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The Oligocene Rensen Pluton (Eastern Alps, South Tyrol): Magma emplacement and structures during plate convergence

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Abstract

The Rensen Pluton, located at the smallest north-south section between the Tauern Window and the South Alpine, is an excellent example of magma emplacement in a tectonic setting of plate convergence.

Two magmatic components within the Rensen are discerned: a thin tonalitic marginal facies to the north and a dominant granodioritic sequence that constitutes central and southern areas. Magmatic and magnetic fabric patterns within the pluton, compared to structural fabrics within the host rocks, give evidence for two tectonic stages of magma emplacement. 1. An early stage of intrusion of tonalitic magma in a dominant compressional regime related to oblate fabrics of E-W preferred oriented biotite and hornblende. 2. A later stage of emplacement of granodioritic magma in a predominantly extensional regime related to sinistral movements along the Deffereggen-Antholz-Vals-Line. During a late stage of magma cooling, the entire region was affected by dextral shear. This transition between sinistral ductile fabrics and a low temperature dextral overprint, also reflected by quartz-C-axis patterns, is related to anticlockwise rotation of the main convergence between the Adriatic and the European Plate from Early Oligocene to Late Miocene. Aplitic veins, occurring mainly north of the massif, show ductile fabrics overprinted by dextral shear as well, and are therefore syngenetic to the Rensen.

According to Al^{tot}-in-hornblende barometry (~7.5 kbar), the tonalitic facies reached its solidus at a depth of around 20 km and hence represents the deepest part exposed between the Tauern Window and the South Alpine.

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1. Introduction

Combined studies on plutons and their surrounding country rocks provide constraints about the regional tectonic setting before, during and after emplacement of magma. Correlation of deformation increments during magmatic flow and subsequent cooling of magma gives some hints of the intrusion mechanism, especially by comparing the internal magmatic foliation with the surrounding country rocks. During magma emplacement the development of magmatic fabrics depends on mode of late stage of solidification (PATERSON et al., 1989) and reflects relations between overall stress/strain regime, cooling rate of the melt and time required for emplacement. Magma emplacement within a regional tectonic setting tends to preserve internal fabrics that are partly a response to the internal magmatic force and partly to the external regional kinematics, while magma cools and solidifies (HUTTON, 1988).

This paper focuses on regional fabric development within the Oligocene Rensen Pluton and its country rocks and the relation to the overall kinematics, which is dominated by complex fault zoning patterns. These faults are the sinistral Defferegen-Antholz-Vals line (DAV) and the dextral Periadriatic Lineament (PL). From the elongated shape of the Rensen Pluton and geochronological data (BORSI et al., 1978b; BARTH et al., 1989; MÜLLER et al., 2001), a direct relationship with the closely adjacent DAV-line can be assumed. Relevant emplacement mechanisms of plutons within strike-slip settings are discussed in the frame of models presented by TIKOFF & TEYSSIER, 1992; ST. BLANQUAT et al., 1998; HUTTON & REAVY, 1992; HUTTON, 1988; JOHN & BLUNDY, 1993; FERRE et al., 1995; PATERSON et al., 1991. All those authors emphasize the important interplay between igneous activity and regional tectonics.

Our study is based on a detailed geological map of the Rensen massif and its surrounding country rocks and considers space producing mechanisms during emplacement of granitic magma and post-magmatic modification of the magma host-rock system. The magmatic flow is estimated by measuring the anisotropy of magnetic susceptibility (AMS). Additionally, the relationship of pluton related veins, the contact aureole to the regional tectonics and the depth of the magma emplacement are established.

2. Geological setting

The Rensen pluton forms part of the Oligocene intrusion chain south of the Tauern Window (Fig. 1) and is an E-W elongated intrusive body about 7 km long and up to 1 km wide located within the Austroalpine basement of the Eastern Alps (for an overview about the main tectonic units within the Austroalpine south of the Tauern Window see SCHULZ et al., 1989; STÖCKHERT, 1982 and MANCKTELOW et al., 2001). Here, the Austroalpine is affected by several fault systems which are geochronological well characterized (e. g. MÜLLER et al., 2000, 2001; MANCKTELOW et al., 2001). Two main fault systems occur, namely the 700 km long Periadriatic Lineament (PL) or Puster-Valley Line and the E-W-trending Deffereggen-Antholz-Vals line (DAV). The dextral PL separates Austroalpine from Southalpine nappe complexes. Both suffered intense thrusting since Cretaceous time.

The DAV fault, north of the PL, separates rocks with different grade of Alpine metamorphism (BORSI et al., 1973; STÖCKHERT et al., 1999). Tertiary and Cretaceous ages, reported for different isotopic systems, occur in the north of the DAV and pre-Alpine ages to the south (BORSI et al., 1973; 1978a; STÖCKHERT et al., 1999). Therefore the DAV-line represents the southern limit of alpine (Cretaceous) metamorphism (SAM-line: HOINKES, 1999). The DAV has been periodically active from Late Paleocene to Oligocene as known from K/Ar- and Rb/Sr-mica cooling ages (BORSI et al., 1973; BORSI et al., 1978b; SASSI et al., 1980; SCHULZ, 1994; STÖCKHERT, 1982; STÖCKHERT et al., 1999). KLEINSCHRODT (1978) first established the sinistral character from asymmetric quartz fabrics within the mylonites.

Based on the regional distribution of the Periadriatic plutons and on the isotopic composition of magma, the origin of melts along the PL and along the DAV line is interpreted as consequence of a slab-break off (BLANCKENBURG et al., 1989; BLANCKENBURG & DAVIES, 1995). The magma bodies thereby may have suffered a shear component (EXNER, 1976). As result, the Oli-

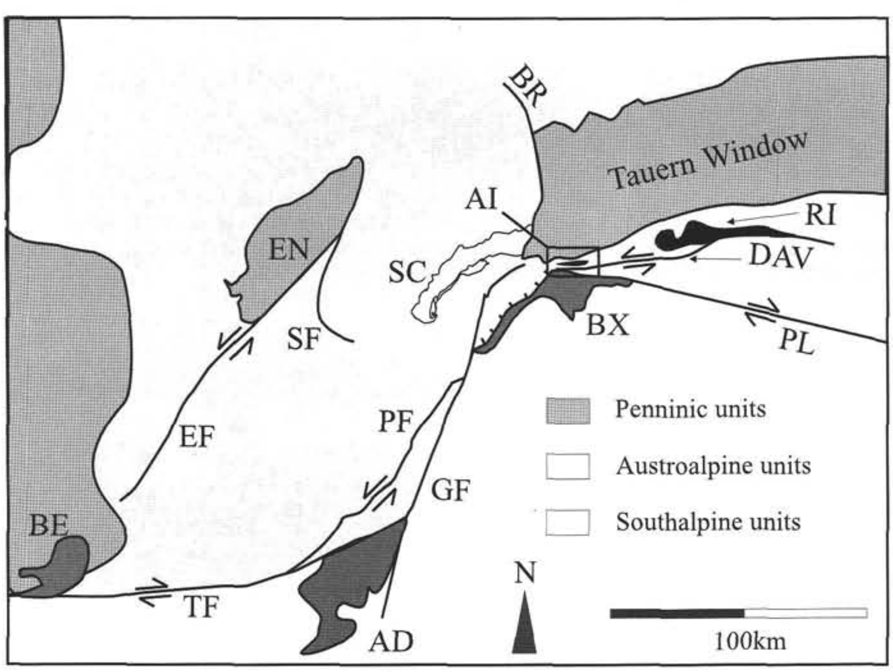

Fig. 1
Schematic tectonic overview of the south western part of the Tauern Window modified after SCHULZ et al. (1989). EN: Engadinger Window, BR: Brenner fault, SC: Schneeberg Complex, DAV: Defferegen Antholz Vals line, KV: Kalkstein Vallarga Line, PL: Periadriatic Lineament, BX: Brixen Pluton, GF: Giudicarie Fault, PF: Pejo Fault, SF: Schlinig fault, EF: Engadine Fault, TF: Tonale Fault, BE: Bergell Pluton, AD: Adamello Pluton, RI: Rieserfernern Pluton.

gocene Bergell, Adamello, Rieserferner intrusives and tonalitic lamellae at northern rims of Permian intrusives (e. g. Brixen) are partly deformed (see MARTIN et al., 1993; STÖCKLI, 1995; ELIAS, 1998).

Within the study area, three main tectonic units can be discerned (Fig. 1):

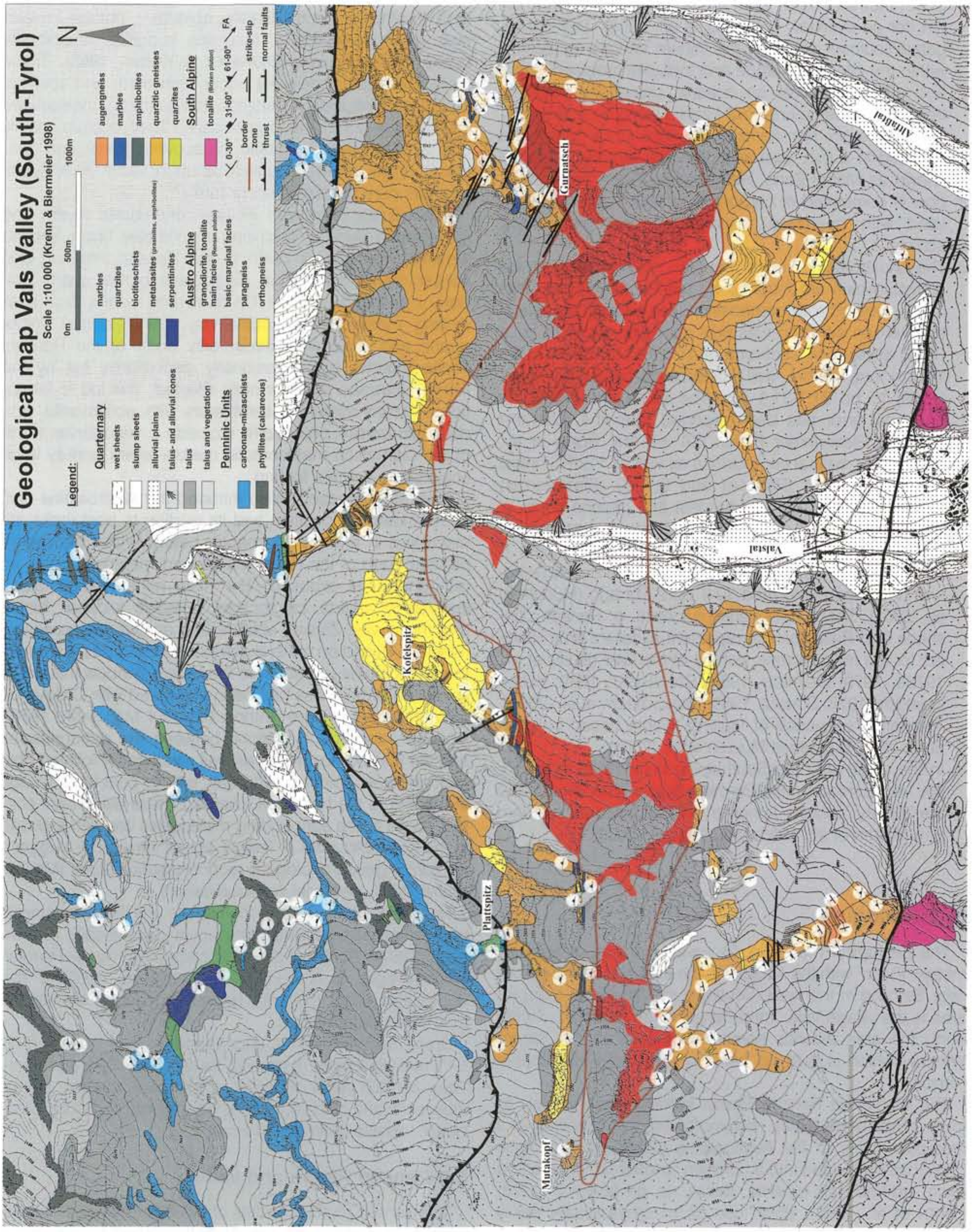

Fig. 2
Geological map of the Rensen Pluton and its surrounding rock units.

1. The Tauern Window as part of the Penninic unit consists of several nappes including pre-Alpine basement (Zentralgneis, Lower Schieferhülle) and Mesozoic cover sequences that were deposited either within the oceanic South Penninic basin or at the continental passive margin (for an overview see KURZ et al., 1998). The investigated southern sector of the Tauern Window is located within the Glockner nappe and includes metasediments and serpentinites of an oceanic basin and turbiditic trench slope sediments that formed along an active continental margin. Remnants of the continental margin are exposed in a thin, east-west trending tectonic melange known as Matrei Zone. Here, the southern Tauern Window is comprised of carbonate schists that are intercalated with quartzites, metabasites and garnet-mica schists.
2. The Austroalpine units contain mainly garnet-mica schists, which are intruded by the Rensen Pluton, with mainly tonalitic rock composition (see below). The age of the Rensen intrusion was first poorly constrained by a Rb/Sr whole rock isochrone of 41 ±19 Ma (BORSI et al., 1978b) and further well constrained by BARTH et al. (1989) to be 31.7-31.1 Ma. The same age within the analytical error has been reported from the eastward adjacent Rieserferner Pluton (30 ±3 Ma: BORSI et al., 1979). Bulk mineral composition as well as $^{87}Sr/^{86}Sr$ initial values of 0,7097 (Rensen) and 0,7069 (Rieserferner) have been interpreted to suggest that plutons south of the Tauern Window represent crustal contaminated melts (BELLIENI et al., 1981; BORSI et al., 1979; GRATZER & KOLLER, 1993). Veins, occurring north of the Rensen massive have been deformed 30.9 ±0.2 Ma ago (MÜLLER et al., 2001). These Oligocene plutons (i. e. Rensen, Zinsnock and Rieserferner), represent excellent time markers for the main tectonic activity of the DAV (BORSI et al., 1978a, 1979; DEUTSCH, 1984; STÖCKHERT, 1982; KLEINSCHRODT, 1978; SCHULZ, 1989; MANCKTELOW et al., 2001). A detailed sequence of faulting events based on geochronology is given in MÜLLER et al. (2001).
3. In the study area the Southalpine units south to the PL are represented by the Permian Brixen granodiorite and the Tertiary "tonalite lamellae" that intruded its northern rim (MARTIN et al., 1993; MÜLLER et al., 2001).

3. Lithologies

The geological map (Fig. 2) covers an area of approximately 40 km^2 with the Altfaßtal in the east and the Mutakopf near Sterzing in the west. Southern margin of the mapped area is the village Vals, immediately south to the PL. To the north the area extends some 100 meters to the Tauern Window which is built up here by rocks of the Glockner Nappe.

The elongated Rensen Pluton intruded greenschist- to lower amphibolite-facies metamorphosed metapelites and metapsammites of the Austroalpine basement. Magmatic rocks can be divided into a northern tonalitic rim zone and a main granodioritic-tonalitic facies (e. g. NOLLAU, 1974; BARTH et al., 1989), which can be macroscopically easily distinguished. The roof of the intrusion is not preserved. A small contact aureole developed along the northern contact of the pluton to surrounding country rocks.

3.1 Austroalpine units

Rocks from the Austroalpine are mostly characterized by metapelitic mineral assemblages. Paragneisses contain Ms+Bt+Grt+Chl+Pl+Qtz±St, accessory minerals are apatite, tourmaline, zircon, titanite, epidote ± potassium feldspar. The occurrence of staurolite suggests amphibolite facies metamorphism (BIERMEIER & KRENN, 1998). These metapelites (paragneisses) occur both north and south of the Rensen intrusion. Quartzites and quartzitic gneisses are intercalated within the pargneisses. They contain mainly quartz, plagioclase ± biotite, muscovite, garnet and apatite. Quartzitic gneisses appear as up to 100 m thick layers, whereas pure quartzites occur rarely.

Subordinate lithologies include amphibolite layers and rare marble beds. E-W-striking amphibolite layers around 1 meter thick appear north of the Rensen intrusion and contain mainly hornblende, plagioclase, biotite, quartz, epidote ± garnet ± chlorite. Up to several meters thick E-W-striking marble layers, containing mainly calcite, minor quartz and muscovite, occur only north of the Rensen. These marbles are occasionally discordantly cut by the Rensen intrusion and thermally affected. This led to formation of scarn mineral assemblages with wollastonite, epidote, clinozoisite, phlogopite, diopside ± vesuvianite. North of the Gurnatsch metasomatic marble layers portray large scale south-vergent folding.

Several magmatic bodies intruded the Austroalpine unit. The Rensen composition and its relation to host rocks are discussed in a separate chapter below. Within the paragneisses north of the Rensen a second magmatic body, an orthogneiss, is exposed. The main mineral assemblage consists of quartz, plagioclase, potassic feldspar, biotite and muscovite. Zoisite, epidote and apatite are accessory minerals. Based on mineral composition and position within the Austroalpine unit south to the Tauern Window this weakly foliated orthogneiss has been correlated with Ordovician metagranitoids of type Antholz (434 ±4 Ma: SATIR, 1976). However, discordant relations between the orthogneisses and the foliated host rocks as well as internally foliated host rock enclaves point to a younger, syn- to post tectonic age in respect to the host rock foliation. These discordant contact zones to the surrounding metapelites are well exposed at the Kofelspitz area. A Tertiary age of intrusion is suggested from a geochronological reconnaissance study (MANCKTELOW, 2001: personal communication).

Near the south-western contact to the Rensen massif, pegmatites of type Uttenheim occur occasionally (STÖCKHERT, 1987). Rb/Sr whole rock chronology gave Permian intrusive ages of 262 ±5 Ma (BORSI et al., 1980). These pegmatites show overprint by heterogeneous sinistral Alpine shear deformation.

Small occurrences of augengneisses are observed as E-W striking lenses north and south of the Rensen Pluton. They contain alkali feldspar, plagioclase, quartz, biotite, muscovite and chlorite, with minor amounts of garnet, clinozoisite, apatite, titanite and zircon.

3.2 Rensen Pluton and veins

The Rensen Pluton consists of two different types of magmatic rocks, which are mainly distinguished by the occurrence of hornblende. The so called "tonalitic rim facies" (NOLLAU, 1974) is only found on the northern rim of the intrusion and is characterized by the presence of hornblende (alumino-ferro-tschermakite: see section 6.1), biotite, plagioclase, potassic feldspar, quartz, and epidote. Biotite aggregates form oriented cluster with <001>-axes, trending north-south. C-axis of hornblende crystals are preferentially E-W oriented. At the northern rim biotite is intensely retrogressed to chlorite.

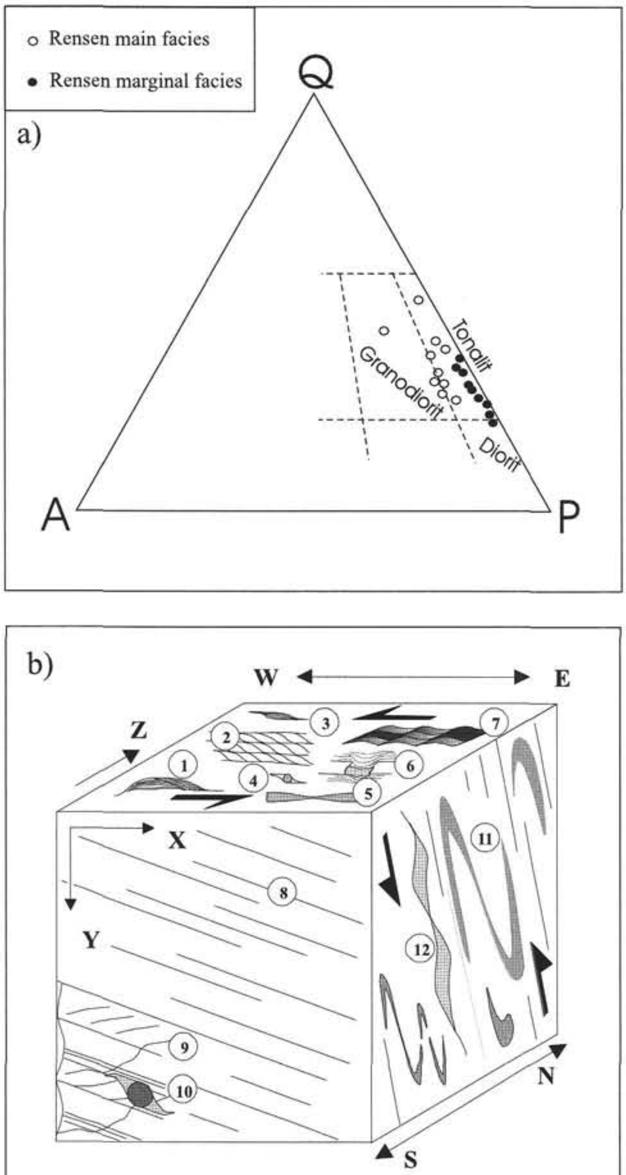

Fig. 3
a) Modal content of the main and marginal facies of the Rensen Pluton, using a simplified Streckeisen diagram (after NOLLAU, 1974).
b) 3D-block model including main shear sense indicators, which occur at the southern margin of the Tauern Window. Point 1 to 7 within x-z-section contains: SC-fabrics (pos. 1 & 2), mica-fish (pos. 3) and σ-clasts (pos. 4), boudins and boudin-necks (pos. 5 & 6), shear bands (pos. 7); x-y-section contains: stretching lineation (chlorite & mica) suggesting lateral E-W-movement (pos. 8), crenulation (pos. 9); y-z-section: steep isoclinally folded carbonate and quartz layers (pos. 10 see also Fig. 5a) and asymmetric boudins of quartz (pos. 11) are interpreted as thrusting towards the south.

The main granodioritic-tonalitic facies of the Rensen, which comprises more than 90% of the whole intrusion (NOLLAU, 1974), consists of plagioclase, quartz, biotite, epidote, chlorite, muscovite and accessory minerals (Fig. 3a).

Two groups of xenolithic inclusions within the Rensen Pluton can be distinguished. 1. Xenoliths of metapelitic to psammopelitic composition occur frequently along the northern rim zone of the pluton. They show E-W-striking internal foliations and include partly mylonitic fabrics (Fig. 4c). To the south no preferred orientation of enclaves is visible. 2. Microgranular enclaves of tonalitic composition occur mainly in the north, showing oblate ellipsoid geometry with an axial ratio of 2:1 up to 3.3:1 (maximum versus minimum axis) and E-W oriented long ellipsoid axes (see Fig. 4d).

Syn- and postmagmatic veins occur mainly north of the intrusion within the Austroalpine unit and the Tauern Window. They are distinguished by their grade of deformation and mineral assemblage and grouped into quartz, granitic and aplitic vein types (SCOLARI & ZIRPOLI, 1972). Mafic dykes occur rarely. Most of the aplitic veins exhibit a mylonitic fabric and are further distinguished by temperature dependent rheological behaviour of their mineral components and the grade of deformation (see below).

3.3 Penninic units

Calcareous micaschists of the Tauern Window (Glockner Nappe) contain mainly calcite, quartz, minor graphite, white mica and plagioclase with epidote, clinozoisite, apatite, titanite and zircon as accessory minerals. Metabasites (prasinites and amphibolites) occur mainly as E-W-elongated lenses together with serpentinites. Both lithologies represent relicts of Penninic ocean floor sediments. For an overview about lithostratigraphy and metamorphic evolution of the Tauern Window see KURZ et al. (1998). Small occurrences of marble beds together with quartzites and biotite schists at the tectonic contact to the Austroalpine units may represent the westernmost remnants of the Matrei Zone.

In outcrop- and map scale calcareous micaschists are isoclinally folded together with carbonatic phyllites. A west-east trend of fold axes, axial planes are dipping steeply to the north, is characteristic for the large amount of N-S shortening within this area (see Fig. 4a). Line balancing of folds gave up to 70% (BIERMEIER & KRENN, 1998). Asymmetry of folds suggests a thrusting direction to the south.

Outcrop-scale structures, nicely seen in the gorge north of the Vals pasture and summarized in Fig. 3b, show both, west-east horizontal shear and north-south shortening together with top south thrusting. Sinistral shear along steeply north dipping foliation planes is evident from S-C-fabrics (BERTHÈ et al., 1979a), shear bands (e. g. PLATT & VISSERS, 1980) and sheared and back-rotated boudinaged structures. Arguments for south-vergent folding and thrusting arises from outcrop-scale thrusts, thrust related folds and asymmetric boudinaged structures (Fig. 3b).

4. Structural evolution

Distributed deformation with steeply north dipping foliation and west-east oriented stretching lineation is, as mentioned above, a characteristic feature in the study area. It is

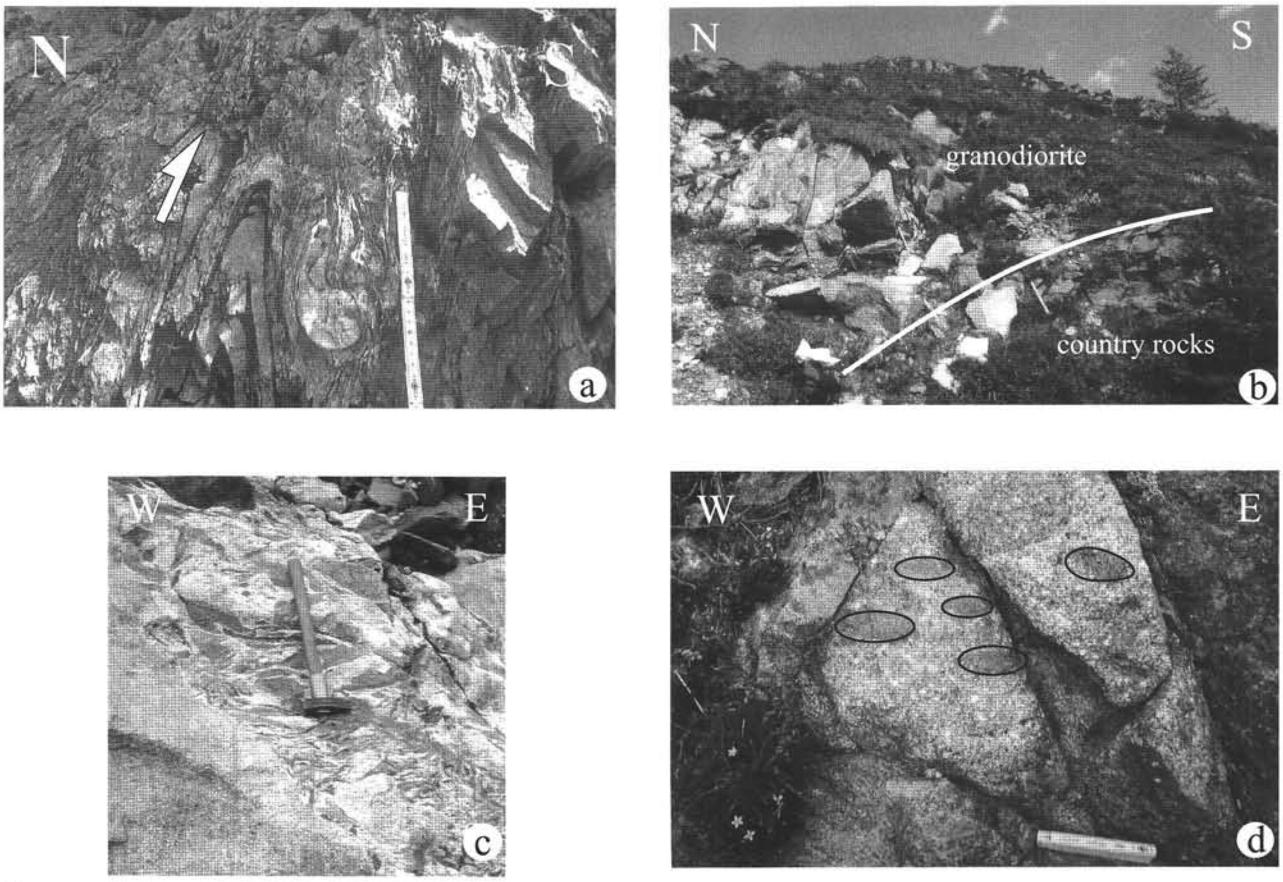

Fig. 4
a) Steep vertical folds showing inverse folding to the south within the carbonate schists of the southern Tauern Window. Isoclinal folds are results of the high amount of compression. Vertical scale bar: ca. 20 cm.
b) Southern border zone between the granodioritic rock (left) and metapelitic country rocks (right). Field observations suggest overthrusting to the south.
c) Xenoliths at the eastern margin of the intrusion, containing E-W-oriented foliation planes.
d) E-W oriented enclaves with tonalitic composition. Scalebar: 10 cm.

worth noticing that there is coherence in the structural assembly across the Penninic – Austroalpine boundary. Sinistral shear is the dominant deformation regime; however, deformation intensity virtually decreases from north to south. One exception is a high strain domain of ca. 50 meter thickness midway between the southern margin of the Rensen and the Periadriatic Lineament which is likely equivalent to the DAV (MANCKTELOW et al., 2001). The Periadriatic Lineament is a pronounced morphological feature but appears as a poorly exposed cataclastic zone in the mapped area.

4.1 Austroalpine and Penninic units

North of the Rensen, a steep N-dipping foliation (50°-80°dip) and an approximately E-W-oriented sub-horizontal

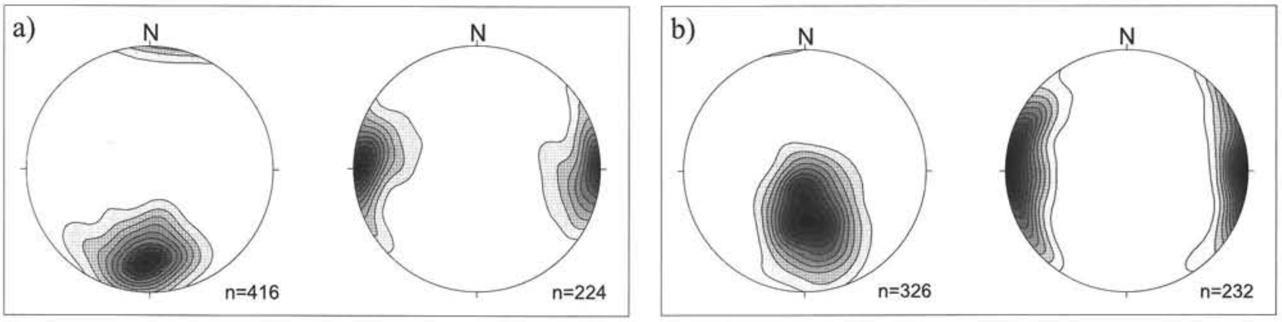

Fig. 5
Contour plots of field data north a) and south b) of the Rensen massive plotted at the lower hemisphere of the Schmidt net. Left plots in a) and b) show poles that reflect more steepened foliation planes in the north of the Rensen. Right plots in a) and b) give direction of lineation that strikes overall E-W, whereas south of the Rensen more variation in direction of lineation is shown. n gives number of measurements.

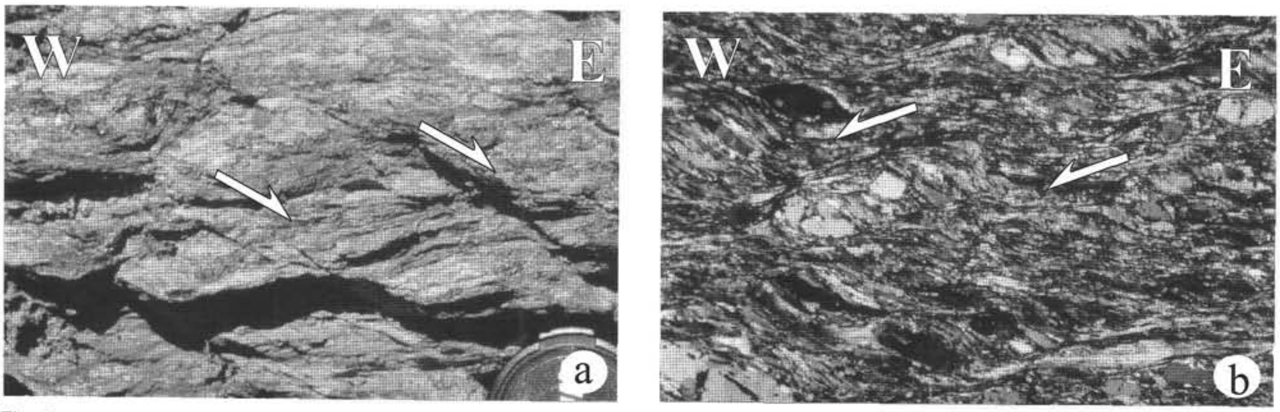

Fig. 6
a) Dextral low temperature shear bands south of the Rensenpluton within the Austroalpine.
b) Thin section of a small zone of biotite-muscovite schists at the southern part of the Tauern Window. Well developed shear bands indicate sinistral movements from east to west (width of view 3 mm).

stretching lineation are developed (Fig. 5a). Foliation planes adjacent to the pluton appear to have been deflected during magma intrusion, especially at the southern rim zone, where foliation and lineation differ from the overall regional strike. This results in greater variation of lineation directions (Fig. 5b) and shallower dipping foliation planes are compared with northern parts. The intrusion of the Rensen pluton is apparently parallel to foliation planes with steep margins in the north and shallow northward dipping margins in the south. Here, the pluton is in a hangingwall position to southerly adjacent host rocks (Fig. 4b).

Microstructures display a complex pattern of successively evolving deformation increments. A penetrative (from protomylonitic to mylonitic) high temperature sinistral shear deformation is overprinted by localised, low temperature dextral shear (Fig. 6a, b). Sinistral high temperature shear deformation is dominant, especially in northern and northwestern portions of Austroalpine metapelites, but it affected also aplitic and granitic veins. Localised dextral shear zones concentrate around the eastern Gurnatsch peak (Fig. 2) where numerous dextral shear zones displace and dissect the intrusive body. Finally, brittle faults and slicken-slide striations define a conjugate fault system with dextral brittle shear along NW-SE trending steeply dipping faults and sinistral shear along NE-SW trending faults. Approximately N-S shortening and W-E extension during final cooling of the region is derived from fault plane solution data (BIERMEIER & KRENN, 1998).

4.2 Rensen Pluton

As a whole, the Rensen Massif appears homogeneous at outcrop scale and within the main magmatic facies only a very weak orientation of magmatic minerals is visible. By contrast, the tonalitic rim facies shows a pronounced preferred E-W-trend of biotite flakes and hornblende crystals that parallel the general orientation of mafic enclaves (Fig. 4d). These features may be directly related to cooling of the magma within a stress field. Beside magmatic fabrics that are described below, several deformational overprints related to post-magmatic shearing are preserved. They reflect continued deformation after pluton emplacement. Microstructures within the Rensen Pluton itself range between magmatic and sub-magmatic foliation, high temperature solid-state deformation and features attributed to low temperature solid-state deformation.

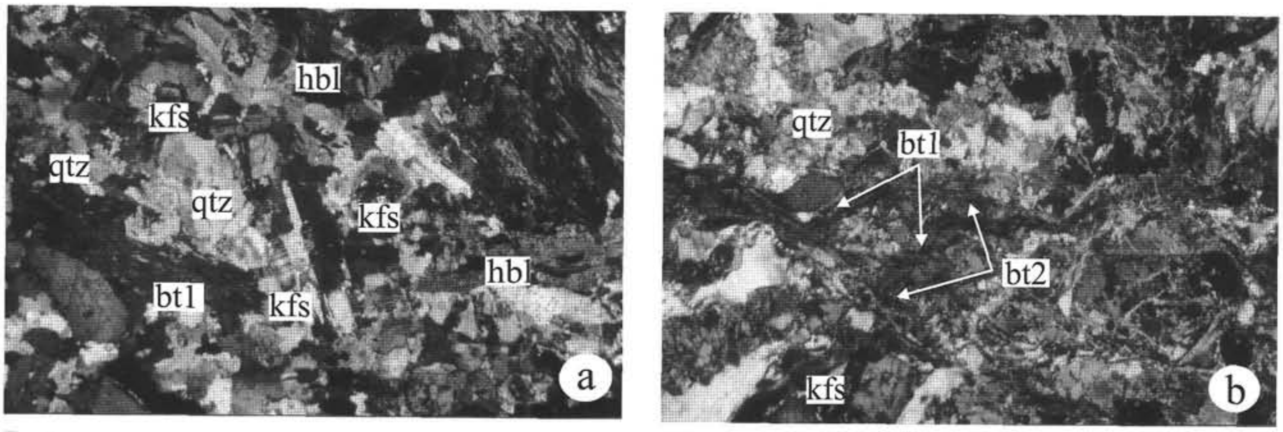

Fig. 7
a) Magmatic foliation from the tonalitic rim zone of the Rensen. Recrystallized feldspar crystals are shown; recrystallized quartz aggregates show nearly chessboard patterns.
b) High temperature solid state deformation shows no intense recrystallization of feldspar. Progressive development of biotite shear bands (bt2) and GBM recrystallization of quartz aggregates. Biotite shows no evidence for retrogression to chlorite. Width of views: 3 mm, CPL.

Figure 7a shows the magmatic to sub-magmatic foliation from the transition zone between the marginal tonalitic facies and the main granodioritic-tonalitic facies. Almost undeformed biotite (bt 1: Fig. 7a) and hornblende define a weak shape preferred orientation, which increases towards the northern margin. Plagioclase is euhedral with a well developed magmatic zonation, K-feldspar lacks any intracrystalline deformation (center in Fig. 7a). Quartz which is very sensitive to deformation shows chessboard-pattern (left in Fig. 7a), related to high temperature prism <a> and prism <c> slip of quartz (KRUHL, 1996) and consistent with a temperature range around 600°C.

High temperature solid state sinistral shear is concentrated predominantly within the aplitic veins and produced a pronounced mylonitic fabric. Only within the northern pluton portions transition to solid-state deformation is visible predominantly in elongated quartz and biotite shear bands (bt2: Fig. 7b). Grain boundary migration crystallisation (GBM) is the dominant deformation mechanism in quartz. Non-retrogressed kinks of biotite (bt 1: Fig. 7b) developed in shear bands show stability of biotite during deformation. Feldspar shows only undulose extinction but rare occurrences of twin lamellae points to some intracrystalline deformation. With decreasing temperature, layers of biotite (bt2) together with recrystallized quartz develop, which replace the primary magmatic framework.

Low temperature solid state deformation occurs mainly in mylonitic veins and distinct zones within the pluton. Especially within eastern portions of the pluton (Gurnatsch) semiductile low temperature shear zones and faults with dextral sense of shear developed. Replacement of biotite by chlorite during low temperature shearing and late stage fluid infiltration changes the overall appearance of the magmatic rocks. Increasing greenish colour of intrusive rocks next to late stage deformation zones is easily recognised in the field. Such zones are especially found within northern portions of the Rensen Massif but also within the

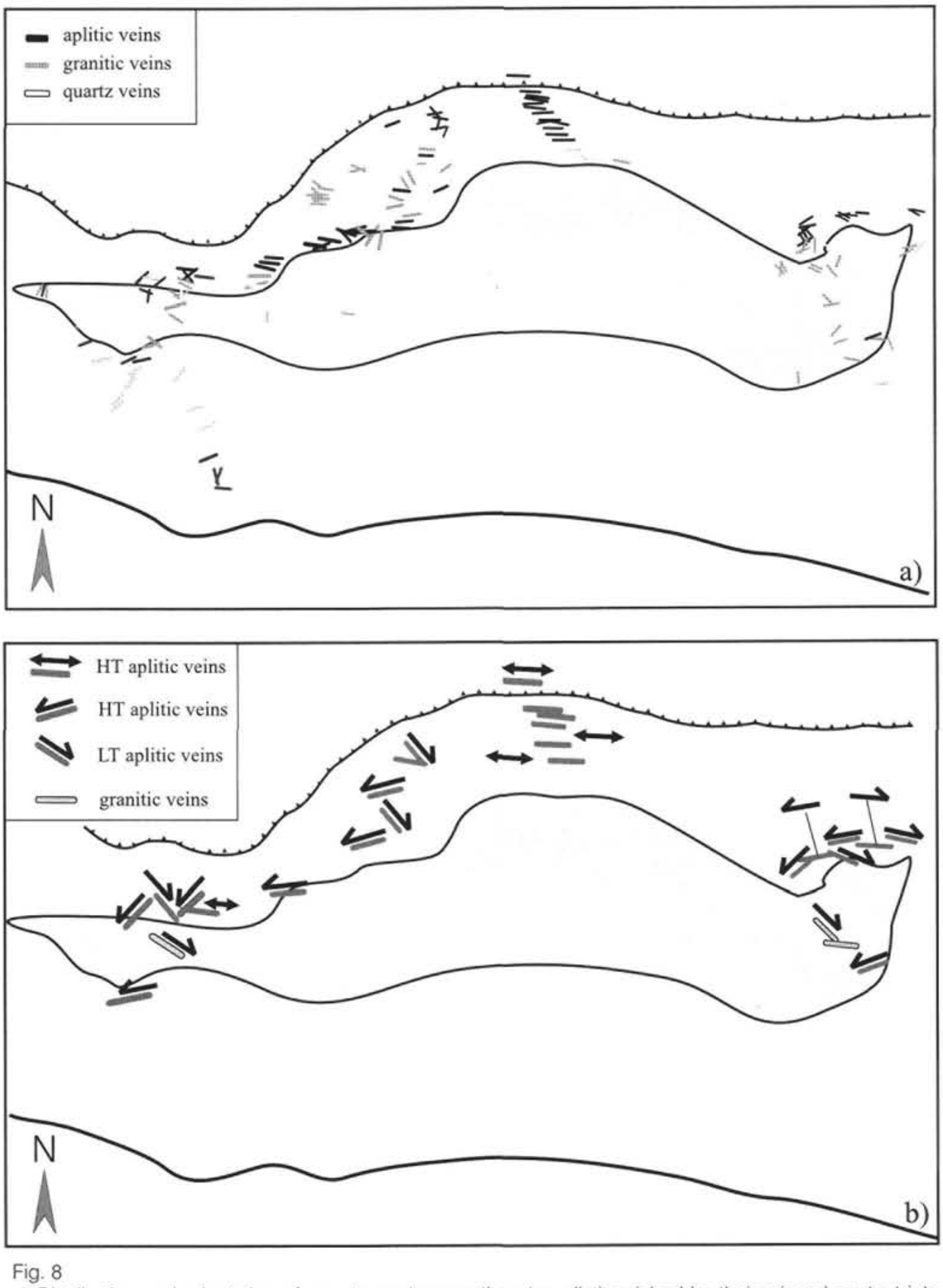

Fig. 8
a) Distribution and orientation of syn- to postmagmatic veins, distinguished by their mineral content into quartz, granitic and aplitic veins. Vein symbols define the strike-direction of the veins.
b) Northeast-southwest trending mylonitic veins are deformed under high temperature (HT aplitic veins) and show indication of sinistral shear. Younger low temperature deformed veins trend northwest-southeast and show low temperature dextral fabrics (LT aplitic veins). Veins from the central region north of the Rensen are high temperature coaxially deformed. Granitic veins within the Rensen reflect the same trend. Vein symbols include summarized groups of vein samples.

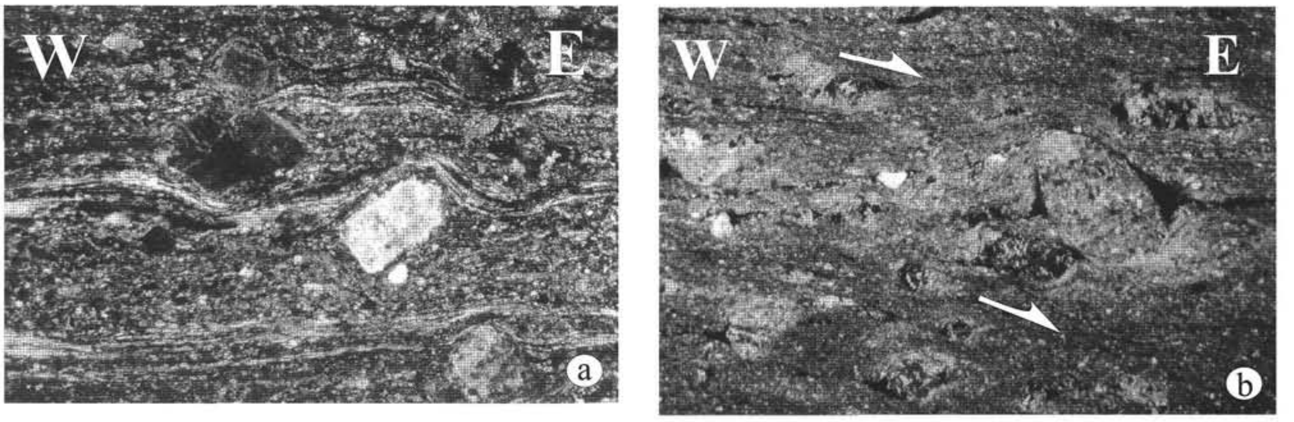

Fig. 9
Thin sections of two different vein samples show
a) high temperature mylonite from E-W-trending deformed aplitic dyke. Feldspar porphyroblast shows beginning recrystallization features (in the centre).
b) NW-SE striking veins that include a mylonitic fabric with ecc-planes and asymmetric strain shadows, indicating low temperature dextral deformation. Width of views: 1.5 mm.

Tertiary intrusives south of the Periadriatic Lineament.

4.3 Veins and dykes

143 vein samples were investigated for their mineral content and deformational features. Especially the Austroalpine unit north to the Rensen is heavily invaded by veins and dykes, but aplitic dykes occur occasionally also within the Penninic unit. The orientation of sub-vertical veins is shown in Fig. 8a. Whereas the Rensen magmatic body shows only minor solid state deformation features, solid state deformation is virtually concentrated within veins. Beside coarse grained granitic and quartz veins fine grained aplitic veins with mylonitic fabrics occur as the main vein type. Based on deformation mechanisms, kinematic and vein orientation, three groups of mylonitic veins are distinguished (Fig. 8): 1. East-west to NE-SW trending veins exhibit a mylonitic fabric that evolved under high temperature sinistral shear deformation. Dynamically recrystallized feldspar suggests syn-deformative temperature conditions above 500-550°C. 2. Consistently W-E trending veins exposed along the Vals valley north of the intrusive body exhibit also a high temperature mylonitic fabric with recrystallized feldspar. However, neither pronounced fabric asymmetries nor consistent shear sense indicators have been observed, and hence a major coaxial flow regime is suggested (Fig. 9a). 3. NW-SE trending aplitic and granitic veins within the pluton and the host rock suffered low temperature dextral shear. Feldspar within these veins is altered but not recrystallized (Fig. 9b). Quartz shows a stronger grade of undulatory extinction. Pronounced shape preferred orientation and grain boundary features suggest low temperature plasticity (Hirt & Tullis, 1992; Passchier & Trouw, 1996). Widely spaced S-C fabrics (Berthé et al., 1979) and shear bands are nicely developed in mica rich domains. Biotite is often retrogressed to chlorite and arranged in shear planes.

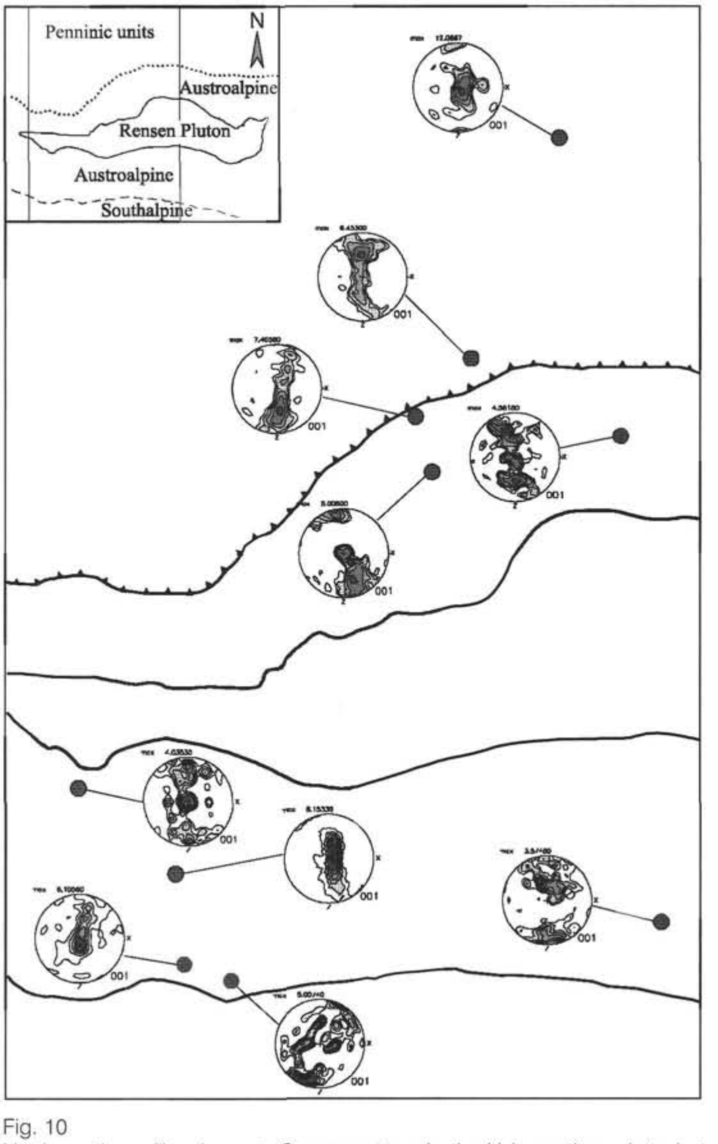

Fig. 10
North-south profile of quartz C-axes pattern in the Vals section, plotted at the lower hemisphere of the Schmidt net. See text for details.

4.4 Texture evolution

Nineteen quartz samples, collected in a section from north (Tauern Window) to the south (close to PL), were measured with an X-Ray texture goniometer to analyse prevalent glide systems (for analytical procedure see appendix). Quartz c-axis are displayed in lower hemisphere equal area projection where x is the trace of the foliation in sections cut parallel to the lineation and z is perpendicular to foliation (sample reference frame). Data and sample localities are plotted in Fig. 10. Quartz c-axis show mainly oblique girdle- and asymmetric peripheral cluster-distributions that are typical for shear deformation under medium to low grade metamorphic conditions (e. g. SCHMID & CASEY, 1986; LAW et al., 1990; HIRTH & TULLIS, 1992). Except the two samples immediately north of the PL, all textures are consistent with sinistral shear. We interpret these two samples to mirror low temperature dextral motion along the PL. For the rest of the samples following trends are observed: 1. There is an evolutionary trend from peripheral cluster distributions over cross girdle distributions to y-axis maxima (y is perpendicular to x and z) from south to north that is interpreted to reflect increase in syn-deformational temperature conditions towards north (STIPP et al., 2002). This temperature increase is also constraint by a study on deformation mechanisms within quartz (MANCKTELOW et al. 2001). 2. The pronounced oblique girdle midway between the southern Rensen margin and PL represents the high strain zone of the DAV (KLEINSCHRODT, 1987). 3. Asymmetries in quartz axis pattern, and inferred degree of non-coaxiality, are most

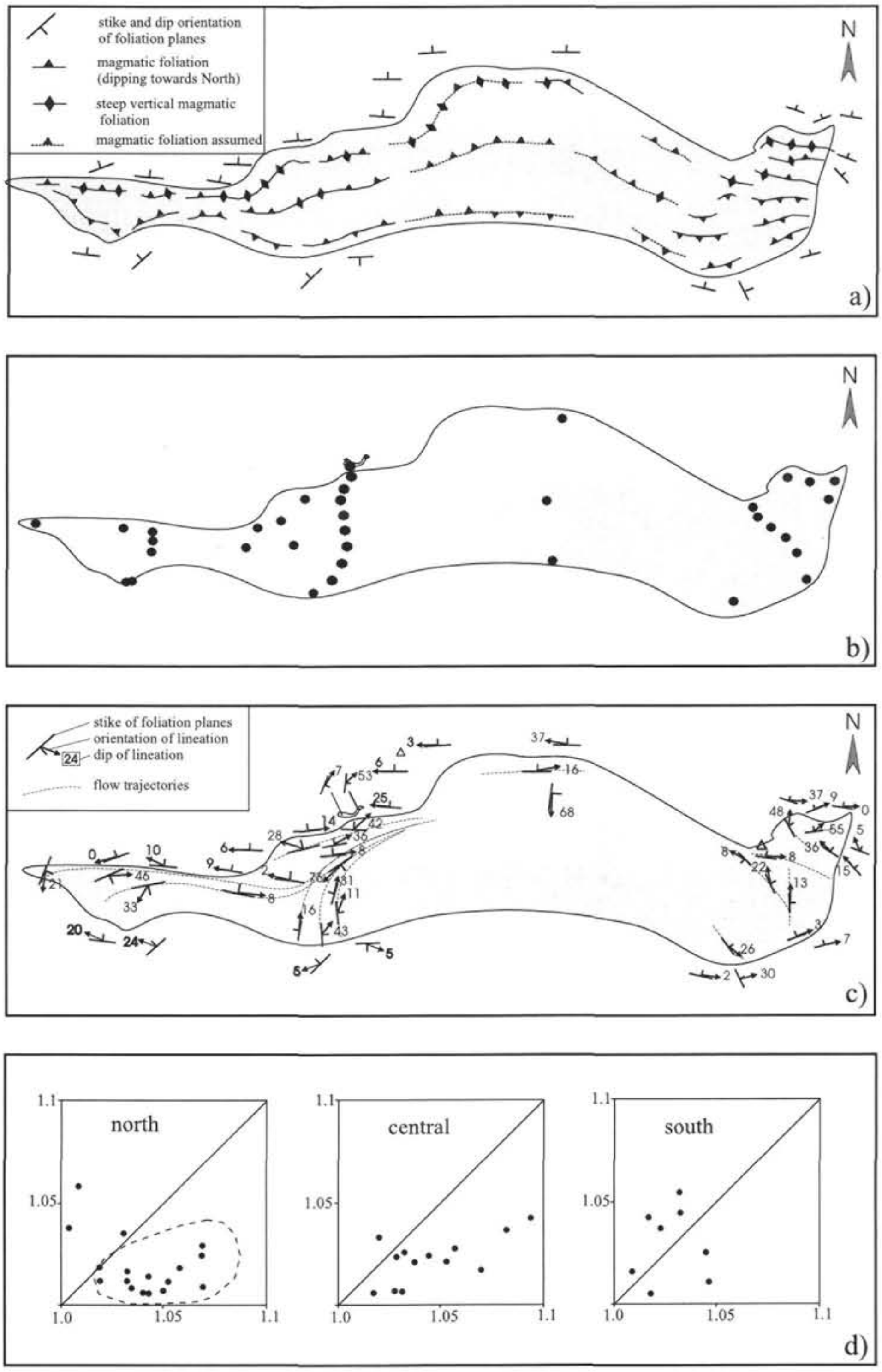

Fig. 11

a) Magmatic foliation planes from field observations and foliation planes of country rocks. Because of the intense erosion of the granitoid massif, the style of foliation is assumed along the Vals Valley.

b) Sample points for AMS measurements within the Rensen massif.

c) AMS data, only from samples with magmatic and sub-magmatic textures, indicate strike and dip of magnetic foliation and lineation within the pluton. Amount of magnetic lineation dip is indicated. Field measurements of cleavage in country rocks are shown outside the pluton. The magnetic lineation and foliation is predominantly E-W oriented north of the pluton. Central and southern areas indicate no directly preferred orientation of magnetic lineation and foliation.

d) Flinn plots show prolate and oblate geometries within different sectors of the massif. Samples of the northern area (tonalitic rim) plot mostly within the oblate section whereas samples of central and southern parts show variable patterns trending to prolate geometries.

pronounced at the Austroalpine / Penninic boundary and the DAV. Apart of this zones minor obliquity and hence enhanced contribution of coaxial component of flow is observed. This might be hint for partitioning of shear.

5. Magnetic fabrics of the Rensen

Techniques to reconstruct magmatic flow by use of anisotropy of magnetic susceptibility (AMS) were established by e. g., HENRY (1975). AMS data may provide information on (1) the magmatic flow during pluton emplacement, (2) the geometry of magmatic flow and, (3) the syn- to postmagmatic tectonic overprint. Forty-five sites from the tonalitic rim facies and the granodioritic/tonalitic main facies of the Rensen Pluton were sampled for the AMS study (Fig. 11). We emphasise that only samples that lack hints for solid state deformation have been used (for criteria see e. g. PATERSON et al., 1989). The measurements of the magnetic fabric (magnitudes and orientations of the principal susceptibilities) were carried out on a computer linked slow-spinner magnetometer at Gams (Institute of Geophysics, University of Leoben). For details of the procedure and instrumental settings see appendix. Magnetic fabrics reflect essentially distribution of biotite with presumably an additional influence from the preferred orientation of hornblende crystals which occur only in the northern rim zones. It turned out that the macroscopically observed discontinuity planes within the Rensen Pluton are perpendicular to the K_{min} axis of the AMS ellipsoid. Hence we argue that this weak foliation represents a magmatic fabric. Sample sites, trace of macroscopically observed discontinuity planes (magmatic foliation), orientation of the magnetic fabric and host rock foliation data are displayed in Fig. 11. Axial ratios, i. e. shape of the susceptibility ellipsoid are plotted in "Flinn graphs" for different sites of the pluton (Fig. 11d).

Very homogeneous data are obtained from the northern part of the Rensen Pluton. The susceptibility ellipsoid has an oblate shape with a steeply north dipping magnetic foliation and a west-east trending magnetic lineation. Both, magnetic lineation and foliation parallel roughly fabric elements of the northerly adjacent host rocks. Moreover, orientation and shape of mafic enclaves within northern pluton portions are very similar to the magnetic fabric. However, plunge angles of the magnetic lineations are generally high compared with host rock lineations. Further south magnetic lineations generally trend north-south and fabric geometries become variable. Oblate to prolate susceptibility geometries are observed (Fig. 11d).

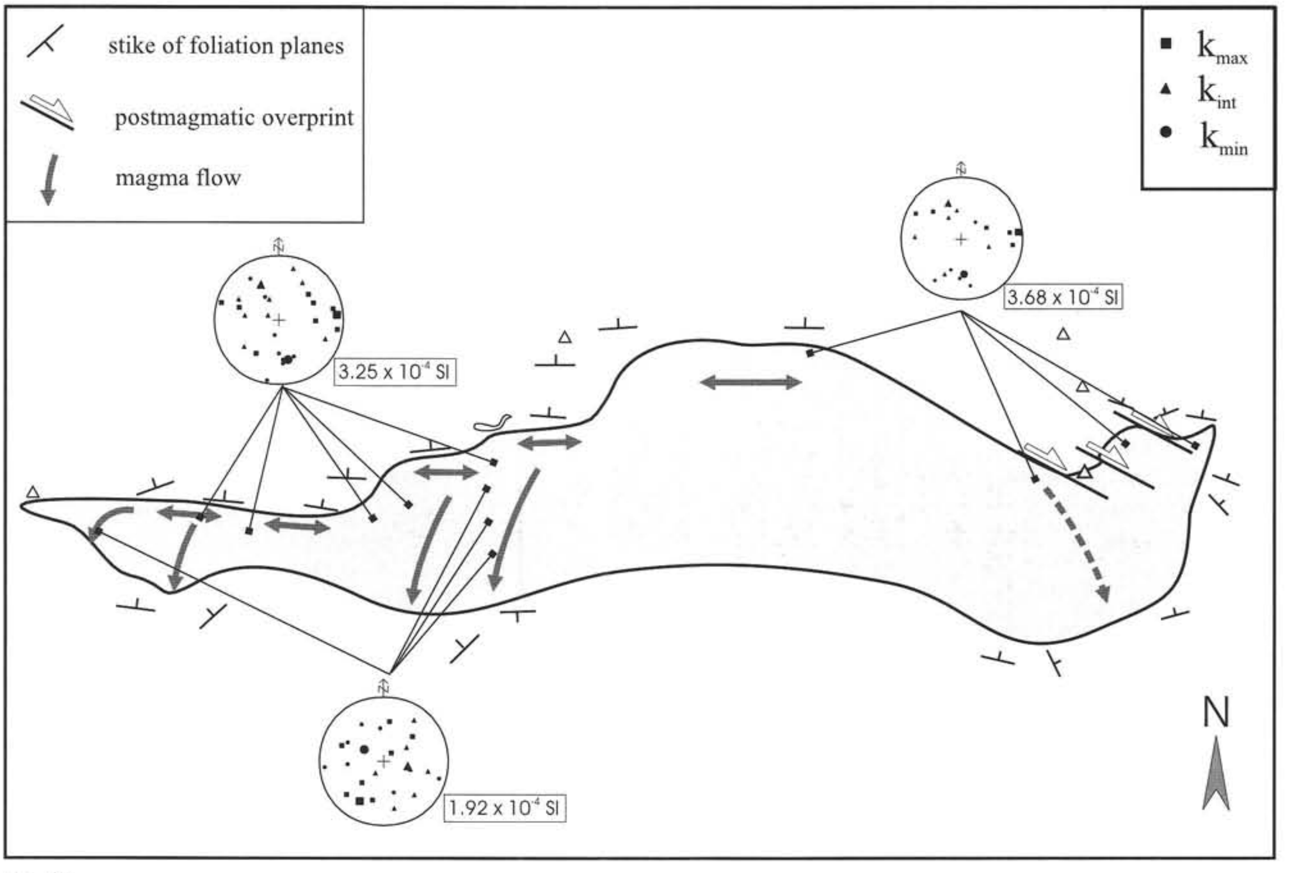

Fig. 12
Summarized AMS data (only samples with magmatic and sub-magmatic textures) translated into direction of magmatic flow; k_{max} represents main flow direction. Pole distribution diagrams (lower hemisphere) show main areas of different susceptibility axes and bulk susceptibility values K. K_{max} is the magnetic lineation and k_{min} normals the magnetic foliation plane, which is defined by the k_{max}-k_{int} plane. Plots show higher intensities around 3.5×10^{-4} SI in the north. Samples at the eastern parts of the Rensen show influence of late-magmatic overprints (sub-magmatic to solid state textures) reflecting near same orientations as within the country rocks. To the south magnetic foliation planes are approximately N-S oriented.

Mean susceptibility values reflect average mineral composition of the Rensen Pluton. The northern tonalitic rim zone with significant amount of biotite and hornblende shows significantly higher values around 3.25 to 3.68×10^{-4} SI than the granodioritic / tonalitic main body which is free of hornblende and has minor biotite (mean is 1.92×10^{-4} SI).

Since no solid-state deformation has been observed in the studied samples we interpret the magnetic fabric as result of magmatic flow (e. g. BOUCHEZ, 1997; STEENKEN et al., 2000). Based on the usually well defined k_{max} axis and on foliation trajectories an east-west magmatic flow is proposed for the northern pluton portions. Magma flow within the southern granodioritc/tonalitic body was approximately from north to south (Fig. 12).

6. Magma – host rock system

Interaction of magma and country rocks offers opportunities to constrain the thermal regime and post cooling modification of the contact aureole. Pressure estimates during magma crystallization may also be used to reconstruct tectonic processes during upward migration of magma (e. g. FRITZ & PUHL, 1997).

6.1 Pressure estimates (Al^{tot} –in-hornblende)

The calc-alkaline granodioritic to tonalitic Rensen exhibits a hypidiomorphic, granophyric fabric with E-W-oriented biotite and hornblende crystals within the marginal facies. The main constituents are plagioclase, potassic feldspar, quartz, hornblende, biotite and epidote. Accessory minerals are apatite, titanite, zircon, rutil and tourmaline.

The Al-in-hornblende barometer, used to estimate the crystallisation depth of the magma (HAMMERSTROM & ZEN, 1986; SCHMIDT, 1992), relates the Al^{tot} content of magmatic hornblende linearly with crystallization pressure of the intrusive body. The fact that hornblende equilibrates in the presence of melt close to the solidus (e. g. SCHMIDT, 1992) allows the solidification depth of an intrusion to be estimated.

Forty-five spots of unzoned magmatic hornblende from samples within the tonalitic marginal facies (see Fig. 13) were measured using an ARL-SEMQ microprobe on the Institute of Mineralogy and Petrology University Graz. The hornblende is compositional an alumino-ferro-tschermakite with Al-contents of 11-13 wt% and Na contents of 1.3-2.0 wt%. Al^{tot} cations per formula unit (calculation based on 23 cations) range between 2.1 and 2.4, which correspond to pressures of 7-8 kbar (see Fig. 13). These data refer to the northern areas of tonalitic composition within the Rensen massif with very homogeneous alumina contents of hornblende. Southern parts of the massif do not contain hornblende. Assuming a rock density of ca. 2800 kg/m^3 the hornblende crystallized in the presence of melt at depth of ca. 20-22 km.

6.2 Temperature estimates

E-W-trending marble layers north of the Rensen are thermal affected by the intrusion, leading to formation of scarn mineral assemblages, which are mainly developed as a network of small metasomatic veins, indicating strong fluid transport. The mineral assemblages consist of quartz (qu),

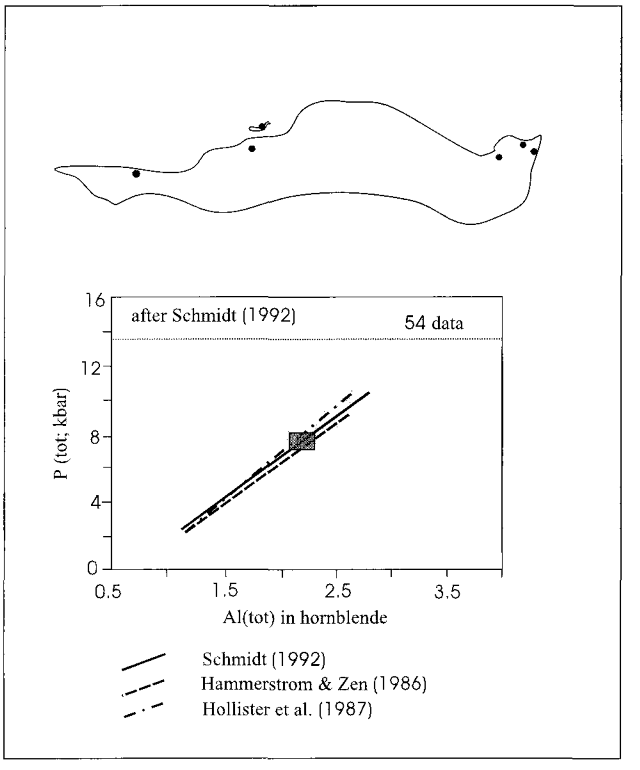

Fig. 13
Estimate of pressure during crystallisation of tonalite within the Rensen intrusion using Al^{tot} in hornblende. Box indicates range of pressure using different calibrations and range of hornblende analyses. Shape of the Rensen shows locations of sample points for barometric estimates.

calcite (cc), wollastonite (wo), grossular (grs), diopside (di), vesuvianite (vsv), phlogopite (phl), alkali feldspar (kf), plagioclase (pl), zoisite (zo), clinozoisite (cz), epidote (ep) and titanite (sph). Temperature conditions for the contact aureole immediately at the pluton – host rock interface can be constrained by CaO-saturated KCMASCH systems (cc+wo+di+kf+phl+qu+pl+cz+vsv) and SiO_2-saturated CMASCH systems (qu+grs+vsv+di+pl+cz+cc±sph). Univariant reaction lines and invariant points were calculated for 7.5 kbar (estimate derived from hornblende barometry) using the program package Perplex (CONNOLLY, 1990) and the thermodynamic data set of HOLLAND & POWELL (1990). The occurrence of vesuvianite limits the $X(CO_2)$ content to a maximum of 0.15 within a water dominated metasomatic fluid.

Results are plotted in a combined T(°C)-$X(CO_2)$ diagram (Fig. 14) that includes both systems. The shaded field is based on microscopic observations of two balanced temperature controlled mineral reactions 1) cz → an+grs and 2) di+kf → phl+wo. The fact, that an+grs are not in equilibrium together with the stability field of cz in equilibrium with phl + wo (Fig. 15a), the temperature at the interface is between 590-670°C.

It should be emphasized that contact metamorphism was not purely static. Occasionally, thin sections show deformational features (see Fig. 15b) such as recrystallized quartz subgrains within metasomatic zones, showing that the contact metamorphism cooled within a stress field. Additionally, preferred orientation of wollastonite crystals (E-W) also indicates intrusion within a regional stress field.

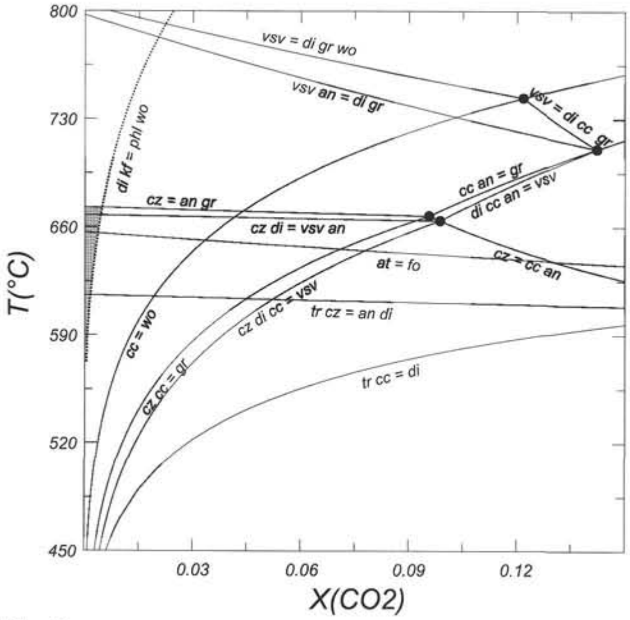

Fig. 14
Temperature estimate for the contact aureole based on scarn mineral assemblages. The diagram includes the constructed univariant mineral reaction lines and invariant points of the SiO_2 saturated system combined with a univariant reaction line (di kf = phl wo) of the CaO saturated system (dotted line). It is constructed by using the software Perplex (after CONNOLLY, 1990). Calculations are performed for 7.5 kbar, based on hornblende barometry; X_{CO2} ranges between 0 and 0.15. Information for the temperature results by the occurrence of phlogopite and clinozoisite (shaded field), which occur together in equilibrium. Reaction equations are written by considering high temperature assemblages on the right of the "=" sign. Abbreviation of minerals is defined in the text.

7. Implications for magma emplacement

Based on microstructures, magnetic fabrics and AMS data, the following chronology of events is proposed.

1. E-W oriented magmatic flow and oblate ellipsoidal shape suggest a large amount of N-S compression during emplacement of northern areas of the pluton (tonalitic rim facies). Southern pluton portions (main facies) may represent a younger successively evolving magmatic event and have been emplaced during north-south flow.
2. High temperature solid state deformation is interpreted as melt enhanced deformation during intrusion of hot aplitic veins with mylonitic textures. We emphasize that the pluton itself suffered very minor solid state deformation and strain is almost entirely accommodated in veins. The mylonitic fabrics within high temperature deformed NE-SW trending veins show mainly sinistral strike slip. E-W oriented veins in central northern portions of the study area (south of Vals pasture) are coaxially deformed.
3. NW-SE striking aplitic veins exhibit low temperature solid state deformation and dextral sense of shear. Dextral shear also overprints northern parts of the Rensen pluton.
4. Youngest brittle tectonics is characterized by a conjugate NE-SW and NW-SE fault system.

The overall shape of the Rensen Pluton, i. e. the "staircase pattern" is a result of sinistral shear along NE-trending shear zones and dextral shear along NW-trending shear zones.

A large number of emplacement models have been proposed for pluton intrusions, ranging from passive emplacement models, like stopping (e. g. PITCHER, 1970), to magmatic wedging (e. g. PITCHER & READ, 1959) to models for extension by ballooning (e. g. HOLDER, 1979). The results from the current study indicate emplacement related to regionally developed fault zones (HUTTON & REAVY, 1992; GUGLIELMO, 1993; TOBISCH & CRUDEN, 1995), which were active during magma emplacement. Similar scenarios had been described from oblique convergent fault zones that exhibit strike-slip partitioning (GLEDHILL & STUART, 1996; SAINT BLANQUAT et al., 1998). We consider that emplacement of the Rensen Pluton was related to shear deformation within the Austroalpine unit. This is consistent with studies from the Rieserferner Pluton further east, where the DAV has been interpreted to represent a feeder zone (MAGER, 1985; STEENKEN et al., 2000). We emphasize that the Rensen intrusion was not strictly related to the DAV which is exposed south of it. The whole Austroalpine unit between the southern Tauern margin and the PL is characterized by distributed shear and the DAV simply defines a very high strain domain within this zone.

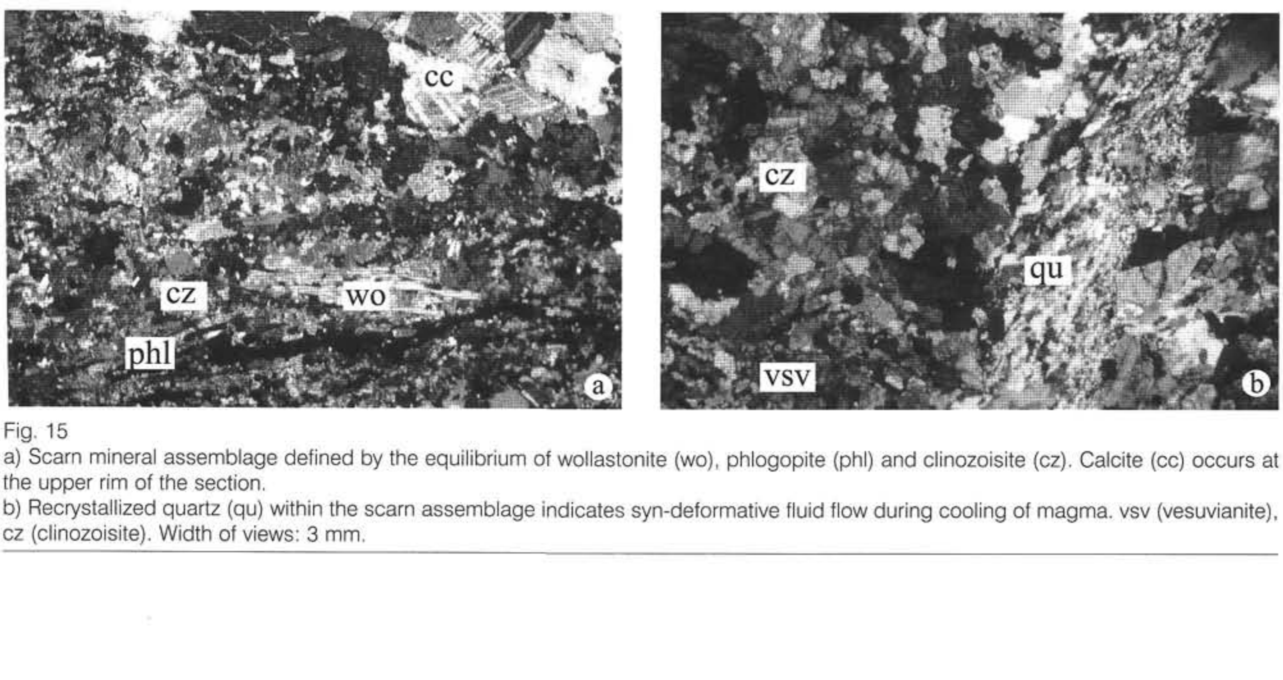

Fig. 15
a) Scarn mineral assemblage defined by the equilibrium of wollastonite (wo), phlogopite (phl) and clinozoisite (cz). Calcite (cc) occurs at the upper rim of the section.
b) Recrystallized quartz (qu) within the scarn assemblage indicates syn-deformative fluid flow during cooling of magma. vsv (vesuvianite), cz (clinozoisite). Width of views: 3 mm.

Our data are in good agreement with mechanisms combining vertical movements with lateral extrusion. Foliation and lineation from pluton and country rocks, shape of AMS ellipsoids as well as successively evolving fault patterns indicate ongoing sub-horizontal north-south compression during emplacement and cooling of the pluton. The amphibole-rich tonalitic marginal facies is interpreted to represent first batches of magma, emplaced during general W-E extension and sinistral shear. Early phase magma emplacement is considered as a combination of magma overpressure pushing to open its own space plus sinistral strike-slip tectonics along the wrench corridor (Fig. 16a). Such a scenario has been discussed for other transcurrent shear zones by TOMASSI et al. (1994), NEVES et al. (1996) and SAINT BLANQUAT et al. (1998).

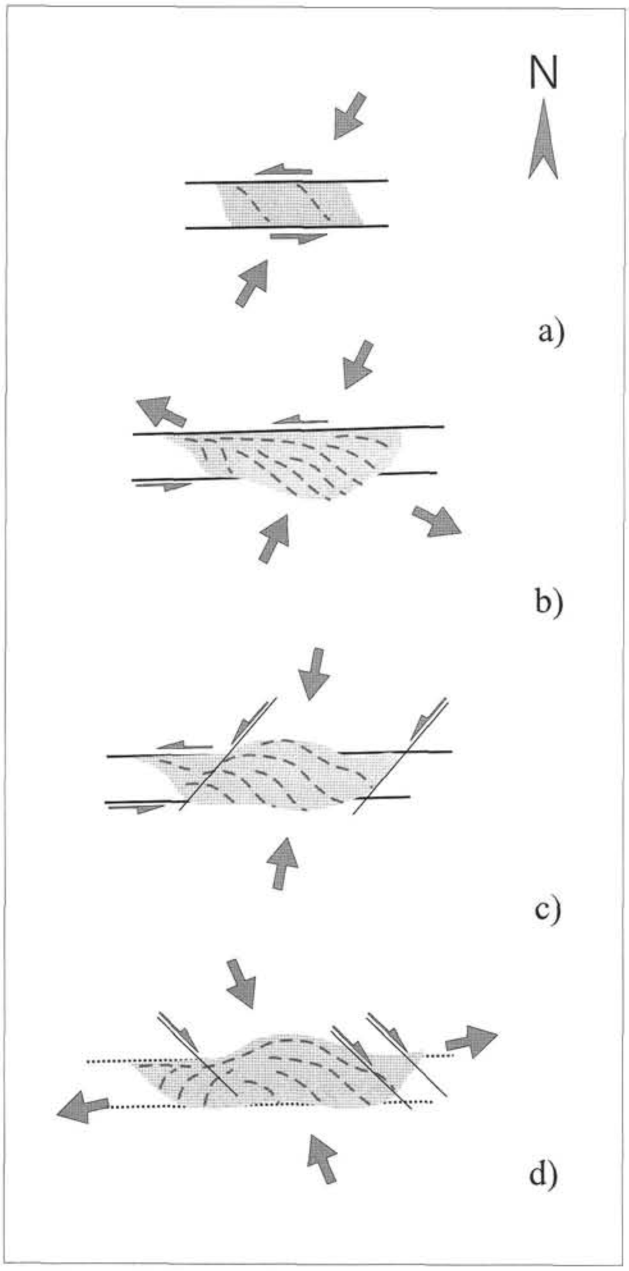

Fig. 16
Simplified emplacement model of the Rensen pluton.
a) The first step of magma intrusion is due to a combination of overpressurized magma, which opens its own space, and strike-slip tectonics. Both mechanisms led to rotation of foliation (flattening plane) with respect to the orientation of main compression.
b) Magma bulges over the southern border into direction of extension caused by the high amount of shortening within this area. Northern areas of the intrusive complex shows its final E-W-foliation. Strike-slip tectonics and the N-S compression forces the E-W-elongated shape.
c) Activation of sinistral Riedel shear zones forms the shape of the Rensen during cooling.
d) Late stage dextral shear zones due to rotation of main compressive direction provides the tectonic overprint after cooling of magma. Model follows work by ST. BLANQUAT et al. (1998).

Our model for pluton emplacement involves lateral W-E stretch that may occur over a wide range of convergent plate motions (Fig. 16). Lateral movements may even be released during shift from sinistral to dextral oblique plate convergence between the European and Adriatic Plate as described by several authors (e. g. DEWEY et al., 1989; SCHMID et al., 1989). Early pulses of intrusion have been emplaced during sinistral shear and early formed magmatic foliations, best seen in the northern rim zone, have been rotated towards parallelism to the shear zone boundaries (Fig. 16a, b). Successively evolving granodioritic to tonalitic batches of magma bulge towards the south which resulted in a deflection of the surrounding host rock foliation compared to the regional strike. Synthetic Riedel faults may provide space for the latest magma phases and contribute to the present shape of the Rensen (Fig. 16c). During onset of cooling late aplitic veins accommodated by sinistral shear deformation and high temperature sinistral mylonites developed. Those mylonites have been dated by MÜLLER et al. (2001) and gave ages of 30.9 ±0.2 Ma. Subsequently magmatic rocks and host rocks cooled down and low temperature dextral shear zones and brittle faults developed. Dextral shear zones and faults dissect the pluton and the host rocks predominantly at the north eastern margin of the study area. This contributes to the final shape of the pluton (Fig. 16d). The change from sinistral high temperature structures to dextral low temperature shear is consistent with anti-clockwise rotation of the main stress field orientation from NNE-SSW to NW-SE as described by SCHMID et al. (1989) and MANCKTELOW et al. (2001).

8. Discussion and Conclusion

Penninic units from the southern Tauern Window and the Austroalpine Unit are interpreted as a sinistral transpressive wrench corridor with significant amount of west-east stretch. Both units are deformed by distributed shear deformation and there is no break in the structural evolution along the Penninic – Austroalpine boundary. Domains of higher shear strain intensity include the area between Rensen Pluton and Tauern Window and a more than 100 meters wide shear zone, midway between Rensen Pluton and Periadriatic Lineament. The latter is interpreted as western continuation of the DAV. Aside this shear dominated domains a major coaxial component of flow is evident from quartz textures. Hence, some component of displacement partitioning has to be considered. We emphasize that beside west-east lateral movement, there was a significant vertical component of motion associated with southward thrusting along steeply north dipping planes. Dextral shear is of low temperature type and restricted to the vicinity of the PL and distinct zones within eastern portions of the study area.

A northward increase in syntectonic temperatures during sinistral shear is inferred from quartz textures with major contribution of basal glide systems in the south to prism glide systems in the north. This is in concordance with variations of quartz deformation mechanisms observed by MANCKTELOW et al. (2001). Subgrain rotation mechanisms dominate southern parts and grain boundary migration recrystallisation northern portions of the mapped area. According to calibrations by STIPP et al. (2002), this translates to an approximate south-north temperature range between 400 °C to 550 °C.

The Rensen Pluton is interpreted as syntectonic intrusion emplaced during sinistral shear. Oldest pluton portions are represented by the northern tonalitic rim facies, younger granodioritic/tonalitic magma pulses evolved in the south. A complete succession of structural events is recorded and correlated with the cooling history of the pluton. Magmatic fabrics with west-east flow (northern rim facies) and north-south flow (main plutonic facies) evolved coevally with sinistral shear. High temperature (ca. 500 °C) solid state sinistral shear and west-east stretch is concentrated in aplitic dykes that suffered mylonitisation immediately after their emplacement. Low temperature dextral shear occurred after final cooling of the pluton and host rocks as evident from semi-ductile to brittle structures.

The age of pluton emplacement and vein deformation is well constraint. The Rensen has been dated by 31.7-31.1 Ma (BARTH et al., 1989), and a sinistrally sheared dyke from the Plattspitz (Fig. 2) gave 30.9 ±0.2 Ma (MÜLLER et al., 2001). The shift from sinistral to dextral shear is correlated with changing plate motion direction of the Adriatic indenter (e. g. DEWEY et al., 1989; KURZ et al., 1998) and occurred between 30 Ma and 20 Ma (MANCKTELOW et al., 2001).

Along the northern rim of the Rensen a very small zone of contact metamorphism developed. This suggests a relative deep intrusive level, supported by our data. Temperatures of 590-670 °C at the pluton host-rock interface were to low for a significant thermal overprint of metapelitic host rocks that suffered at minimum 450 °C. Estimates on intrusion depth based on Al-in-hornblende barometry gave ca. 20 km (7.5 kbar) and support deep level crystallisation of northern portions of the Rensen Pluton. This contrasts data from the Rieserferner Pluton, ca. 50 km to the east, where a wide contact aureole developed and ca. 7 km intrusion depth has been reported (CESARE, 1992).

We interpret the west-east variation in emplacement levels between the Rensen and the Rieserferner pluton and the different extend of the contact aureole as result of Oligocene/Miocene transpression and lateral extrusion tectonics between Tauern Window and PL. Within the Vals section major N-S shortening was accompanied by large amount of vertical motion and simultaneous erosion. Hence, a relatively deep crustal section and the supposed root zone of the Rensen Pluton (northern rim zone) are exposed. Further to the east the wrench corridor extends and minor amount of N-S shortening corresponds to minor vertical exhumation. There, a shallow crustal level and the roof of the Rieserferner are preserved.

9. Acknowledgements

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10. Appendix

10.1 AMS analysis and technique

Anisotropy of magnetic susceptibility is a useful tool for determining the conditions of emplacement of granitoids by interpretation of the internal structure (STACEY, 1960; HROUDA and LANZA, 1989; BOUCHEZ et al., 1990; STEENKEN et al., 2000) and the relationship between rock fabrics and magnetic fabrics (e. g. HROUDA, 1982; BOUCHEZ, 1997). Most rocks contain small percentage of ferromagnetic minerals that become deformed and/or reoriented, and are strained as a part of the whole rock. For granitoids, iron bearing silicates, especially biotite and amphibole, carry paramagnetic properties. Therefore the magnetic fabric can be directly related to the crystallographic preferred orientation (CPO) of the paramagnetic carriers (HROUDA, 1982). In ferromagnetic rocks, iron bearing ore minerals like magnetite and hematite obliterate paramagnetic properties. Therefore magnetic fabrics are related to primary shape anisotropies or inhomogeneous grain distribution (ROCHETTE et al., 1992). The magnitudes of the principal magnetic susceptibilities and their orientations within the rock, the magnetic susceptibility anisotropy, constitute the rock magnetic fabric. The study of magnetic fabrics was initiated by GRAHAM (1954) and since then it has been established that magnetic susceptibility anisotropy ellipsoids in all rocks reflect the strain ellipsoids (e. g. HROUDA et al., 1973; KING, 1966; WOOD et al., 1976). The axial ratios of the susceptibility ellipsoids are related exponentially to the strain axial ratios of the strain ellipsoids (WOOD et al., 1976) indicating the possibility of obtaining complete strain ellipsoid data from the magnetic fabric.

The low field anisotropic susceptibility of a rock sample can be interpreted as an oriented strain ellipsoid with three mutually perpendicular axes $K_{max} \geq K_{int} \geq K_{min}$, which are defined by their orientation and intensities (SI). The bulk susceptibility is given by the parameter $K=1/3\ (K_{max}+K_{int}+K_{min})$; the total anisotropy by the parameter $P=K_{max}/K_{min}$; the linear anisotropy by the parameter $L=K_{max}/K_{int}$ (lineation L) and the planar anisotropy by $F=K_{int}/K_{min}$ (foliation F). The ratio, $L/F=E$, is the ellipticity of the susceptibility ellipsoid, thus if $E>1$ the ellipsoid is prolate and the lineation is more developed than the foliation and conversely if $E<1$ the ellipsoid is oblate and the foliation is more developed than the lineation.

For a detailed overview about AMS systematics and sample preparation see HROUDA, 1982; RATHORE and HEINZ, 1980.

10.2 Analytical procedure of texture analysis

Polished rock chips were placed in the x-ray beam of a texture goniometer (wavelength CuKα = 1.5418, beam current = 40 kV and 30 mA) used in reflection mode. Eight lattice planes (<100>, <110>, <102>, <200>, <201>, <112>, <211>, <113>) have been directly measured at α-angles between 0° (centre) and 80° (periphery), corrected for defocusing effects and completed (a = 0°-90°) by Fourier analyses. Lattice planes <001>, <101> and <011> were calculated using the orientation density function (ODF) based on the harmonic method of ROE (1965) and BUNGE (1969). Only the most valuable c-axes <001> orientation distributions are shown as pole figures. For detailed description see WENK (1985).

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