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Micro- to macroscale interactions between deformational and metamorphic processes, Tauern Window, Eastern Alps

by *Jane Selverstone*[1]

Abstract

Rocks from the western Tauern Window preserve a complex record of deformational and metamorphic processes at all scales. Syn- and post-kinematic fabrics can be combined with P-T-t data to reconstruct the history of N–S continental convergence and subsequent E–W extension from at least Paleocene through Miocene time. Petrologic data from the Lower Schieferhülle (LSH) indicate progressive metamorphism along a clockwise P-T-t path that reached P ≥ 10 kbar and T ~ 550 °C during collision. The overlying Upper Schieferhülle (USH) followed a similar path, but reached pressures of ≤ 7 kbar and T ~ 450–500 °C. The ~3 kbar difference in P_{max} conditions attained by the units implies ~10 km of structural separation of the LSH and USH at depth, yet the sampled localities are now ≤ 2 km apart in the field. P-T paths of garnet growth from the LSH and USH imply that garnets grew simultaneously in the two units during the early stages of unroofing. Rb/Sr dating of garnet segments and matrix material in both units confirms this interpretation (Christensen et al., 1991). However, garnets are postkinematic in the LSH and synkinematic in the USH, implying that the two units responded very differently to the same tectonothermal event. This observation, combined with synmetamorphic shear indicators and evidence for thinning of the section after P_{max}, can be accounted for by significant W-directed normal shear beginning at or prior to 35 Ma, with most of the strain initially accommodated by extensional ductile shearing of the USH. Ductile fabrics in the USH were subsequently overprinted by increasingly brittle fabrics with the same sense of shear towards the west; these fabrics grade into the low-angle Brenner Line normal fault zone that unroofed the west end of the window in the Miocene.

Strain heterogeneities in the western part of the window profoundly affected metamorphic development in a variety of ways. Within the Greiner shear zone, Si-scavenging fluids transformed granodiorite into aluminous schist at ~40 km depth, thereby producing assemblages that were sensitive monitors of P-T history. Shearing elsewhere in this zone may have contributed to formation of hornblende garbenschiefer horizons by a combination of extreme grain-size reduction, diffusion creep, and rapid grain-boundary diffusion processes at ~35 km depth. Shearing along the Brenner Line resulted in channelized fluid flow and alteration of the USH over a depth interval from ~15 to 5 km. Initial fluid flow along this zone at depth may have subsequently controlled the location of the brittle Brenner Line normal fault. Localized deformation at depths of 5–40 km thus affected bulk chemistry, fluid migration properties, and development of P-T-sensitive assemblages, all of which contribute to our ability to read the tectonometamorphic rock record.

Keywords: P-T-t path, shear zone, fluid flow, hornblende garbenschiefer, Tauern Window, Eastern Alps.

Introduction

Rocks that have undergone regional metamorphism provide the unique opportunity to reconstruct simultaneous records of deformational history and depth-temperature history during orogenesis. In many cases, they also provide a record of the interactions and feedback effects between these deformational and metamorphic processes. Reading these records, however, is not always an easy matter, and ambiguities can lead to widely opposing viewpoints of the rock record (e.g. Rosenfeld, 1968 vs Bell and Johnson, 1989). This paper represents an attempt to review some of the evidence for interactions between tectonic events and the metamorphic evolution of the

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western Tauern Window, on scales ranging from individual mineral grains to those of plate motions. It is clearly only one person's view of a small part of a large mountain range, however, and other interpretations may be equally consistent with the available data. The overall intention is first to present a series of observations at different scales, and second to stimulate a discussion of how best to reconstruct a complex history of strain heterogeneity in a regime of rapidly changing depths and temperatures.

Geologic setting

The Tauern Window (Fig. 1) is a large tectonic window in the Eastern Alps that exposes rocks associated with continental Europe and the neo-Tethys ocean basin beneath overthrust nappes derived from the Adriatic plate during Late Cretaceous–Early Tertiary continental convergence. Convergence initially resulted in north-directed emplacement of the Austroalpine nappes over the rocks of the window, but subsequent west-directed motion of the Adriatic plate (e.g. SMITH and WOODCOCK, 1982) led to east-west extension of the overthickened crust in the vicinity of the Tauern Window (SELVERSTONE, 1988; BEHRMANN, 1988; see RATSCHBACHER et al., 1991 for alternative explanation of extension).

The rocks within the window can be subdivided into three main lithotectonic packages (Fig. 1). The structurally lowest unit is the Zentralgneis (ZG), which is composed of Hercynian granodiorites, tonalites, migmatites, and minor amphibolites (MORTEANI, 1974). In the western part of the window, the ZG occurs in two chemically distinct lobes, the granodioritic Tuxer Kern and the tonalitic Zillertaler Kern (MORTEANI, 1974; FINGER et al., in press), which are separated by a NE-trending shear zone that is described further below. Overlying the ZG in autochthonous to parautochthonous contact is the Lower Schieferhülle (LSH), which comprises Permo-Carboniferous amphibolites and graphitic schists (FRANZ et al., 1991) that were the country rock into which the plutonic rocks of the ZG intruded and a Mesozoic cover sequence of quartzites, marbles, and pelitic and calcareous schists. The Upper Schieferhülle (USH), a sequence of greenstones, marbles, and graphitic schists derived from the floor of the neo-Tethys ocean basin, is the structurally highest unit in the window. It is separated from the ZG and LSH by a folded thrust fault that appears to pre-

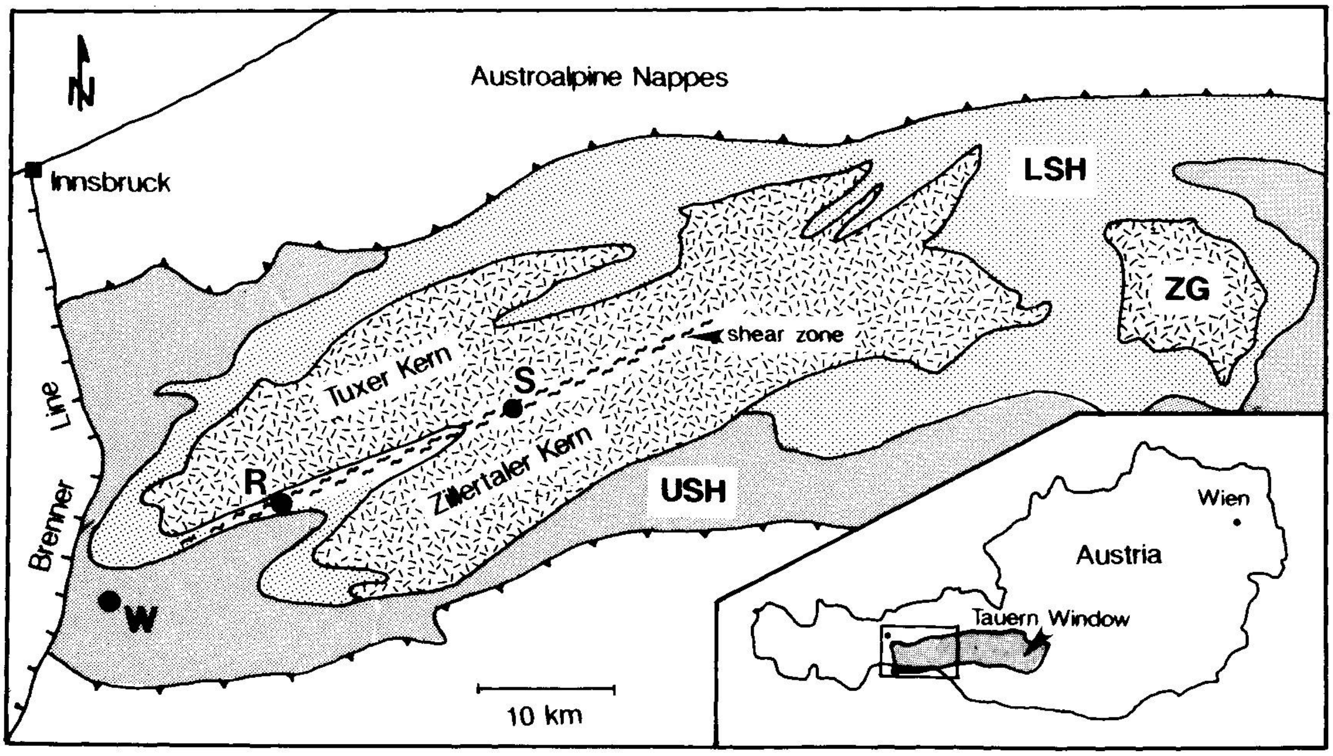

Fig. 1 Simplified geologic map of the western and central parts of the Tauern Window. ZG = Zentralgneis, which is divided into the granodioritic Tuxer Kern and tonalitic Zillertaler Kern in the west. LSH = Lower Schieferhülle; USH = Upper Schieferhülle. Brenner Line is a low-angle normal fault that unroofed the western part of the window in the Miocene. S = Stillup Tal; R = Rotbachlspitze; W = Weißspitze, which is a small klippe of Austroalpine material juxtaposed against the USH by the Brenner Line.

date most of the Alpine metamorphic signature in the western part of the window.

The southern border of the window is thought to represent the original thrust contact between rocks of the window and the overlying Austroalpine nappes. In contrast, the western border of the window is a recently recognized low-angle normal shear zone along which several kilometers of the Austroalpine section were excised (SELVERSTONE, 1988; BEHRMANN, 1988). Although significant motion on the fault itself is Miocene in age, ductile extension with the same sense of shear affected rocks within the Tauern Window beginning at least as early as the Eocene and continuing throughout the Oligocene (SELVERSTONE, 1988).

Interactions between deformation and metamorphic processes

REVIEW OF P-T-t HISTORY

The pressure-temperature evolution of rocks from the Lower and Upper Schieferhülle series in the western part of the window has been described in detail by SELVERSTONE et al. (1984) and SELVERSTONE and SPEAR (1985); SELVERSTONE (1985, 1988) subsequently correlated the P-T histories of these rocks with their fabric development to arrive at a tectonic model for metamorphism in this part of the Tauern window. The results of these papers are briefly reviewed here in the context of interactions between large-scale deformational and metamorphic processes (see Fig. 2), but interested readers are referred to the original studies for greater detail.

Samples from the Lower Schieferhülle in the western part of the window consistently indicate burial to depths of ~35–40 km (~10–11 kbar) in response to overthrusting of the Austroalpine nappes (i.e. partial subduction beneath the Adriatic plate). Reconstruction of the burial history itself has thus far proven impossible owing to pervasive recrystallization of the rocks at depth, but pseudomorphs after lawsonite in a few LSH samples (SELVERSTONE et al., 1984) indicate that the rocks passed through the lawsonite blueschist facies during burial; such a path is consistent with the relatively rapid burial to be expected in a subduction environment, despite the relatively low-density makeup of the Tauern crust. Following the overthrusting of the Austroalpine nappes, the LSH experienced unroofing and minor heating to the conditions of final mineral rim equilibration at ~550 °C and 7 kbar (~24–25 km). Subsequent unroofing, as constrained by fluid inclu-

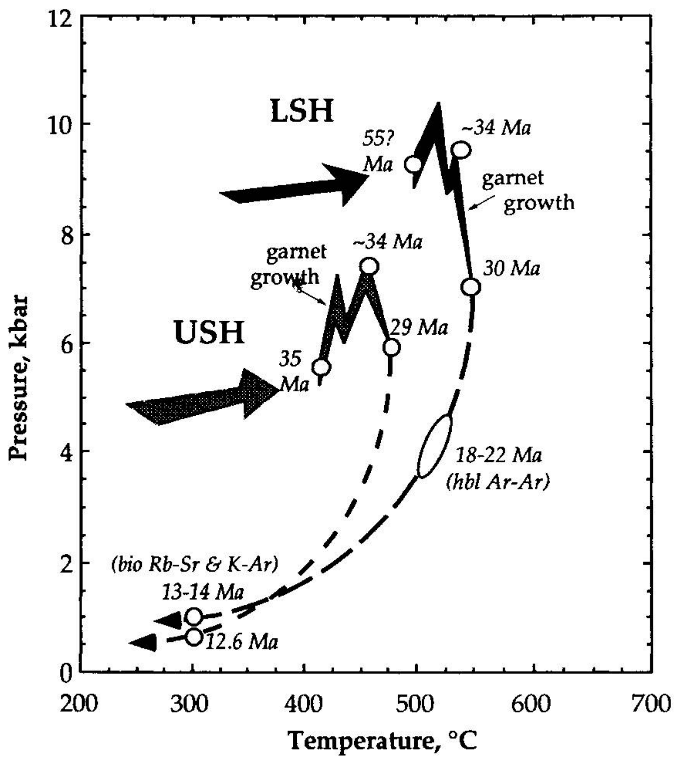

Fig. 2 Pressure-temperature diagram summarizing the P-T-t histories of the LSH and USH from the SW corner of the Tauern Window. P-T paths are from SELVERSTONE et al. (1984) and SELVERSTONE and SPEAR (1985); garnet growth ages are from CHRISTENSEN (1992); hornblende ages are from BLANCKENBURG et al. (1989); other age data are reviewed by SELVERSTONE (1985, 1988).

sion data, brought the LSH to within 5 km of the surface while still at elevated temperatures.

Rocks from the Upper Schieferhülle followed a P-T path of similar form, but with quite different extremes (Fig. 2). Maximum pressures recorded in USH samples from the western part of the window are ~7 kbar (24–25 km), and there is no evidence for burial of these rocks to any greater depth in this area (in contrast to the USH in the central part of the window, e.g. HOLLAND and RAY, 1985). Unroofing and heating resulted in final equilibration conditions of only ~475 °C and 5–6 kbar (~18–21 km), but fluid inclusion data again indicate that continued unroofing brought the rocks to within 5 km while still at temperatures in excess of 350 °C (SELVERSTONE and SPEAR, 1985).

STRAIN HETEROGENEITIES BETWEEN THE LSH AND USH

Despite the 10 km difference in maximum depth of burial of the LSH and USH in this area, SELVERSTONE (1985) postulated on the basis of

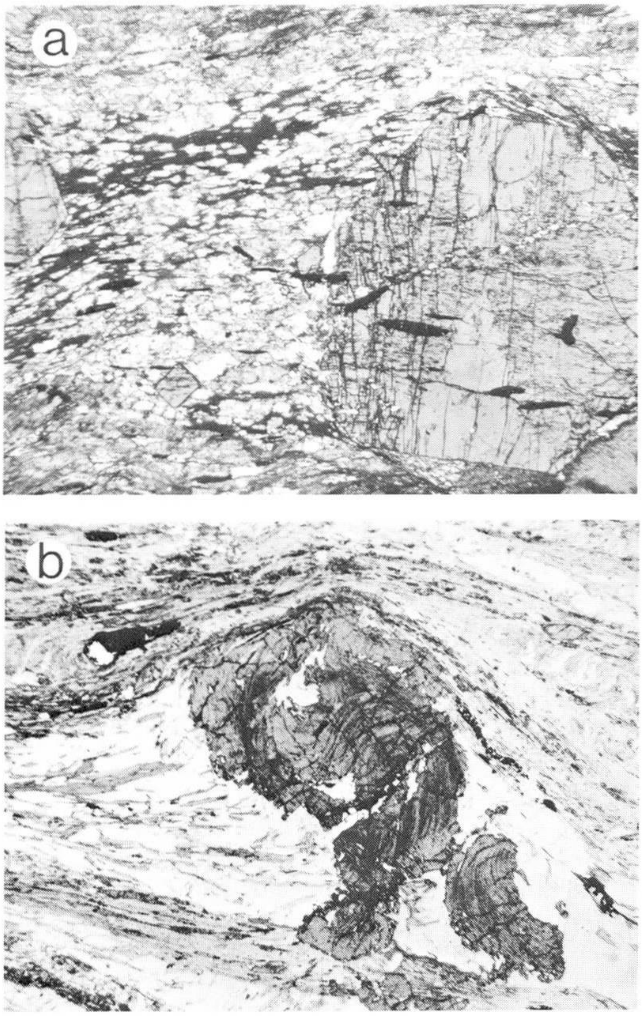

Fig. 3 Photomicrographs showing (a) typical postkinematic LSH garnet and (b) synkinematic USH garnets (section not oriented). Long dimension is 13 mm. Both photos taken with partially crossed nicols to show internal garnet structures.

similar garnet growth paths that the two units were buried and heated in response to the same tectonothermal event. The sample localities from which the P-T paths were reconstructed are currently separated by only 2 km of section in the field, indicating that if the units shared a common burial history, extreme thinning of the intervening section must have occurred after emplacement of the overlying Austroalpine nappes. New Rb/Sr age data obtained by CHRISTENSEN (1992), CHRISTENSEN et al. (1991 and in preparation) on individual garnets from the LSH and USH now bear out this interpretation. As shown in figure 2, garnet growth in the LSH began as early as 55 Ma (only one analysis) but continued until 30 ± 1 Ma. USH garnets apparently grew over a shorter but overlapping time interval, from 35 ± 1 Ma to 29 ± 1 Ma. (The dated garnets are from different samples from those on which the P-T studies were done, but show similar zoning patterns and assemblages.)

Correlation of the P-T path lengths recorded by garnets in the LSH and USH indicates that significant differential movement must have occurred between the two units during the time of simultaneous garnet growth, i.e. the LSH experienced less burial and greater unroofing than the USH between 35 and 30 Ma. Interestingly, garnets in the LSH grew postkinematically during this interval, whereas USH garnets are all synkinematic (Fig. 3). This observation, combined with the age data indicating synchronous garnet growth in the two units, requires that deformation was heterogeneously distributed between the LSH and USH, at least throughout the Early Oligocene. Sense of shear indicators in oriented samples of the USH show that garnet growth was coincident with top-to-the-west extensional shear (SELVERSTONE, 1988), and correlation of rotational fabrics in the dated garnets with the duration of garnet growth yields minimum shear strain rates of ~3×10^{-14} sec^{-1} (CHRISTENSEN, 1992). Numerous field examples of coaxial shear fabrics in some USH horizons (e.g. symmetric tails on quartz knots; pancake garnets lacking rotational fabrics; conjugate shear bands), however, suggest that there was also a significant pure shear component to the deformation during the thinning.

The key question to address at this point is why postkinematic LSH porphyroblast growth was synchronous with synkinematic mineral growth in the USH, i.e. why was strain partitioned between the two units? A likely answer to this question comes from comparing (a) the overall mineralogy of the two units as they approached their maximum temperatures, and (b) the structural positions of the two units. On average, the LSH is a plagioclase-rich lithology with only minor carbonate; in the area of this study, it is also confined to a tight septum between two lobes of Zentralgneis that still retain Hercynian fabrics and hence were not highly strained during the Alpine orogeny. In contrast, the USH contains numerous marble horizons and calcmica schists, and much of it is also highly graphitic. Clearly, the rheologies of the two units were significantly different at depth, with the calcite- and graphite-rich portions of the USH able to flow readily in response to onset of west-directed extension at midcrustal levels. The greater strength of the LSH, coupled with its protected position in the ZG, resulted in partitioning of the extensional strain into the more ductile USH, which in turn resulted in thinning of the intervening section from ~10 km to 2 km during unroofing of the window.

On a large scale, the pressure-temperature evolution of the LSH and USH reflects the major tectonic processes associated with the Alpine orogeny: collision between the European and Adriatic plates, which caused the burial of the LSH and USH, and west-directed extension, probably in response to a change from northward to westward motion of the Adriatic plate (e.g. SMITH and WOODCOCK, 1982; SELVERSTONE, 1988), which controlled the unroofing history during most metamorphic mineral growth. The metamorphic development of the LSH and USH is thus largely a *response* to crustal-scale deformation. The following sections focus in more detail on the *interplay* between deformation and metamorphism in areas of extreme strain partitioning in the western part of the Tauern Window.

GREINER SHEAR ZONE

As mentioned above, the Zentralgneis in the western Tauern Window occurs in two distinct lobes that are separated by a steep, ENE-trending ductile shear zone (Fig. 1) referred to as the Greiner shear zone. This shear zone continues to the SW through both the LSH and USH, and must therefore be a structure of Alpine age. BEHRMANN and FRISCH (1990) describe dominantly sinistral motion on this shear zone, but in the areas familiar to the author, the sense of shear is typically ambiguous. Petrologic and structural features at two localities along this shear zone will be described to illustrate interactions on a variety of scales between deformational and metamorphic processes.

Volume-loss shearing

In the Stillup Tal (S in Fig. 1), metagranodiorite of the Zentralgneis is transformed along the Greiner shear zone into a highly aluminous schist that has recently been described by SELVERSTONE et al. (1991). The shear zone boundary is sharp and separates the unsheared granodiorite protolith from increasingly metasomatized rocks over a distance of a few meters. Immediately adjacent to the shear zone boundary, the granodiorite has been transformed into a biotite-white mica-garnet schist; with increasing distance from the wallrock, the schists become increasingly depleted in silica to the point that they lack free quartz and are composed almost entirely of garnet (up to 10 cm across), chlorite, and staurolite. This transformation produced mineral assemblages that are much more sensitive monitors of the P-T history of this locality than the unaltered granodiorite protolith. Thermobarometric calculations indicate final equilibration of the shear zone samples at 560 ± 20 °C, 7–8 kbar on a path similar to that described above for the LSH to the west; modeling of several zoned garnets in the shear zone indicates that garnet growth began at conditions of ~550 °C and 11 kbar (SELVERSTONE et al., 1991). Near the margins of the zone, these garnets show rotational fabrics in their cores that pass outward into the shear foliation, but in the center of the zone they overprint the shear fabric (SELVERSTONE et al., 1991). These observations suggest that garnet growth began in the latest stages of shearing and continued after movement in the zone had ceased. The P-T conditions at which garnet growth began thus indicate that shearing of the granodiorite must have occurred while the rocks were at depths of ~40 km. Delineation of this P-T history is only possible as a result of the significant alteration and development of new mineral assemblages that occurred in the shear zone.

Whole rock chemical data indicate that SiO_2 decreases from > 65 wt% in the metagranodiorite to ≤ 32 wt% in the center of the shear zone. Ca, Sr, and Na also show dramatic decreases across the shear zone, whereas Fe, Mg, Al, Ti, and Zn all increase towards the center of the zone. SELVERSTONE et al. (1991) used isocon diagrams to show that these chemical trends could not be easily explained by isovolumetric shearing and alteration. Rather, the whole rock data were most consistent with metasomatism accompanying significant volume loss in the shear zone. Minimum estimates of volume loss increase from ~12% adjacent to the unaltered granodiorite to ~60% in the center of the shear zone. Thus, movement on the shear zone must have had a large pure shear component associated with progressive volume loss, which is consistent with the general absence of asymmetric fabrics adjacent to the boundary of the shear zone.

It is clear that removal of such large volumes of material must have required passage of large amounts of fluid through the shear zone during deformation. In an effort to quantify this fluid volume, SELVERSTONE et al. (1991) used silica solubility data to calculate both volumetric fluid/rock ratios and time-integrated fluid fluxes. The resultant fluid/rock ratios range from 120 : 1 to 1200 : 1 in the center of the shear zone, depending upon the assumptions made concerning the initial Si content of the infiltrating fluid. Fluid fluxes range from 10^8 to 10^9 cm^3 cm^{-2} across the zone, indicating extreme metasomatism in the classification scheme of FERRY (1989). Regardless of the calculation technique, it is clear that enormous amounts of fluid must have passed through the shear zone in order to explain the observed chemical and mineralogical changes. The surrounding rock, however, is granodiorite with only 1.5 wt% H_2O. What then is the source of this fluid? Selverstone et al. (1991) noted that, by analogy with the dated P-T path of the LSH to the west, the rocks were most likely at ~40 km depth during the Eocene, and that according to TOLLMANN (1980), this was the time that movement on the Northern Penninic subduction zone carried material of the Flysch Belt southwards beneath the Zentralgneis. If this is the case, the shaly rocks of the Flysch Belt (5–10 wt% H_2O) would have been undergoing significant devolatilization immediately beneath the incipient shear zone, and could have provided the necessary volume of fluid (see Fig. 7 of SELVERSTONE et al., 1991). Furthermore, migration of flysch-derived water into the overlying and hotter Zentralgneis would result in an increase in silica solubility of the fluid, and hence would permit the ascending fluid to scavenge large amounts of silica as it passed through the shear zone. A possible sink for silica removed by this process is present in a structurally higher portion of the same shear zone exposed on the Rotbachlspitze, 15 km to the WSW ("R" in Fig. 1); at this locality, a prominent silicified zone is exposed that may represent silica deposition during cooling of upward-migrating fluids.

The extreme heterogeneity of strain evident in the Stillup Tal portion of the shear zone suggests that a feedback loop between deformation and metamorphism may have been set up during the shearing event. Using the least altered rocks of the shear zone as a guide, it is clear that even modest amounts of fluid flux through a zone of weakness in the Zentralgneis caused a sufficient change in bulk chemistry to produce a rock composed almost entirely of micas at ~550 °C and 40 km depth. Such a rock would be inherently weaker than the adjacent feldspar-rich granodiorite, and would act to further localize strain (e.g. JANECKE and EVANS, 1988). Increasing fluid flux through this now well-established zone of weakness further changed the rock chemistry such that all remaining plagioclase was removed and large amounts of chlorite were produced. Again, this recrystallized rock would have been significantly weaker than the wallrock and could have continued to localize the strain, thereby eventually producing a zone in which ~60% volume loss occurred three meters away from the undeformed granodioritic protolith. In the absence of a fluid influx and concomitant metamorphic recrystallization, it is likely that the strain would have been more broadly distributed throughout the Zentralgneis in this region.

Development of hornblende garbenschiefer

Several km to the WSW of the Stillup Tal, the Greiner shear zone passes through both Paleozoic and Mesozoic rocks of the Lower Schieferhülle series. Where it cuts through rocks of volcanic and volcaniclastic origin, these rocks are typically transformed into one of the more spectacular rock types of the area, the hornblende garbenschiefer. The garbenschiefer is characterized by large, radiating sprays and bundles of hornblende ("garben", or sheaves; see Fig. 4a) set in a fine-grained matrix that is variably plagioclase-rich, micaceous, or epidote-rich. The hornblende sprays in some cases lie within the plane of foliation and in other cases crosscut the foliation; even in the former case, however, they appear to be largely postkinematic with respect to foliation development. Thermobarometric studies (SELVERSTONE et al., 1984 and unpublished data) indicate that unzoned hornblende cores grew at conditions of ~500–530 °C and ~10 kbar, consistent with the conditions calculated for the final phase of shearing in the Stillup Tal to the ENE, but that narrow zoned hornblende rims grew during decompression to final equilibration at ~550 °C and ~7 kbar.

The origin of the garbenschiefer texture has received surprisingly little attention to date, despite the spectacular appearance of these rocks and their widespread development in the Alps and other collisional mountain belts. Several observations on both the hornblende grains and the matrix minerals provide clues into the development of this unusual metamorphic fabric. The radiating bundles of hornblende suggest that hornblende grew under conditions that favored hornblende growth relative to nucleation; that is to say, as soon as a stable hornblende nucleus formed, material was able to diffuse rapidly to the site of the nucleus and cause growth of elongate, intergrown hornblende grains. This contrasts noticeably with neighboring amphibolites at the margins of the Greiner shear zone that are composed of smaller, discrete hornblende grains that do not display a radiating habit.

The plagioclase + quartz matrix of the garbenschiefer samples is anomalously fine-grained (typically 0.04 to 0.1 mm in diameter) for rocks metamorphosed to temperatures of ~550 °C, as is evident from comparison with the consistently coarser grained rocks of similar bulk composition on either side of the shear zone. Despite this fine grain size, however, it is clear that matrix grain coarsening occurred during hornblende growth. This is evident from the fact that the hornblende garben contain microinclusions of

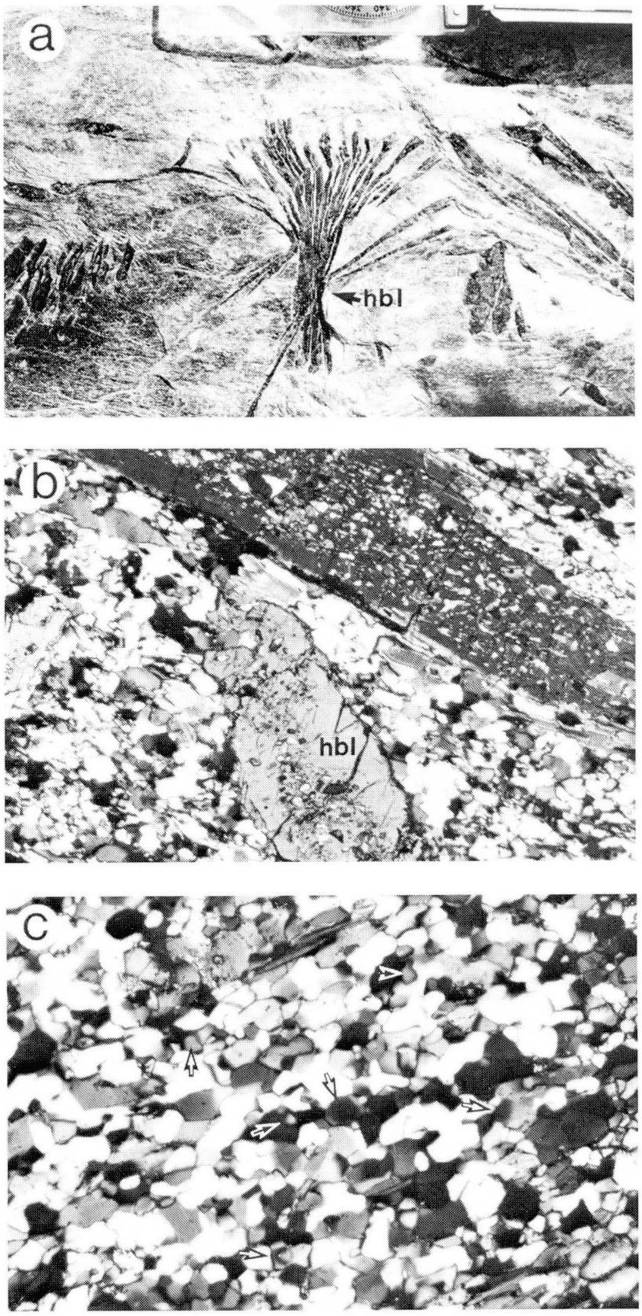

Fig. 4 (a) Typical outcrop appearance of hornblende garbenschiefer showing radiating spray of hornblende crystals. (b) Photomicrograph of hornblende garben in matrix of plagioclase and quartz; note grain coarsening indicated by change in grain size between plagioclase inclusions in hornblende and plagioclase in the matrix. Long dimension is 4 mm. (c) Detail of plagioclase-rich matrix showing asymmetric compositional zoning of grains (several indicated by arrows). Long dimension is 2 mm.

plagioclase and quartz in their cores that are an order of magnitude smaller than the same minerals in the matrix (Fig. 4b). Furthermore, plagioclase grains in the matrix show complex, asymmetric zoning that strongly suggests that dissolution and reprecipitation processes accompanied the grain coarsening (from An_{10-18} in the cores to An_{25-40} on the rims; Fig. 4c). Similar features are also well-developed in epidote in samples with an epidote-rich rather than a plagioclase-rich matrix. There is no preferred orientation of matrix grains visible when thin sections are viewed with the gypsum plate inserted, and the matrix grains appear optically to be nearly strain-free.

These observations provide some clues to the development of the hornblende garben. To summarize, they suggest that an episode of matrix grain-size reduction preceded hornblende growth, that plagioclase grain coarsening accompanied hornblende growth, that plagioclase zoning developed in response to solution and reprecipitation, that the matrix material is strain-free and shows no preferred orientation, and that hornblende growth rates probably dominated over nucleation rates. Combined with the P-T data, they suggest a scenario in which movement on the Greiner shear zone resulted in extreme grain-size reduction at ~35 km depth, followed by initial grain growth in a regime characterized by high grain boundary mobilities of the necessary phase components.

Tullis and Yund (1991; see also Yund and Tullis, 1991) recently presented experimental data on deformation of plagioclase by a diffusion creep mechanism that may be relevant to development of the garbenschiefer fabric. They concluded from their experiments that, for fine grain sizes and in the presence of at least small amounts of water, plagioclase is capable of passing directly from a cataclastic flow regime to a diffusion creep regime in which grain boundaries are wetted by a fluid phase and material is able to diffuse rapidly along grain boundaries. The microstructural evidence they present in favor of plagioclase deformation by grain boundary diffusion creep includes (a) evidence for progressive grain growth, (b) asymmetric overgrowths indicating solution and reprecipitation of material during growth, (c) low average dislocation density, (d) generally little preferred orientation of the grains, and (e) the presence of open, fluid-filled pores along the grain boundaries. Features (a) through (d) are readily observable in the garbenschiefer; it is not possible to determine a priori whether a free fluid (e) lined the grain boundaries during garbenschiefer metamorphism, but it is reasonable to assume that fluid did indeed migrate through the shear zone as at the Stillup Tal locality. Thus, based on empirical observations, the matrix microstructures of the garbenschiefer are consistent with deformation in a regime of grain boundary diffusion creep.

What are the implications of deformation in a diffusion creep regime for development of the hornblende garben? Although there are no experimental data on hornblende behavior in such a regime, we can make some plausible assumptions. It is likely that in a regime of rapid grain-boundary transport of hornblende constituents, hornblende nuclei would be eradicated by diffusion almost as quickly as they formed; for any nucleus that reached some critical radius, however, subsequent growth would be rapid, resulting in development of the radiating garben. If this interpretation is correct, grain size reduction during shearing at depth was a necessary precursor to development of the Greiner garbenschiefer; this shearing at depth apparently initiated a diffusion creep regime that accomodated the final increments of strain and enabled rapid, late- to post-kinematic hornblende growth. Subsequent grain coarsening of the fine-grained matrix during prolonged unroofing at high temperatures may have been inhibited by the presence of small mica and chlorite grains on many of the plagioclase grain boundaries (e.g. OLGAARD, 1990). This model may not apply directly to other localities, but it explains many of the macroscopic and microscopic features of the garbenschiefer in the southwest Tauern Window, and in particular their intimate association with zones of deep crustal shearing.

BRENNER LINE NORMAL SHEAR ZONE

The west end of the Tauern Window is marked by a zone of low-angle normal shear that was described in detail by SELVERSTONE (1988) and BEHRMANN (1988). Several kilometers of Austroalpine basement section were excised along this shear zone, and the Brenner Line now juxtaposes the Upper Schieferhülle in the window almost directly against the Brenner Mesozoic cover of the Austroalpine basement nappe. Much of the extensional motion on the fault zone occurred in the Miocene (see SELVERSTONE, 1988, for discussion of age relations), but ductile structures showing the same sense of normal shear developed as early as Eocene or Oligocene time throughout the southwestern part of the window (SELVERSTONE, 1988). Extensional movements thus began shortly after the deep burial of the Tauern area and dominated the subsequent unroofing history of the region.

At several localities along the length of the Brenner Line, a chlorite-rich horizon is present immediately beneath the rocks of the hanging wall. West and southwest of Brennerbad, the chloritic zone is developed in rocks of the "Zwischen-Serie", a tectonic mixture of Upper Schieferhülle and Altkristallin basement of the Austroalpine nappes. At these localities, the chloritic horizon is only a few meters in thickness and is characterized by the assemblage chlorite + plagioclase + epidote + quartz ± carbonate; all of the samples contain large crystals of pyrite that have been extensively altered to hematite, and a few contain porphyroclasts of plagioclase that have undergone partial dynamic recrystallization and subsequent brittle fracturing. The alteration zone is more prominently developed beneath a klippe of Brenner Mesozoic marbles on the summit of the Weißspitze, 5 km east of the town of Gossensass (Figs 1 and 5a). At this locality, the hanging wall marbles are directly juxtaposed against graphitic schists of the Upper Schieferhülle. Within a 50-meter thick zone beneath the fault, the USH is transformed from a biotite-phengite-graphite ± carbonate ± pyrite schist containing small, concordant quartz pods into a strongly lineated chlorite-phengite-carbonate schist that lacks graphite and contains both concordant and discordant quartz + carbonate pods (Fig. 5b). Many of the pods in this latter zone contain early pyrite that has been extensively altered to hematite. The lower boundary of the altered zone is parallel to the fault surface and is discordant with respect to lithologic variations and folds within the USH.

Permissible reactions between the graphitic USH and the rocks within the altered zone imply that the zone was infiltrated by aqueous fluids that became progressively more oxidizing as the alteration progressed: transformation of biotite to chlorite required a large influx of water, and the change from graphite- and pyrite bearing assemblages to carbonate- and hematite-bearing assemblages required an increase in f_{O_2} of ~3 log units (ARNASON and SELVERSTONE, 1988).

The localized nature of the alteration zone beneath the hanging wall suggests that fluid channeling along the fault zone accompanied movement along the Brenner Line. Density data from fluid inclusions in quartz knots within the altered zone imply a somewhat more complex scenario, however. Four generations of fluid inclusions occur in the quartz + carbonate pods in the altered zone (ARNASON and SELVERSTONE, 1988; AXEN et al., 1992; SELVERSTONE, unpublished data). The oldest contain brines with 3–5 wt% NaCl equivalent and daughter crystals of pyrite; owing to the presence of the pyrite daughters, it is not possible to construct isochores for these inclusions. The first generation (Type 1) for which isochores can be constructed is composed

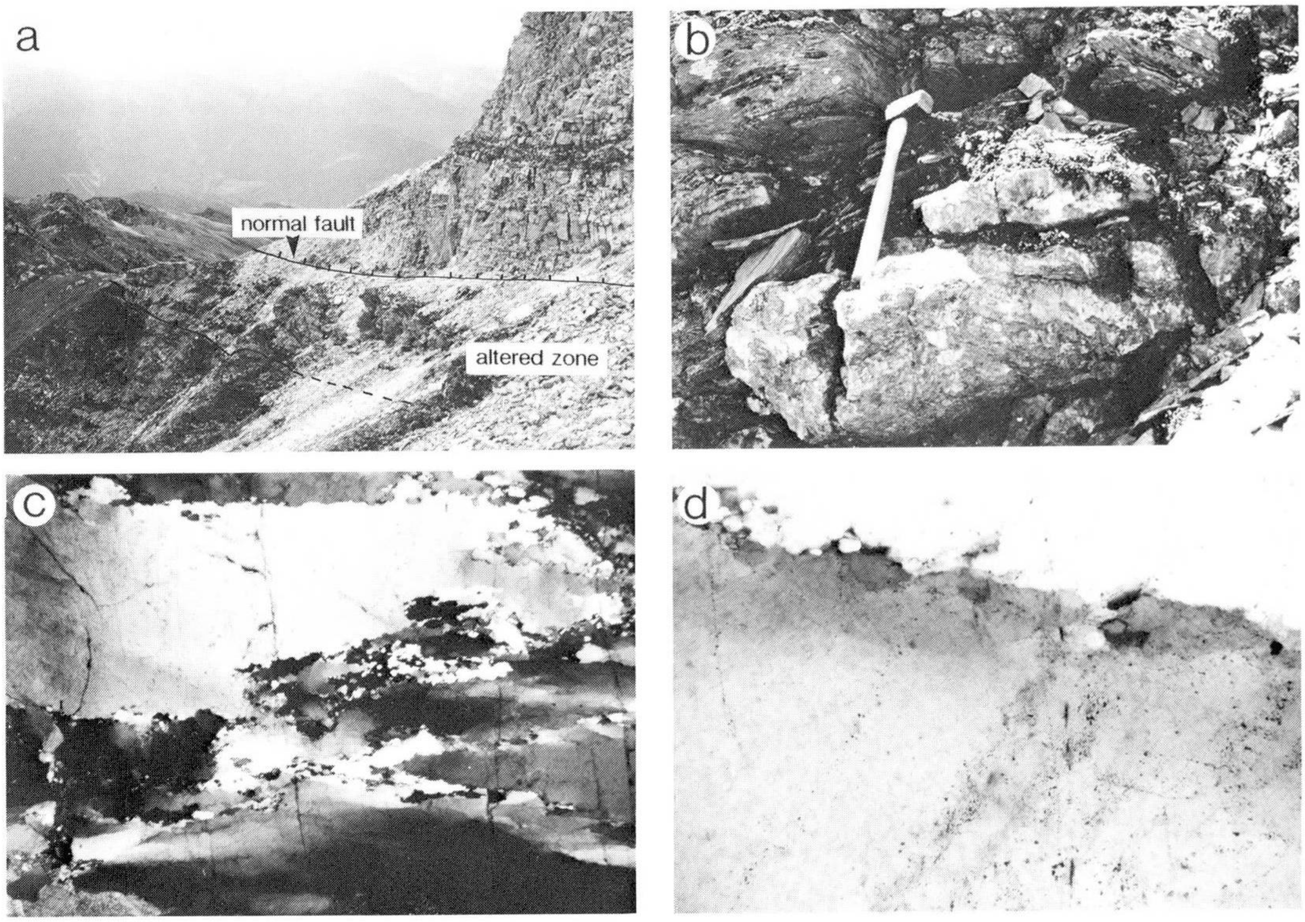

Fig. 5 (a) Klippe of Brenner Mesozoic member of Austroalpine nappes juxtaposed against the USH on the summit of the Weißspitze. Altered zone of graphite-free USH underlies the normal fault. (b) Typical quartz + carbonate lens in the USH alteration zone. (c) Photomicrograph showing ductilely deformed quartz in lens similar to that in (b); note brittle fractures and late fluid inclusion bands (Type 3) that crosscut all quartz grain boundaries. Long dimension is 8 mm. (d) Photomicrograph showing type 2 fluid inclusion planes that terminate at quartz grain boundary and type 3 inclusion plane that crosscuts boundary. Long dimension is 2 mm.

of H_2O–CO_2 ± CH_4 ± NaCl fluids for which bulk homogenization occurs at ~300 °C. These inclusions are typically isolated in grain interiors. The next generation is similar in composition to type 1, but has lower density and occurs on healed fractures that are typically truncated by quartz grain boundaries (Fig. 5d). The youngest inclusions, type 3, are composed of low-salinity brines and occur on healed fractures that parallel late brittle fractures and crosscut all quartz boundaries (Figs 5 c and d); macroscopic observations show that brittle fractures with the same orientation also occur in the hanging wall at this locality, suggesting that type 3 inclusions postdate juxtaposition of the units along the Brenner Line.

Isochore ranges for each of these fluid inclusion types are shown in figure 6, from which it can be seen that type 1 inclusions were trapped at pressures of at least 3.5 kbar and possibly as high as 5 kbar. These pressures correspond to burial to depths of ~12–17 km. The sharp fault contact evident at this locality, coupled with the brittle fabric overprint on a thick zone of ductile mylonites with the same sense of shear, suggests that the fault as presently exposed became localized while the rocks were in the brittle regime, but that there had been a lengthy history of ductile shearing prior to this localization. Type 1 fluid inclusions are in pods found only in the alteration zone and have compositions that may reflect removal of graphite by the reaction 2 C + 2 H_2O = CH_4 + CO_2. The textural occurrence of these inclusions and their minimum trapping temperatures indicate that these inclusions were entrapped while quartz was still behaving ductilely. These inclusions, and hence also the alteration zone, thus

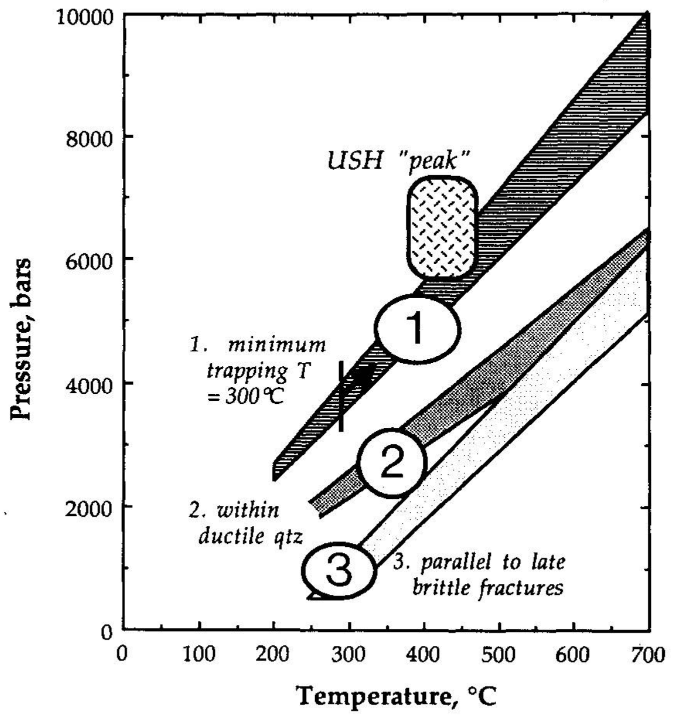

Fig. 6 Pressure-temperature diagram showing isochore ranges for fluid inclusion types 1, 2, and 3. Type 1 inclusions show bulk homogenization at ~300 °C, so must have been entrapped at higher temperature. Type 2 inclusions are on healed fractures that terminate at grain boundaries of ductilely deformed quartz. Type 3 inclusions are on late brittle fractures that crosscut all grain boundaries.

predate the brittle faulting and may represent localized fluid infiltration during distributed ductile normal shearing at depth.

One interesting possibility is that fluid infiltration at mid-crustal levels preceded and in fact aided the subsequent localization of the Brenner Line in the brittle regime. As suggested by AXEN (1992), generation of a localized zone of high pore pressure can result in modification of the local stress field and initiation of low-angle normal faulting. Formation of ductile mylonites during regional top-to-the-west motion could have resulted in anisotropic permeability that would have channelized fluids parallel to the shear planes at mid-crustal levels (see review in AXEN, 1992). Such a zone could evolve into a brittle detachment either up-dip or during unroofing of the mid-crustal zone. Thus, in this case, the metamorphic alteration of the ductile mylonites could have subsequently localized the deformation along what is now the Brenner Line normal fault during unroofing. If this is the case, the alteration zone beneath the Weißspitze klippe would at least in part predate the Brenner Line fault. The Brenner Line itself would have become the active fault system at some depth intermediate between the isochores for fluid inclusion types 1 and 3 (Fig. 6).

Conclusions

The examples described above illustrate some of the complex interactions that occur between deformational and metamorphic processes at a variety of scales and crustal levels. In some cases, such as development of the garbenschiefer, the metamorphic features of the rocks appear to be a direct response to the deformational processes. In other cases, such as the Stillup Tal and Brenner Line shear zone samples, there appears to have been a feedback between strain localization and metamorphism, with initial strain heterogeneities resulting in fluid channeling and metamorphic recrystallization that served to further localize strain in the same zones. In all cases, the rocks are sensitive monitors of deformational processes throughout a prolonged history of continental collision and tectonic unroofing. By selectively correlating the metamorphic and deformational features, it is possible to establish the depths and temperatures at which different processes were operative, and hence to gain a better understanding of crustal rheologies and metamorphic response during orogenic events.

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