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Tectonophysics 316 (2000) 327–342

TECTONOPHYSICS

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Microstructural and textural development of calcite marbles during polyphase deformation of Penninic units within the Tauern Window (Eastern Alps)

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Received 11 March 1999; accepted for publication 22 September 1999

Abstract

The evolution of calcite microstructures and crystallographic preferred orientations (CPOs) is well understood due to well constrained experimental studies. However, the interpretation of naturally deformed calcite marbles is more difficult because of less constrained strain paths, a multiphase deformation history, and variable *P–T* conditions. The Penninic units within the Tauern Window (Eastern Alps) have been affected by several deformation events and metamorphic overprint. Generally, three major deformational events can be distinguished. D_1 is related to underthrusting of Penninic units beneath the Austroalpine nappe complex, and top-to-the-N nappe stacking within the Penninic continental units. Deformation stage D_2 is interpreted as reflecting the subsequent continent collision between the Penninic continental units and the European foreland. D_3 is related to the formation of the dome structure of the Tauern Window. This polyphase deformation history can be partly reconstructed by the evolution of calcite microfabrics and CPOs.

Three types of calcite-fabrics are distinguished within the Penninic units of the Tauern Window and the Lower Austroalpine unit. D_1-fabrics are characterized by equilibrated microstructures and LT-CPOs. The CPOs are generally strong and symmetric, with one well developed cluster near the *Z*-axis of the finite strain ellipsoid. These fabrics have locally been overprinted by subsequent amphibolite to greenschist facies metamorphism. Generally, the occurrence of LT-fabrics coincides with the occurrence of amphibolite facies metamorphic mineral assemblages in the central part of the Tauern Window, while HT-fabrics have been observed outside this area. Fabrics from the central part of the Tauern Window have likely been strengthened during subsequent thermal equilibration, while the fabrics that have been observed at the peripheral parts have been less affected by subsequent metamorphic overprint. Therefore, D_1-fabrics do not reflect D_1 conditions, but subsequent thermal equilibration. Similar observations have been made for the evolution of D_2-fabrics. LT-fabrics dominate inside the amphibolite facies isograde, HT-fabrics occur outside (greenschist facies metamorphic conditions). The fabrics are characterized by high finite strains near the margins of the Tauern Window, the intensity of which decreases towards the central parts, where microstructures are characterized by recrystallization and thermal equilibration due to amphibolite facies metamorphic overprint. The strong CPOs document this influence. The HT-fabrics and microstructures within peripheral areas indicate that they have less been affected by this thermal event, and, therefore, are more indicative for the deformational conditions during D_2. D_3 is restricted to distinct shear zones along the tectonic boundaries of the Tauern Window. From the central parts to the

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PII: S0040-1951(99)00257-7

shear zone boundaries, a clear evolution of microfabrics can be observed. In internal parts, microstructures are characteristic for intracrystalline plasticity with a dominating activity of r^--glide. Twinning was less important during the final phases of deformation. On approaching the shear zone boundaries, the grain size decreases due to dynamic recrystallization and secondary grain size reduction until ultramylonites are formed. Within these domains grain boundary sliding seems to have been dominant.

In conclusion, calcite CPOs from polyphase areas do not only include information on the deformation conditions, but also bear information about the thermal overprint subsequent to the main deformational event.

Keywords: calcite; crystallographic preferred orientations (CPOs); Eastern Alps; microstructures; polyphase deformation; Tauern Window

1. Introduction

The evolution of textures and crystallographic preferred orientations (CPOs) of calcite is well constrained by experimental studies (e.g., Dietrich and Song, 1984; Schmid, 1982; Schmid et al., 1987; Wenk et al., 1987; Tome et al., 1991; Burkhard,1993; De Bresser and Spiers, 1997; and references cited therein). Wenk et al. (1987) distinguished between low-temperature (LT) and high-temperature (HT) CPOs. LT-fabrics are characterized by single maxima near the *Z*-axis of the finite strain ellipsoid and HT-fabrics form two small maxima with the tendency to be distributed along a small circle centred on *Z* and a great circle at small angles to the *Y*–*Z*-plane. The interpretation of naturally deformed calcite marbles is difficult because of under-constrained strain paths, multiphase deformation history and variable *P*–*T* conditions. Calcite fabrics generally reflect the final phases of crustal deformation at decreasing temperatures (e.g., Burkhard, 1993). As calcite is an important rock-forming mineral, the investigation of its microstructures and CPOs give important information on the deformation mechanisms within the crust.

Underthrust continental crust is often exposed within tectonic windows in internal zones of collisional orogens. Generally, underthrust crust will be exhumed during the final stages of continent–continent collision, in an extensional regime (e.g., Platt, 1986, 1993; Dewey, 1988), and exposed as metamorphic domes within the internal zones of collisional orogens (Selverstone, 1988; Genser and Neubauer, 1989). Removal of hanging-wall crust is achieved by detachment along ductile low-angle normal faults along the margins of such dome structures. Consequently, deformational structures in the inner parts of exhumed domes often document the evolution that was related to the underthrust history. Microstructural studies combined with the evaluation of CPOs are important tools in obtaining information on the deformation mechanisms operating in naturally deformed rocks. Due to the plastic behaviour of calcite at rather low-temperature conditions (e.g., Wenk, 1985), data on the microstructural evolution of calcite are very useful for the documentation of the final phases of an orogenic event. This study presents data on calcite microstructures in the Tauern Window (Eastern Alps), which have been affected by a polyphase deformation and metamorphic history.

2. Geological setting

The Tauern Window exposes the Penninic nappe complex in the footwall of the Austroalpine nappe complex (Fig. 1). The Austroalpine nappe complex formed the hanging-wall plate during Late Cretaceous and Early Tertiary continent–continent collision in the Alps. The Penninic nappe-stack includes both passive and active continental margin sequences (Kurz et al., 1998b), which have been deposited on continental basement units and ophiolitic sequences. From bottom to top the following tectonic units are distinguished (Tollmann, 1975, 1977; Frank et al., 1987; Kurz et al., 1996, 1998b) (Fig. 1b and c):

1. The Venediger and Wolfendorn Nappes (Frisch, 1974, 1975), which comprise a pre-Variscan

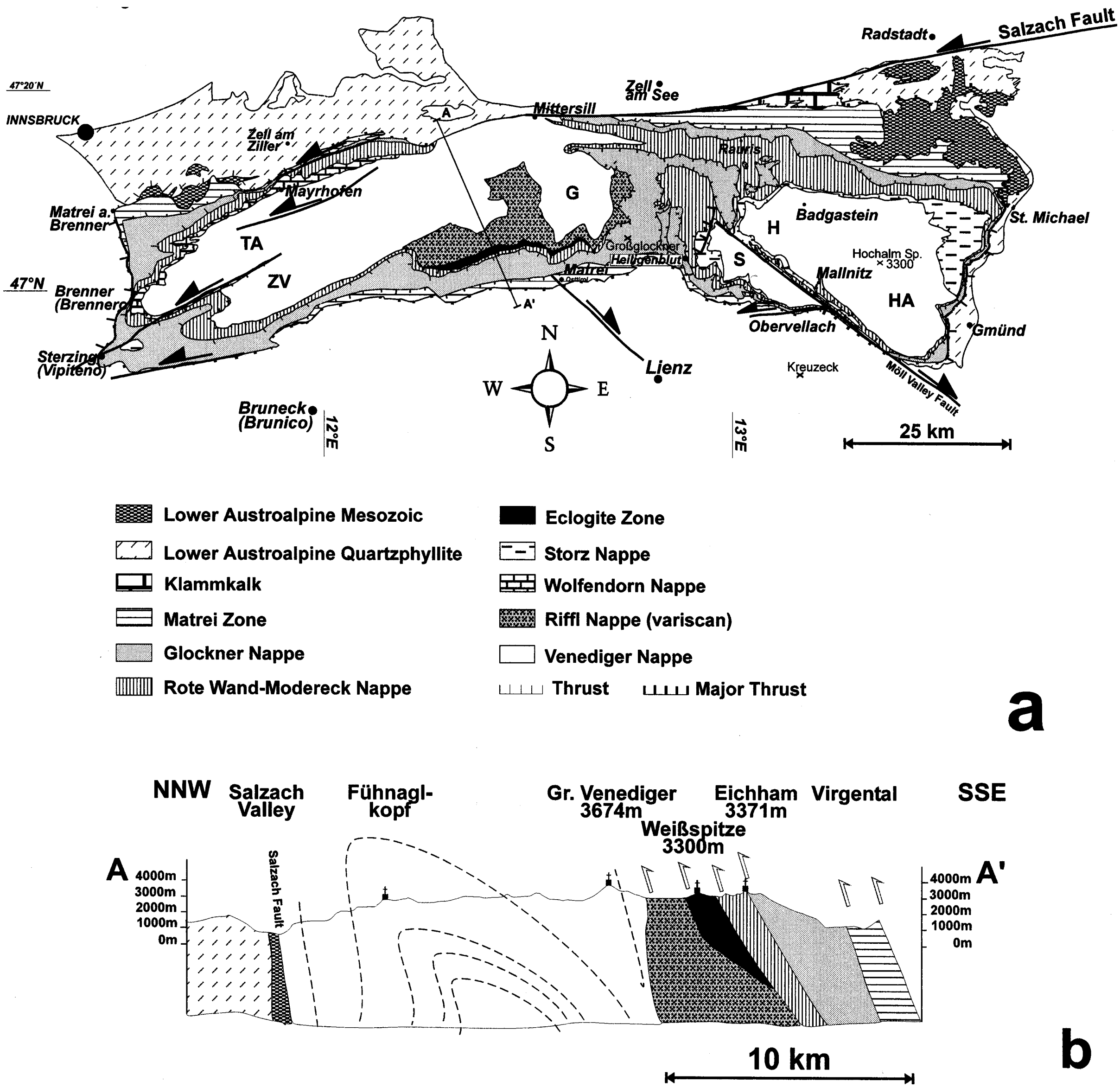

Fig. 1. (a) Tectonic sketch map of the Tauern Window; S, Sonnblick Dome; HA, Hochalm–Ankogel Dome; H, Hölltor–Rotgülden Dome; G, Granatspitz Dome; ZV, Zillertal–Venediger Domes; TA, Tux–Ahorn Domes; A–A′, location of cross-section in (b) (after Kurz et al., 1998b). (b) Section across the central part of the Tauern Window [for location see (a)].

basement (e.g., the Riffl Nappe) intruded by Variscan granitoids (the Zentralgneis), and Jurassic to Cretaceous cover sequences;

2. The Storz Nappe comprising Variscan and Alpidic polymetamorphic basement rocks covered by late Paleozoic (?) or Cretaceous (?) metapelites and graphitic quartzites (Murtörl Group);
3. The Eclogite Zone, restricted to the central southern Tauern Window, characterized by a Mesozoic volcano-sedimentary sequence of a distal continental slope;

4. The Rote Wand–Modereck Nappe, formed of basement rocks, covered by Permian to Triassic quartzites and Triassic metacarbonates, Jurassic breccias, calcareous micaschists and metatuffs, and Cretaceous metapelites and metapsammites. All these units were part of the southern margin of the Penninic continental unit prior to collision with the Austroalpine unit.
5. The Glockner Nappe, comprising a former oceanic basement (serpentinites and other ultramafic rocks), and an incomplete ophiolitic sequence, containing micaceous marbles and calcareous micaschists;
6. The Matrei Zone, including the Klammkalk unit, which represents an accretionary wedge (Frisch et al., 1987).

These Penninic units are surrounded by Austroalpine units, all together affected by Cenozoic amphibolite to greenschist grade metamorphism subsequent to nappe stacking. The metamorphic grade decreases continuously from the central to the peripheral parts of the Tauern Window.

The Tauern Window is bordered along its northern and southern margins by sinistral strike–slip faults, linked with several major dextral faults (Ratschbacher et al., 1991a; Kurz et al., 1994; Wang and Neubauer, 1998), and by low-angle normal faults along its eastern and western margins (Selverstone, 1988; Behrmann, 1988, 1990) (Fig. 1). The arrangement of these major faults was interpreted in terms of a pull-apart structure, which triggered unroofing and subsequent exhumation and uplift of underplated lithosphere in the area of the Tauern Window (Genser and Neubauer, 1989).

Generally, three major phases of deformation (D_1, D_2, D_3) are distinguished (Bickle and Hawkesworth, 1978; Droop, 1981; Lammerer, 1988; Behrmann, 1990; Genser, 1992; Kurz et al., 1996, 1998a, b). D_1 is related to the top-to-the-N emplacement of several nappes, which resulted in the development of a first foliation (S_1), and a N-trending stretching lineation (L_1). D_2 is characterized by the development of a second foliation S_2, and a W- to NW-trending stretching lineation L_2. D_2 is related to the emplacement of the Penninic nappe stack onto the European foreland. Especially the western and southeastern parts of the Tauern Window have been pervasively affected by D_2; within the central part of the Tauern Window, D_1 fabrics have been preserved. D_1 and D_2 are separated by a phase of lower amphibolite to greenschist facies metamorphism ('Tauern Crystallization'), which was related to the thermal equilibration subsequent to the subduction of the Penninic unit and collision with the Austroalpine unit. Locally, D_2 was contemporaneous with this metamorphism phase. D_3 is related to the formation of the dome structure of the Tauern Window. This D_3 phase is characterized by the interference of multiply developed structures, and by deformation partitioning and shear localization along the dome margins (Behrmann and Frisch, 1990; Kurz and Neubauer, 1996), where a new foliation S_3, associated with a stretching lineation L_3, was developed. The exhumation history of the Penninic units (Fig. 1) is constrained by petrological and geochronological (Cliff et al., 1985; Droop, 1985; Selverstone, 1985, 1988, 1993; Christensen et al., 1994), and by structural data (Behrmann, 1988; Genser and Neubauer, 1989; Kurz and Neubauer, 1996; Selverstone, 1988). Although modern microstructural studies combined with the investigation of CPOs exist for many areas within the Tauern Window, these data have only been used for kinematic interpretations in terms of shear criteria (e.g., Behrmann and Ratschbacher, 1989; Behrmann, 1990; Behrmann and Frisch, 1990; Wallis et al., 1993; Wallis and Behrmann, 1996). However, these data only exist for limited areas. In order to constrain the deformational behaviour of several units during distinct phases of deformation, and to constrain the relation between deformation and metamorphism, representative examples of calcite microfabrics and CPOs have been chosen for this presentation. The entire set of data will be published separately (Kurz et al., in press).

3. Methods

In this section we discuss the evolution of calcite microstructures and CPOs along several structural sections across the Tauern Window. The representative samples have been chosen from areas where the distinction between D_1, D_2, and D_3 is clear. X-ray texture analyses of calcite-mylonites were carried out with a Siemens D500 X-ray texture goniometer at the University of Graz (Austria). We derived incomplete pole figures of $<f>[102]$, $<r>[104]$,

<*a*>[110], [113], [202], and [116]. <*c*>[006] pole figures are difficult to be measured directly. Therefore, Orientation Distribution Functions (ODFs) have been calculated from the X-ray pole figures. <*c*>[001], <*m*>[100], [101] and [011] have been recalculated from the ODF. The evaluation of pole figures and recalculation was done with the program TEXAT v. 2.2c/ODF AT v.1.1a provided by Siemens Co. (Harmonic Method, Bunge, 1981, 1985; Bunge and Esling, 1985), and with the program MENTEX (Vector Method, Schaeben et al., 1985; Schaeben, 1994). Both program packages include corrections for background and beam defocusing. Several packages use Bravais crystallographic indices for the description of crystallographic directions, leaving the index {*i*} of the {*hkil*} notation. Optical CPOs were measured with standard universal stage methods.

4. D_1 microstructures

The central part of the Tauern Window has generally not been affected by D_2. Therefore, microstructures and CPOs developed during or subsequently to D_1 are well preserved. The microstructures of calcite marbles are very similar within all tectonostratigraphic units. Calcite is characterized by the formation of isometric, polygon-shaped grains ca. 0.5 mm in size (Fig. 2a). These grains mainly show straight grain boundaries, rarely slighty serrated grain boundaries. The grains contain e-twins, in particular in coarse-grained rocks (Fig. 2a) with a grain size of up to 1 mm. Most twins show moderately thick to thin straight lamellae with straight boundaries, similar to the geometric types I and II described by Burkhard (1993). Within the distinct domains thick patchy twins with sutured boundaries, similar to type IV, occur. The majority of grains displays two sets of conjugate e-twins (Fig. 2a), both oblique to the S_1 foliation traced by layers of white mica. The geometrical arrangement of these twins is related to a simple shear component indicating a top-to-the-N sense of shear. Most of the calcite marbles are intercalated with dolomite marbles on a centimetre, decimetre and metre scale. Dolomite marbles occur as fine-grained rocks with a uniform grain size that does generally not exceed 0.2 mm (Fig. 2b). The grains are slightly elongated subparallel to the S_1 foliation ($R_f = 1.5$–2.0; R_f defines the ratio between the long and short axis of single grains in the *X*–*Z*-section). The grain boundaries are generally straight and meet in triple junctions, whereas the serrate grain boundaries are less developed. Few grains are twinned, but these grains show only one set of twins. Only within the Matrei Zone along the northern margin of the Tauern Window dolomite marbles occur as massive, coarse-grained dolomites without internal foliation.

Locally, especially in the southeastern and eastern parts of the Tauern Window, coarse, isometric or slightly elongated calcite grains with a size of up to 0.5 mm, show serrated grain boundaries and the development of polysynthetic twin lamellae. These grains are surrounded by dynamically recrystallized grains with a size of ca. 0.2 mm (Fig. 2c), which indicates a different deformation–recrystallization mechanism.

5. D_1 crystallographic preferred orientations

Calcite CPOs related to D_1 are generally characterized by LT-fabrics (Fig. 3). The *c*-axes [001] form clusters near the *Z*-axis of the finite strain ellipsoid (Fig. 2a). In places, these clusters are asymmetrically arranged; the fabric asymmetry documents top-to-the-N sense of shear. Within calcite-dolomite marbles, the calcite *c*-axes form single girdle distributions within the *Y*–*Z*-plane (Fig. 2b). However, this might be interpreted in terms of an effect of a second phase, for example, deformation partitioning between calcite and dolomite. In the central southern part of the Tauern Window, the *c*-axis distributions are characterized by HT-fabrics (Fig. 3). The *a*-axes [110] and the poles to the prism planes [100], as well as the poles to the rhombs [101] [011], form a girdle within the *X*–*Y*-plane; in places, this girdle is oblique to the foliation plane; the angle of the fabric asymmetry is 1–10°.

6. D_2 microstructures

D_2-related calcite microstructures are very homogeneous within the Penninic units over the

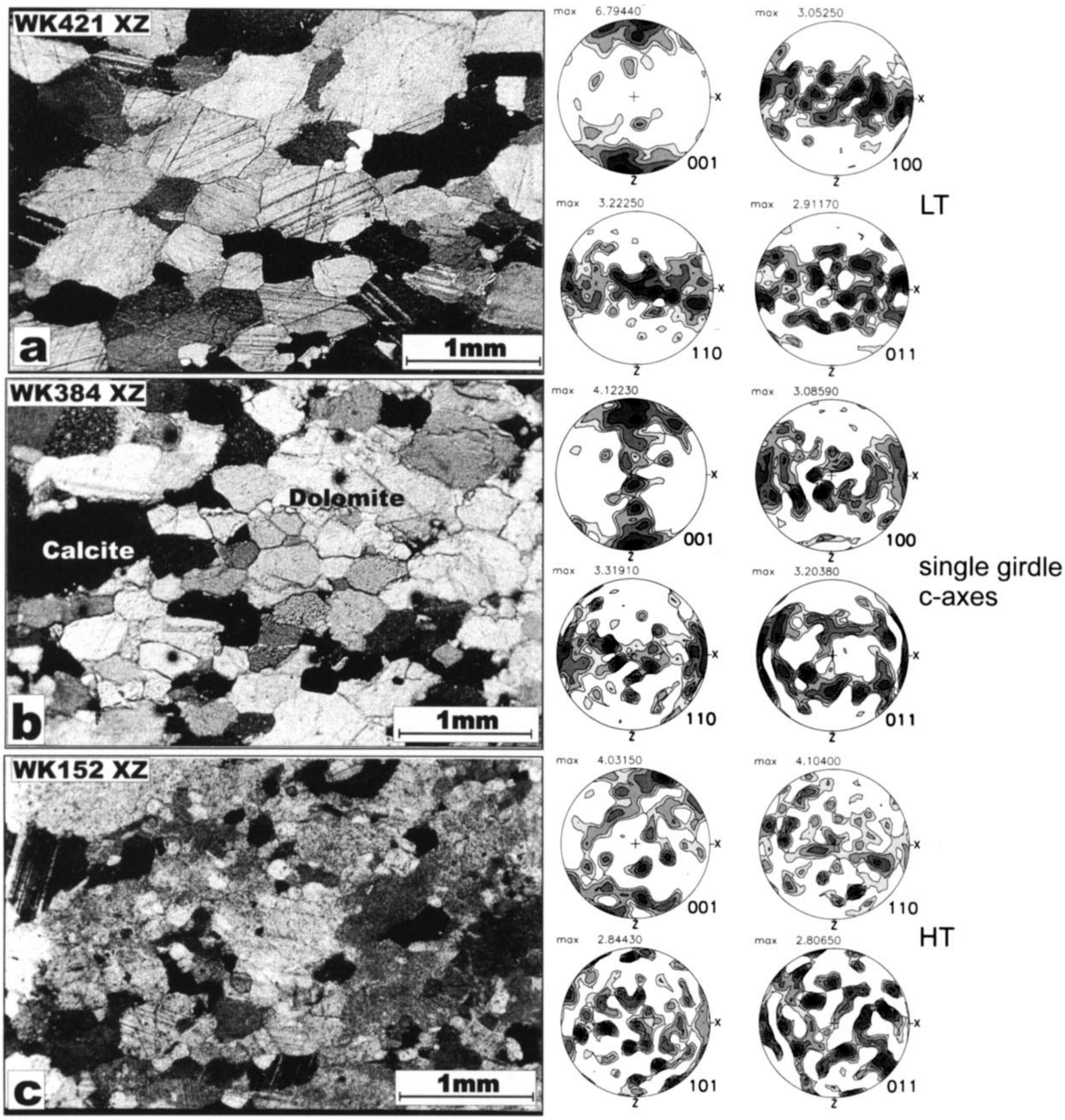

Fig. 2. D_1-related calcite microstructures and textures. (a) Slightly elongated grains, Rote Wand–Modereck Nappe, central Tauern Window; LT-*c*-axes distributions. (b) Calcite–dolomite marble, Rote Wand–Modereck Nappe, central Tauern Window; single girdle distribution of the *c*-axes. (c) Dynamically recrystallized grains along the grain boundaries of coarse calcite. X-ray textures (equal angle projections; logarithmic gradation of isolines; first isoline: uniform distribution; fifth isoline: 85% of maximum).

entire Tauern Window. Calcite grains are strongly elongated (R_f ca. 5–8), and form a shape-preferred orientation either parallel, or oblique to the S_2 foliation plane (Fig. 4). The mesoscopically high-strain appearance is reflected by the elongation of the grains. Therefore, the macroscopic shear plane

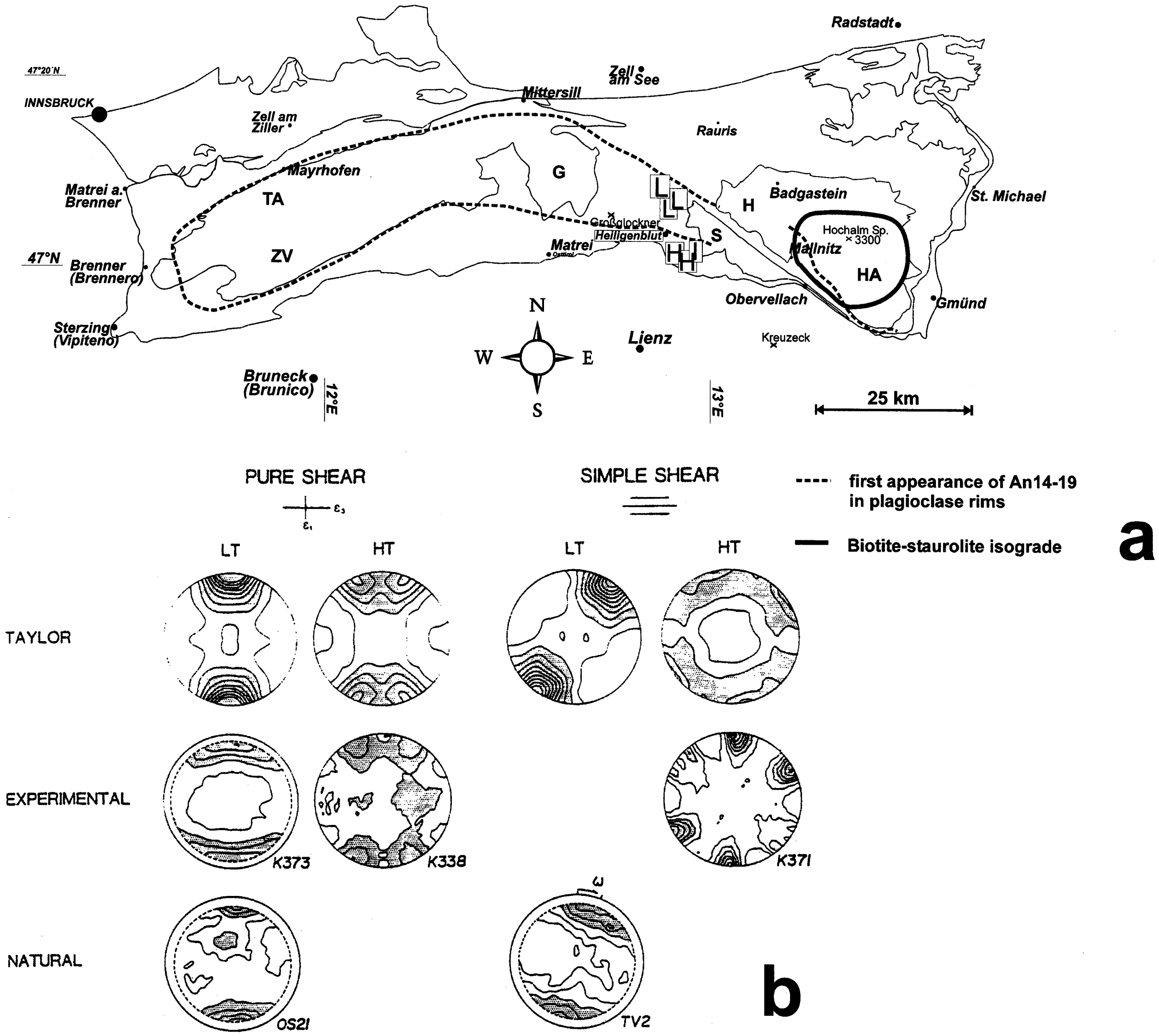

Fig. 3. (a) Simplified tectonic map of the Tauern Window (for explanation see Fig. 1a) displaying the distribution of D_1-related CPOs. L, LT-fabrics; H, HT-fabrics; I, single girdle distributions. (b) Classification of LT- and HT-fabrics (from Wenk et al., 1987).

is assumed to be in close coincidence with the mesoscopic foliation. In single domains the grains define a plane of mean elongation which is slightly inclined (10–15°) to the mesoscopic foliation. However, the elongation of the calcite grains is stronger near the margins of the Tauern Window (R_f 5–8; Fig. 4a) than within the central parts (R_f 1–3; Fig. 4b). In the peripheral parts of the Tauern Window the calcite grains show either straight, or slightly sutured boundaries. In the central parts, the grain boundaries commonly meet in triple junctions. Grain size is variable and strongly depends on the presence of additional mineral phases, especially white mica and graphite, that take influence on the size of recrystallized grains. The average grain size of pure marble mylonites is 0.5–1 mm. Generally, the grain size increases towards the inner parts, according to the general trend of increasing metamorphic grade. In the central parts the grain size reaches up to 1.5 mm,

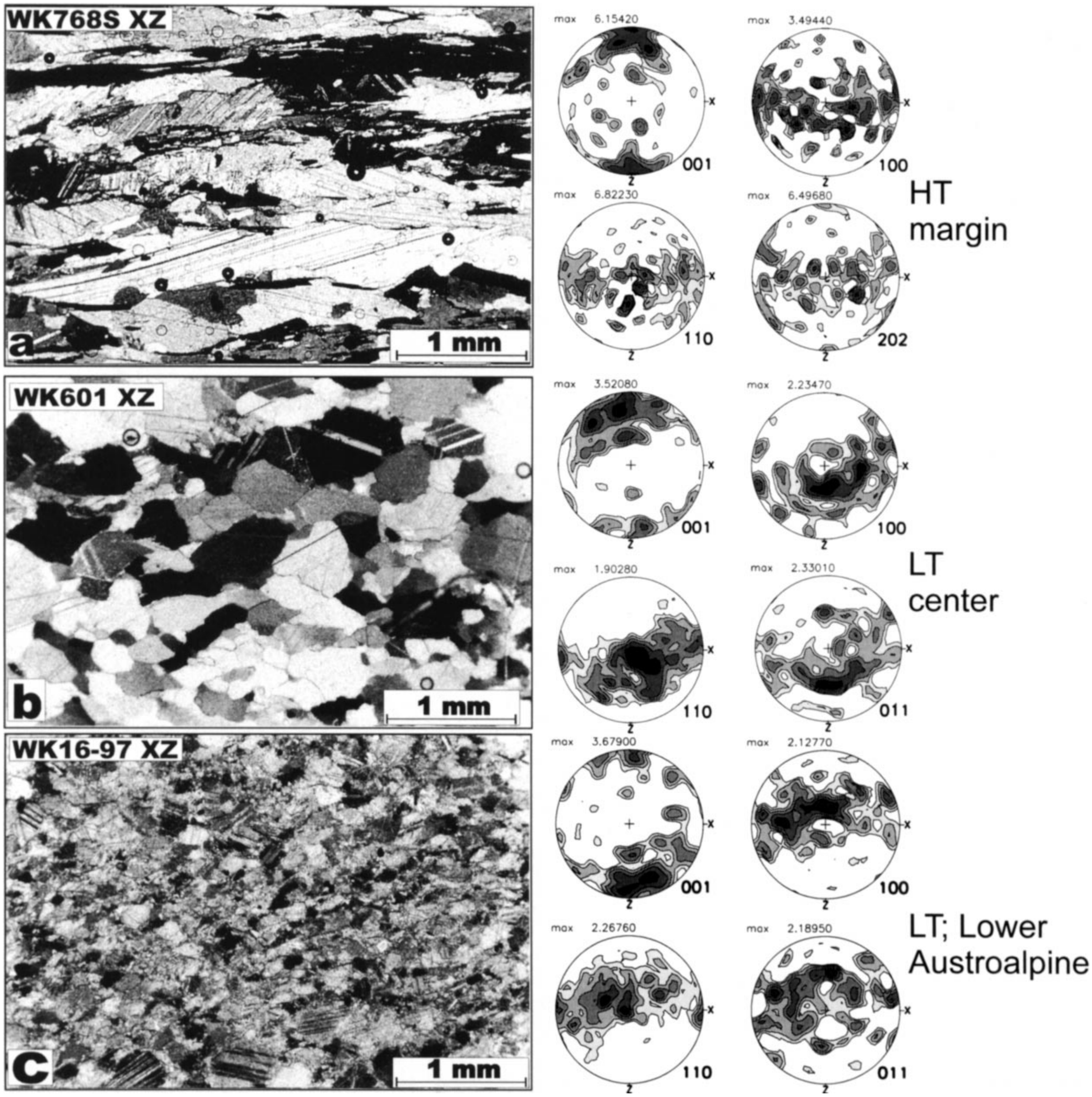

Fig. 4. D_2-related calcite microstructures and textures. (a) Highly elongated calcite grains with lobate grain boundaries, Glockner Nappe, southwestern Tauern Window; HT-fabrics with two maxima. (b) Slightly elongated calcite grains, Wolfendorn Nappe, northwestern Tauern Window; LT fabrics. (c) Dynamically recrystallized grains surrounding coarse grains, Lower Austroalpine unit, northeastern Tauern Window; LT-fabrics.

in the peripheral parts 0.5 mm at maximum. The calcite grains show multiple sets of twins; however one set of e-twins, generally oriented subparallel to the S_2 foliation plane, dominates, especially along the margins of the Tauern Window. Most calcite twins show moderately thick to thick twins and straight lamellae, similar to the geometric types I and II described by Burkhard (1993). In general, twin widths are larger near the margins of the Tauern Window and decrease towards the

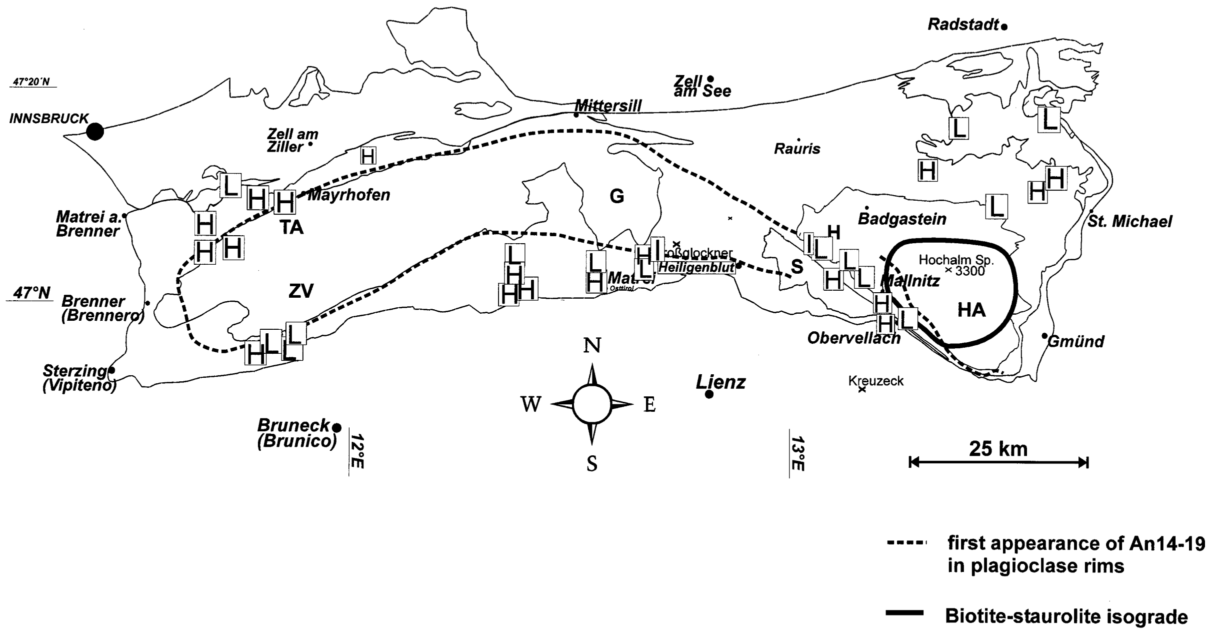

Fig. 5. Simplified tectonic map of the Tauern Window (for explanation see Fig. 1), displaying the distribution of D_2-related calcite microstructures and CPOs. L, LT-fabrics; H, HT-fabrics; I, single girdle distributions.

central parts, from 0.02 to 0.1 mm. In most cases, the grains are not twinned in the innermost parts of the Tauern Window. Within the Lower Austroalpine unit of the northeastern Tauern Window calcite forms dynamically recrystallized grains with a maximum size of 0.1 mm, that are surrounding coarse grains a maximum of 0.5 mm in size (Fig. 4c). These grains may show multiple sets of twins.

7. D_2 crystallographic preferred orientations

D_2-related CPOs are similar over the entire Tauern Window, and within several tectonostratigraphic units (Figs. 4 and 5). *c*-axes distributions that are typical for HT-fabrics along the margins of the Tauern Window, and by LT fabrics in the central parts. The HT-fabrics generally show two maxima near *Z* with the tendency to be distributed along single girdles near the *Y*–*Z*-plane of the finite strain ellipsoid. One maximum is centred near the *Z*-axis, two maxima are situated between the *Y*- and *Z*-axis of the finite strain ellipsoid. The *a*-axes [110] and the poles to the prism planes [100] are distributed along a girdle within the *X*–*Y*-plane, with one maximum near the *Y*-axis. The poles to the rhombs [202] plot along girdles subparallel to the *X*–*Y*-plane, too. The LT-fabrics form clusters near *Z*. The CPOs are commonly characterized by rather symmetric fabrics. Only in distinct domains, they are asymmetrically arranged; however, the fabric asymmetry reaches 5° at maximum and documents a top-to-the W sense of shear. The *a*-axes [110] and the poles to the prism planes [100] are distributed along a girdle within the *X*–*Y*-plane, with one maximum near the *Y*-axis. Within the Lower Austroalpine unit the calcite *c*-axes [001] form well defined clusters near *Z*. The *a*-axes [110] and the poles to the prism planes [100] are distributed along a girdle within the *X*–*Y*-plane, with one maximum near the *Y*-axis. The poles to the rhombs [101] [011] plot along girdles subparallel to the *X*–*Y*-plane, too. In the eastern part of the Tauern Window, twin-c-axis-pairs indicate an orientation of the maximum principal stress (σ_1) oblique to the S_2 foliation (Kurz and Neubauer, 1996).

However, these σ_1 directions are more asymmetric than the *c*-axis pole figures.

8. D_3 microstructures

In zones that are affected by low-angle normal and strike–slip faults bordering the Tauern Window, calcite displays uniform grain size between 0.3 and 1 mm. Within these shear zones a new S_3 foliation has been formed. Calcite is homogeneously twinned by single sets of e-twins that are oriented either subparallel or slightly oblique to the penetrative foliation (Fig. 6a). Most twins are thick (0.1–0.2 mm) and curved, and locally show features of polyphase twinning ('twins in twins'), similar to type III of Burkhard (1993). Such fabrics are typical for synmetamorphic intracrystalline deformation (r- and f-glide). Twins are often bent due to intracrystalline plasticity of calcite within micro-scale shear zones, while domains between conjugate sets of shear bands are less deformed (Fig. 6a). The grains show serrated and sutured, irregular boundaries; in places they are surrounded by fine recrystallized grains (<0.1 mm). Core-mantle textures are occasionally recognized. Twin-*c*-axis-pairs indicate an orientation of the maximum principal stress (σ_1) subparallel to the pole of the penetrative foliation (Kurz and Neubauer, 1996). The mesoscopically high-strain appearance is reflected by the elongation of the grains and by the rotation of initial twins into an orientation subparallel to the S_3 foliation. If twins would have formed during the last stages of deformation, the σ_1 orientation should be at 45° to the shear plane in simple shear, and coincide with the foliation normal in pure shear (Ratschbacher et al., 1991b). However, if twins form throughout the deformation history, old twins progressively rotate relative to the shear plane and σ_1 should be $<45°$ to the shear plane. Along the Salzach Fault, which forms the northern margin of the Tauern Window, the calcite grains are extremely elongated (R_f ca. 8–12). Generally, the elongated grains show a shape preferred orientation subparallel to the macroscopic foliation. These grains show only one set of e-twins that are subparallel to the foliation plane (Fig. 6b). Approaching the Austroalpine units around the Tauern Window, ultramylonites with optically indiscernible calcite grains are developed within the shear zones (Fig. 6c).

9. D_3 crystallographic preferred orientations

Calcite *c*-axes [001] fabrics from D_3-shear zones are characterized by clusters close to the *Z*-axis of the finite strain ellipsoid (Fig. 6). Locally, especially along the northern margin of the Tauern Window (Salzach–Ennstal fault, Fig. 7), *c*-axes distributions are typical for HT-fabrics. *c*-axes tend to form single girdles within the *Y*–*Z*-plane of the finite strain ellipsoid (Fig. 6b). One maximum is centred near the *Z*-axis, two maxima are situated between the *Y*- and the *Z*-axes. The *a*-axes [110] and the poles to the prism planes [100] are distributed along a girdle within the *X*–*Y*-plane, with one maximum near the *Y*-axis. The poles to the rhombs [101] [011] plot along girdles subparallel to the *X*–*Y*-plane. At a further distance from the main fault, LT-fabrics are developed. HT-fabrics dominate along the eastern margin of the Tauern Window. LT-fabrics dominate along the southern and southeastern margins of the Tauern Window (Fig. 6a and c). The asymmetry of the CPO-fabrics depends on the orientation of the shear zones bordering the Tauern Window. Along the northern margin of the Tauern window (Salzach fault), the asymmetry ranges from 5 to 20° (Fig. 7); this has also been been observed along the E–W-striking shear zones along the southern margin of the Tauern Window (Kurz and Neubauer, 1996; Fig. 7). Along the NW–SE striking Möll Valley Fault, the asymmetry ranges between 0 and 5° (Kurz and Neubauer, 1996; Fig. 7), which implies a higher pure shear component according to Wenk et al. (1987). These observations are consistent with a NNE to NE orientation of the maximum principle stress (σ_1): the higher the angle between σ_1 and the shear zone, the higher the pure shear component. Generally, CPOs from coarse-grained mylonites and ultramylonites do not differ significantly. Referring to Schmid (1983), the equant fine-grained ultramylonites should indicate a grain-boundary-dominated flow mechanism with a weak CPO. However, this is not supported by the

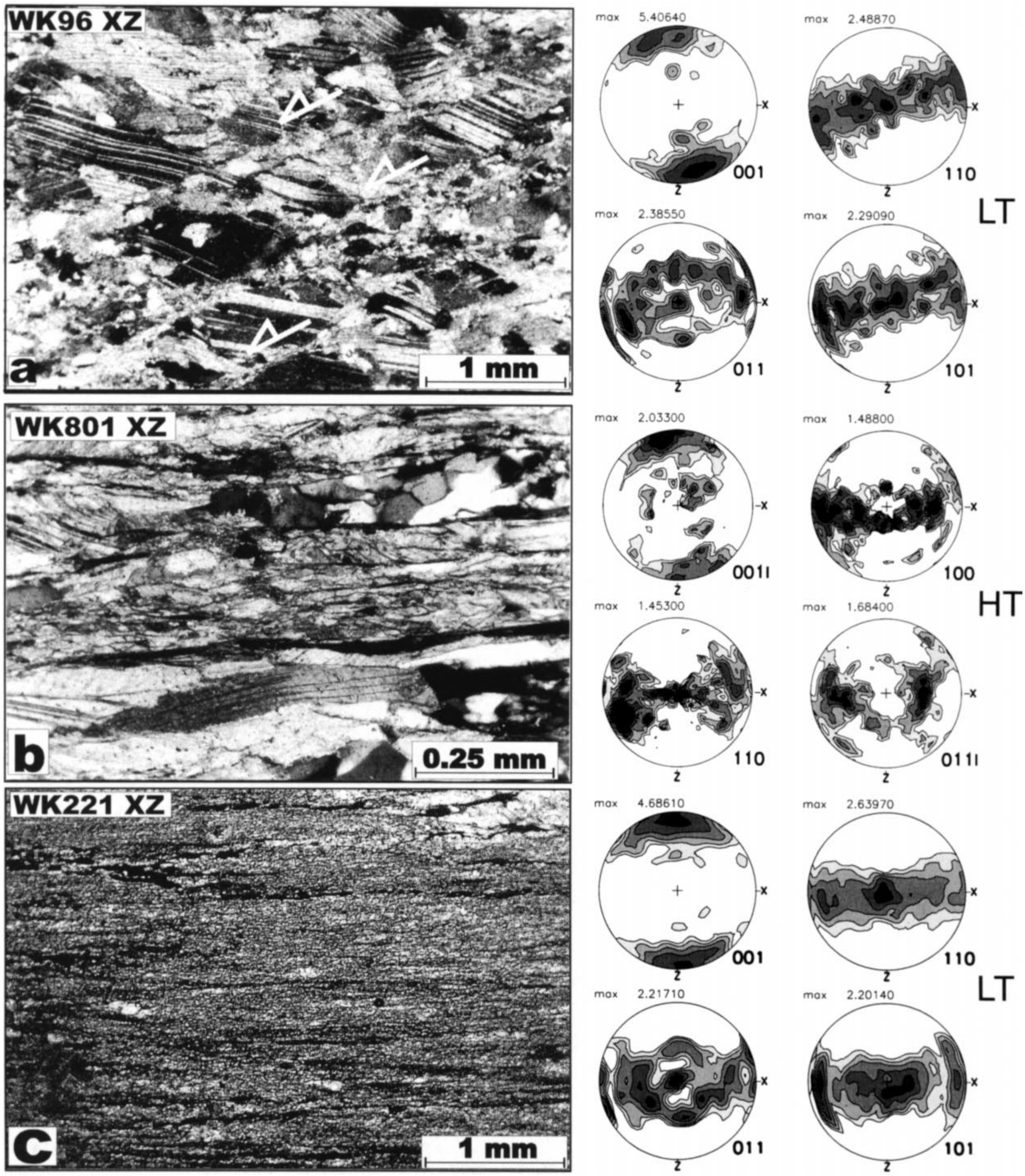

Fig. 6. D_3-related calcite microstructures and textures. (a) Dynamically recrystallized grains surrounding coarse grains, Moser Fault, southeastern Tauern Window; LT-fabrics. (b) Highly elongated calcite grains, Salzach Fault; HT fabrics. (c) Calcite ultramylonite, Möll Valley Fault, southeastern Tauern Window; LT-fabrics.

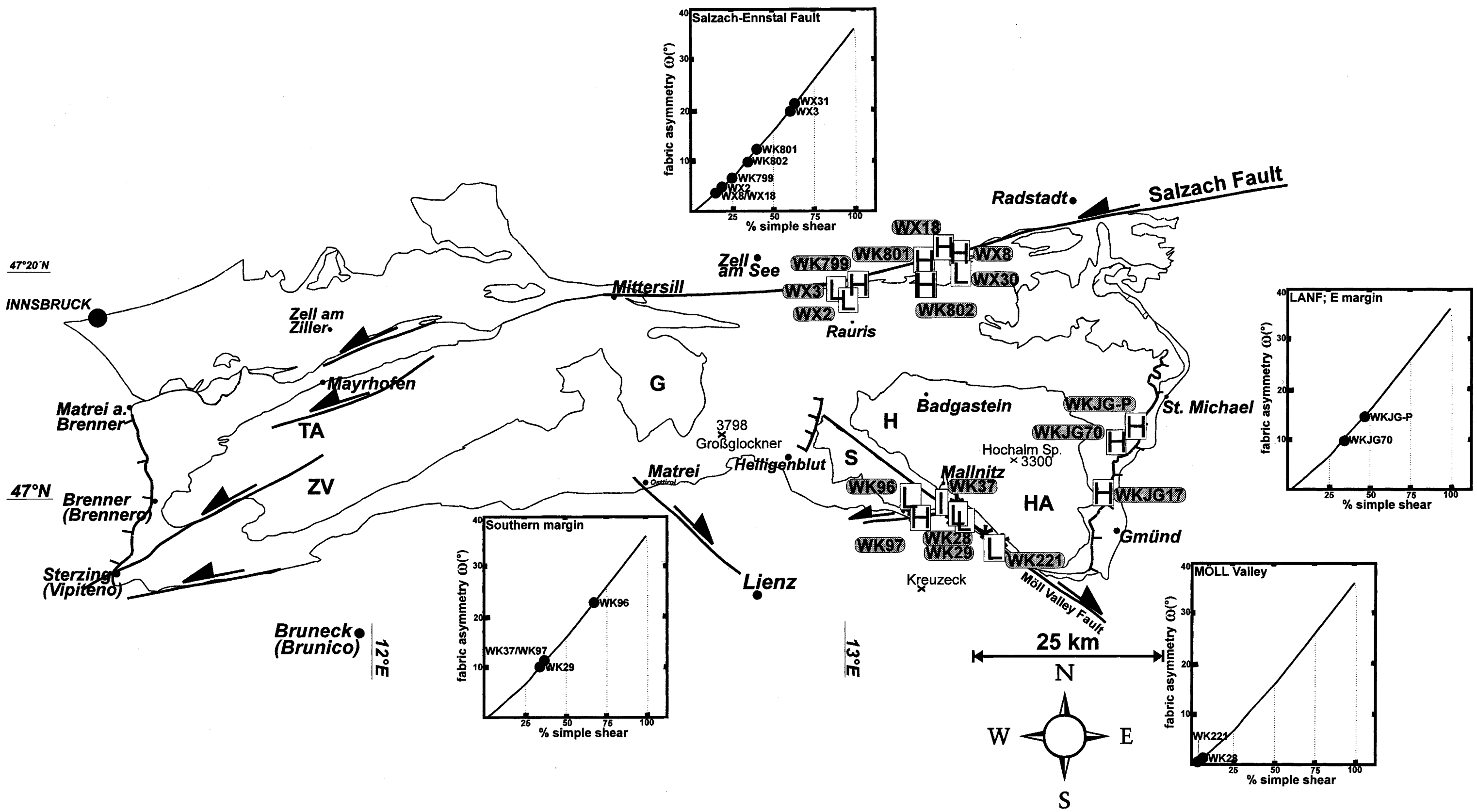

Fig. 7. Simplified tectonic map of the Tauern Window displaying the distribution of D_3-related calcite microstructures and CPOs; the diagrams along the margins of the map show the fabric asymmetries and corresponding simple shear percentages along faults forming the margins of the Tauern Window, evaluated from calcite CPOs; diagrams after Wenk et al. (1987); LANF, low angle normal fault along the eastern margin of the Tauern Window. L, LT-fabrics; H, HT-fabrics; I, single girdle distributions.

presence of strong CPOs that have been observed along the D_3 shear zones bordering the Tauern Window.

10. Summary and discussion

Three types of calcite-fabrics can be distinguished within the Penninic units of the Tauern Window and the Lower Austroalpine unit. Each type is characteristic for a distinct phase of deformation and metamorphism:

1. D_1-fabrics are characterized by well equilibrated microstructures. The strong and symmetric CPOs seem to indicate a dominating flattening component. However, the fabrics have been overprinted by subsequent amphibolite to greenschist facies metamorphism, which can be observed from the associated rock assemblages (e.g., Kurz et al., 1996). Subsequent twinning did not highly affect the microstructures and CPOs; <30% of the grains have been twinned, commonly only by one set of twins (Fig. 2a). The occurrence of LT-fabrics dominates the area of amphibolite facies metamorphic conditions in the central part of the Tauern Window (Fig. 3; Höck, 1980; Droop, 1985). HT-fabrics are restricted to the peripheral parts and approximately coincide with the occurrence of greenschist facies metamorphic assemblages (Fig. 3). Therefore, we assume that the deformation conditions during D_1 were appropriate to produce HT-fabrics. However, these fabrics have been modified during subsequent metamorphism. Fabrics occurring inside this isograde seem to have been strengthened during subsequent equilibration [according to Schmid and Casey (1986)] by forming single maxima near Z [LT-fabrics of Wenk et al. (1987)]. Accordingly, the fabrics outside the isograde have less been affected because of the lower metamorphic grade (greenschist facies); within this area the deformational HT-fabrics have been preserved. In this case the CPOs are not only significant for the conditions during deformation (D_1) in terms of LT- and HT-fabrics, but also bear information about the thermal equilibration subsequent to the main deformational event.
2. Similar observations have been made for the evolution of D_2-fabrics. However, D_2 was generally contemporaneous to the metamorphic overprint. LT-fabrics dominate inside the amphibolite facies isograde (Fig. 5), HT-fabrics occur outside. Therefore, the CPOs within the central parts seem to reflect the influence of subsequent thermal overprint (similar to the fabrics that have been described for D_1), which has strengthened the CPOs, while the HT-fabrics and microstructures within the peripheral areas of the Tauern Window are significant for the deformational conditions during D_2. However, the occurrence of HT-fabrics only indicates temperature conditions above 350° C (Wenk et al., 1987). In the central parts, the microstructures are characterized by recrystallization and thermal equilibration, coinciding with amphibolite facies metamorphic conditions in the core of the Tauern Window. In this area, the CPOs are sharper. Approaching the margins of the Tauern Window, microstructures are characterized by strong elongation and multiple twinning, defining high finite strain decreasing towards the central parts. Concerning these strongly deformed calcite tectonites, we assume that the foliation and lineation coincide with the macroscopic shear plane and shear direction. However, since such high finite strains cannot be achieved by twinning alone [only up to 15% by e-twinning; Burkhard (1993)], plastic deformation of calcite grains is assumed to be the major deformation mechanism prior to twinning. Since CPOs, especially the concentration of *c*-axes, generally remain constant at finite strains of 20% and more, it can be assumed that subsequent twinning did neither affect the CPOs nor the general microstructure of these marble mylonites. Only within the Lower Austroalpine unit the LT-fabrics seem to reflect the low-grade metamorphic conditions during D_2.
3. D_3 is restricted to distinct shear zones along the tectonic boundaries of the Tauern Window. During exhumation and D_3 doming, deformation occurred during cooling (Kurz and Neubauer, 1996). Microstructures suggest intracrystalline plasticity with a dominating

r^--glide. Twinning was less important during the final deformation phases. However, curved twins indicate that plasticity was an important deformation mechanism subsequent to twinning too. Assuming that temperatures did not rise during this deformational event, this feature may be interpreted in terms of fast strain rates. Twin occurrence decreases continuously towards the shear zone boundaries of the Tauern Window. The grain size is decreasing due to dynamic recrystallization and secondary grain size reduction until the formation of ultramylonites. Within these shear zones grain boundary sliding, respect to the grain size sensitive flow, seems to dominate. The ultramylonites show stronger CPOs and well defined single *c*-axis maxima near Z, which is similar to the experimental results described by Casey et al. (1998). The calcite textures are very similar: the *c*-axes are either aligned subparallel to the foliation normal or are rotated away from this axis against the sense of shear. The fabric asymmetry of the CPOs depends on the orientation of the distinct shear zones with respect to the external stresses. Along the E–W-striking northern and southern margins of the Tauern Window (Salzach fault), the asymmetry ranges from 5 to 20° (Fig. 7). Along the NW–SE-striking Möll Valley Fault, the asymmetry ranges between 0 and 5° (Fig. 7), which implies a higher pure shear component according to Wenk et al. (1987). These observations are consistent with a NNE to NE orientation of the maximum principle stress (σ_1) during dome formation (Kurz and Neubauer, 1996).

11. Conclusions

Calcite microstructures and CPOs that have been observed within the Tauern Window (Eastern Alps) partly reflect a polyphase deformation and metamorphic history. However, this evolution not only depends on the deformational conditions, but also on the subsequent phases of metamorphic overprint. Generally, the occurrence of LT-fabrics coincides with the occurrence of amphibolite facies metamorphic conditions in the core of the Tauern Window, whereas HT-fabrics have been observed outside this isograde, which is in contradiction to the general classification of LT-and HT-fabrics by Wenk et al. (1987). Accordingly, fabrics that have been observed in the central part of the Tauern Window have been modified and strengthened during thermal equilibration at amphibolite facies metamorphic conditions. Fabrics that have been observed at the peripheral parts have less been affected by overprint at greenschist facies metamorphic conditions, and approximately reflect the original deformation conditions. Generally, assumptions on deformational fabrics of calcite are only significant at low grade metamorphic conditions.

Acknowledgements

The authors appreciate discussions on the topics presented in this study with Harry Fritz, Niko Froitzheim, Neil Mancktelow and Robert Handler. They gratefully acknowledge suggestions by Jean-Pierre Burg and Karel Schulmann on an earlier version of the manuscript, and the formal reviews by Martin Burkhard and Karel Schulmann. The authors also gratefully acknowledge the software packages provided by Eckard Wallbrecher and Helmut Schaeben for the documentation of several orientation data. The studies presented in this paper have been carried out within the project P12179-GEO of the Austrian Research Foundation.

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