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Exhumation

Sequence of Tertiary Brittle Deformations in the Eastern Tauern Window (Eastern Alps)

WALTER KURZ, FRANZ NEUBAUER, JOHANN GENSER & HANNES HORNER*)

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Tertiäre Sprödstrukturen im östlichen Tauernfenster (Ostalpen)

Zusammenfassung

Untersuchungen von mesoskopischen Sprödstrukturen im östlichen Tauernfenster ergaben eine klare Abfolge ihrer Prägung, die im gesamten Untersuchungsgebiet sehr einheitlich ist. Die ältesten Sprödstrukturen sind subvertikale, sulfidführende Quarzgänge, welche anscheinend nur im zentralen Teil der Hohen Tauern auftreten. Sie streichen NE–SW und zeigen eine rechtslaterale, staffelförmige Anordnung. Diese Gänge werden von flachen, semiduktilen Abschiebungen geschert und abgeschnitten und in weiterer Folge von NNE-streichenden Quarzgängen geschnitten, die ebenfalls sulfidische Erzminerale führen und manchmal über linkslaterale Relaisstrukturen verbunden sind. Die Quarzgänge und andere hydrothermale, erzführende Gänge treten bemerkenswerterweise am Ende der Mölltalstörung, einer NW–SE-streichenden, dextralen Blattverschiebung, gehäuft auf. Wir erklären dies als Ausdruck der Aufnahme eines Teils der Blattverschiebungskomponente in Form von Dehnungsstrukturen im Endbereich dieser Störung. Manche dieser Gänge werden später als Abschiebungen wiederbetätigt und zeigen somit im Wesentlichen eine Dehnung in E–W-Richtung an. Die Abschiebungen treten einerseits in den inneren Bereichen des Tauernfensters als flache diskrete Scherzonen auf, andererseits wird diese Abschiebung am Ostrand des Fensters in der Schieferhülle gefügeprägend.

Paläospannungsanalysen an Hand von Orientierungen von Störungen und Striemungen ergeben eine subhorizontale, NNE–SSW-gerichtete Orientierung der Hauptnormalspannung σ_1 im Bereich der dextralen Mölltalstörung. Diese Orientierung von σ_1 ist mit der Bildung der NNE–SSW-streichenden Dehnungsgängen in Übereinstimmung.

Alle diese Sprödstrukturen belegen eine subhorizontale Orientierung der Hauptnormalspannung σ_1 innerhalb des NE-Quadranten und eine Rotation der subhorizontalen Hauptnormalspannung σ_1 bzw. der Orientierung der σ_1-Trajektorien gegen den Uhrzeigersinn während der Bildung dieser Sprödstrukturen. Diese Entwicklung gibt Hinweise auf die Existenz eines großräumigen sinistralen, E–W-streichenden Seitenverschiebungskorridors, der für den Aufstieg des Tauernfensters innerhalb einer Stufe von zwei Blattverschiebungen verantwortlich gemacht werden könnte. Ein Wechsel der Hauptnormalspannungen σ_1 und σ_2 während der andauernden E–W-gerichteten Dehnung (σ_3) beweist das Durchschreiten einer neutralen, isotropen Fläche während des Aufstiegs des metamorphen Tauerndoms.

Abstract

Investigations of brittle outcrop-scale structures within the eastern sectors of the Tauern Window provide a clear succession of structures that are coherent over the entire study area. The oldest brittle structures are subvertical sulphide-bearing extensional quartz veins which dominate the central part of the Tauern Window. They trend NE and show a right-lateral en echelon arrangement. These veins are sheared and crosscut by low-angle normal faults and subsequently overprinted by NNE-trending extensional quartz-veins bearing sulphidic ore minerals. Occasionally vein arrays are linked by left-lateral bridge structures. The hydrothermal quartz and ore veins are concentrated at the

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end of the Mölltal strike-slip fault. This phenomenon is explained as an accomodation zone in which the dextral strike-slip components along this fault have been partly compensated by extension in ESE–WNW-direction. Some of the hydrothermally mineralized veins have subsequently been used as normal faults, bearing evidence of extension in E–W-direction. These normal faults are widespread over the internal sectors of the Tauern window as localized shear zones dominating the roof zones of the Tauern Window as well.

The results of the paleostress-analyses from the orientation of slickensides and striae point to a subhorizontal, ca. NNE–SSW orientation of the principal stress axis σ_1 at the NW–SE-trending right-lateral Mölltal fault. The orientation of σ_1 is compatible with the formation of NNE-trending extensional veins. All these brittle structures documented display evidence of a subhorizontal orientation of the principal stress axis σ_1 in the northeastern quadrant and a counterclockwise rotation of the subhorizontal orientation of σ_1-trajectories during the formation of these brittle structures. The combination of these structures is interpreted to represent the stress distribution within a sinistral step of a left-lateral, east-trending wrench-corridor which accomodated the exhumation of the Tauern window. During the subsequent subhorizontal extension in E–W-direction an exchange of the principal stresses σ_1 and σ_2 is documented. This change is interpreted to document the passage through the neutral, isotropic surface during the uplift of the metamorphic dome of the Tauern Window.

1. Introduction

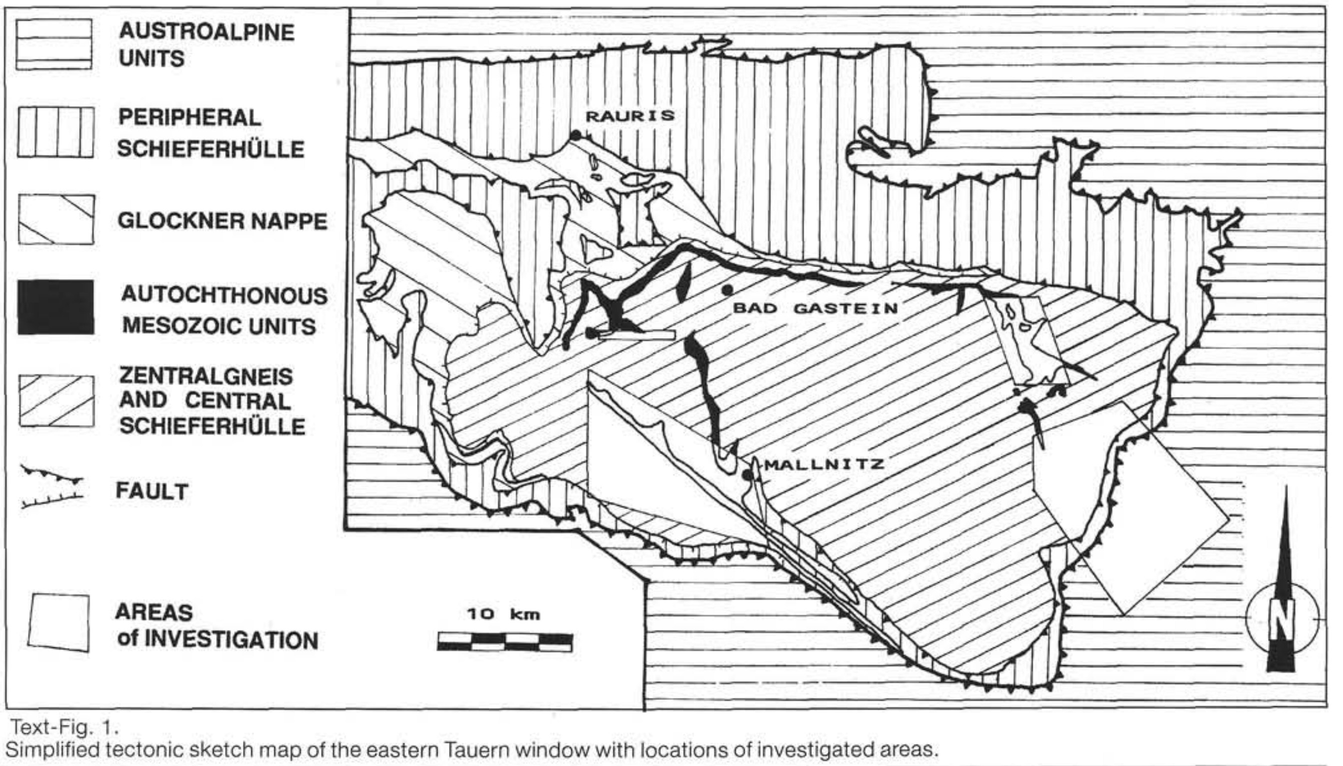
Underplated metamorphic continental crust is often found within tectonic windows in internal zones of collisional orogens. The ideas on conditions of exhumation of such crustal pieces are controversial and many models have been proposed. Many authors agree that exhumation mainly occured during the late stages of the orogenic evolution in an extensional regime (DEWEY, 1988; ENGLAND & MOLNAR, 1990; PLATT, 1986, 1993; RATSCHBACHER et al., 1989; HILL et al., 1992). Removal of the hangingwall crust was achieved by operation of ductile low-angle normal faults on the roofs of uplifted metamorphic domes. Geometrically, the displacement along these extensional faults are directed either towards the foreland (Lister et al., 1984) or largely subparallel to the orogen (BEHRMANN, 1988, 1990; SELVERSTONE, 1988; GENSER & NEUBAUER, 1989; NEUBAUER & GENSER, 1990; RATSCHBACHER et al., 1989).

During uplift and cooling the orogenic crust crossed the transition from plastic to brittle deformation. Thus the orientations of the extensional fractures can be used to document strain and stress orientations during the late stage of orogenic deformation (ANGELIER & MECHLER, 1977; ANGELIER, 1979, 1989; DYER, 1988; ENGELDER & GEISER, 1980; HANCOCK, 1985; RAWNSLEY et al., 1992).

We investigated the eastern part of the Tauern Window to obtain information on the kinematics of orogen-parallel tectonic escape and to deduce the stress conditions of the uplift of such metamorphic domes (GENSER & NEUBAUER, 1989; RATSCHBACHER et al., 1991).

2. Geological Setting of the Tauern Window

The Tauern Window exposes Penninic units below the Austroalpine Nappe Complex that represents the hangingwall continental plate during the Tertiary plate collision (Text-Fig. 1). The Penninic units include a continental basement composed of Paleozoic metamorphic units and the widely distributed Variscan Central Gneiss with a parautochthonous Permian to Mesozoic cover, overlain by the Peripheral Schieferhülle (basically within the Glockner nappe: TOLLMANN, 1980) which represents a Mesozoic ophiolite sequence (HÖCK & MILLER, 1987). The burial of the Penninic units during plate collision resulting in high pressure metamorphism is believed to have occurred in the Cretaceous, followed by Eocene to Oligocene regional metamorphism ("Tauern crystallization") (CLIFF et al., 1985; DROOP, 1985; FRANK et al., 1987). Uplift and cooling of the Tauern Window



Text-Fig. 1.
Simplified tectonic sketch map of the eastern Tauern window with locations of investigated areas.

apparently started during the late Oligocene and continued throughout the Neogene (CLIFF et al., 1985; GRUNDMANN, 1987; STAUFFENBERG, 1987) with formation of ductile low-angle normal faults with top west displacement along the western margins (BEHRMANN, 1988; SELVERSTONE, 1988) and top east displacement along the eastern margins of the Tauern Window (GENSER & NEUBAUER, 1989; ELSNER, 1991, 1992; GENSER, 1992). Several studies reported structural expressions like normal faults for extension and rock uplift along eastern margins of the Tauern window during uplift (EXNER, 1989; GENSER & NEUBAUER, 1989; ELSNER, 1991, 1992). Presently, portions of the Tauern window are still uplifting with a rate of ca. 1.5 mm/a (SENFTL & EXNER, 1973).

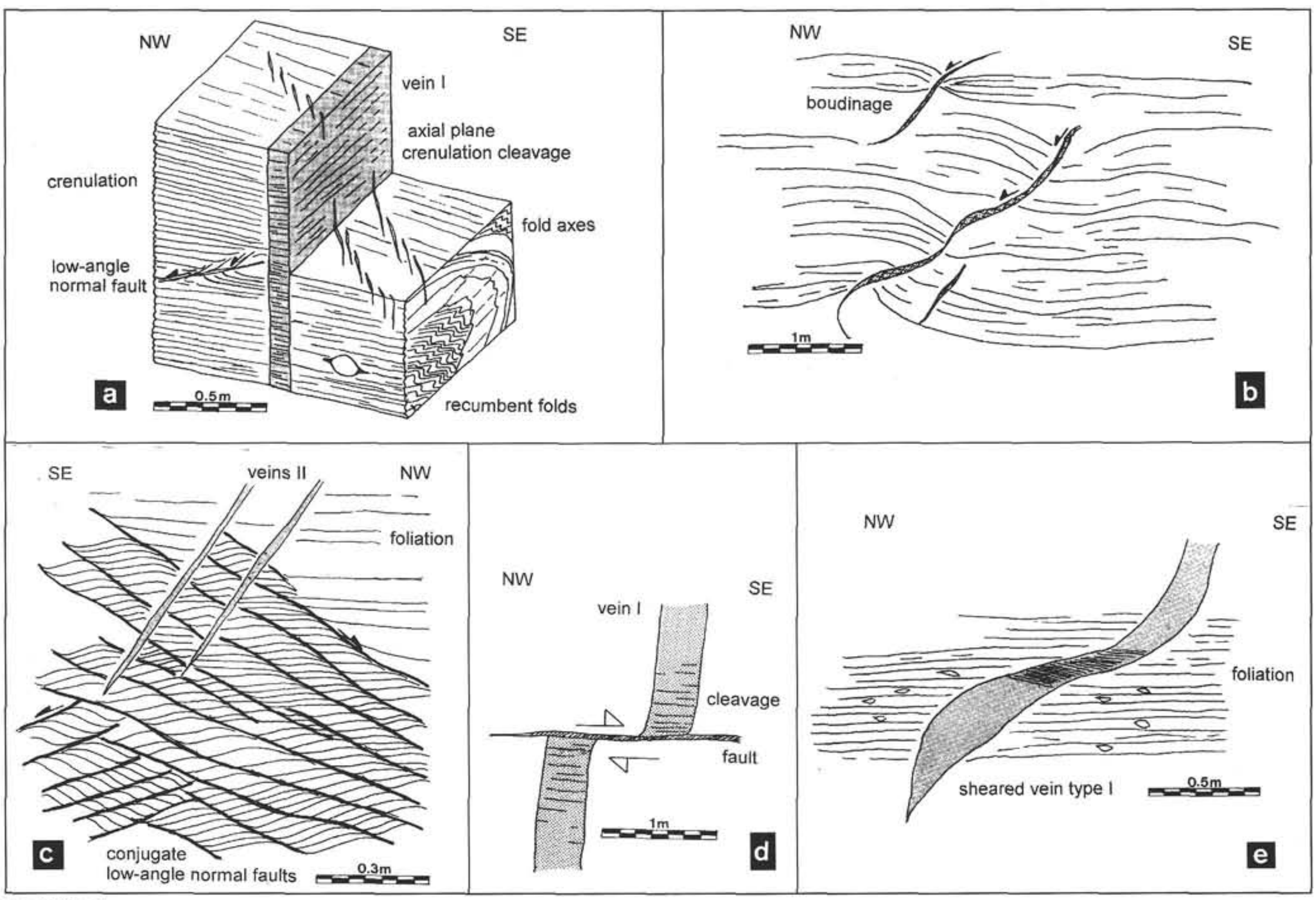
3. Methods

Methods applied in the field largely followed those described by ENGELDER & GEISER (1980), HANCOCK (1985), and RAMSAY & HUBER (1987). Data for paleostress orientation analysis were collected following the methods initially proposed by ANGELIER & MECHLER (1977). The shear criteria along brittle faults have been described by PETIT (1987). Only the slickenside and striae data from single exposures have been used for paleostress orientation analysis to keep control on possible overprint and multistage formation of faults. Note that not the number of measured fault data is essential for quality of the diagram but the distinct orientations. Only in a few cases an overprint by a second set of striae along faults has been observed. Numerical calculations of possible paleostress orientations have been performed by means of a computer program of WALLBRECHER & UNZOG (Graz) which follows the algorithms described by ANGELIER & MECHLER (1977) and ANGELIER (1979).

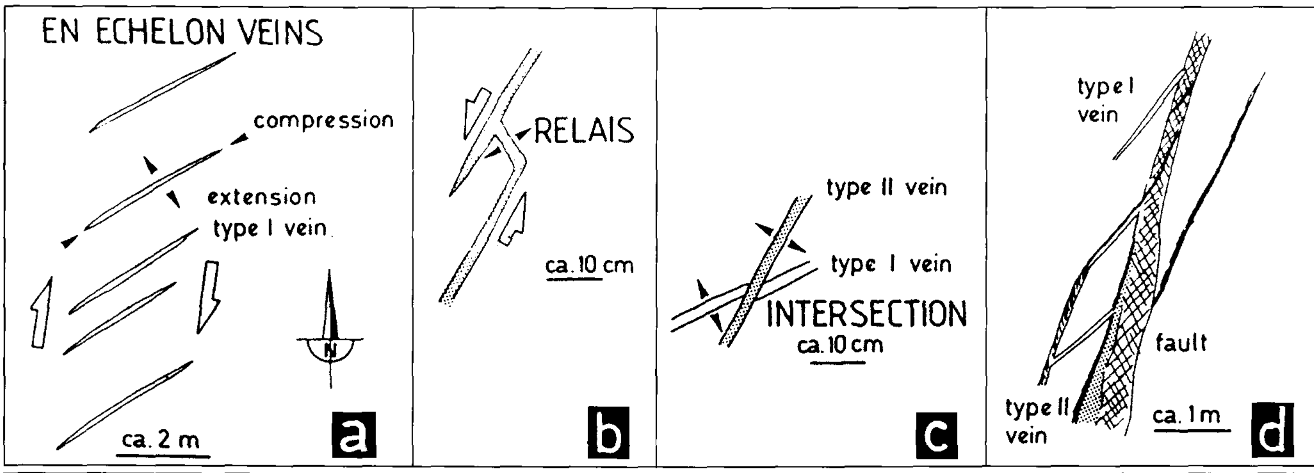
4. Brittle Deformation within the Eastern Tauern Window

We investigated three areas in more detail (Text-Fig. 1):

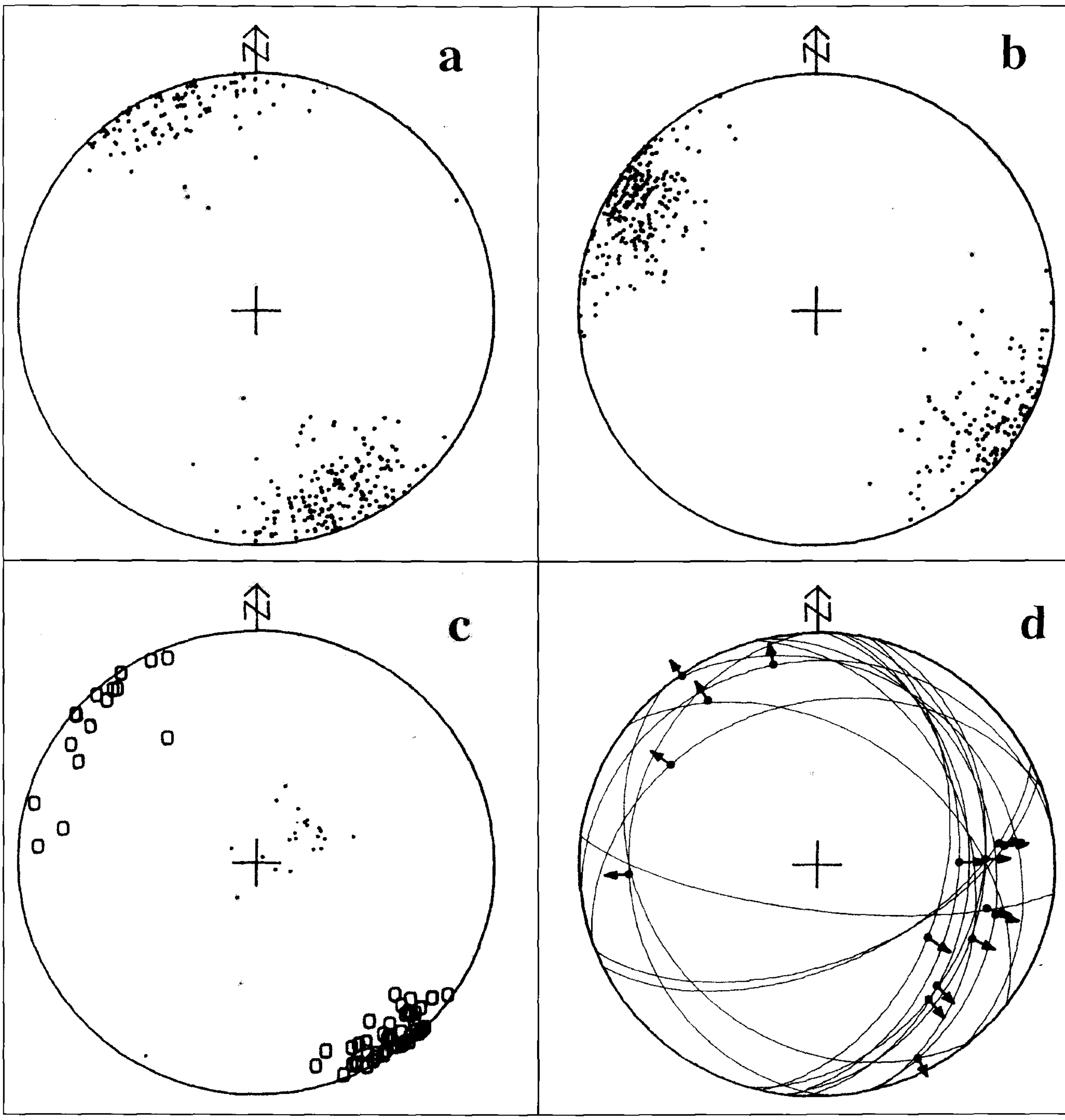
1) The area along the Mölltal fault ("Mölltal Line") within the Mallnitz-Fragant area. This fault is a major NW-trending subvertical, apparently dextral strike-slip fault zone which offsets the southern margin of the Tauern Window. The area is of major interest because many subvertical NE- to NNE-trending hydrothermal ore veins are located within it (TORNQUIST, 1931; 1933; HIESSLEITNER, 1937; KIESLINGER, 1937; FEITZINGER & PAAR, 1991; FEITZINGER, 1992; VAVTAR, 1982).
2) The Silbereck area, which includes a major NNW-trending synform with Penninic Permian to Mesozoic metasediments within Paleozoic basement rocks (EXNER,



Text-Fig. 2.
Brittle deformation in the Fragant area (W of Mallnitz).
All here documented structures are from mountain tracks below the Wurten Kees, between the Eisseehaus (2795 m) and the quarry 100 metres south of the Wurtenspeicher dam (Fragant area).
a) Structural summary of all observed brittle structures within the Central Gneiss (taken from outcrops along mountain tracks 100–200 m south of the Eisseehaus).
b) Foliation boudins and mineralized necks (outcrop along mountain track, approximately 300 metres west of the Duisburger Hütte).
c) Semibrittle to ductile normal faults and type II extension veins (quarry 100 metres south of the dam of the Wurtenspeicher).
d) Mineralized type I vein with secondary cleavage parallel to fault plane (like b).
e) Sheared type I vein due to low-angle normal faulting (like c).

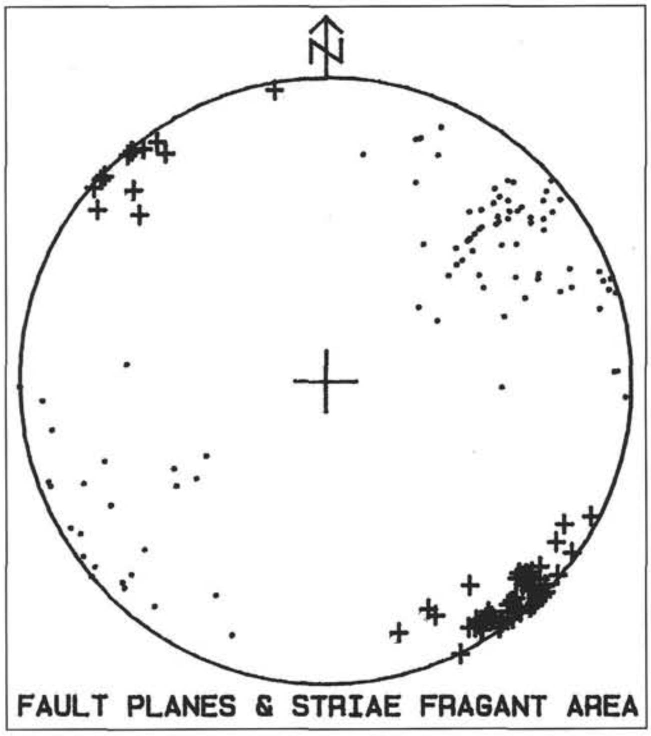


▲▲▲ Text-Fig. 3 • • • Text-Fig. 4 ▼▼▼

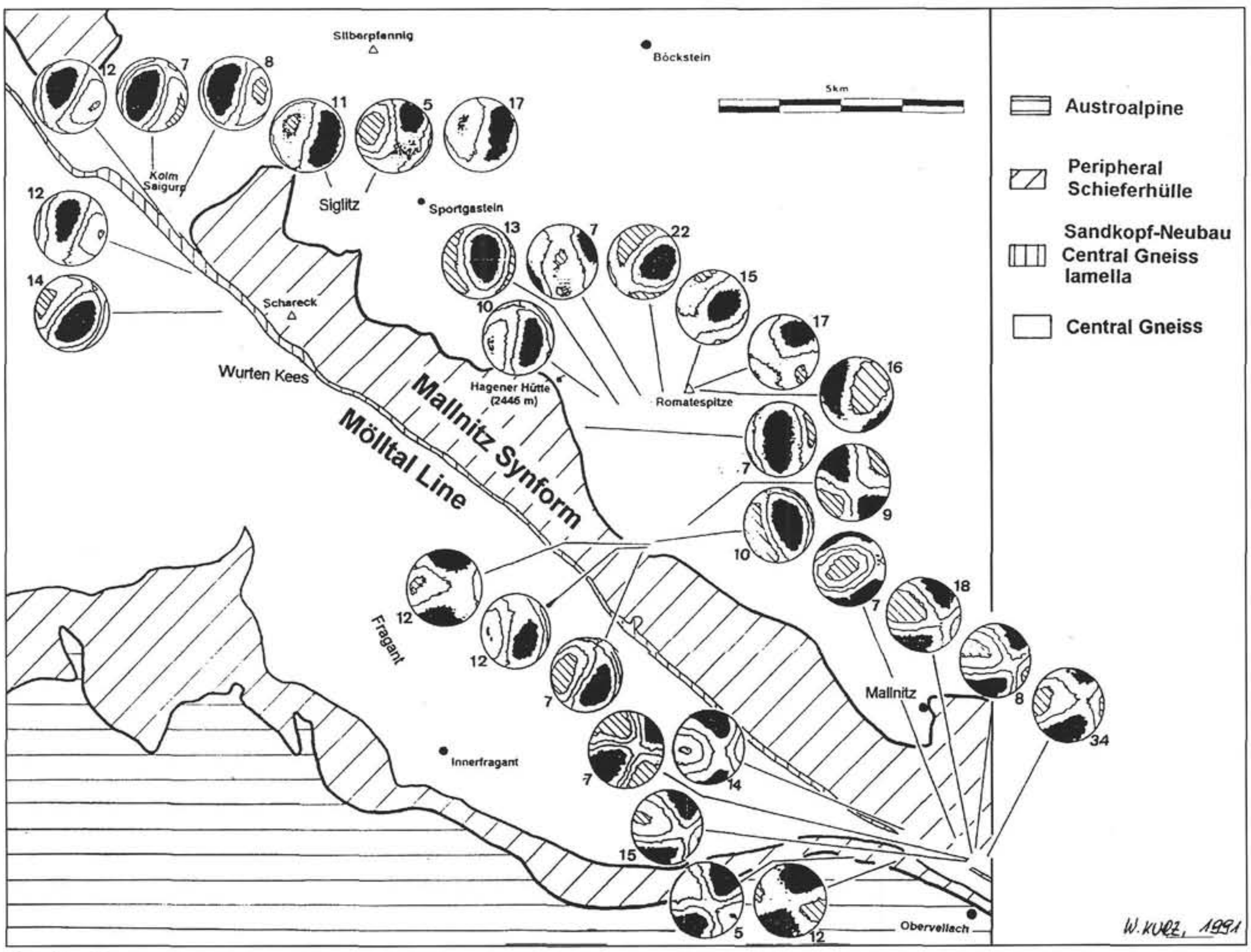


Text-Fig. 3. ◄
Schematic presentation of brittle structures in the Siglitz area southwest of Badgastein.
a) NE-trending tension gashes with right-handed en-echelon arrangement (type I vein).
b) NNE-trending tension gashes with a sinistral relais (or bridge structure) of type II veins.
c) Intersection between NE- and NNE-trending veins.
d) Brittle normal faults affecting tension veins from type I and II.
All sketches are in plan view.

Text-Fig. 4. ◄
Orientation data of extension veins.
a) Poles to type I veins.
b) Poles to type II veins.
c) Fold axes (□) and related subhorizontal axial surface cleavage (•).
d) Low -ngle normal faults (see Text-Fig. 2c): great circles = fault planes; points with arrows = striae with sense of hangingwall displacement.
Lambert's projection, lower hemisphere.



Text-Fig. 5. ►►
Orientation data of the brittle structures along the Mölltal Line.
• = fault planes; + = striae.
Lambert's projection, lower hemisphere.



Text-Fig. 6.
Orientations of principal stress axes deduced from slickenside and striae data along the Mölltal Line.
Black area in diagrams: possible orientations of σ_1 orientations; stippled area in diagram: possible σ_3 orientation. Number on diagrams refers to the number of faults on a single locality with measured fault plane, striae, and sense of shear defining to a complete slip system.

1983). Epigenetic hydrothermal mineralizations within extensional fissures and shear and fault zones are of some importance (FRIEDRICH, 1934, 1935; EXNER, 1989; WEIDINGER & LANG, 1991).

3) The Malta valley area at the eastern margin of the Tauern Window, which exposes the transition from the tectonic hangingwall units of the Tauern Window to the internal portions of the Central Gneiss cores.

4.1. Mölltal Line Area

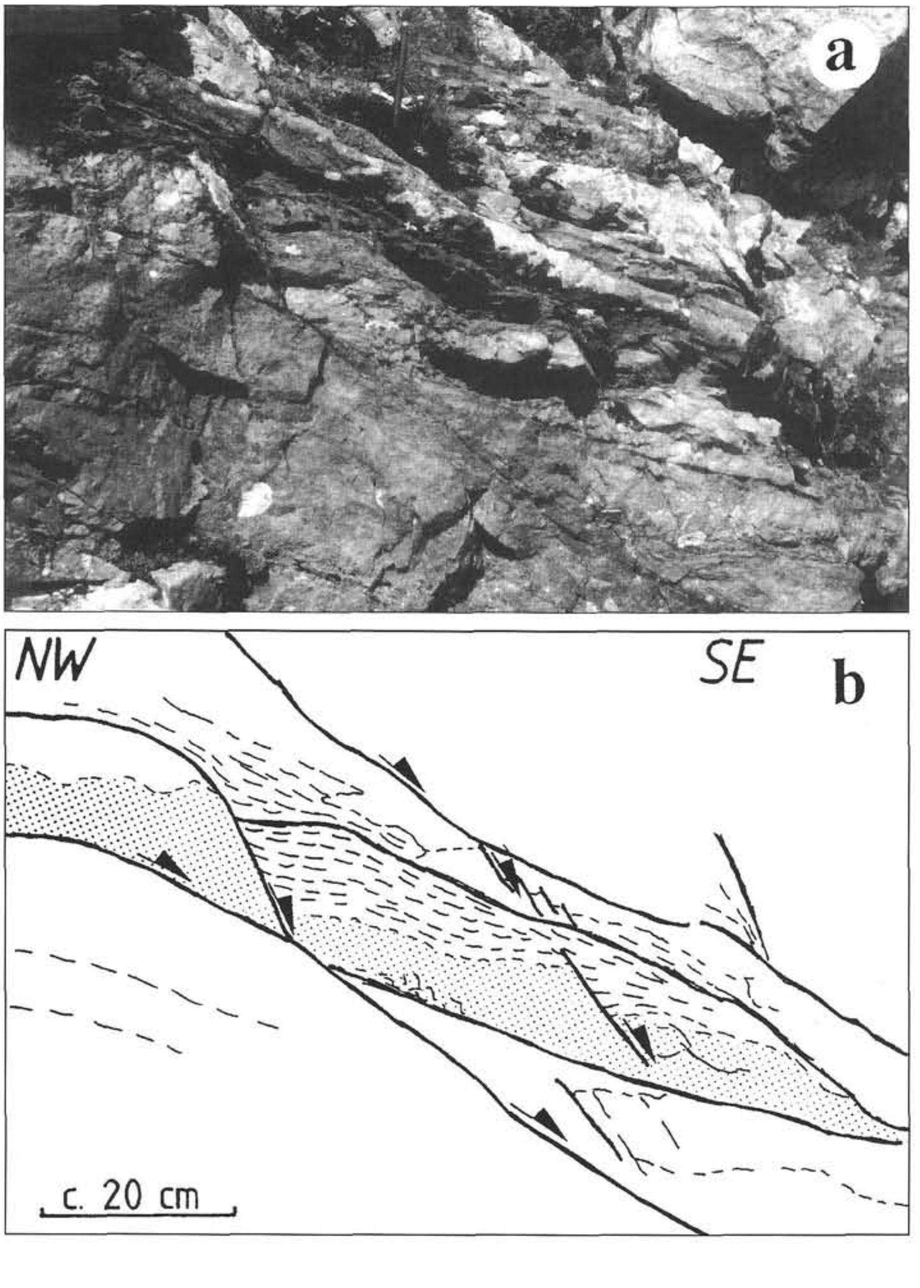
In the area along the Mölltal Line (EXNER, 1962, 1964) we observed a progressive sequence of deformation structures which are developed in the Siglitz valley and the Fragant area in an exemplary fashion.

Subvertical extensional sulphide-bearing quartz veins of cm to dm thickness are the oldest brittle structures. They trend NE and show right-lateral en echelon arrangement (Text-Figs. 2a, 3a, 4a). These veins are affected by open to tight, NE-facing recumbent folds which are formed by folding of the penetrative foliation around subhorizontal, SE-striking fold axes. These folds are associated with a flat-lying axial plane crenulation cleavage (Text-Figs. 2a, 4c).

These structures are crosscut and sheared by conjugate sets of low-angle normal faults dipping to the WNW and ESE, respectively (Text-Figs. 2a, 4d). Extensional veins are sheared and offset by these low-angle normal faults (Text-Fig. 2e). Sometimes an asymmetric foliation boudinage is related to normal faulting (PLATT & VISSERS, 1980) (Text-Fig. 2b).

The NE-trending veins, the folds and the low-angle normal faults are also crosscut by NNE-trending extensional quartz veins bearing sulphidic ore minerals (Text-Figs. 2a, 3b, 4b). They are sometimes linked by left-lateral bridge structures (Text-Fig. 3b). Extensional fissures of small dimensions displaying chlorite mineralization parallel to NNE-trending veins show right-lateral and left-lateral en echelon arrangements, respectively, depending on the major fault they are related to. NE-trending quartz veins may show right-lateral offset by NW-trending subvertical brittle faults and cleavages parallel to these faults (Text-Fig. 2d). Both types of veins have subsequently been used as normal faults or are crosscut by NW- to WNW-dipping high-angle normal faults (Text-Fig. 3d). Subvertical N-trending joints occur together with subvertical Riedel-en-echelon fractures which indicate subvertical shearing. These structures are due to this final stage of brittle deformation (mode III shearing: POLLARD & AYDIN, 1988).

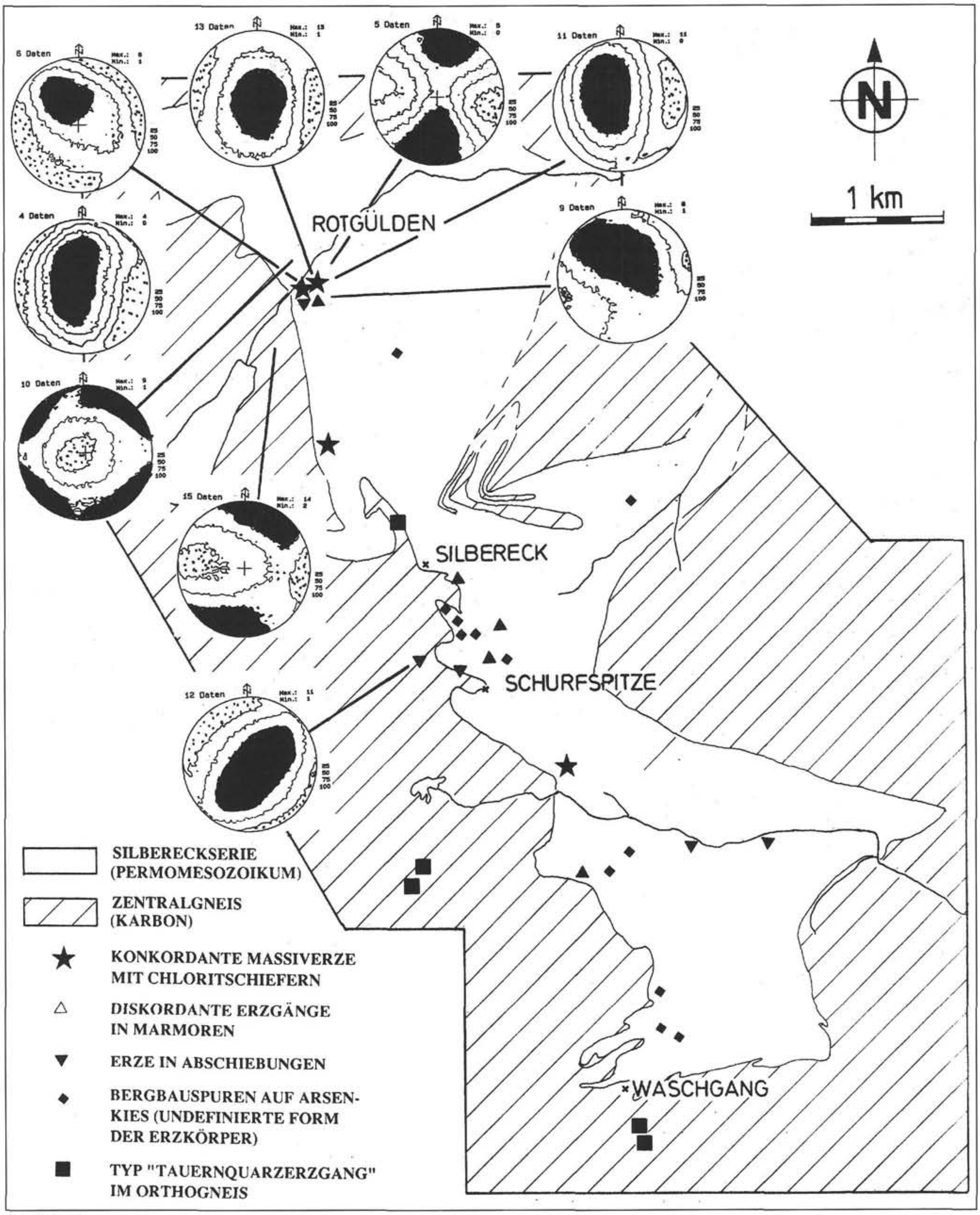
Ductile deformation structures with a steep penetrative foliation and a flat-lying SW-trending stretching lineation apparently predominate along the Mölltal Line. Brittle segments of the fault zone which overprint earlier ductile structures are very limited in the field. In such segments, like in the Fragant area, subvertical fault surfaces are associated with a subhorizontal striation and/or Riedel shears indicating dextral displacement (Text-Fig. 5a,b). These faults often contain mineralizations with chlorite, calcite and subordinate quartz indicating hydrous fluids from which these minerals have been precipitated.



Text-Fig. 7.
Brittle shear zone displaying the interaction between normal faults and extensional horse tails with mineralized veins.
Base of the Silbereck Group west of the Schurfspitze (for location, see Text-Fig. 8).

The results of paleostress analyses from the orientation data of slickensides and striae (ANGELIER & MECHLER, 1977; ANGELIER, 1979, 1989) indicate a subhorizontal NNE–SSW orientation of the principal stress axis σ_1 at the NW-trending Mölltal strike slip fault. This orientation of σ_1 is compatible with the formation of NNE–SSW striking extensional veins.

Some of these veins have subsequently been reactivated as normal faults which documents an exchange of σ_1 and σ_2 aside and at the end of the Mölltal Line.



Text-Fig. 8.
Orientations of principal stress axes as deduced from slickenside and striae data from the Silbereck area.
For explanation of diagrams, see Text-Fig. 6.

4.2. Silbereck Area

The Silbereck area (Text-Fig. 1) mainly exposes par-autochtonous Mesozoic carbonates, black schists and mi-caschists within the Variscan "Central Gneiss" and the mig-matitic Storz Group (EXNER, 1983) which represents another basement unit (Text-Figs. 1, 8). Complex ductile deforma-tion of the area is followed by local brittle deformation. Basic observations are the presence of subvertical mineralized, mostly NNE-trending tension gashes which include a three-step mineralization:

1) In a first mineralization phase mostly muscovite has been formed within such gashes,
2) a second phase resulted in precipitation of quartz, chlorite and other silicates, and
3) sulphides which have been precipitated on silicates of the first two phases.

The last phase is often combined with brittle shear zones along the contact zones of rocks with a large competence contrast like the boundary of the Central Gneiss to basal formations of the Mesozoic cover sequence. Brittle shear zones gradually change into extensive horse tails which include mineralized tension fissures (Text-Fig. 7). These fissures often contain sulphides. Extension veins both in the Central Gneiss and in the Mesozoic Silbereck sequence have the same subvertical und predominantly NNE-trending orientation (Text-Fig. 7b).

Orientations of brittle shear faults, which have been collected from several localities, imply a predominant subvertical orientation of σ_1 (Text-Fig. 8). Only very few data sets yielded patterns with subhorizontal σ_1. Depending on country rocks, these faults often contain some mineralizations with chlorite, calcite, and sulphides.

4.3. Malta Valley

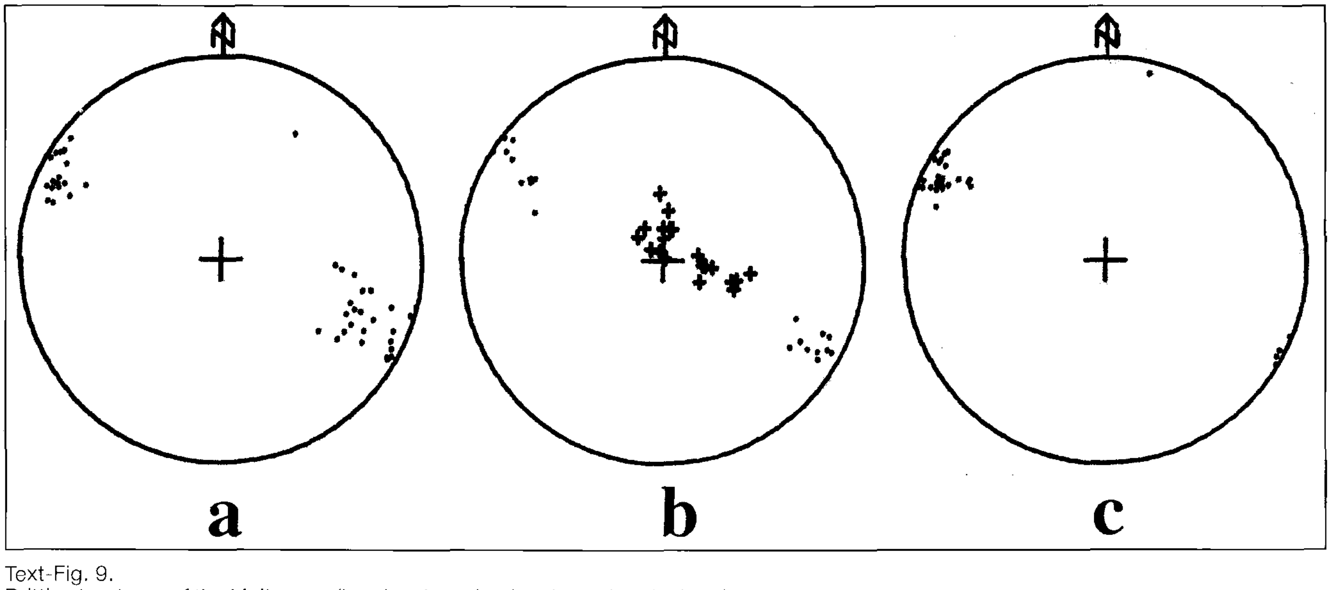
At the eastern margin of the Tauern Window tectonic units from the Gößkern, the deepest exposed tectonic level, up to the Austroalpine unit have been studied. They exhibit a complex sequence of ductile deformation, followed by brittle structures. The last main ductile deformation is low-angle normal faulting, concentrated in the Peripheral Schieferhülle, displacing the Austroalpine unit to the ESE (GENSER & NEUBAUER, 1989).

The oldest brittle structures in the Penninic unit are mineralized tension gashes, which occur mostly in conjunction with semiductile normal faults. These tension gashes occur in more competent layers, whereas extension in the incompetent layers is accomodated by listric normal shear zones, passing into the fractures and the main foliation, respectively. The fractures trend NNE (Text-Fig. 9a). Some are gently folded around subhorizontal axes (Text-Fig. 9b). Quartz, chlorite, biotite, calcite, albite and other hydrothermal minerals have grown, indicating elevated temperatures during their formation. Similar open gashes occur in neck areas of foliation boudins. Especially within amphibolites close to the Peripheral Schieferhülle, which are affected by low-angle normal faulting, NNE-trending calcite-filled veins are developed.

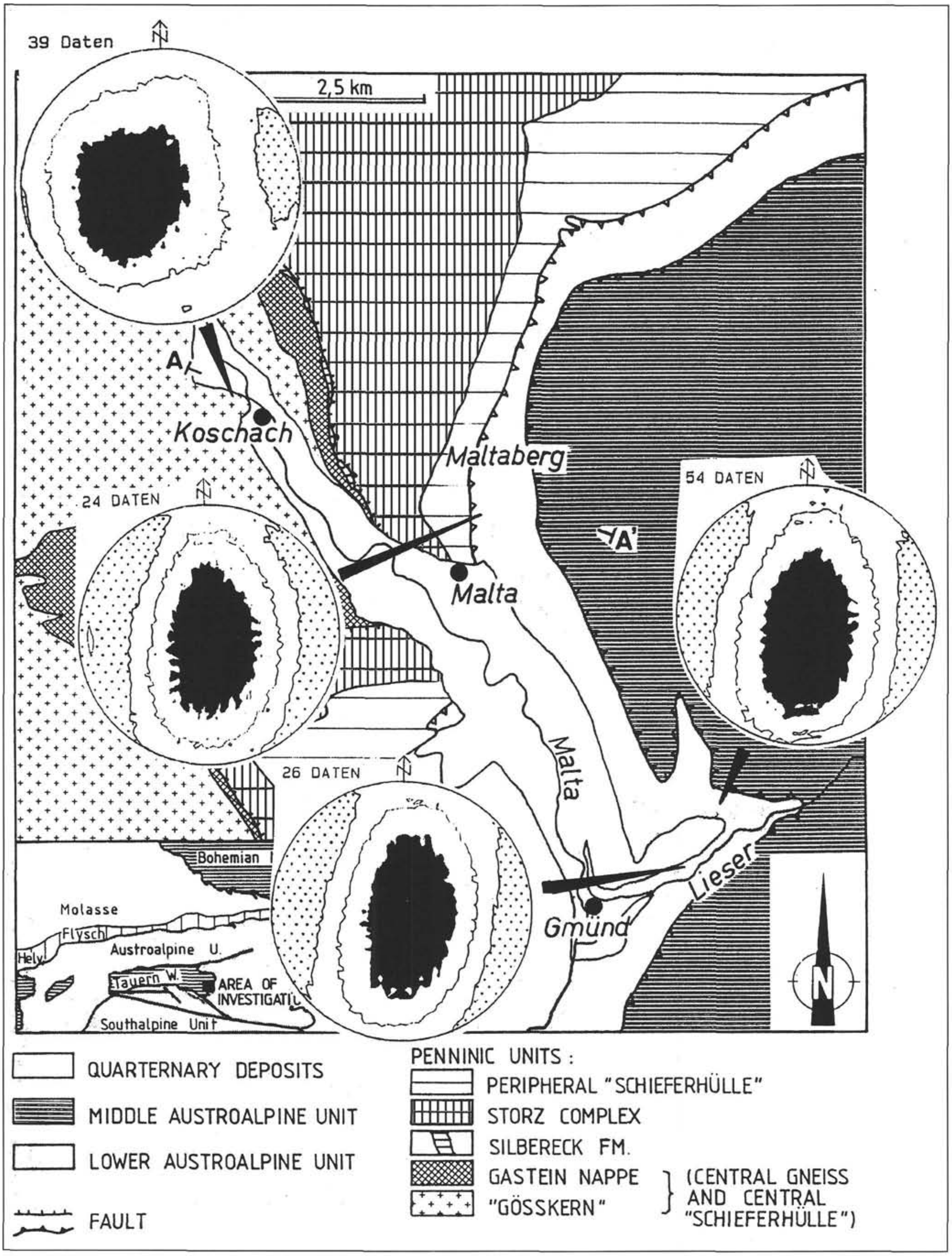
In the homogeneous granodioritic gneisses of the Gößkern, steep NNE-trending subvertical chlorite-filled joints (Text-Fig. 9c) indicate ESE–WNW-directed extension as well. These joints occur in sets which are about half a meter in width and which are in distances of more than several meters from each other. The surfaces are smooth, the areal extent of individual joints is up to several square metres.

Slickensides on shear fractures in the granodioritic gneisses display a continuous evolution from discrete surfaces to ductile shear zones mm to cm wide. Hydrothermal minerals like quartz, calcite, and chlorite in releasing bends of slickensides point to the formation of the slickensides at elevated temperatures. Paleostress analyses based on orientations of slickensides and striae yield a steep, W-directed plunge of the principal stress axis σ_1 and a subhorizontal, E–W-orientation of the principal stress axis σ_3 (Text-Fig. 10).

Ductile, low-angle normal faults in the Peripheral Schieferhülle gradually change into often mineralized shear fracture with slickensides within the Austroalpine unit. Therefore, they must be older than the brittle structures in the Penninic unit. The brittle deformation, forming cataclasites and fault gouges is concentrated in the Lower Austroalpine unit and especially at the former thrust contact between the Lower Austroalpine and the Middle Austroalpine units, reactivating



Text-Fig. 9.
Brittle structures of the Malta area (Lambert's projection, lower hemisphere).
a = orientation data of tension gashes; b = folded tension gashe: tension gash (•), foliation in the country rock (+); c = chlorite-mineralized extension veins (Gößkern, Koschach).



Text-Fig. 10.
Orientations of principal stress axes deduced from slickenside and striae data from the Malta valley.
For explanation of diagrams, see Text-Fig. 6.

the thrust surface as brittle normal fault. Paleostress analyses result in vertical orientations of σ_1 and ESE–WNW orientations of σ_3 (Text-Fig. 10).

5. Sequence of Deformations

From the data presented above a clear succession of brittle deformation events can be recognized in the central and eastern portions of the Tauern Window.

The oldest brittle structures occur in the central part of the Hohe Tauern. These are subvertical extensional sulphide-bearing quartz veins (FEITZINGER & PAAR, 1991; FEITZINGER, 1992). They trend NE and display right-lateral en-echelon arrangement. These veins are crosscut by NNE-trending extensional quartz-veins bearing sulphide ore minerals. Sometimes a second set of veins is linked by left-lateral relais structures. However, both the relais structures and the en-echelon arrangement of veins indicate a subhorizontal σ_1 direction during formation of these extensional gashes (NICHOLSON, 1991; POLLARD et al., 1982; POLLARD & AYDIN, 1988; RAMSAY & HUBER, 1987). In the Mallnitz-Fragant area the formation of both sets of veins is separated by formation of ductile low-angle normal faults and recumbent folds which both result from subvertical shortening.

Both sets of quartz and other hydrothermal veins containing ore minerals are concentrated remarkably at the end of the Mölltal strike-slip fault. This phenomenon suggests an explanation of these structures as the result of an accomodation zone which partly compensated the strike-slip component of this fault by extension in ESE–WNW-direction (following a model of GRATIER & GAMOND, 1990) and occasionally within the extensional steps of overlapping brittle faults (GAMOND, 1987).

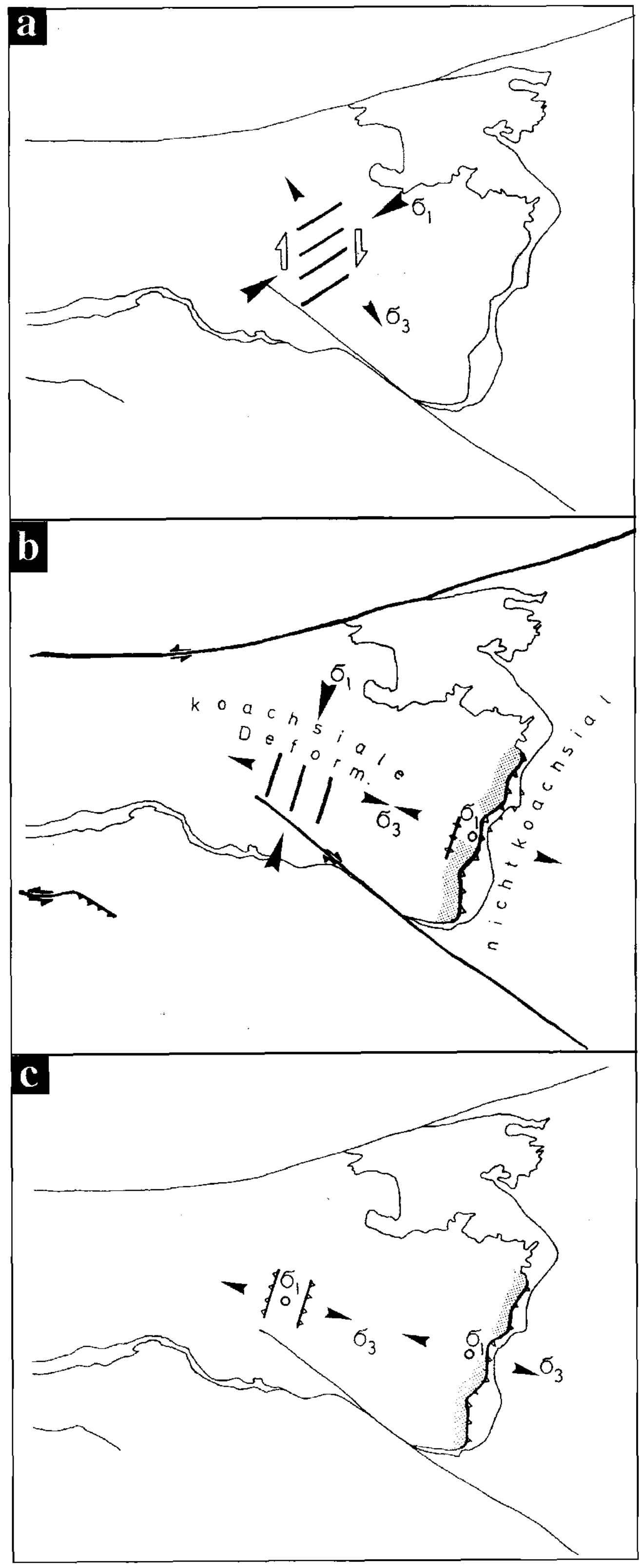
The results of paleostress analyses from the orientation of slickensides and striae (ANGELIER & MECHLER, 1977; ANGELIER, 1979) point to a subhorizontal, ca. NNE–SSW orientation of the principal stress σ_1 at the NW-trending right-lateral Mölltal fault. This orientation of σ_1 is compatible with the formation of NNE-trending extensional veins.

Some of these veins have subsequently been used as normal faults, basically bearing evidence of extension in ESE–WNW-direction. Especially in areas with competence contrasts, e.g. between the Central Gneiss and the covering Permian and Mesozoic metasediments, there is proof of a linkage between subvertical extensional veins and listric low-angle normal faults.

These normal faults are widespread over the internal part of the Tauern Window as localized shear zones. They dominate at the eastern margin of the Hohe Tauern near the fossil plate margin. Similar orientations of brittle structures within the Austroalpine unit suggests that they could have formed contemporanously with the ductile shear zones of the Penninic unit.

6. Discussion

Tension gashes as well as hydrothermal quartz veins are mineralized with quartz, silicates and sulphides which formed at elevated temperatures. FEITZINGER & PAAR (1991) estimated the temperature of sulphide formation of ca. 365–410°C. REDEN & GÖTZINGER (1990) assumed 300°C as a minimum temperature of quartz formation within quartz veins. The origin of hydrous fluids is uncertain but open veins suggest an origin from lower levels within the Tauern window. Ascending hydrous fluids may supply additional water to trigger hydrolytic weakening of main rock constituents like quartz within shear zones along the upper margin of the window. Similarly, transformation of feldspars into hydrous minerals like sericite often observed along axial plane surfaces and ductile shear zones postdating formation of type I veins might have been triggered by the same process.



Text-Fig. 11.
Model for the progressive development of brittle structures in the eastern part of the Tauern Window.
For explanation, see text.

Furthermore, an elevated water pressure respectively overpressure could have significantly lowered the strength of rocks within middle and upper levels of the orogenic crust.

The conjunction of documented brittle structures with mineralizations formed within a temperature interval between ca. 400° and 300°C as well as associated ductile structures like conjugate shear zones argue for formation of these structures on the cooling path of the rocks within the Tauern window. According to geochronological results of mineral age dating within the area under consideration (CLIFF et al., 1985; STAUFFENBERG, 1987) we assume, therefore, that these structures were formed within the Neogene.

All these documented brittle structures give evidence of a subhorizontal orientation of the principal stress axis σ_1 in the NE-quadrant and a counterclockwise rotation of the subhorizontal orientation of σ_1, respectively the orientation of σ_1 -trajectories, during the formation of these brittle structures (Text-Fig. 11a,b). This phenomenon points to the existence of a large-scale left-lateral bridge (GAMOND, 1987) within an approximately east-trending wrench corridor parallel to the strike of the orogen causing the uplift of the Tauern Window at a left-lateral step (GENSER & NEUBAUER, 1989). Furthermore, in conjunction with the existence of confining strike-slip faults, patterns of tension gashes as well as internal strike-slip faults indicate that significant rock uplift occurred in an transpressive, contractional setting.

During the subsequent subhorizontal extension in E–W-direction an exchange of the orientations of principal stress axes σ_1 and σ_2 is documented. This change is interpreted to represent the passage of a neutral, isotropic surface of principal stresses during the uplift of the metamorphic dome of the Tauern Window (Text-Fig. 11c).

7. Conclusions

Metamorphic underplated crust passes the transitional domain from plastic to brittle deformation during uplift and cooling. Several general trends may be recognized from the investigations in the eastern Tauern Window:

❶ Early brittle structures are tension gashes that formed within a strike-slip regime. Associated hydrothermal vein systems may have been channelways for escaping metamorphic fluids.

❷ In the interior of metamorphic domes mesoscale structures gradually change from predominantly subhorizontal pure shear extension with formation of mineralized extension gashes and ore veins to subhorizontal simple shear deformation resulting in (semi-)brittle shear zones.

❸ Ductile to brittle simple shear deformation expressed structurally as low-angle normal faults, is located along the upper margins of the uplifted metamorphic domes.

❹ Orientations of tension gashes and mineralized ore veins exhibit a gradual counterclockwise rotation of the maximum instantaneous xtension direction and therefore also of the applied principal stress orientations.

❺ The structures created during rock uplift and cooling display a gradual change from subhorizontal contraction within a strike-slip regime to subvertical contraction. We interpret this transition as an effect of the passage of the neutral surface within an upbending plate.

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