, arranged along the S–N-section presented in Fig. 2; the sampling sites are displayed in Fig. 5; X marks the direction of the stretching lineation and the strike of the shear zone boundary; line through the dominating *a*-axis maxima and arrows in pole figures 13, 15 and 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.

show the same textural evolution. This subject has been described and discussed in detail by Kurz and Unzog (1999).

## 7. Discussion

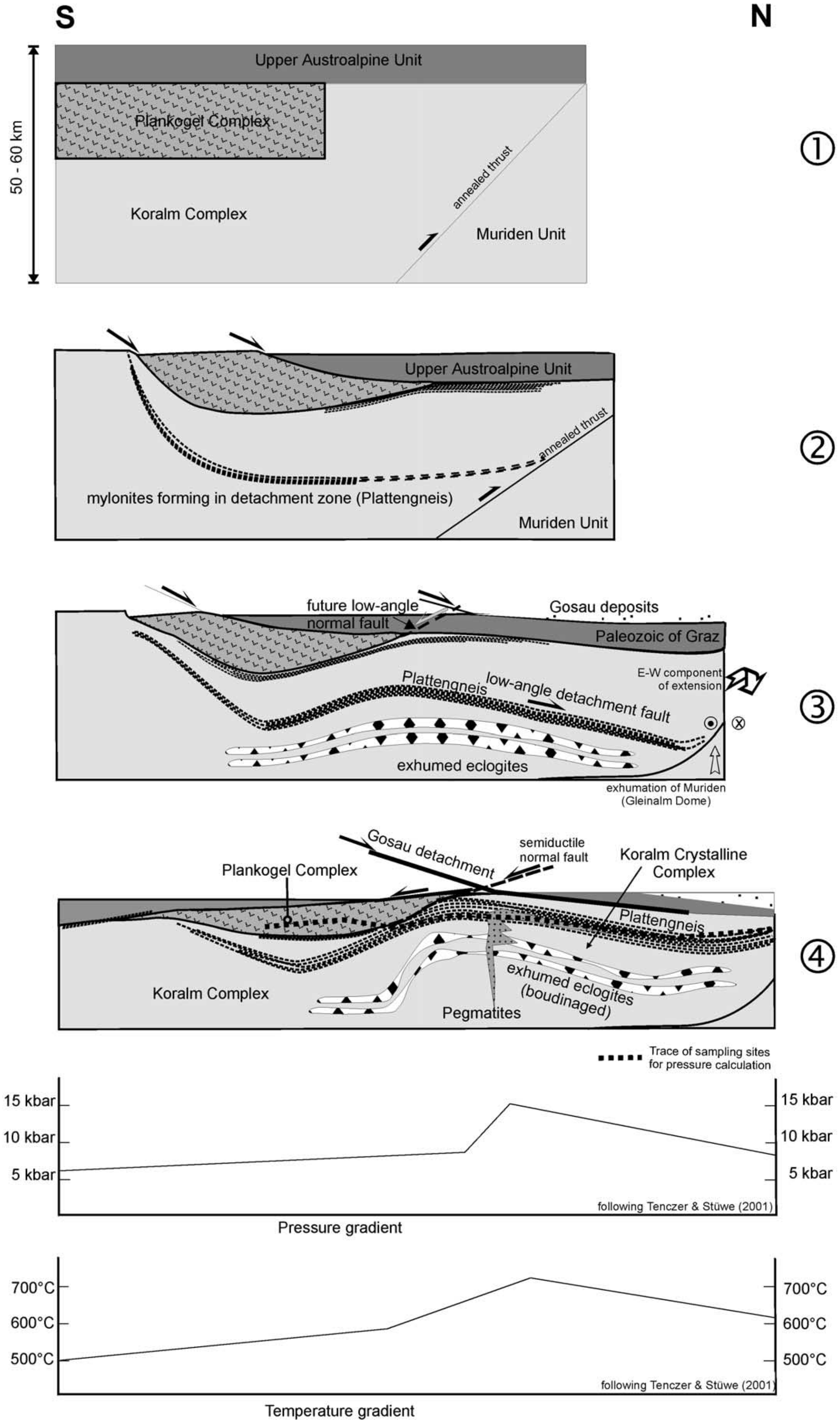
Several LPO that have been previously described from the Plattengneis (e.g. Schmid, 1983; De Roo, 1983; Simpson and Schmid, 1983; Schmid and Casey, 1986; Flöttmann et al., 1986; Krohe, 1987; Kurz and Unzog, 1999) show approximately the same features as our study. The *c*-axes form either two maxima between *Y* and *Z*, which can be interpreted in terms of preferred slip on the rhombs (e.g. Schmid and Casey, 1986), or a strong maximum near the *Y*-axis with the tendency to be distributed along a single girdle, similar to the patterns of, e.g. the pole figures 12, 13 and 15–22 in Fig. 6. These fabrics display three corresponding maxima of *a*-axes near the margin of the pole figure. Generally, such strong LPO are characteristic for high grade metamorphic conditions. It was shown by Kurz and Unzog (1999) that these pronounced fabrics developed from either type I or type II crossed girdle distributions. Despite the high finite strain of the Plattengneis, which can be observed at the mesoscale, the deformation during the evolution of this major shear zone was partitioned in distinct zones with different general shear at millimeter- to centimeter-scale (Kurz and Unzog, 1999).

At a larger scale, the change of the LPO from the South to the North may be interpreted either in terms of different strain geometries, or by a temperature gradient. The independence of the LPO from the modal composition argues for both high finite strain and high-grade metamorphic conditions (which is a matter of fact), which caused a decreasing ductility contrast (Kurz and Unzog, 1999). The LPO evolution may be interpreted in terms of a stronger component of flattening strain in structurally shallower levels of the Plattengneis shear zone, which are exposed in the southern part of the study area. This is indicated by small circle *c*-axes distributions. The deformation geometry in the central parts of the Koralm Complex is located closer to plane strain, documented by the occurrence of type I crossed girdles. These features are similar to observations by Law (1987) and Law et al. (1990). However, this evolution also coincides with increasing peak temperatures from structurally higher levels exposed in the South, to deeper levels exposed in the central parts (Fig. 5).

Furthermore, different glide systems seem to have been activated within different structural settings. Slip along the basal plane parallel ⟨a⟩ seems to dominate in structurally shallower levels, indicated by small circles around *Z* (pole figures 1 and 2 in Fig. 6), while the dominance of slip along the rhombs continuously increases towards deeper structural levels, exposed in the internal parts of the Koralm Complex. In the central southern parts *c*-axis maxima between *Y* and *Z* suggest dominant ⟨a⟩-slip on the rhombs (e.g. pole figure 3), while maxima around *Y* suggest dominant ⟨c⟩ slip on the prism planes (e.g. pole figures 12, 13, 16, 17 and 19 in Fig. 6). The *P–T* data of the metamorphic field gradient (Tenczer and Stüwe, 2001) indicate a continuous increase of the peak temperature from the South towards the North, from approximately 550 °C to approximately 750 °C in the central parts of the Koralm Complex (Figs. 5 and 7). From the central parts towards the North, temperatures decrease to approximately 650 °C in the investigated area. The corresponding pressures increase from 8–10 kbar in the South to 16 kbar in the central parts, and then continuously decrease towards the North down to approximately 10 kbar (Fig. 7). Hence, the evolution of the LPO seems to be the result of temperature dependence for the activation of different glide systems, and of the syn-deformational metamorphic grade. The textural evolution shows that different slip systems of quartz have been preferentially activated during the formation of the Plattengneis shear zone, depending on the structural position within this shear zone (prior to subsequent folding and doming). The activation is primarily related to the syn-deformational metamorphic temperature, which decreases from the structurally shallow to the deep levels across the shear zone. This evolution is very well pronounced in the southern part of the Koralm Complex (compare the succession of pole figures 1–4 in Fig. 6); from the central parts towards the North, this feature is less pronounced due to a rather slight decrease of peak temperatures (Figs. 5 and 7).

## 8. Implications for Alpine orogeny during the Cretaceous

The Plattengneis forms an important shear zone within the Austroalpine nappe complex of the Eastern Alps. It is interpreted to have developed during the Early Cretaceous collisional event within the Austroalpine unit (e.g. Frank, 1987; Krohe, 1987; Neubauer et al., 1992; Ehlers et al., 1994, 1995; Stüwe and Powell, 1995; Stüwe, 1998). Some kinematic data that are related to the emplacement of the Austroalpine nappes indicate a top-to-the-W sense of nappe emplacement (e.g. Ratschbacher, 1986; Fritz, 1988; Ratschbacher and Neubauer, 1989; Fritz et al., 1991; Neubauer et al., 1992, 2000; Linzer et al., 1995) (Fig. 1). Only in the area of the Koralm Complex, and especially within the Plattengneis shear zone, a top-to-the-N sense of shear is documented. However, remnants of E–W oriented stretching lineations have also been observed in this part of the Eastern Alps (Krohe, 1987; Neubauer, 1991). Moreover, the microstructures within the Plattengneis clearly document synkinematic high-grade metamorphic conditions, while in the sorrounding units, especially in the Micaschist–Marble Complex of the Muriden Unit underlying the Koralm Complex, the deformational fabrics are statically annealed during Eo-Alpine metamorphism (e.g. Neubauer et al., 1992, 1995). The Muriden Unit is exposed within the Gleinalm Dome north of the Koralm Complex (Fig. 3). The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50 - 60 km
Upper Austroalpine Unit
Plankogel Complex
Koralm Complex
annealed thrust
Muriden Unit
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Upper Austroalpine Unit
annealed thrust
mylonites forming in detachment zone (Plattengneis)
Muriden Unit
②
future low-angle normal fault
Gosau deposits
Paleozoic of Graz
E-W component of extension
Plattengneis
low-angle detachment fault
exhumed eclogites
exhumation of Muriden (Gleinalm Dome)
③
Gosau detachment
semiductile normal fault
Plankogel Complex
Koralm Crystalline Complex
Plattengneis
exhumed eclogites (boudinaged)
Koralm Complex
Pegmatites
④
Trace of sampling sites for pressure calculation
15 kbar
10 kbar
5 kbar
following Tenczer & Stüwe (2001)
Pressure gradient
700°C
600°C
500°C
following Tenczer & Stüwe (2001)
Temperature gradient

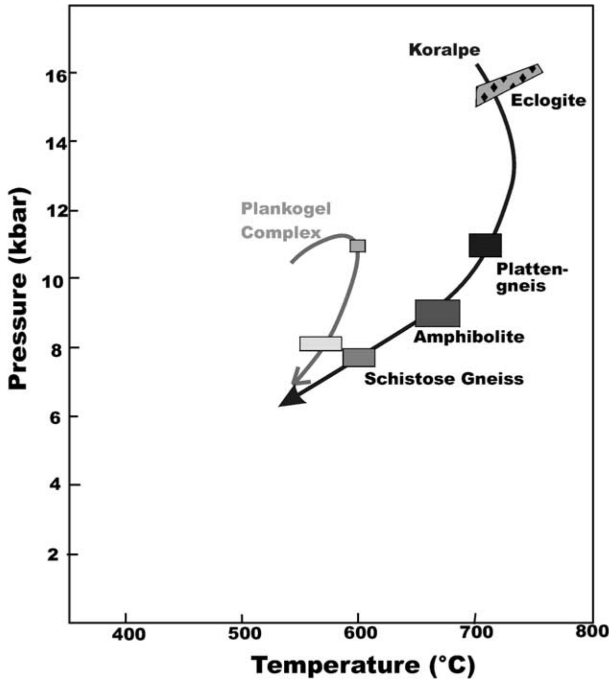

Fig. 8. Pressure–temperature evolution of the Koralm Complex and the Plankogel Complex (after Gregurek et al., 1997).

development of the mylonitic fabric within the Plattengneis was interpreted to have started during the Eo-Alpine eclogite facies metamorphism (at minimum pressures of 16 kbar, and temperatures in excess of 700 °C) (Frank et al., 1983; Wimmer-Frey, 1984; Krohe, 1987; Stüwe and Powell, 1995; Thöni and Miller, 1996). This is evidenced by calculated pressures of approximately 16 kbar in the central part of the area of investigation (Tenczer and Stüwe, 2001). The metamorphic field gradient displays pressures decreasing to 10–11 and 8–10 kbar towards north and south, respectively (Fig. 7). The gradient of peak temperatures is less pronounced and reaches from approximately 570 °C in the south, to 750 °C in the central part, and 620–650 °C in the northern part of the Koralm Complex.

Hence, we suggest that the central parts of the Koralm Complex represent a crustal section that has been exhumed by larger amounts than the northern and the southern parts. Therefore, structurally deeper parts are exposed in the central parts. This process is also related to the exhumation of the eclogites underlying the Plattengneis shear zone and started subsequent to nappe emplacement of the Austroalpine nappes during the early Late Cretaceous. Accordingly, deformation within the Plattengneis shear zone started at elevated temperatures and pressures, and continued along the decompressional path. Therefore, we assume that the Plattengneis shear zone was formed within an extensional regime. Exhumation propagated continuously from the central to the peripheral parts of the Koralm Complex (Fig. 7). The deformation within the Plattengneiss shear zone was progressively localized along the margins of the updoming parts, at shallower lithospheric levels (Fig. 7). The evolution of quartz LPO described above is interpreted to be related to this evolution and displays the temperature dependence for the activation of different gliding planes at different lithospheric levels according to the gradient of peak temperatures.

Further to the south, the barometric calculations of Tenczer and Stüwe (2001) (Fig. 7) document an abrupt pressure decrease across the border between the Koralm Complex (8–10 kbar) and the Plankogel Complex (5–6 kbar). The temperature gap is less pronounced (Fig. 7). The pressure gap indicates that a crustal section of approximately 10–15 km is missing between the Koralm Complex (including the Plattengneis in the uppermost sections), and the Plankogel Complex. This gap may be interpreted in terms of different ages of metamorphic overprint of both units. However, it was documented by Gregurek et al. (1997) that both units experienced their metamorphic evolution contemporaneously. While the rocks within the Koralm Complex experienced eclogite facies conditions in the range of 15–16 kbar and temperatures in excess of 700 °C, the Plankogel Complex resided at shallower depth at pressures of 10–11 kbar and temperatures less than 600 °C. The emplacement of the Plankogel Complex onto the Koralm Complex took place at shallow crustal levels along the decompressional path (at approximately 6–8 kbar and 550 °C) (Fig. 8). After their juxtaposition both units were affected by amphibolite to greenschist facies metamorphic overprints. Hence, we suggest that the contact between the Koralm Complex and the Plankogel Complex is an extensional fault, which emplaced the low pressure rocks of the Plankogel Complex onto the high-pressure rocks of the Koralm Complex, with a southward direction of displacement. This low-angle normal fault (Figs. 3 and 7) is, therefore, related to the juxtaposition of exhumed high-pressure rocks of the Koralm Complex, and medium- to low-pressure rocks of the Plankogel Complex.

To the northeast, the Koralm Complex is tectonically overlain by the Upper Austroalpine Unit of the Paleozoic of Graz (Figs. 2, 3 and 7) (for a summary see Flügel and Neubauer, 1984; Fritz, 1988, 1991; Fritz et al., 1991), which is overstepped by the Upper Cretaceous Gosau deposits (see Ebner and Rantitsch, 2000, with references). These deposits are related to the formation of sedimentary basins in the Late Cretaceous, which formed within a wrench system bounded by NE-trending sinstral strike-slip faults, linked by low-angle normal faults (Neubauer et al., 1995). The Paleozoic of Graz has only been affected by very low-grade metamorphism (approximately 200 °C, 2–3 kbar) during the Alpine orogeny. Hence, the juxtaposition of the Koralm

Fig. 7. Structural model presenting qualitatively the evolution of the Plattengneis shear zone and the contemporaneous exhumation of high-pressure units in the Koralm Complex; the pressure and temperature gradients are based on barometric calculations of Tenczer and Stüwe (2002) and are adopted to stage 4 of the structural model; modified after the core complex model described by Lister and Davis (1989).

Complex and the Paleozoic of Graz results in a pressure gap of 12–14 kbar between these two units. This cannot be achieved by a thrust fault. This suggests that these units have been juxtaposed during the exhumation of the Koralm Complex. The normal faults along the base of the Paleozoic of Graz and the Gosau basin show only semiductile to brittle deformational conditions, which cannot contribute to the exhumation of deeply seated high-pressure rocks in the footwall. Therefore, another detachment within the lower crust is required that causes the exhumation of the high-pressure rocks of the Koralm Complex (see also Neubauer, 1991; Kurz et al., 1999). This detachment is interpreted to be represented by the Plattengneis shear zone (Fig. 7). Therefore, we suggest that the Plattengneis shear zone formed within an extensional regime, which is structurally indicated by the boudinage of eclogite layers within the Plattengneis, and the boudinage of garnet at the microscale. Deformation was continued along the decompressional path, contemporaneous to the exhumation of the high-pressure rocks of the Koralm Complex from the lower crust. Moreover, the units that were situated between the Plattengneis shear zone and the base of the Paleozoic of Graz must have been affected by vertical shortening, which was partly accomodated by a certain amount of E–W extension (Fig. 7). A transition from top-to-the-N to top-to-the-ENE kinematics is documented in the northern part of the Koralm Complex, and within the Muriden Unit (e.g. Neubauer et al., 1995) (Fig. 3a).

## 9. A working hypothesis for the evolution of the Plattengneis shear zone

Based on these assumptions we suggest that the evolution of the Plattengneis shear zone started at eclogite facies conditions (at minimum pressures of 16 kbar, and temperatures in excess of 700 °C) above the eclogite bearing unit within an extensional regime. This resulted in the exhumation of the eclogites of the Koralm Complex (Kurz et al., 1999) (Fig. 7). Extension, probably at an elevated strain rate, resulted in elevated heat flow and increasing temperatures during the exhumation process, which is documented by geothermometric data displaying heating along the decompressional path (Stüwe and Powell, 1995) (Fig. 8), and the intrusion of partial melts (pegmatites) into the eclogite-bearing units and the Plattengneis (Fig. 7). Moreover, the metamorphic field gradient indicates that the central parts of the Koralm Complex have been exhumed by larger amounts than the southern and northern parts. The LPO evolution corresponds to the evaluated peak temperatures along this gradient.

The initiation of exhumation may also be indicated by geochronological ages in the range from approximately 89 to 85 Ma from gabbro and eclogite host rocks (garnet–whole rock Sm–Nd ages from metapelites) (Miller and Thöni, 1997). These ages post-date the early Alpine nappe stacking (e.g. Dallmeyer et al., 1996; Neubauer et al., 2000) and the peak of eclogite facies metamorphism (Thöni and Jagoutz, 1992, 1993; Thöni and Miller, 1996; Miller and Thöni, 1997), and are contemporaneous to the onset of sedimentation within the Gosau Group (Ebner and Rantitsch, 2000). Along the cooling path, still under amphibolite facies conditions, the Plattengneis shear zone was cut by a normal fault, which separated the Koralm Complex and the Plankogel Complex in the southern part (Figs. 3 and 7). Displacement along this normal fault resulted in the juxtaposition of high-pressure rocks of the Koralm Complex with the Plankogel Complex, and the final exhumation of both units to shallow lithospheric levels. Towards the North the Plattengneis shear zone either merged into, or was overprinted by, an E- to SE-dipping low-angle shear zone, which was related to the initial normal displacement of the Paleozoic of Graz and the formation of the Gosau extensional basins (Figs. 2, 3 and 7), and which developed continuously at decreasing temperature conditions.

## 10. Conclusions

- Quartz LPO from the Plattengneis shear zone show a continuous change from quartz-*c*-axis small circle distributions in the south of the Koralm Complex, to two maxima between $Y$ and $Z$ of the finite strain ellipsoid, girdle distributions, and finally single maxima in $Y$ in the northern parts.
- This evolution can be correlated to a continuous increase of syndeformational peak temperatures from the South (550–600 °C) to the central parts (685–750 °C); from the central parts to the North the temperatures slightly decrease down to 650 °C.
- The central parts of the Koralm Complex were exhumed to a larger extent than the northern, and in particular the southern parts, which is indicated by a continuous decrease of pressures towards north and south.
- We suggest that the Plattengneis shear zone was not related to the compressional phase during nappe stacking within the Austroalpine Unit, but to the exhumation of the Middle Austroalpine basement complexes in the central part of the Eastern Alps, which have prior been affected by eclogite facies metamorphism.
- The microstructures and LPO from the Plattengneis shear zone document the deformation during the initial phases of the exhumation of the high-pressure rocks of the Koralm Complex within the lower crust. At shallow crustal levels, deformation was localised within distinct ductile to (semi-) brittle low-angle normal faults, which crosscut the Plattengneis shear zone.

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