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Quartz, Dolomite and Calcite Microstructures and Textures within the Tauern Window (Eastern Alps)

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Quarz-, Dolomit- und Kalzitmikrostrukturen und Texturen im Tauernfenster (Ostalpen)

Zusammenfassung

Im Tauernfenster sind penninische kontinentale Lithosphäre und die darüberliegende, obduzierte penninische ozeanische Kruste in einer großen antiformen Domstruktur innerhalb der Internzone der Ostalpen aufgeschlossen. Grundsätzlich können innerhalb des Tauernfensters drei Deformationsphasen unterschieden werden. D_1 ist auf die Unterschiebung der penninischen kontinentalen Kruste im Tauernfenster und eine damit verbundene nordvergente Deckenstapelung zurückzuführen. Die Deformationsphase D_2 wird mit der darauffolgenden Kontinentkollision zwischen den penninischen kontinentalen Einheiten und dem europäischen Vorland in Zusammenhang gebracht, D_3 steht mit der Bildung der Domstruktur innerhalb des Tauernfensters in Verbindung. Während der Verdickung kontinentaler Lithosphäre und der Deckenstapelung (D_1) und der darauf folgenden intrakontinentalen Krustenverkürzung (D_2) wurden alle tektonischen Einheiten innerhalb des Tauernfensters weitgehend homogen verformt. Es wurden die Bedingungen für die plastische Verformung der wichtigsten gesteinsbildenden Mineralphasen (Quarz, Feldspat, Dolomit, Kalzit) während dieser Phasen krustaler Verformung erreicht. Generell können zwei Typen von Quarzmikrostrukturen, die sich auf D_1 zurückführen lassen, innerhalb des Tauernfensters unterschieden werden.

1) Equilibrierte, ausgeheilte Gefüge ohne kristallographische Vorzugsorientierung wurden nur im zentralen Teil des südöstlichen Tauernfensters festgestellt; das Vorkommen dieser Gefüge fällt ungefähr mit dem Erreichen amphibolitfazieller Metamorphosebedingungen im Zentralteil des Tauernfensters zusammen.
2) Im nordöstlichen und zentralen Teil des Tauernfensters sind die Mikrostrukturen für Quarz ebenfalls durch Gleichgewichtsgefüge charakterisiert, allerdings findet man gute kristallographische Vorzugsregelungen mit Kreuzgürtelverteilungen vom Typ I, die eine Verformungsgeometrie nahe der ebenen Verformung andeuten.

Für D_2 können ebenfalls zwei Typen von Quarzmikrostrukturen unterschieden werden:

1) Quarzkörner mit ausgeheilten Gefügen, aber gut erhaltenen kristallographischen Vorzugsregelungen. Die Quarz-c-Achsenverteilungen sind generell durch Kreuzgürtel vom Typ I charakterisiert, lokal findet man auch Kreuzgürtel vom Typ II oder schiefe Einfachgürtelverteilungen.
2) Ein zweiter Gefügetyp ist durch stark gelängte Körner und Gefüge charakterisiert, wie sie für Versetzungskriechen und Korngrenzwandern typisch sind. Man findet gut ausgebildete kristallographische Vorzugsregelungen.

Die Quarz-c-Achsenverteilungen zeigen Kreuzgürtel vom Typ I im Westteil des Tauernfensters und Einfachgürtel im Südostteil des Tauernfensters. Im westlichen Tauernfenster kann ein kontinuierlicher Übergang von Gefügen vom Typ (2) im Süden zu Gefügen vom Typ (1) im Norden dokumentiert werden. Die mikrostrukturelle Entwicklung zeigt auch, dass die Dombildung im Tauernfenster bereits während D_2 begonnen hat und nach der Equilibrierung unter amphibolit- bis grünschieferfaziellen Metamorphosebedingungen fortgesetzt wurde.

Kalifeldspat zeigt während D_1 die Bildung von Subkörnern. Im zentralen und östlichen Teil des Tauernfensters zeigt Plagioklas typische Gefüge für dynamische Rekristallisation.

Die Dolomitmikrostrukturen sind innerhalb des gesamten Tauernfensters und während aller Deformationsphasen sehr ähnlich. Sie dokumentieren dynamische Rekristallisation und sekundäre Korngrößenverkleinerung. Entlang des Nordostrandes des Tauernfensters ist Dolomit nicht von plastischer Verformung betroffen.

Die Kalzitmikrostrukturen sind in den zentralen Teilen des Tauernfensters sehr ähnlich. Die kristallographischen Vorzugsregelungen der D_1-bezogenen Gefüge sind während der darauffolgenden Metamorphose noch verstärkt worden; allerdings sind alle kristallographischen Vorzugsregelungen durch niedrigtemperierte Gefüge gekennzeichnet. Kristallographische Vorzugsregelungen, die auf D_2 bezogen werden, sind durch höhertemperierte Gefüge gekennzeichnet.

D_3 ist auf distinkte Zonen semiduktiler bis spröder Verformung beschränkt. D_3-Quarzgefüge sind durch die Bildung von Bandquarzen gekennzeichnet; die c-Achsen zeigen Kleinkreisverteilungen. D_3-bezogene Kalzitgefüge zeigen dynamische Rekristallisation und sekundäre Korngrößenverkleinerung, die bis zur Bildung von Ultramyloniten geht. Während der Exhumation und Dombildung (D_3) erfolgt die Deformation unter kontinuierlich abnehmenden Temperaturbedingungen. Entsprechend wurde die Deformation in rheologisch schwächere Bereiche verlegt. Während die plastische Verformung vom Quarz, Feldspat und Dolomit kontinuierlich abgeklungen ist, ist Kalzit bis in die letzten Phasen krustaler Verformung plastisch deformiert worden.

Abstract

The interior of the Tauern Window exposes underplated Penninic continental lithosphere and the overlying obducted Penninic oceanic crust within a large antiformal dome in the internal zone of the Eastern Alps. These units have been affected by a polyphase deformation history. Generally, three deformational events can be distinguished. D_1 is related to underplating of and top-to-the-N nappe stacking within the Penninic continental units of the Tauern Window. Deformation stage D_2 is interpreted to reflect the subsequent continent collision between the Penninic continental units and the European foreland, D_3 is related to the formation of the dome structure within the Tauern Window. During thickening of continental lithosphere and nappe stacking (D_1), and subsequent intracontinental shortening (D_2), these tectonic units have been deformed homogeneously. Conditions for the plastic deformation of the main rock-forming mineral phases (quartz, feldspar, dolomite, calcite) have been reached during these phases of crustal deformation. Generally, two types of quartz microstructures that are related to D_1 can be distinguished within the Tauern Window.

1) Equilibrated and annealed fabrics without Crystallographic Preferred Orientations (CPOs) have only been observed in the central part of the southeastern Tauern Window, which is in coincidence with amphibolite-grade metamorphic conditions.
2) In the northeastern and central part of the Tauern Window microstructures are characterized by quartz grains that show equilibrated fabrics, but well preserved CPOs with type I cross girdle distributions, indicating a deformation geometry close to plane strain.

During D_2, two types of quartz microstructures can be distinguished too:

1) Quartz grains that show equilibrated fabrics, but well preserved CPOs. The c-axes distributions are generally characterized by type I cross girdles, locally by type II cross girdles, and in places, oblique single girdle distributions.
2) A second type is characterized by highly elongated grains and fabrics typical for dislocation creep and grain boundary migration, and strong CPOs.

The c-axis distributions show type I cross girdles in the western part of the Tauern Window and single girdles in the southeastern part of the Tauern Window. In the western part of the Tauern Window, a continuous transition from type 2 microstructures in the south to type 1 microstructures in the north can be documented. The microstructural evolution also documents, that the dome formation in the southeastern and western Tauern Window has already started during D_2 and was continued subsequent to the equilibration during amphibolite to greenschist facies metamorphism.

K-feldspar partly exhibits subgrains. In the central part of the eastern Tauern Window, plagioclase is dynamically recrystallized during D_1.

The dolomite microstructures are very similar over the entire Tauern Window and for several phases of deformation. They indicate dynamic recrystallization and secondary grain size reduction. Along the northeastern margin of the Tauern Window, dolomite is not affected by plastic deformation.

The calcite microstructures are very similar in the interior parts of the Tauern Window. The CPOs of D_1-related fabrics seem to have been strengthened during subsequent equilibration. However, several CPOs are characterized by LT-microstructures. D_2-related CPOs are dominated by HT-fabrics.

D_3 is restricted to distinct zones of semiductile and brittle deformation. D_3-related quartz fabrics are characterized by the formation of ribbon grains; the c-axis shows small circle distributions. D_3-related calcite microstructures indicate dynamic recrystallization and secondary grain size reduction until the formation of ultramylonites. During exhumation and doming (D_3), deformation occurred at continuously decreasing temperatures. Accordingly, deformation was continuously transferred into rheologically weak lithologies. While the plastic deformation of quartz, feldspar and dolomite ceased continuously, calcite was deformed plastically until the final phases of crustal deformation.

1. Introduction

The evolution of textures and CPOs of quartz and calcite is well investigated, as is the development of active glide and climb systems for these minerals. The textural evolution, combined with microstructural studies, of quartz have been investigated by modern methods by, e.g., TULLIS et al. (1973), BLACIC (1975), BEHRMANN (1985), PRICE (1985), DELL' ANGELO & TULLIS (1986, 1989), PLATT & BEHRMANN (1986), SCHMID & CASEY (1986), LAW (1987), LAW et al. (1990), DEN BROK (1992). The evolution of textures resulting from different active glide and climb systems and different strain geometries has been modelled by LISTER et al. (1978), LISTER & PATERSON (1979), LISTER & HOBBS (1980), ETCHECOPAR (1977), ETCHECOPAR & VASSEUR (1987), JESSEL (1988a, b), WENK et al. (1989), WENK & CHRISTIE (1991), JESSEL & LISTER (1990), MAINPRICE & NICOLAS (1989). Investigations on dolomite were done by, e.g., WENK (1985), LEISS et al. (1994), and LEISS (1996). Calcite data are available from, for example, CASEY et al. (1978), SCHMID et al. (1980, 1987), WENK (1985), WENK et al. (1987), BORRADAILLE & MCARTHUR (1990), and BURKHARD (1993). Generally, calcite fabrics mainly reflect the final phases of crustal deformation at decreasing temperatures (e.g., BURKHARD, 1993). As quartz, dolomite, and calcite are the main rock forming minerals in the upper and middle crust, the investigation of the microstructures and CPOs of these minerals give important information on the deformation mechanisms within these crustal levels, and its rheology.

Underplated continental crust is often exposed within tectonic windows in internal zones of collisional orogens. These exposures often comprise lower plate continental units within metamorphic core complexes. Therefore, these exposures bear important information on the structural and metamorphic evolution of continental lithosphere that was in a lower plate position during continent-continent collision. The exhumation history of such metamorphic core complexes has been intensively studied in the last decades (e.g., CONEY, 1980; DAVIES, 1983; MALAVIELLE, 1987; LISTER & DAVIS; 1989, LISTER et al., 1984; BEHRMANN & FRISCH, 1990). Exhumation occurs mainly during the final stages of continent-continent collision, very often in an extensional regime (BEHRMANN, 1990; DEWEY, 1988; ENGLAND & MOLNAR, 1990; GENSER & NEUBAUER, 1989; HILL et al., 1992; NEUBAUER et al., 1995; PLATT, 1986, 1993; RATSCHBACHER et al., 1989, 1991; SELVERSTONE, 1988; HILL & BALDWIN, 1993). Removal of rigid hanging-wall crust is achieved by downward displacement along ductile low-angle normal faults that are directed either towards the foreland or subparallel to the orogen. However, these structures are generally located along the margins of such metamorphic dome structures, and they only document the final stages of the orogenic evolution. Consequently, deformational structures in the inner parts of the exhumed domes often document the evolution related to the underplating history. Microstructural studies combined with the evaluation of Crystallographic Preferred Orientations (CPOs) are important tools to get information on deformation mechanisms operating in naturally deformed rocks within such crustal sections. Furthermore, these studies give information on the rheological behaviour of the crust during several phases of crustal deformation.

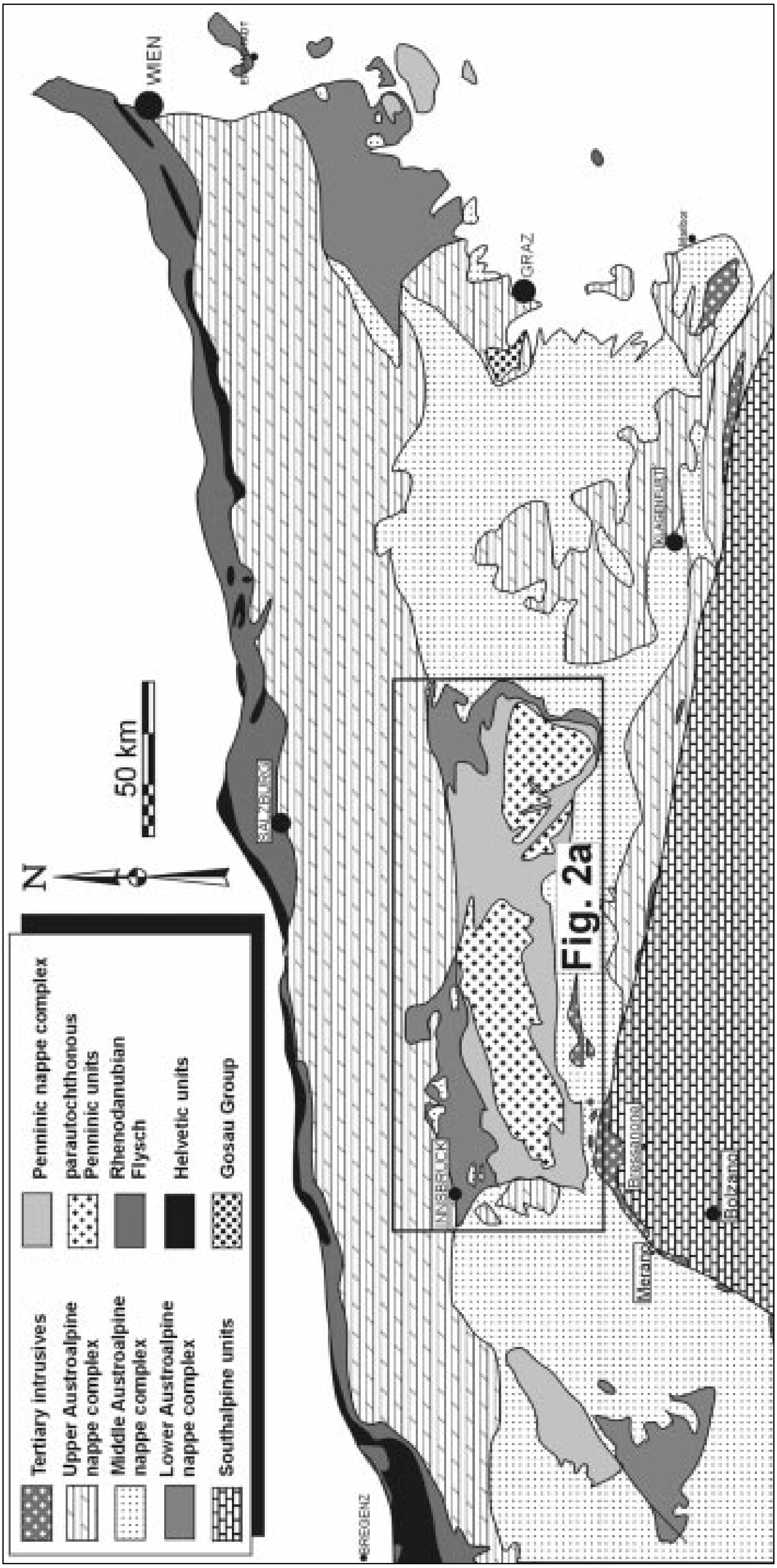
2. Geological Setting

The Tauern Window exposes the Penninic nappe complex in the foot-wall of the Austroalpine nappe complex (Text-Fig. 1), which forms the hanging-wall plate during Late Cretaceous and Early Tertiary continent-continent collision. The nappe stack includes from bottom to top (TOLLMANN, 1975, 1977; FRISCH, 1974, 1975; FRANK et al., 1987; KURZ et al., 1996, 1998b) (Text-Figs. 1,2):

1) The Venediger and Wolfendorn Nappes, which comprise a pre-Variscan basement (e.g., the Riffl Nappe) intruded by Variscan granitoids (the Zentralgneis), and a cover sequence of Jurassic metacarbonates (Hochstegen Marble Fm.), and Cretaceous metapelites and metapsammites (Kaserer Group).
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 (Rote Wand-Modereck Gneiss Lamella), covered by Permian to Triassic quartzites and Triassic metacarbonates, Jurassic breccias, calcareous micaschists and metatuffs, and Cretaceous metapelites and metapsammites. This rock assemblage represents a passive continental margin sequence.
5) The Glockner Nappe, comprising a former oceanic basement (serpentinites and other ultramafic rocks) and other lithologies of an ophiolitic sequence.
6) The Matrei Zone, characterized by metamorphic flysch sediments (mainly calcareous and carbonate-free micaschists), breccias and olistolithes mainly of Austroalpine derivation (FRISCH et al., 1987), including the Klammkalk, interpreted to represent an accretionary wedge.

All these units are affected by Cenozoic amphibolite to greenschist grade metamorphism subsequent to nappe stacking. These units are surrounded by Austroalpine units.

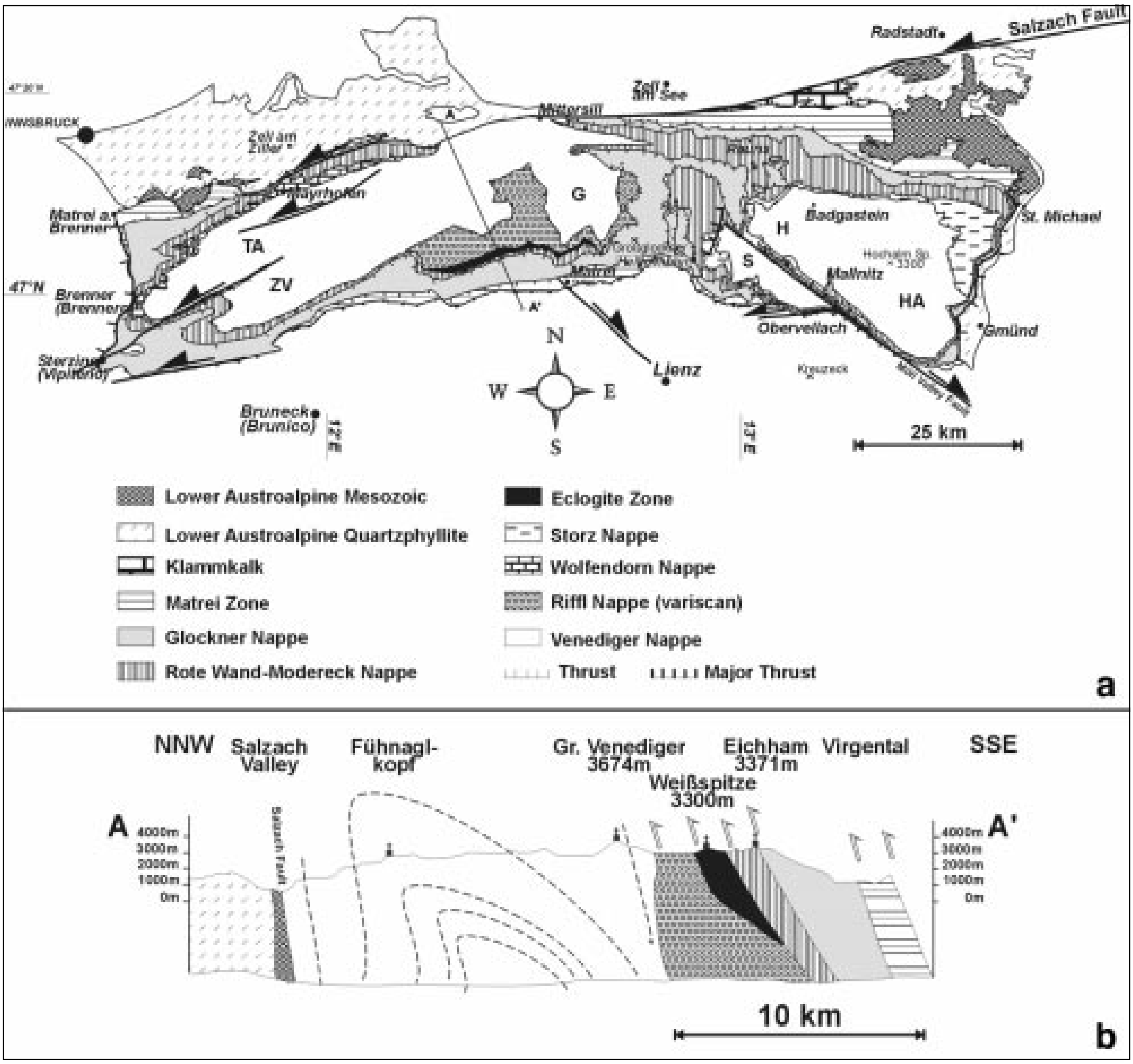
The Tauern Window is bordered by sinistral strike-slip faults along its northern and southern margins, that are linked with several major dextral faults (SCHMID et al., 1989; RATSCHBACHER et al., 1991; KURZ et al., 1994; KURZ & NEUBAUER, 1996; WANG & NEUBAUER, 1998) and by low-



Text-Fig. 1.
Simplified tectonic map of the Eastern Alps with location of the Tauern Window.

angle normal faults along its eastern and western margins (Selverstone, 1988; Behrmann, 1988, 1990; Genser & Neubauer, 1989) (Text-Figs. 1, 2). The arrangement of these major faults was interpreted in terms of a pull-apart structure (Genser & Neubauer, 1989), which triggered unroofing and subsequent exhumation and uplift of underplated lithosphere in the area of the Tauern Window.

The exhumation history of the Penninic units within the Tauern Window (Text-Figs. 1, 2) is well-constrained by petrological and geochronological (Cliff et al., 1985; Droop, 1985; Selverstone, 1985, 1988, 1993; Selverstone & Spear, 1985; Selverstone et al., 1984, 1991; Christensen et al., 1994), and by structural data (Behrmann, 1988; Genser & Neubauer, 1989; Kurz et al., 1994; Kurz & Neubauer, 1996; Selverstone, 1988). Furthermore, many structural field data exist, that are related to the pre-exhumation history of this unit (Bickle & Hawkesworth, 1978; Cliff et al., 1971; Droop, 1981; Ledoux, 1984; Frank et al., 1987; Lammerer, 1988; Behrmann & Ratschbacher, 1989; Behrmann, 1990; Kruhl, 1993; Oehlke et al., 1993; Wallis et al., 1993; Wallis & Behrmann, 1996; Kurz et al., 1996, 1998a; Lammerer & Weger, 1998). However, modern microstructural studies combined with the investigation of CPOs only exist for restricted areas and, generally, have only been used for kinematic interpretations in terms of shear criteria (e.g., Behrmann & Ratschbacher, 1989; Behrmann, 1990; Behrmann & Frisch, 1990; Kruhl, 1993; Wallis et al., 1993; Wallis & Behrmann, 1996), although the western part of the Tauern Window represents one of the classical areas of microstructural research (Sander, 1930, 1939, 1950, and references cited therein). Ge-



Text-Fig. 2.
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 Text-Fig. 2b (from KURZ et al., 1998b).
b) Section across the central part of the Tauern Window (for location see Text-Fig. 2a).

nerally, three major phases of deformation (D_1, D_2, D_3) can be distinguished within the Tauern Window (CLIFF et al., 1971; BICKLE & HAWKESWORTH, 1978; DROOP, 1981, 1985; CLIFF et al., 1985; 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 penetrative foliation (S_1), and a N-trending stretching lineation (L_1). D_2 is characterized by the development of a second penetrative foliation S_2, and an W- to NW-trending stretching lineation L_2. This phase of deformation is related to the emplacement of the Penninic nappe stack onto the European foreland. 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 to this phase of metamorphism. D_3 is related to the formation of the dome structure within the Tauern Window. This phase of deformation is characterized by the interference of multiply developed structures, and by deformation partitioning and shear localization along the dome margins (BEHRMANN & FRISCH, 1990; KURZ & NEUBAUER, 1996). Especially along shear zones bordering the Tauern Window, a new penetrative foliation S_3, associated with a stretching lineation L_3, was developed. Interior parts of the Tauern Window have been affected by multiple folding, too. Structural and kinematic data documenting this evolution have recently been published by KURZ et al. (1994, 1996, 1998a, 2000) and KURZ & NEUBAUER (1996). Additional data concerning the western part of the Tauern Window will be presented in this publication.

The detailed investigation of microstructures within the Tauern Window started with SANDER (1950). Other previous work, especially on quartz and calcite microstructures and CPOs, has been done by: BRUNEL (1980); BEHRMANN (1988, 1990); BEHRMANN & RATSCHBACHER (1989); BEHRMANN & FRISCH (1990); WECH (1991); GENSER (1992); KRUHL (1993, 1996); WALLIS et al. (1993); FUEGENSCHUH (1995); KURZ & NEUBAUER (1996); WALLIS & BEHRMANN (1996); STÖCKHERT et al. (1997), KURZ et al., 2000. However, these data only exist for limited areas. This study presents data of microstructures from several tectonostratigraphic units over the entire Tauern Window in order to constrain the deformational behaviour of several units during distinct phases of deformation, and to constrain the relation between deformation and metamorphism. A more comprehensive and detailed interpretation will be presented elsewhere.

3. Methods

We discuss the evolution of microstructures and CPOs within the Penninic Nappe complex of the Tauern Window during several phases of crustal deformation, and the implications for the rheological constraints during the evolution of a collisional orogen. We investigated several structural sections across the Tauern Window. Deformation geometry and shear sense are deduced from methods as described, for example, by SIMPSON & SCHMID (1983), RAMSAY & HUBER (1983), HANMER & PASSCHIER (1991), and BELL & JOHNSON (1992), and Crystallographically Preferred Orientation (CPO) patterns of quartz, dolomite, and calcite. X-ray texture analyses of quartz-, dolomite-, and calcite-mylonites were carried out with a Siemens D500 X-ray goniometer at the University of Graz (Austria). The evaluation of pole figures was done with the program TexAT v. 2.2c/ODF AT v.1.1a provided by Siemens Co. (Harmonic Method [BUNGE, 1981, 1985; BUNGE & ESLING, 1985]), and with the program MENTEX (Vector Method [SCHAEBEN et al., 1985; SCHAEBEN, 1994]). Both program packages include corrections for background and defocussing. Optical CPOs were measured with standard universal stage methods.

4. D_1 Microstructures

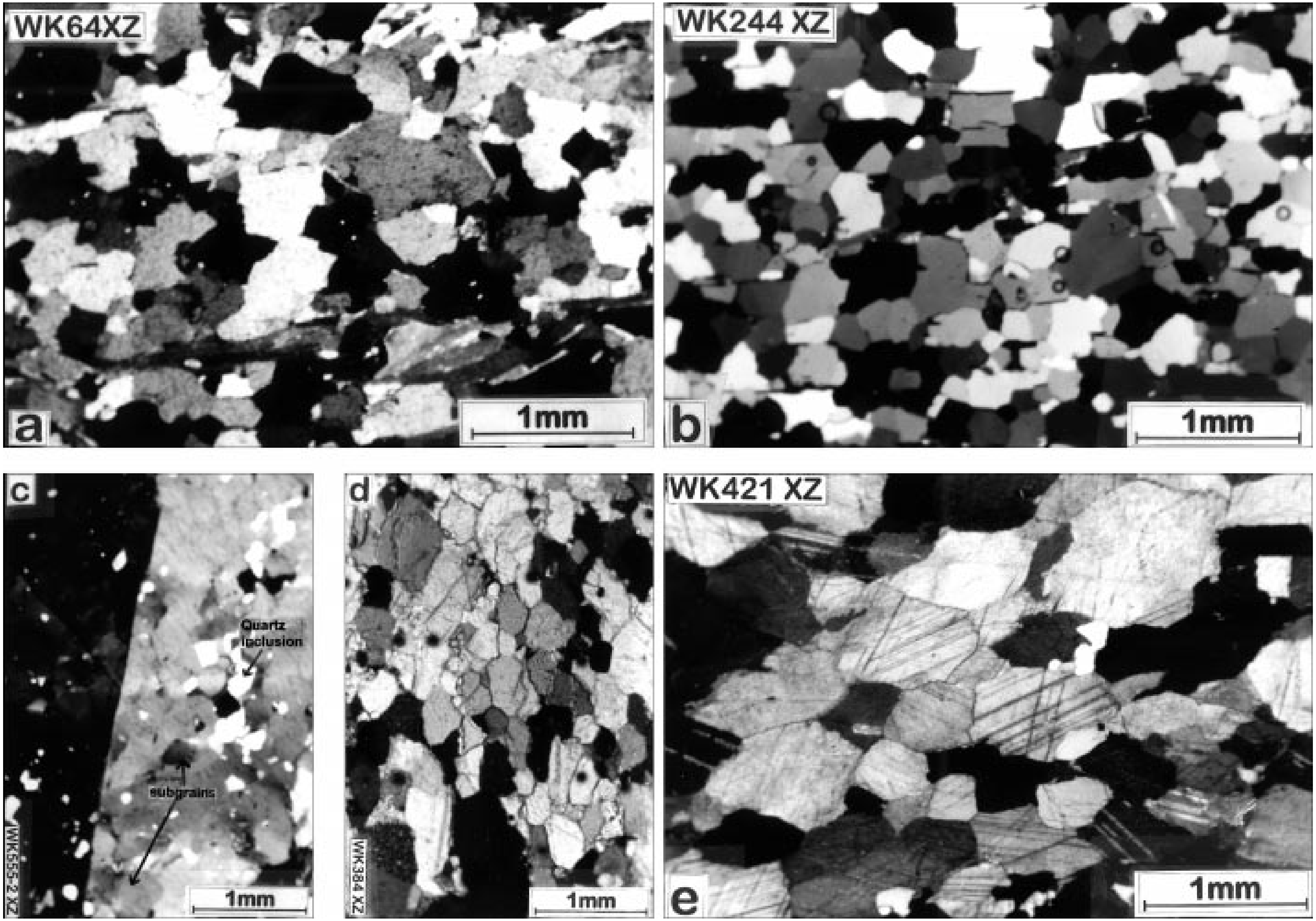
4.1. Quartz

In the southeastern part of the Tauern Window, structures related to D_1 are only observed within the uppermost sections of the Venediger Nappe. Quartz displays partly equilibrated, equigranular, polygonal grains with straight grain boundaries forming 120° triple junctions. The avarage grain size of the quartz grains equals ca. 0.5 to 0.7 mm (Text-Fig. 3a). Preferred orientations of crystallographic axes are missing. These features suggest annealing during subsequent metamorphism. Static annealing is also documented by white mica overgrowing the penetrative foliation. The coexisting mineral assemblage hornblende + clinopyroxene + biotite + epidote + albite that formed during the thermal peak in syenitic gneisses of the Venediger Nappe documents metamorphic conditions close to 500°C and 6 kbar (DROOP, 1982). Within the parautochthonous metasedimentary sequence of the Murtörl Group in the hanging-wall of the Zentralgneis quartz is characterized by equigranular grains that generally show straight grain boundaries forming triple junctions, too. The grain size highly depends on the presence of additional (mineral) phases (esp. graphite). Within graphitic quartzites the grain sizes of quartz equal max. 0.2 mm, within pure quartzites the grains reach 0.5–0.7 mm (Text-Fig. 3a). In places, the quartz grains show slight undulatory extinction.

In the northeastern part of the Tauern Window, D_1-related microstructures can be observed within the uppermost sections of the Venediger Nappe, within distinct sections of the Storz Nappe (especially the foot-wall parts including orthogneisses), the foot-wall part of the Rote Wand-Modereck Nappe, and distinct sections within the Glockner Nappe. Within the Venediger Nappe and the Storz Nappe, quartz forms equigranular, polygon-shaped grains, that exhibit straight grain boundaries forming triple junctions. The avarage size of the quartz grains equals ca. 0.5 to 0.7 mm within the Venediger Nappe, and ca. 0.2 to 0.4 mm within the Storz Nappe, but the grain size highly depends on the presence of additional mineral phases. Graphitic quartzites within the metasedimentary sequence of the Murtörl Group exhibit quartz grains that are significantly smaller (0.1-0.2 mm). Quartz grains show slight undulatory extinction, and in places the formation of subgrains. Subgrain boundaries are subparallel to quartz prism planes. Such grains very often show the development of deformation lamellae subparallel to the basal crystallographic planes, and deformation bands. Pebble quartzites at the base of the Rote Wand-Modereck Nappe contain quartz pebbles with grains of up to 1 mm in size. These coarse grains are elongated (R_f amounts to max. 5.0) and show highly undulatory extinction and formation of subgrains. Subgrain boundaries are oriented subparallel to the prism planes. These grains are characterized by lobate boundaries. Locally, the pebbles are cracked and show strain shadows, which might be an indication of locally elevated strain rates. The strain shadows are filled by dynamically recrystallized quartz grains with an avarage grain size of 0.2 mm. Therefore, the main deformation mechanism of quartz is dislocation creep, the recrystallization mechanism subgrain rotation.

Within the Glockner Nappe, D_1-related quartz fabrics are characterized by polygon-shaped equigranular grains that show a strong crystallographic preferred orientation. The grain boundaries are generally straight and form 120°-triple junctions; only distinct domains are characterized by slightly serrate grain boundaries. The average grain size amounts to 0.2–0.3 mm (Text-Fig. 3b).

The central part of the Tauern Window has generally not been affected by D_2. Therefore, microstructures that have been developed during or subsequently to D_1 are very well preserved. Quartz microstructures and quartz c-axis preferred orientations have been locally documented by WECH (1991). Quartz microstructures are very similar within all tectonostratigraphic units. Quartz is characterized by equilibrated fabrics, like equigranular grains that show a polygonal shape. The grain size highly depends on the occurrence of additional mineral phases. Pure quartzites show grain sizes of 0.2–0.4 mm, the average grain size amounts to ca. 0.3 mm. The grain boundaries are straight and are forming 120° triple junctions, serrated and lobate grain boundaries are weakly developed. In places, the grains were subsequently affected by low-temperature deformation, and, therefore, show undulatory extinction. Subgrains are locally developed as well as deformation lamellae and deformation bands. The subgrain boundaries are subparallel to prism planes. Only along the base of the Rote Wand-Modereck Nappe quartz is characterized by elongated grains (R_f ca. 2-3), serrate and lobate grain boundaries, strong undulatory extinction, and subgrain formation. The subgrains show undulatory extinction, too. Locally, the grains are surrounded by dynamically recrystallized grains. The elongated grains show a shape preferred orientation subparallel to



Text-Fig. 3.
Representative microstructures that are related to deformation phase D_1.
a) Annealed quartz microstructure, Venediger Nappe, southeastern Tauern Window.
b) Equilibrated quartz microstructure, Glockner Nappe, northeastern Tauern Window.
c) K-feldspar with formation of subgrains, central Tauern Window.
d) Dolomite microstructure, Rote Wand-Modereck Nappe, central Tauern Window.
e) Calcite microstructure, Rote Wand-Modereck Nappe, central Tauern Window.

the penetrative foliation. The main deformation mechanism appears to represent dislocation creep.

In the western part of the Tauern Window, quartz microstructures related to D_1 are restricted to local domains, especially to quartzites and dolomite marbles. Quartz is characterized by equigranular, polygon-shaped grains, that exhibit straight grain boundaries forming triple junctions, and only slight undulatory extinction. The average grain size of the quartz grains equals ca. 0.2 to 0.4 mm.

4.2. Feldspar

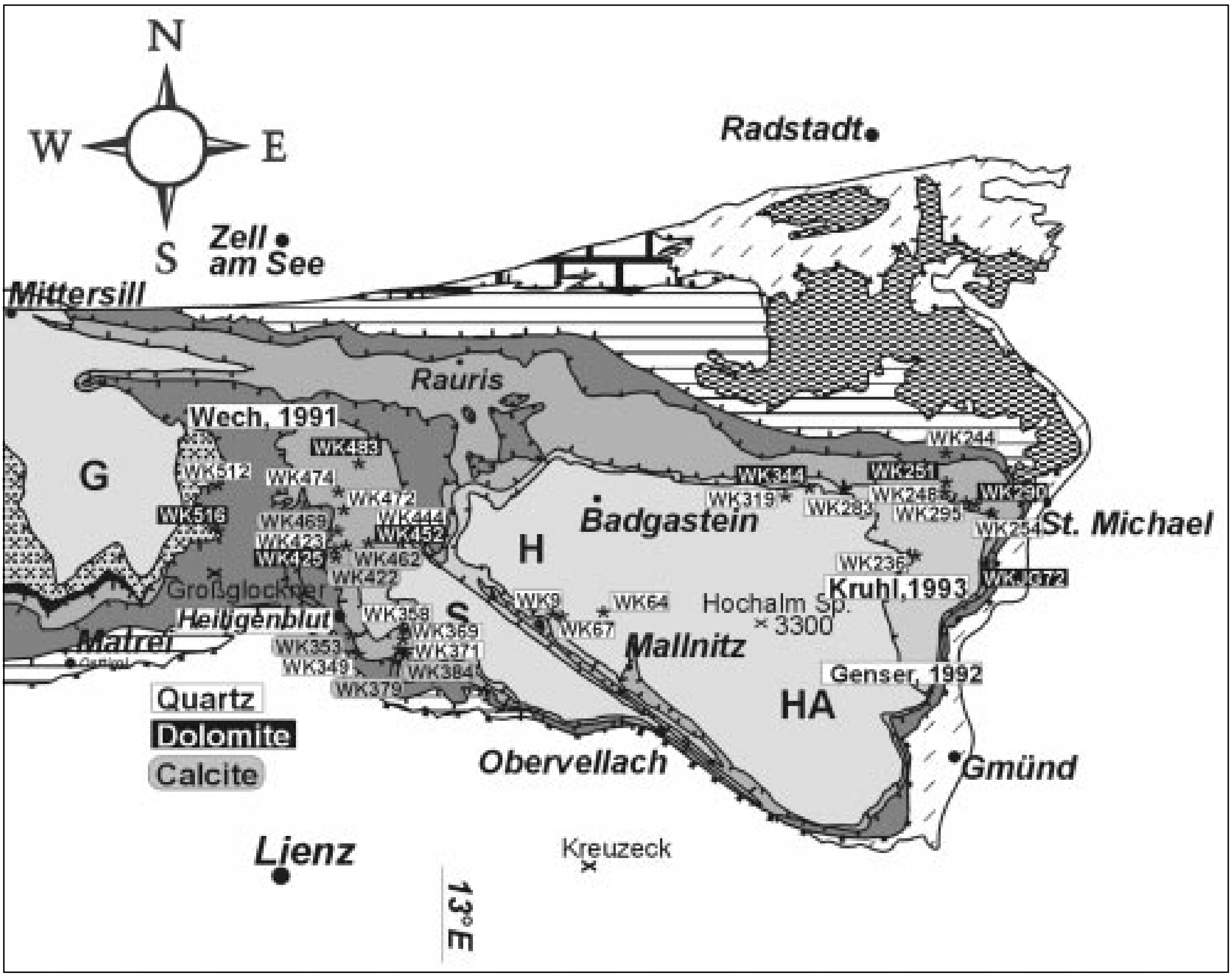
Within orthogneisses, plagioclase and K-feldspar show undulatory extinction. K-feldspar is often characterized by the formation of subgrains. Plagioclase (albite to oligoclase in composition) is slightly optically zoned. Generally, the albitic cores show small rims of oligoclase. Plagioclase is characterized by undulatory extinction, and by minor development of subgrains. This implies that the main deformation mechanism of albite was low temperature plasticity. K-feldspar shows undulatory extinction, too. Within orthogneisses and arkosic gneisses of the Rote Wand-Modereck Nappe, K-feldspar shows high undulatory extinction and locally the formation of subgrains (Text-Fig. 3c) with a size of up to 0.5 mm. Within phyllonites and white schists biotite, K-feldspar and plagioclase are continuously consumed and replaced by phengitic white mica and chlorite.

4.3. Dolomite

Dolomite microstructures are very similar within all tectonostratigraphic units. Dolomite marbles occur as fine-grained mylonites. The dolomite grains show a uniform grain size that does generally not exceed 0.2, max. 0.3 mm (Text-Fig. 3d). Grain sizes of max. 0.3 mm are only locally recorded. The grains are slightly elongated subparallel to the penetrative foliation (R_f ca. = 1.5 to 2.0). The grain boundaries are generally straight and form triple junctions, serrate grain boundaries are less developed. Few grains are twinned, but these grains show only one set of twins. Only within the Matrei Zone dolomite marbles occur as massive, coarse-grained rocks without internal foliation.

4.4. Calcite

Calcite mainly occurs within marbles and calcareous micaschists. The calcite microstructures are very similar within all tectonostratigraphic units. Locally, especially in the southeastern and eastern part of the Tauern Window, coarse, isometric or slightly elongated grains with a size of up to 0.5 mm, show serrated grain boundaries and the



Text-Fig. 4.
Tectonic map of the eastern and central Tauern Window, displaying sample locations for textures documented in Text-Figs. 5–10.
For legend see Text-Fig. 2a.

development of polysynthetic twin lamellae. These grains are surrounded by dynamically recrystallized grains with a size of ca. 0.2 mm. In the central part of the Tauern Window, calcite is only characterized by the formation of isometric, polygon-shaped grains with ca. 0.5 mm in size (Text-Fig. 3e). These grains mainly show straight grain boundaries; slighty serrated grain boundaries are only developed in local domains. The grains generally show the formation of e-twins.

5. D_1 Crystallographic Preferred Orientations (CPOs)

5.1. Quartz

In the southeastern part of the Tauern Window, the quartz c-axes display randomly distributed patterns within the upper sections of the Venediger Nappe (Text-Figs. 4, 5). Within the parautochthonous sedimentary sequence (Murtörl Group) in the hanging-wall of the Zentralgneis, quartz c-axes [001] are characterized by well developed oblique type I to type II cross girdle distributions. The obliquity of the cross girdles documents a top-to-the-N sense of shear. Maxima can be observed near Y, but only show MRD (Multiples of Random Distribution) values of ca. 2.0–2.4 (Text-Fig. 5). The a-axes [110] and the poles to the prisms [100] are distributed along two girdles with small angles to the X-Y-plane of the finite strain ellipsoid. The poles to the positive rhombs $<r>$ [101] are distributed along a girdle within the Y-Z-plane, the poles to the negative rhombs $<z>$ [011] plot along two girdles, with small angles to the Y-Z-plane.

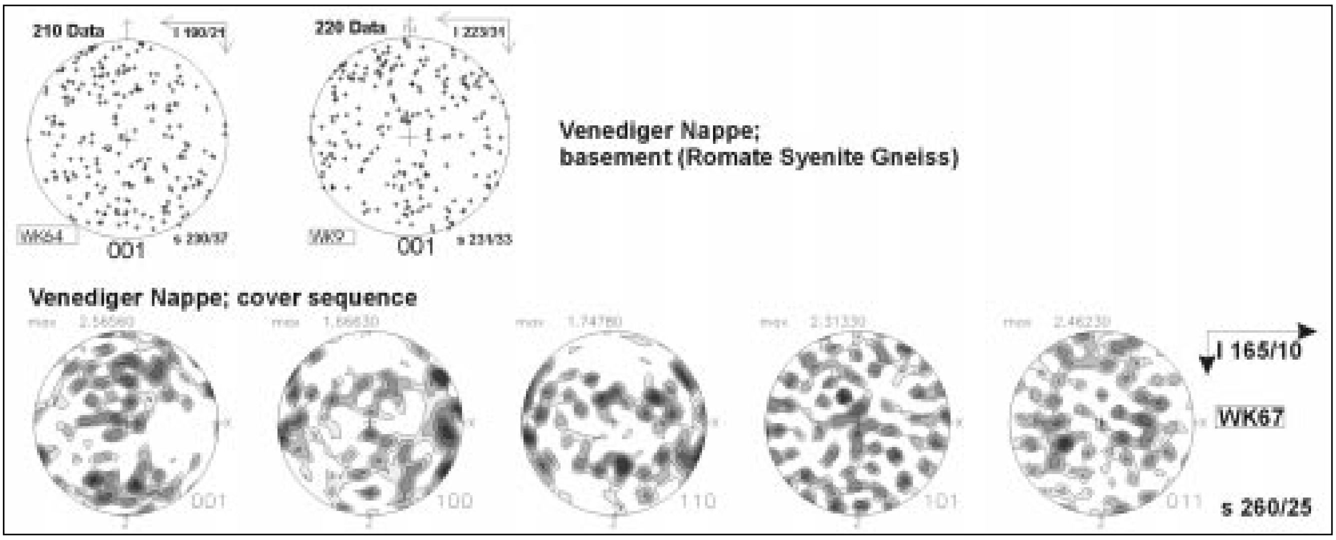
In the central part of the Tauern Window, quartz CPOs that are related to D_1 have been investigated along the base of the Rote Wand-Modereck Nappe, within the central part of the Rote Wand-Modereck Nappe, within the hanging-wall sections of the Riffl Nappe (near the base of the Glockner Nappe), and along the base of the Glockner Nappe (Text-Fig. 4).

The c-axes [001] distributions (Text-Fig. 6) at the base of the Rote Wand-Modereck Nappe are characterized by two clusters that are positioned between the Y- and Z-axes. Relics of small circle distributions are observable. The asymmetric arrangement of the clusters indicates top-to-the-N sense of shear during D_1. The a-axes [110] and the poles to the prism planes [100] are distributed along a great circle which is ca. 30° oblique to the X-Y plane, indicating a top-to-the N sense of shear, too. Two clusters are located near X. Towards the hanging-wall, symmetrical or slightly asymmetrical small circle distributions of the c-axes are developed continuously. One cluster is often located within Y, but continuously diminishes to the hanging-wall, two clusters are positioned between the Y- and Z-axes. The a-axes [110] and the poles to the prism planes [100] are distributed along two girdles running subparallel to the X-Y plane.

The quartz c-axes distributions within the Riffl Nappe, in the central part of the Rote Wand-Modereck Nappe, and along the base of the Glockner Nappe are very similar (Text-Fig. 6). The quartz c-axes show symmetrical type I cross girdles. The two girdles can be distinguished near the Z-axis. They show opening angles between 30 and 40°. Two maxima are located near the periphery of the equal angle projection, two near the Y-axis, one cluster is located within the Y-axis. Leading edges and trailing edges can be distinguished, but single girdle distributions are generally not developed. The asymmetry of these fabrics indicates top-to-the N sense of shear. The a-axes show variable distributions (Text-Fig. 6).

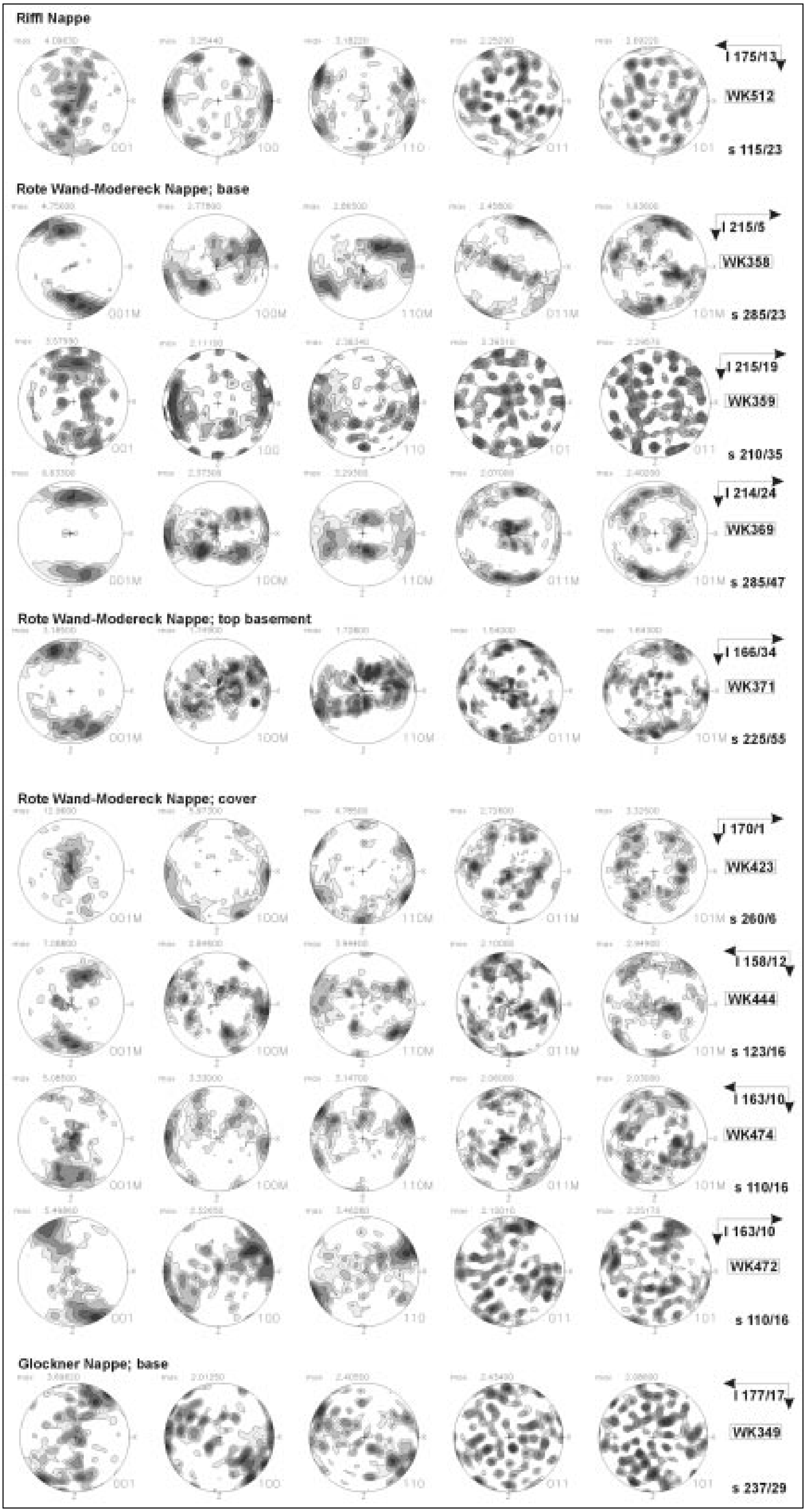
In the central part of the Rote Wand-Modereck Nappe the cluster within Y is stronger, the clusters between Y and Z diminish continuously. If complete cross girdles are developed, the a-axes [110] and the poles to the prism planes [100] are distributed along a small circle centered within the X-axis. Single girdle c-axes distributions are associated with a-axes and prism poles that are distributed along a girdle that is oriented ca. 30° oblique to the X-Y plane. The poles to the positive rhombs $<r>$ [101] are distributed along a great circle within the Y-Z plane; the poles to the negative rhombs $<z>$ [011] plot along two girdles with small angles to the Y-Z-plane.

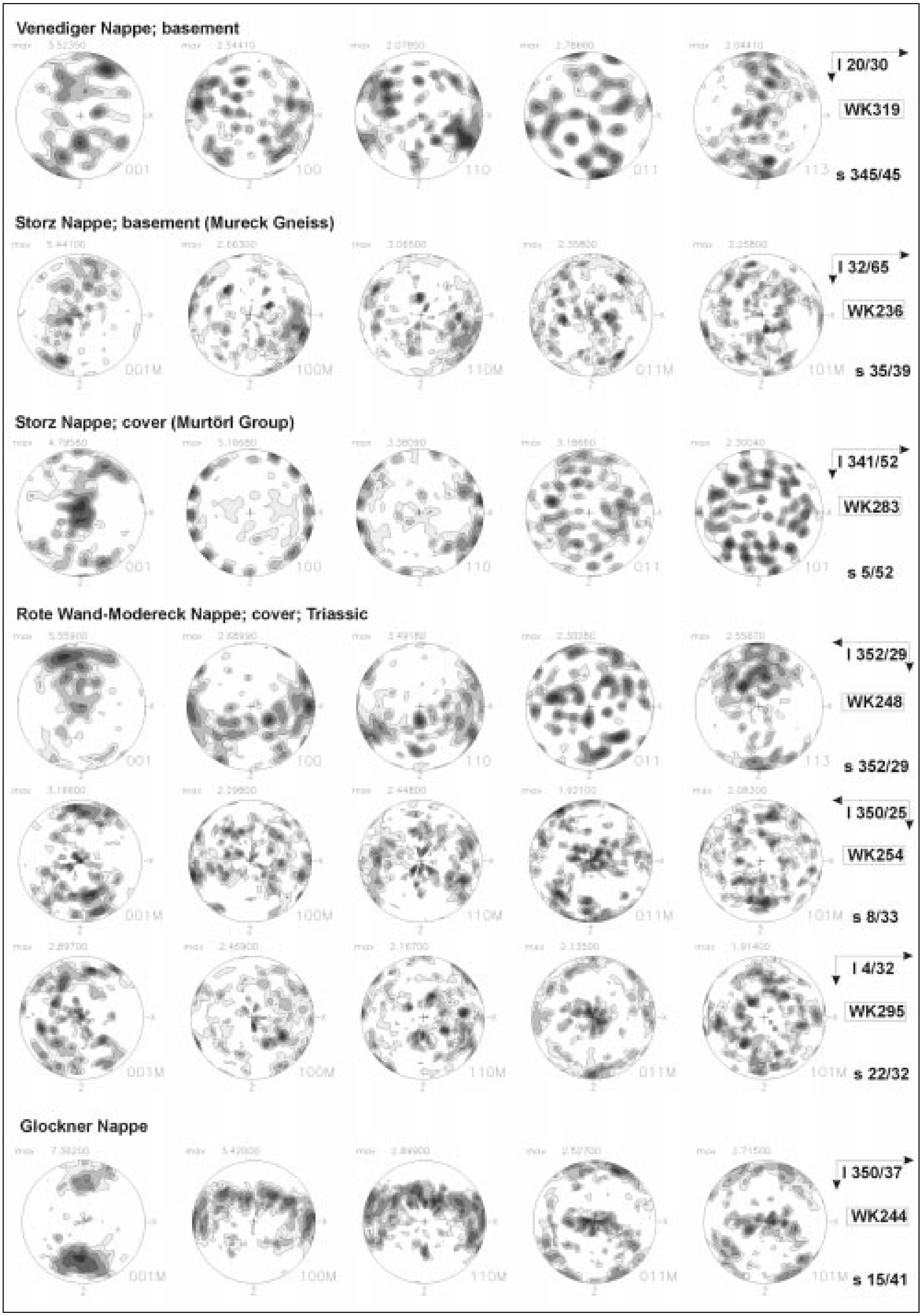
Quartz c-axes distributions within the northeastern part of the Tauern Window (Text-Fig. 4) are generally characterized by type I cross girdles (Text-Fig. 7). The opening angle of the conjugate girdles equals ca. 10-15°. Two maxima are observable near the Y-axis, two clusters are situated near Z. The asymmetry documents a top-to-the



Text-Fig. 5.
Representative quartz Crystallographic Preferred Orientations (CPOs) that are related to deformation phase D_1, southeastern Tauern Window.
Samples WK9 and WK64 (top): U-stage measurements; others: X-ray textures (equal angle projections; logarithmic gradation of isolines; first isoline: uniform distribution; fifth isoline: 85% of maximum; M: calculation by using the Vector method of SCHAEBEN et al. (1985); SCHAEBEN (1994).

Text-Fig. 6.
Representative quartz CPOs that are related to deformation phase D_1, central Tauern Window.
Equal angle projections; logarithmic gradation of isolines.
First isoline: uniform distribution; fifth isoline: 85 % of maximum; M: calculation by using the Vector method of SCHAEBEN et al. (1985); SCHAEBEN (1994).





Text-Fig. 7.
Representative quartz CPOs that are related to D_1 , northeastern Tauern Window.
For explanation see Text-Figs. 5, 6.

NNE sense of shear during D_1. The a-axes [110] and the poles to the prisms [100] are distributed along a girdle within the X-Y-plane, with a maximum near X. The poles to the rhombs [101] [011] form girdle distribution subparallel to the Y-Z-plane. Within the Rote Wand-Modereck Nappe the quartz c-axis distributions are characterized by very well developed symmetrical or just slightly asymmetrical type I cross girdles (Text-Fig. 7). Two small circles around the Z-axis with an opening angle of ca. 30-40° are connected by a single girdle that runs through the Y-axis. Four clusters are arranged symmetrically around the Z-axis at an angle of ca. 45°, two clusters are situated symmetrically near the Z-axis. One cluster is situated in Y. The a-axes [110] and the poles to the prism planes [100] show a symmetrical small circle distribution centered within the X-axis of the finite strain ellipsoid. Four clusters are situated along these small circles, that show an opening angle of ca. 90°. The poles to the rhombs [101] [011] are characterized by a single girdle distribution perpendicular to the foliation plane (Text-Fig. 7).

Within the Glockner Nappe in the northeastern part of the Tauern Window the quartz c-axes are distributed along a symmetrical type I cross girdle, but only relics of the leading and trailing edges are observable. Three clusters are situated along the girdle; one in the Y-axis, two clusters are located ca. 50-60° away from the Y-axis (Text-Fig. 7). The a-axes [100] and the poles to the prism planes [110] are distributed along two great circles with small angles to the foliation plane.

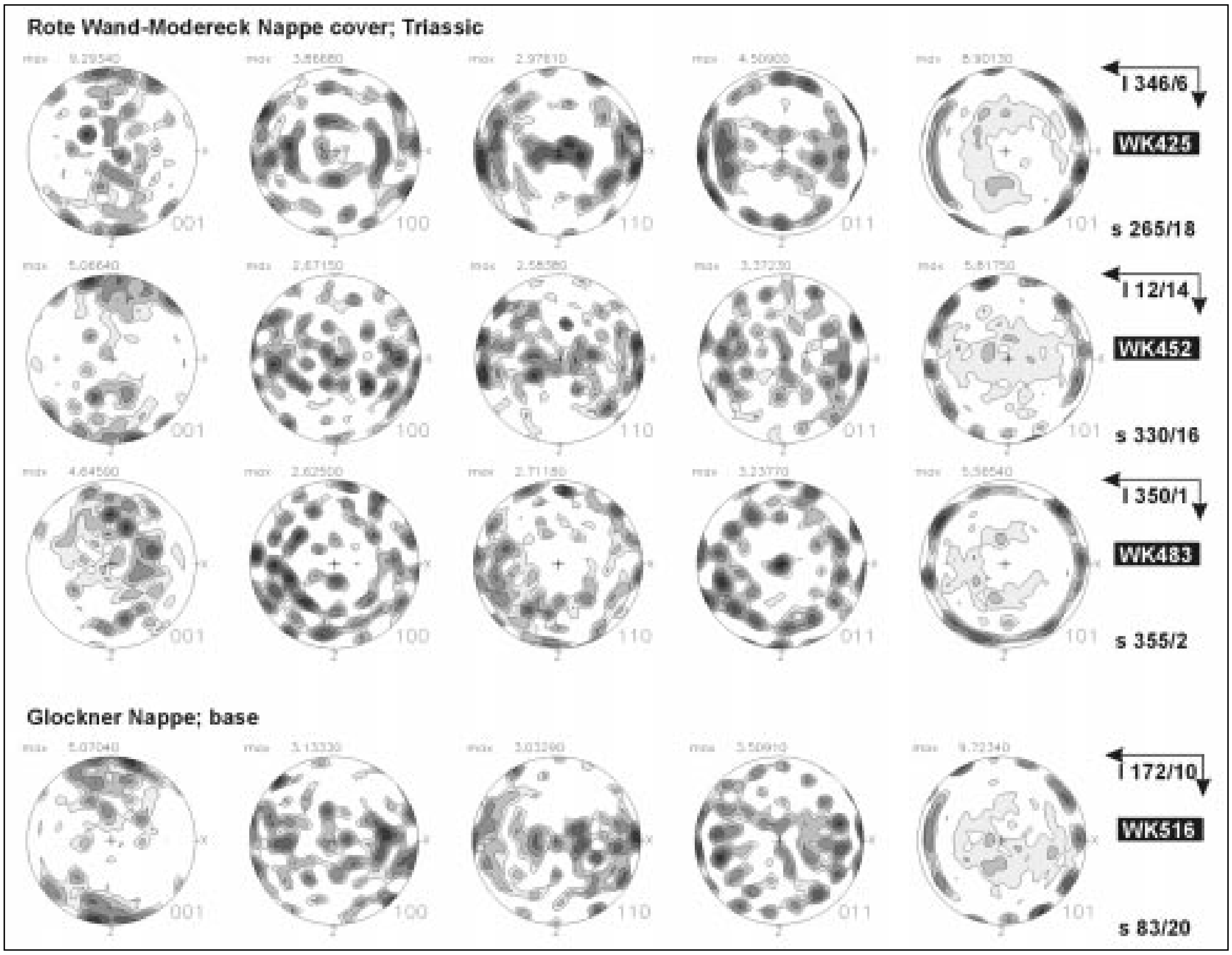
In the western part of the Tauern Window, the c-axes show remnants of a type I cross girdle distribution, the a-axes and the poles to the prisms are characterized by a weak preferred orientation only.

5.2. Dolomite

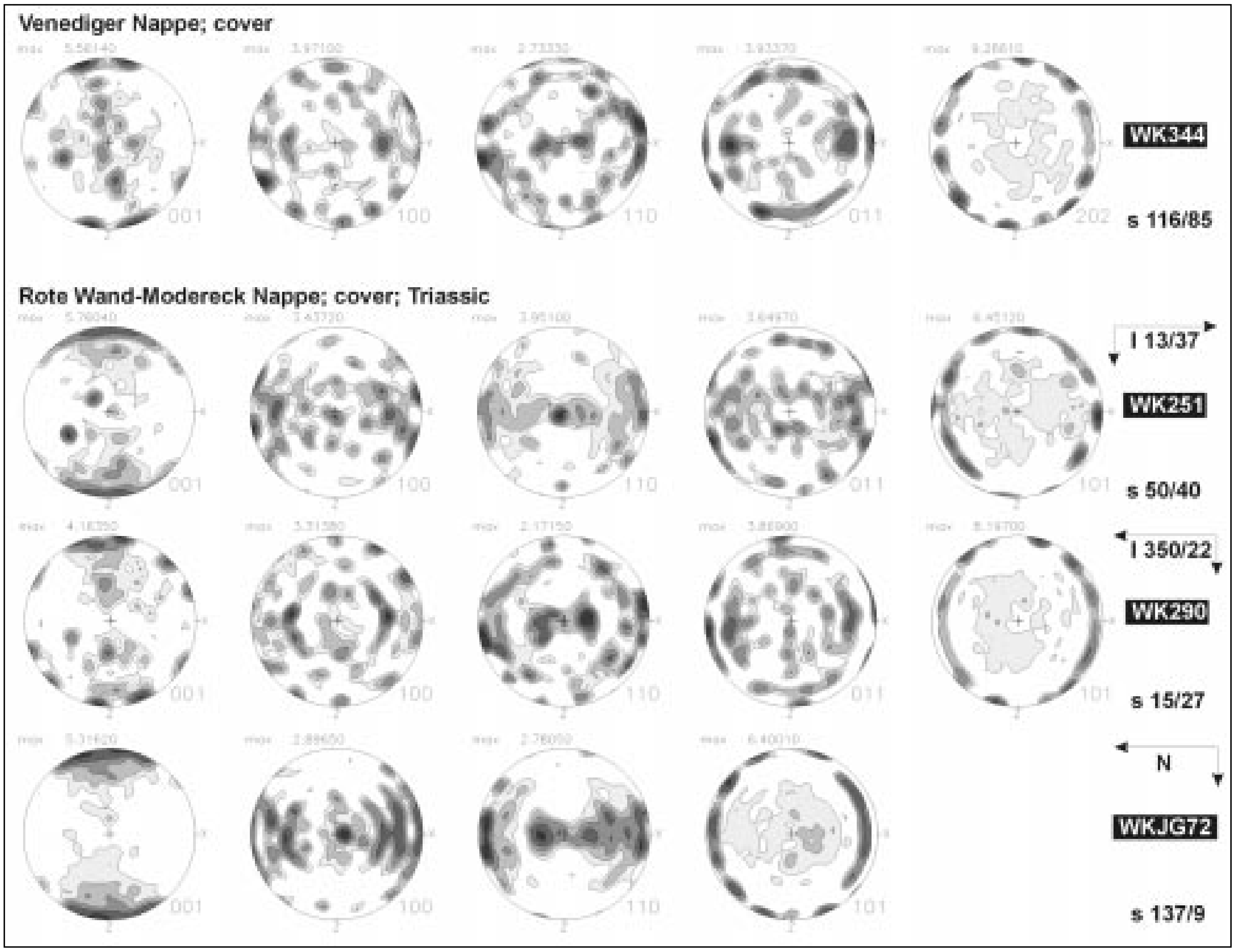
Dolomite CPOs are very similar over the entire Tauern Window, and within several tectonostratigraphic units (Text-Figs. 4, 8, 9). The c-axes [001] generally form single girdle distributions within the Y-Z-plane of the finite strain ellipsoid. One maximum is centered near the Z-axis. The a-axes [110] and the poles to the prism planes [100] are distributed along a girdle within the X-Y-plane, with one maximum near the X-axis. The poles to the rhombs [101] [011] plot along girdles subparallel to the Y-Z-plane.

5.3. Calcite

Calcite CPOs that are related to D_1 can only be observed in the central part of the Tauern Window (Text-Figs. 4, 10). The c-axes [001] generally form clusters near the Z-axis of the finite strain ellipsoid. In places, these clusters are asymmetrically arranged; the fabric asymmetry documents top-to-the N sense of shear. Within cal-



Text-Fig. 8.
Representative dolomite CPOs that are related to D_1, central Tauern Window.
For explanation see Text-Figs. 5, 6.



Text-Fig. 9.
Representative dolomite CPOs that are related to D_1, northeastern Tauern Window.
For explanation see Text-Figs. 5, 6.

cite-dolomite marbles, the calcite c-axes form single girdle distributions within the Y-Z-plane. 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 oriented obliquely to the foliation plane; the angle of the fabric asymmetry equals 1–10°.

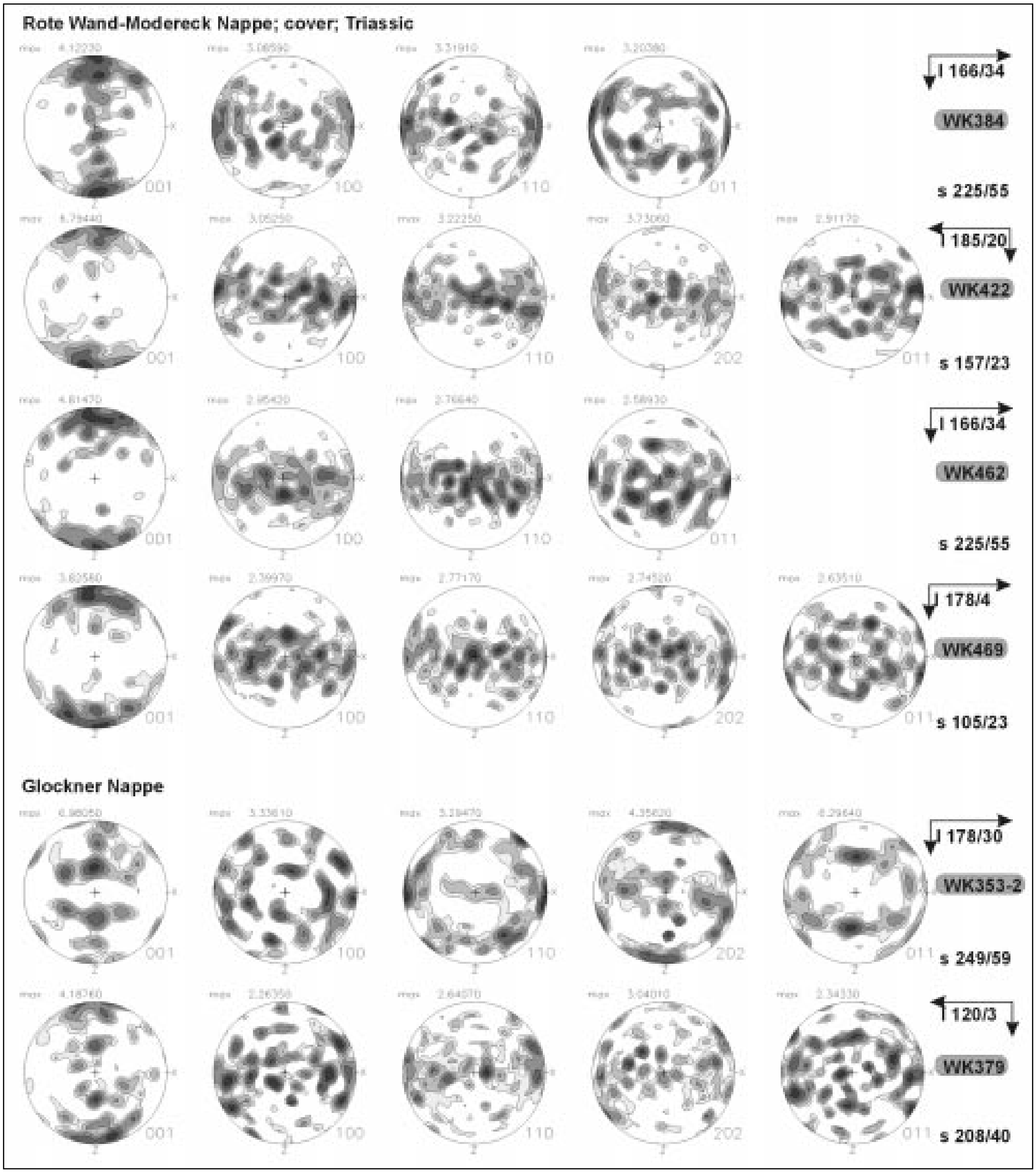
6. D_2 Microstructures

6.1. Quartz

In the southeastern part of the Tauern Window, quartz is characterized by high temperature (HT) fabrics like serrate and lobate grain boundaries, and subgrain formation (Text-Fig. 11a). The subgrains show undulatory extinction. Most of the subgrain boundaries are oriented parallel to the prism-planes. In places the elongated grains show a shape preferred orientation documenting a top-to-the-NW simple shear component during deformation phase D_2. Very often, the elongated grains are oriented subparallel to the penetrative foliation. The main mechanism of dynamic recrystallization is assumed to be grain boundary migration. During grain boundary migration white mica is overgrown by dynamically recrystallized quartz grains. Only within the Storz Nappe quartz is characterized by equigranular grains that generally show straight grain boundaries forming triple junctions. The grain size highly depends on the presence of additional mineral phases. In places, the grains show slight undulatory extinction. The Glockner Nappe in the southeastern Tauern Window is restricted to single small structurally reduced layers and does not exhibit adequate lithologies for the study of quartz microstructures and CPOs.

In this area of the Tauern Window, the quartz fabrics document, that a main part of the D_2 deformational event happened either at peak conditions of, or subsequent to the amphibolite to greenschist facies metamorphic overprint.

In the northeastern part of the Tauern Window, the D_2-related structures are penetrative within the Glockner Nappe and the Matrei Zone. Quartz microstructures are very similar within these units. Quartz forms equigranular, polygon-shaped grains that exhibit straight grain boundaries forming triple junctions. Slightly serrated grain boundaries have locally been observed. The average size of the quartz grains equals ca. 0.2 to 0.4 mm, but the grain size highly depends on the presence of additional (mineral) phases, esp. white mica, chlorite, and graphite; generally, larger grains occur in monomineralic rocks. The quartz grains show slight undulatory extinction and, in places, the formation of subgrains. In this area of the Tauern Window, D_2 generally pre-dates or is contemporaneous to the amphibolite to greenschist facies metamorphic overprint; further low-temperature deformational overprint is just related to subsequent doming (D_3) and does not significantly affect the (quartz) fabrics.



Text-Fig. 10.
Representative calcite CPOs that are related to D_1, central Tauern Window.
For explanation see Text-Figs. 5, 6.

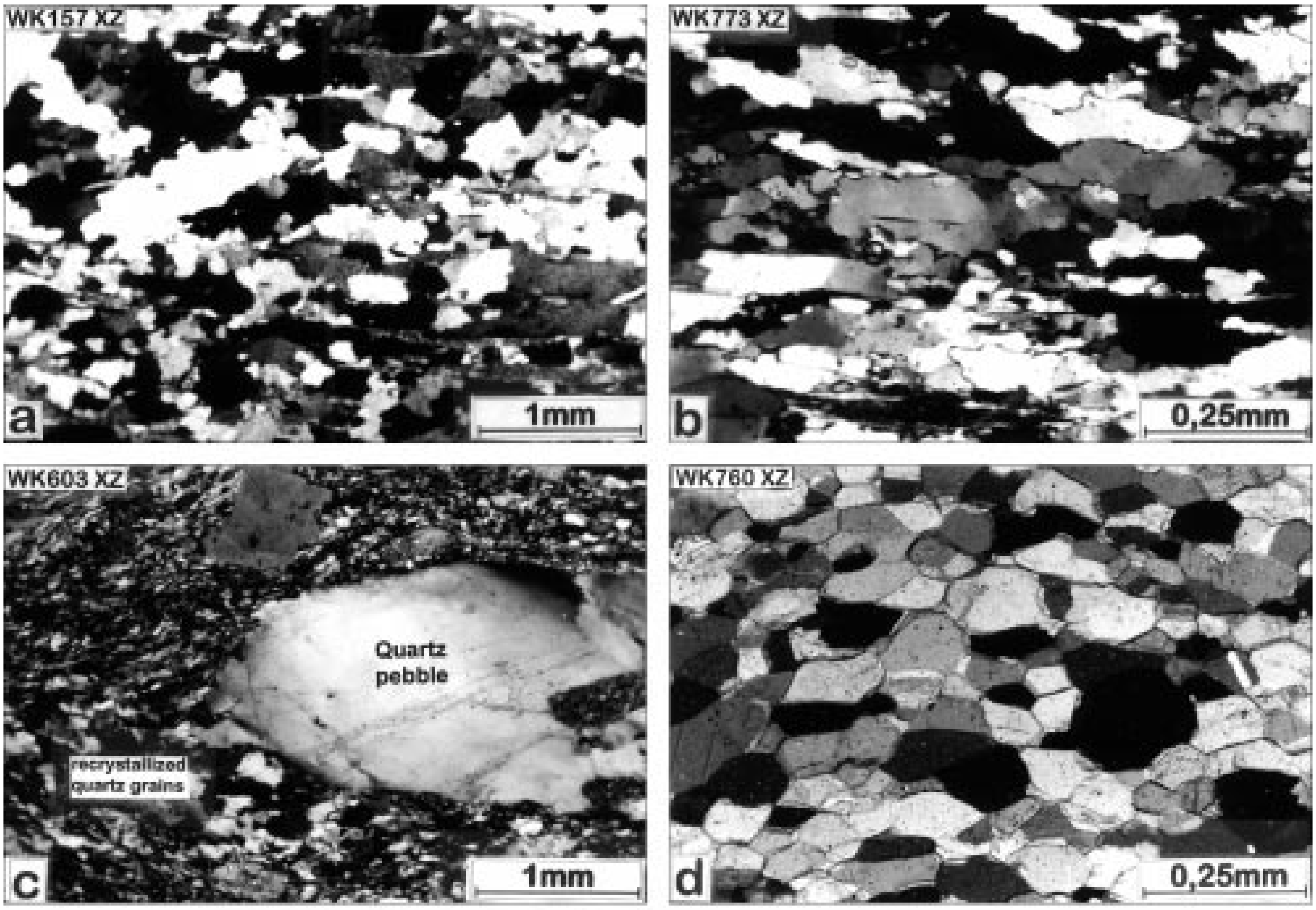
In the central southern part of the Tauern Window, the quartz microstructures are very similar in the majority of tectonic units within this region. Quartz is characterized by equigranular grains that show a polygonal shape. Pure quartzites show a grain size of 0.2–0.4 mm, the average grain size equals ca. 0.3 mm. The grain boundaries are straight and form 120° triple junctions, serrated grain boundaries are less developed. In this area of the central southern Tauern Window, D_2 generally pre-dates or is contemporaneous to the amphibolite to greenschist facies metamorphic overprint; further low-temperature deformational overprint is just related to subsequent doming and does not significantly affect the (quartz) fabrics.

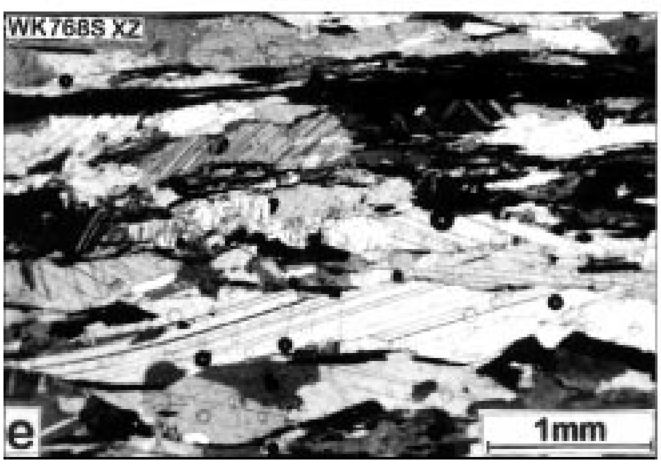
The western Tauern Window (Text-Fig. 12) was nearly entirely affected by D_2. D_1-related fabrics are only locally preseved (Text-Fig. 12). In the southern section of the western Tauern Window, the quartz microstructures that are related to D_2 are very similar within most tectonic units. Quartz is characterized by strongly elongated grains, serrate and lobate grain boundaries, strong undulatory extinction, and subgrain formation (Text-Fig. 11b). The subgrains show undulatory extinction, too. In places, the elongated grains show a shape preferred orientation documenting a top-to-the W simple shear component during deformation D_2, but generally the elongated grains are arranged subparallel to the penetrative foliation. The main deformation mechanism is dislocation creep, the main mechanism of dynamic recrystallization is grain boundary migration.

The deformation of quartz decreases significantly from the south to the north. In the southern part of the western Tauern Window, the elongation of the quartz grains (R_f ca. 3.0–3.5) is significantly higher than in the northern part of the western Tauern Window (R_f amounts to ca. 1.6–2.2). In the northern part lobate grain boundaries are less developed than in the southern part. Very often, straight grain boundaries are still observable in the northern part. Triple junctions may be recorded locally.

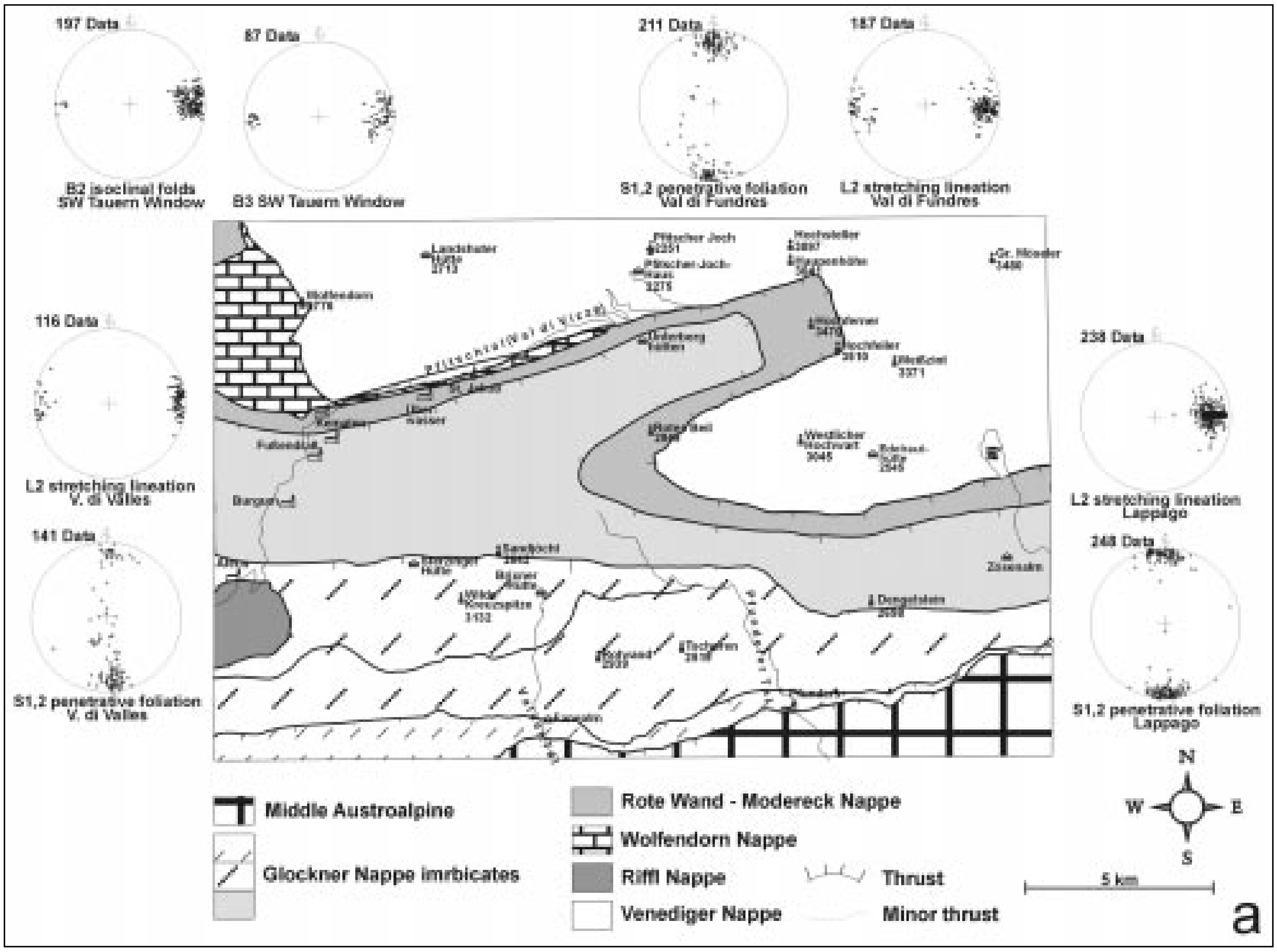
Pebble quartzites within the Rote Wand-Modereck Nappe and the "Porphyrmaterialschiefer" within the Venediger Nappe contain quartz pebbles and quartz grains of volcaniclastic derivation. The grains can reach up to 3 mm in size. These coarse grains are elongated (R_f amounts to max. 8.0) and show high undulatory extinction and strong formation of subgrains (Text-Fig. 11c). The subgrain boundaries are oriented subparallel to the prism planes. The grains are characterized by lobate boundaries.

Locally the pebbles are cracked and show strain shadows, which might be an indication of locally elevated strain rates. The strain shadows are filled by dynamically recrystallized quartz grains with an average grain size of 0.2 mm (Text-Fig. 11c).





Text-Fig. 11.
Representative microstructures that are related to deformation phase D_2.
a) Quartz microstructure, Rote Wand-Modereck Nappe, southeastern Tauern Window.
b) Quartz microstructure, Glockner Nappe, southwestern Tauern Window.
c) Deformed quartz pebble, surrounded by dynamically recrystallized grains, Venediger Nappe, northwestern Tauern Window.
d) Dolomite microstructure, Venediger Nappe, southwestern Tauern Window.
e) Calcite microstructure, Glockner Nappe, southwestern Tauern Window.



Text-Fig. 12.
Tectonic maps of the southwestern Tauern Window (a) and northwestern Tauern Window (b, opposite page) with orientation data of the poles to the penetrative foliation $S_{1,2}$, of the stretching lineations L_1, L_2 and of fold axes B_2 and B_3.
Equal area projections, lower hemisphere (from KURZ, 1997).

These microstructures indicate, that the main deformation mechanism of coarse-grained quartz is dislocation creep (mainly dislocation glide), too; however, the dominant recrystallization mechanism was subgrain rotation (KNIPE, 1989).

Going from N to S, subgrains are stronger developed continuously, and suturing of quartz-quartz grain boundaries becomes stronger. Generally, subgrains, deformation lamellae and deformation bands dominate in the northern part of the western Tauern Window; dynamic recrystallization is dominated by subgrain rotation.

The development of sutured quartz-quartz grain boundaries increases to the south. In the southern part of the western Tauern Window dynamic recrystallization is dominated by grain boundary migration.

Only along the southern margin of the western Tauern Window, the quartz microstructures are again characterized by LT-fabrics, similar to the northwestern part of the Tauern Window. This area coincides with the area of greenschist facies metamorphic conditions (e.g., HÖCK, 1980).

The deformation of quartz also depends on the presence of additional mineral phases. In rocks that contain additional phyllosilicates, like biotite, phengite and chlorite, quartz is less elongated than in rocks that either are pure quartzites or contain plagioclase and K-feldspar as additional mineral phases.

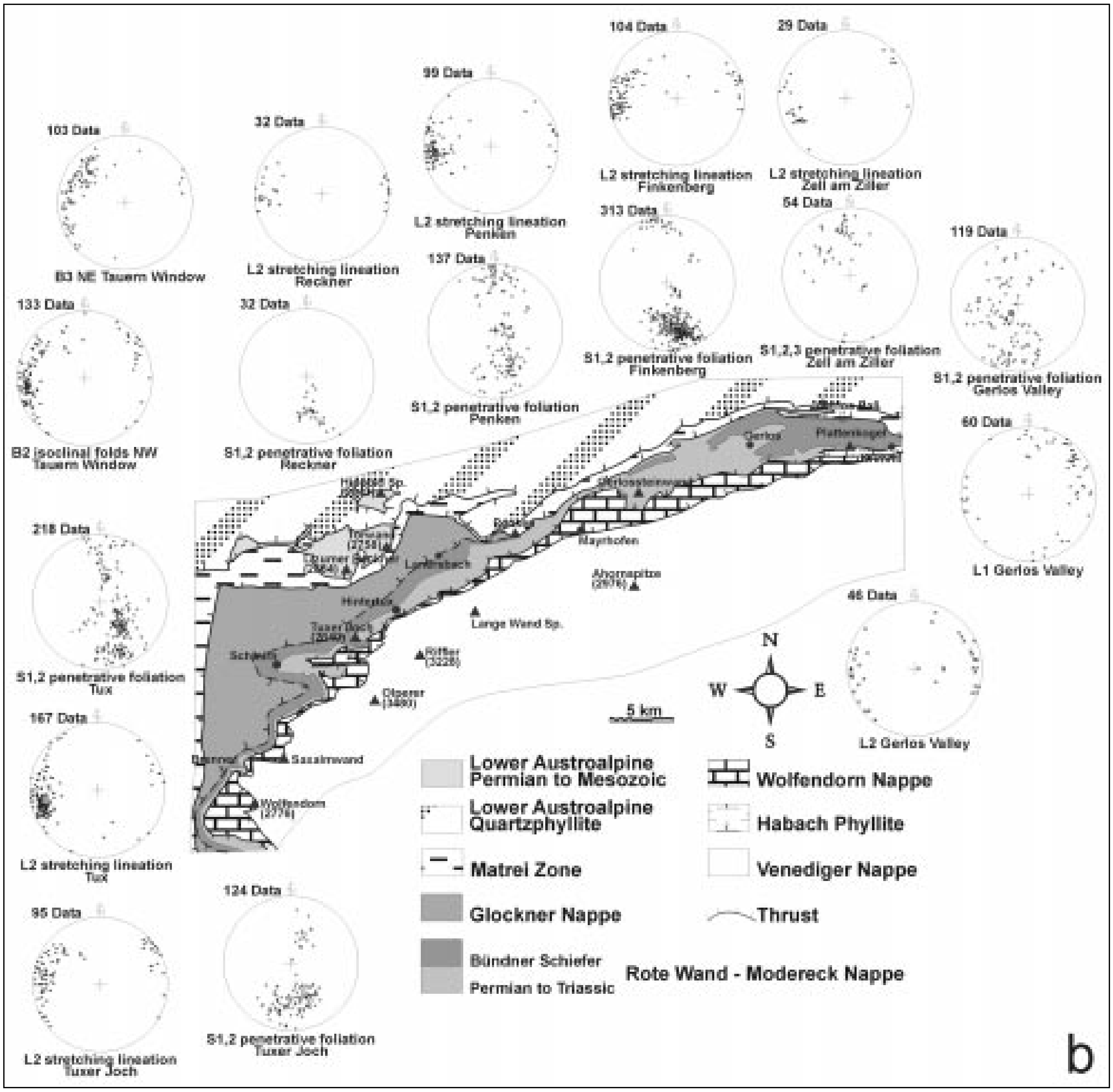
6.2. Feldspar

Within granitoids of the eastern Tauern Window, two generations of plagioclase occur.

In the eastern part of the Tauern Window, a first generation is characterized by oligoclase composition at lower structural levels, and by albite compositions at higher structural levels (GENSER, 1992). Dynamically recrystallized grains show an inverse chemical zonation. The cores of these grains show oligoclase composition at lower structural levels, and albite compositions at higher structural levels, the rims can show andesine composition within the deepest structural levels.

Within greenschists of the Rote Wand-Modereck Nappe and the Glockner Nappe plagioclase displays a continuous zonation with small oligoclase rims, documenting peak temperatures of slightly more than 500 °C. Synkinematically grown albite shows an internal foliation which is folded and defined by epidote, actinolite, and sphene. The matrix assemblage of greenschists is built up of actinolite, plagioclase, quartz, epidote, sphene, and subordinate chlorite and biotite.

In basement units of the Venediger Nappe garnet grew synkinematically as indicated by a rotated internal foliation. Characteristic mineral assemblages within the orthogneisses (amphibole + epidote + biotite + muscovite + K-feldspar + albite + quartz + chlorite + apatite) indicate metamorphism at albite-epidote-amphibolite facies con-



ditions in the units of Venediger Nappe. The characteristic mineral assemblage in the basement slices (orthogneiss lamellae) is biotite + albite + K-feldspar + quartz + amphibole + epidote + sphene. Plagioclase displays a continuous zonation with small oligoclase rims, documenting peak temperatures of slightly more than 500 °C.

Within the Venediger Nappe of the western Tauern Window, plagioclase is optically/chemically zoned and shows small rims of oligoclase. Plagioclase shows undulatory extinction. K-feldspar shows the formation of subgrains that might show undulatory extinction, too. Very often plagioclase and K-feldspar are cracked by shear fractures, that might be filled with quartz.

K-feldspar is characterized by high undulatory extinction and the formation of subgrains, with a size of up to 0.5 mm. The subgrains show undulatory extinction, too.

6.3. Dolomite

Dolomite marbles within the Venediger Nappe and the Riffl Nappe, and at the base of the Glockner Nappe occur as well-foliated, fine- to medium-grained marble mylonites. The dolomite grains show a uniform grain size that generally does not exceed 0.2, max. 0.3 mm (Text-Fig. 11d). The grains exhibit a shape preferred orientation subparallel to the penetrative foliation (R_f = 1.5 to 2.0). The grains are not twinned. The grain boundaries are generally straight and form triple junctions, sutured grain boundaries are less developed.

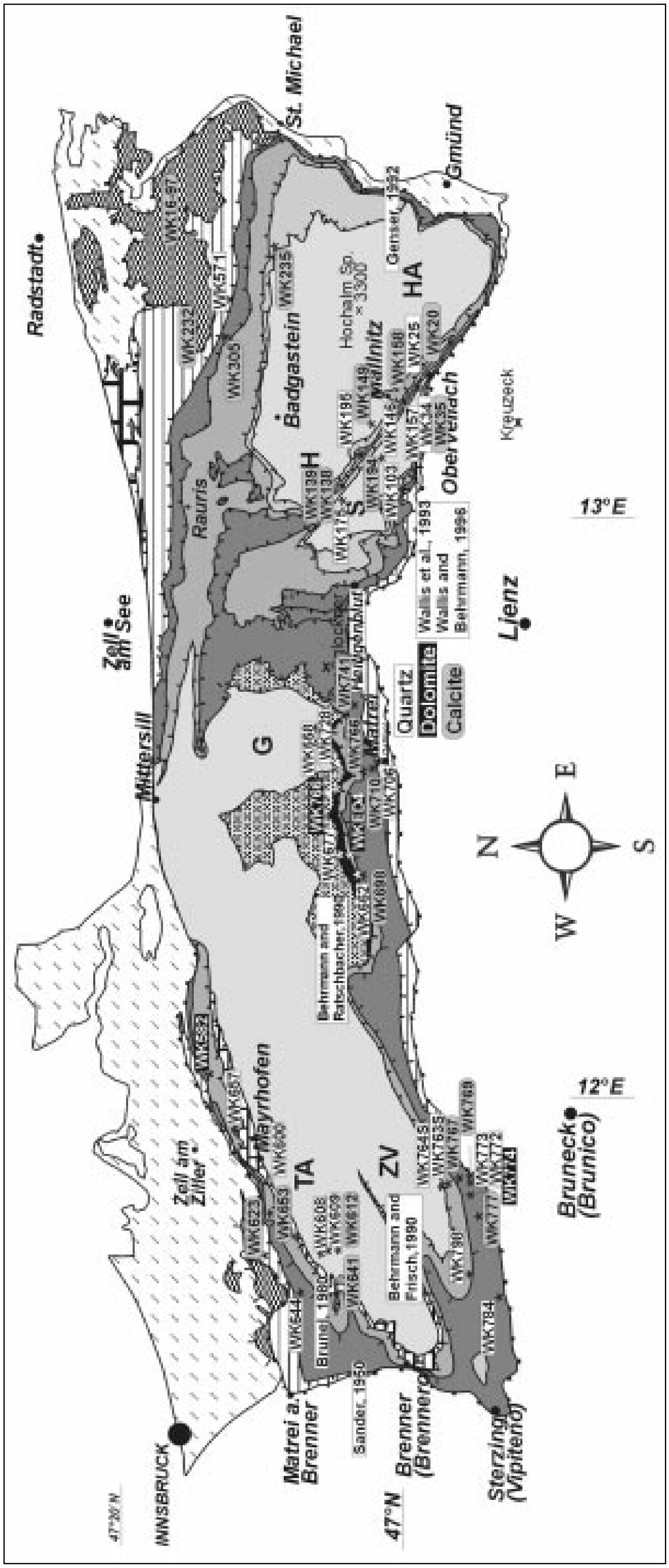
6.4. Calcite

D_2-related calcite microstructures are very homogeneous within the Penninic units over the entire Tauern Window. Calcite is characterized by strongly elongated grains (R_f ca. 5–10), that are forming a shape-preferred orientation either parallel, or oblique to the foliation plane (Text-Fig. 11e). The elongation is stronger near the margins of the Tauern Window than within the central parts. However, it depends on the presence of distinct shear zones that compensate the major part of deformation, too. Grain sizes are variable and strongly depend on the presence of additional mineral phases, especially white mica, and graphite. The average grain size equals 0.5–1 mm. The calcite grains show multiple sets of twins; however one set of e-twins, that is generally oriented subparallel to the foliation plane, dominates. The grains show either straight, or slight sutured boundaries. Within the Lower Austroalpine unit of the northeastern Tauern Window calcite forms dynamically recrystallized grains with a size of 0.1 mm at most. These grains may show polysynthetic twins.

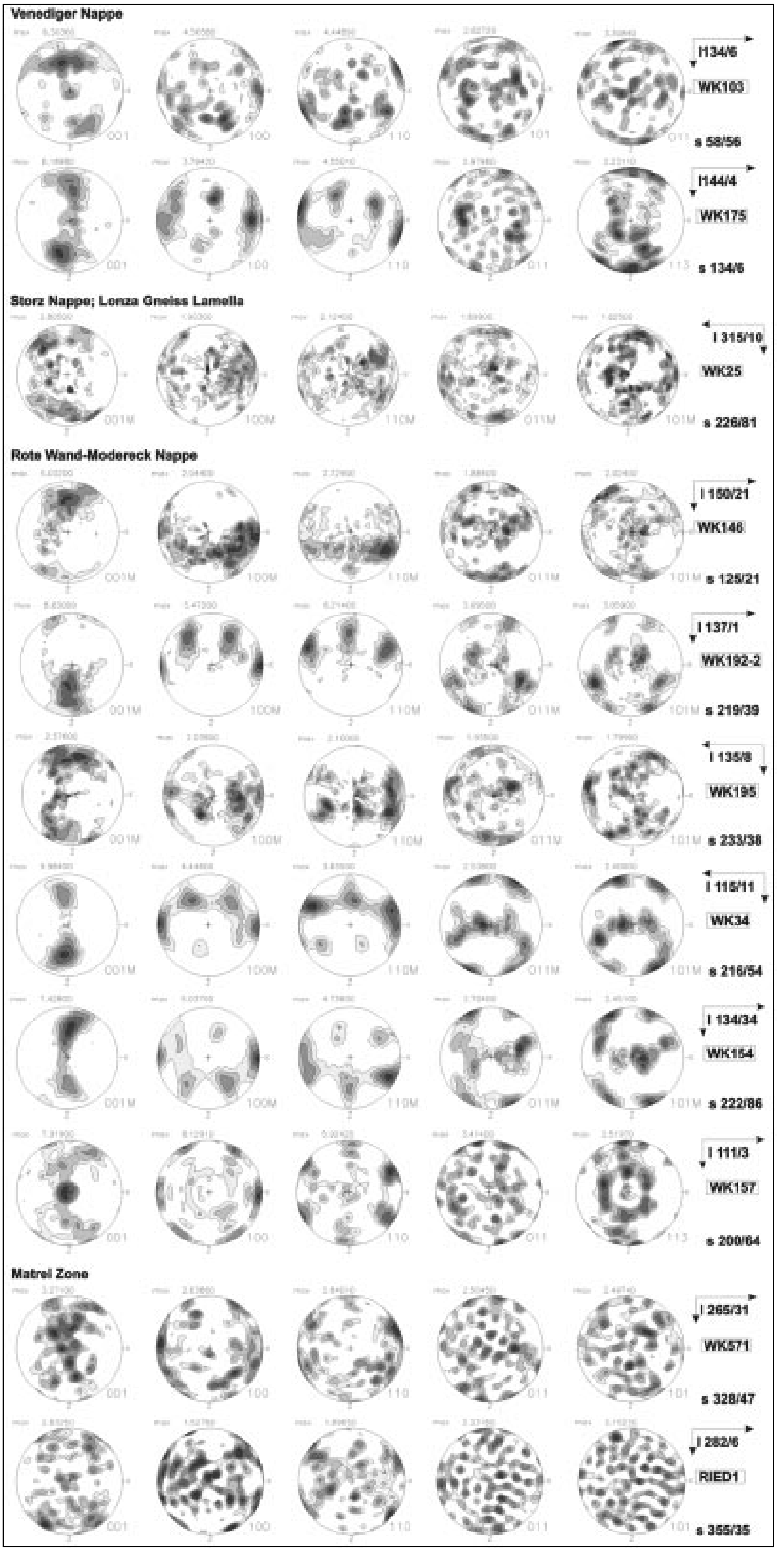
7. D_2 Crystallographic Preferred Orientations (CPOs)

7.1. Quartz

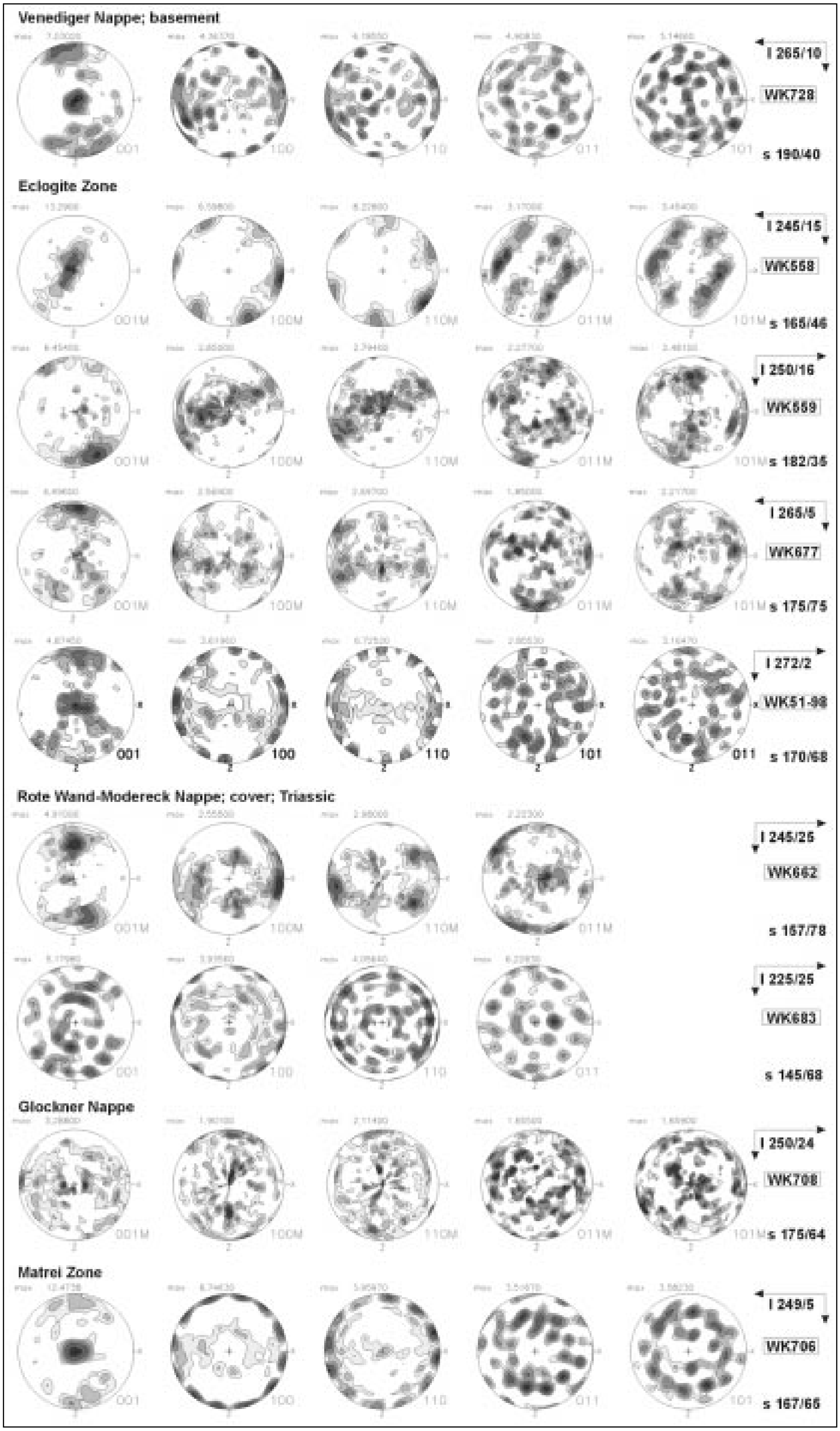
In the southeastern part of the Tauern Window (Text-Fig. 13), the quartz c-axes [001] are distributed along single girdles and incomplete single girdles within the Venediger Nappe. They are oblique where the quartz grains show a shape-preferred orientation oblique to the foliation plane (Text-Fig. 14). Where the elongated quartz grains are oriented subparallel to the penetrative foliation, the quartz c-axes girdles are parallel to the Y-Z-plane of the finite strain ellipsoid (Text-Fig. 14). Two c-axis maxima are located near the Y- and Z-axis. The a-axis [110] and the poles to the prism-planes [100] (Text-Fig. 14) form clusters near the X-axis of the finite strain ellipsoid, or they are distributed along a small circle centered in the X-axis. Within the Storz Nappe the quartz c-axes [001] are characterized by well developed oblique cross girdle distributions. Type I and type II cross girdle distributions have been observed. The trailing edge of the girdle distributions is less developed. The obliquity of the cross girdles documents a top-to-the-NW sense of shear. Where type I girdles are developed, c-axes clusters are observed between Y and Z (Text-Fig. 14). The a-axes [110] and the poles to the prisms [100] form a girdle distribution within the X-Y-plane. The poles to the negative rhombs <z> [011] and the positive rhombs <r> [101] are distributed along two girdles with small angles to the Y-Z-plane. Within the Rote Wand-Modereck Nappe the quartz c-axes [001] generally form oblique single girdle distributions (Text-Fig. 14). In



Text-Fig. 13.
Tectonic map of the Tauern Window, displaying sample locations of textures presented in Text-Figs. 14–23.
For legend see Text-Fig. 2a.



Text-Fig. 14.
Representative quartz CPOs that are related to deformation phase D_2. Eastern Tauern Window.
For explanation see Text-Figs. 5, 6.



Text-Fig. 15.
Representative quartz CPOs that are related to deformation phase D_2. Central southern Tauern Window, incl. Eclogite Zone.
For explanation see Text-Figs. 5, 6.

places, remnants of type I cross girdles can be observed. Three clusters are symmetrically situated along the single girdle. Two clusters plot between the Y- and Z-axis, one cluster plots within the Y-axis. The obliquity of the girdle distributions documents top-to-the-NW sense of shear. The distributions of a-axis [110] and the poles to the prisms [100] (Text-Fig. 14) typically form a girdle within the X-Y-plane. Three clusters are symmetrically situated along this girdle. For the poles to the prisms, two clusters plot between the X- and Y-axis, one cluster plots within the X-axis. For the a-axes, two clusters plot near X, one cluster plots within the Y-axis. The poles to the rhombs [101] [011] are situated along two girdles with small angles to the Y-Z-plane.

Surprisingly, the crystallographic preferred orientations of quartz in the northeastern part of the Tauern Window (Text-Figs. 13, 14) are weaker than observed for the D_1 fabrics, especially within the Glockner Nappe and the Matrei Zone. This might be related to static annealing subsequent to D_1, which could have strengthened the CPO fabric (e.g., SCHMID & CASEY, 1986). Such a strong fabric was either erased or weakened during D_2. The c-axis distributions [001] are characterized by symmetrical type I cross girdles with one cluster situated in the Y-axis (Text-Fig. 14). Submaxima are located symmetrically around the Y-axis. The a-axes [110] and the poles to the prism planes [100] are scattered along a small circle centered within the X-axis of the finite strain ellipsoid. The opening angle of this small circle equals ca. 90°.

The poles to the rhombs [101] [011] are located along two great circles subperpendicular to the foliation plane.

Within the central southern Tauern Window, (Text-Fig. 12) type I crossed girdles have been observed within several tectonostratigraphic units (Text-Fig. 15). Generally, leading and trailing edges can be distinguished; locally the trailing edges are missing and oblique single girdles are developed. One cluster is situated within the Y-axis, two maxima are located near the Y- and Z-axis, sometimes one cluster is situated near the periphery. The obliquity of the single girdle distributions documents a top-to-the WSW sense of shear during D_2. If type I cross girdles are developed, the a-axes [110] and the poles to the prism planes [100] are distributed along a girdle within the X-Y-plane, the poles to the rhombs [101] [011] form girdles subperpendicular to the foliation plane. If oblique single girdles are developed, the a-axes and the poles to the prisms form three clusters at the periphery of the equal area projection, the poles to the rhombs form girdles oblique to the foliation plane.

In the western part of the Tauern Window (Text-Figs. 12, 13) the quartz c-axes [001] are characterized by type I cross girdle distributions, too (Text-Figs. 16).

A leading edge and a trailing edge can be distinguished. Generally the trailing edge is weakly developed, but oblique single girdles have not been observed. The asymmetry of the c-axes distributions indicated a top-to-the-W simple shear component during D_2. Generally, the preferred orientation decreases from the south to the north. In the southern part (Text-Fig. 16a), one cluster is often located within the Y-axis of the finite strain ellipsoid, two clusters are located beween the Y- and Z-axis of the finite strain ellipsoid. The a-axes [110] form three clusters and are symmetrically arranged at the periphery. One cluster is situated within the Z-axis, the two others are located 60° and 120° apart from Z. The poles to the prisms [100] form three clusters at the periphery, too, but one cluster is situated within the X-axis. The poles to the rhombs [101] [011] are distributed along two great circles with small angles to the Y-Z plane. Only along the southern margin of the Tauern Window the quartz-c-axis distributions show a single cluster near Z (Text-Fig. 16b). The asymmetry of the cluster with respect to the Z-axis indicates a top-to-the-W simple shear component. The a-axes [110] and the poles to the prisms form a girdle distribution oblique to the X-Y-plane, with one well pronounced maximum. From the southern margin of the western Tauern Window to the central part a countinuous transition from single c-axis clusters to type I cross girdle distributions is documented. The distribution of the a-axes develops from a girdle oblique to the X-Y-plane to small circles centered near the X-axis, and finally to the formation of three clusters (Text-Fig. 16b). In the northern part of the western Tauern Window, several clusters diminish continuously, and the c-axes are smoothly distributed along type I cross girdles (Text-Fig. 17). Accordingly the a-axes and the poles to the prisms form a girdle distribution either within, or oblique to the X-Y-plane.

7.2. Dolomite

D_2-related CPOs of dolomite are very similar over the entire Tauern Window, and within several tectonostratigraphic units (Text-Figs. 13, 18, 19). The c-axes [001] generally form single girdle distributions within the Y-Z-plane of the finite strain ellipsoid. One maximum is centered near the Z-axis. 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 X-axis. The poles to the rhombs [101] [011] plot along girdles subparallel to the Y-Z-plane.

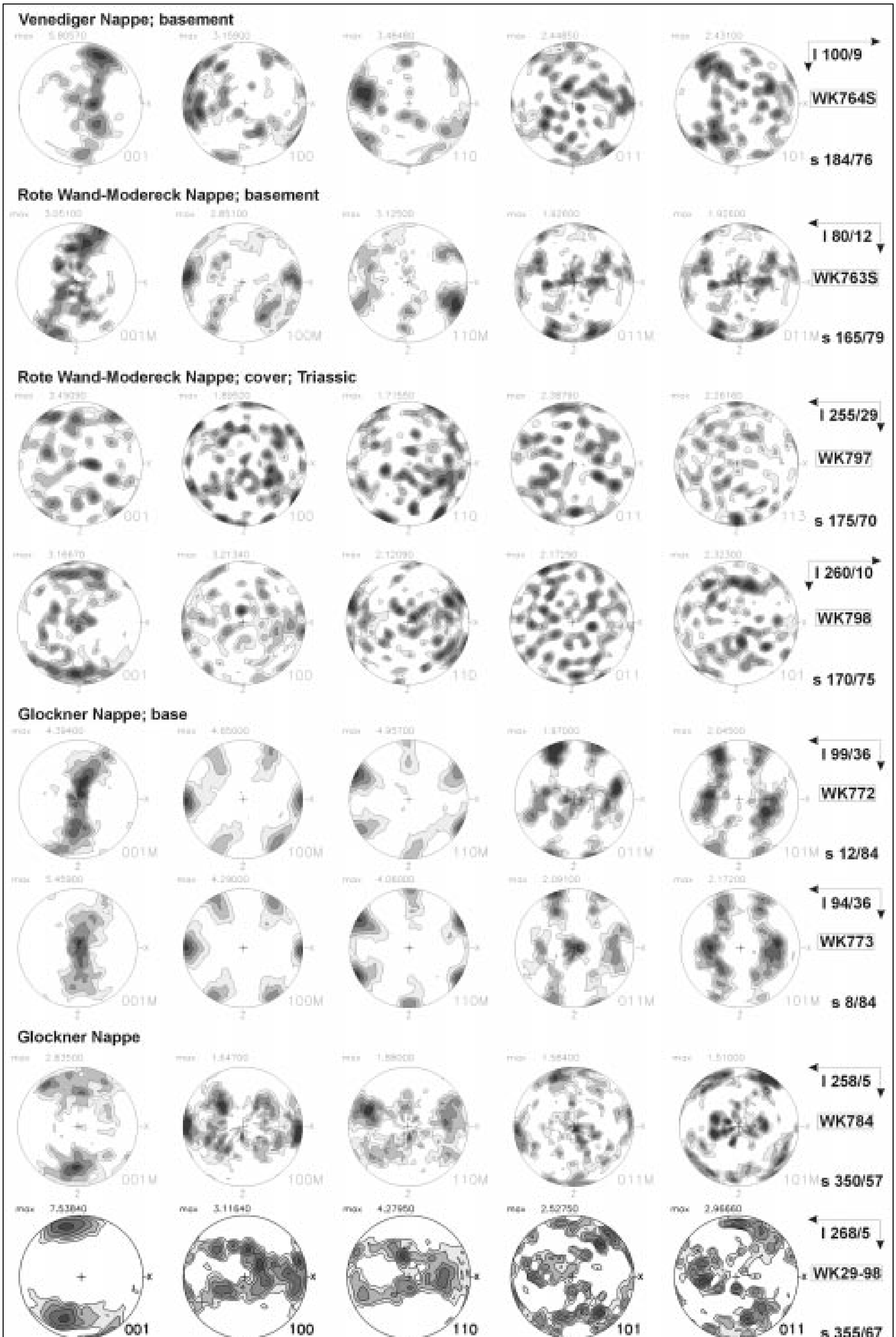
7.3. Calcite

Calcite CPOs that are related to D_2 are very similar over the entire Tauern Window, and within several tectonostratigraphic units, too (Text-Figs. 13, 20, 21, 22, 23a,b). The c-axes are characterized by distributions that are typical for HT-fabrics according to WENK et al. (1987). Generally they form single girdle distributions within the Y-Z-plane of the finite strain ellipsoid. One maximum is centered 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 X-axis. The poles to the rhombs [101] [011] plot along girdles subparallel to the X-Y-plane, too. 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 X-axis. The poles to the rhombs [101] [011] plot along girdles subparallel to the X-Y-plane, too.

8. D_3 Microstructures

8.1. Quartz

In zones that are affected by low-angle normal faults and strike-slip faults, quartz grains are highly elongated, forming ribbon grains ($R_f > 10$) (Text-Fig. 24a). These grains are characterized by undulatory extinction, the formation of subgrains, deformation lamellae and deformation bands, and by sutured and lobate grain boundaries. Single dynamically recrystallized grains (grain size ca.


Venediger Nappe; basement
001
100
110
011
101
l 100/9
WK764S
s 184/76
Rote Wand-Modereck Nappe; basement
001M
100M
110M
011M
011M
l 80/12
WK763S
s 165/79
Rote Wand-Modereck Nappe; cover; Triassic
001
100
110
011
113
l 255/29
WK797
s 175/70
001
100
110
011
101
l 260/10
WK798
s 170/75
Glockner Nappe; base
001M
100M
110M
011M
101M
l 99/36
WK772
s 12/84
001M
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011M
101M
l 94/36
WK773
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Glockner Nappe
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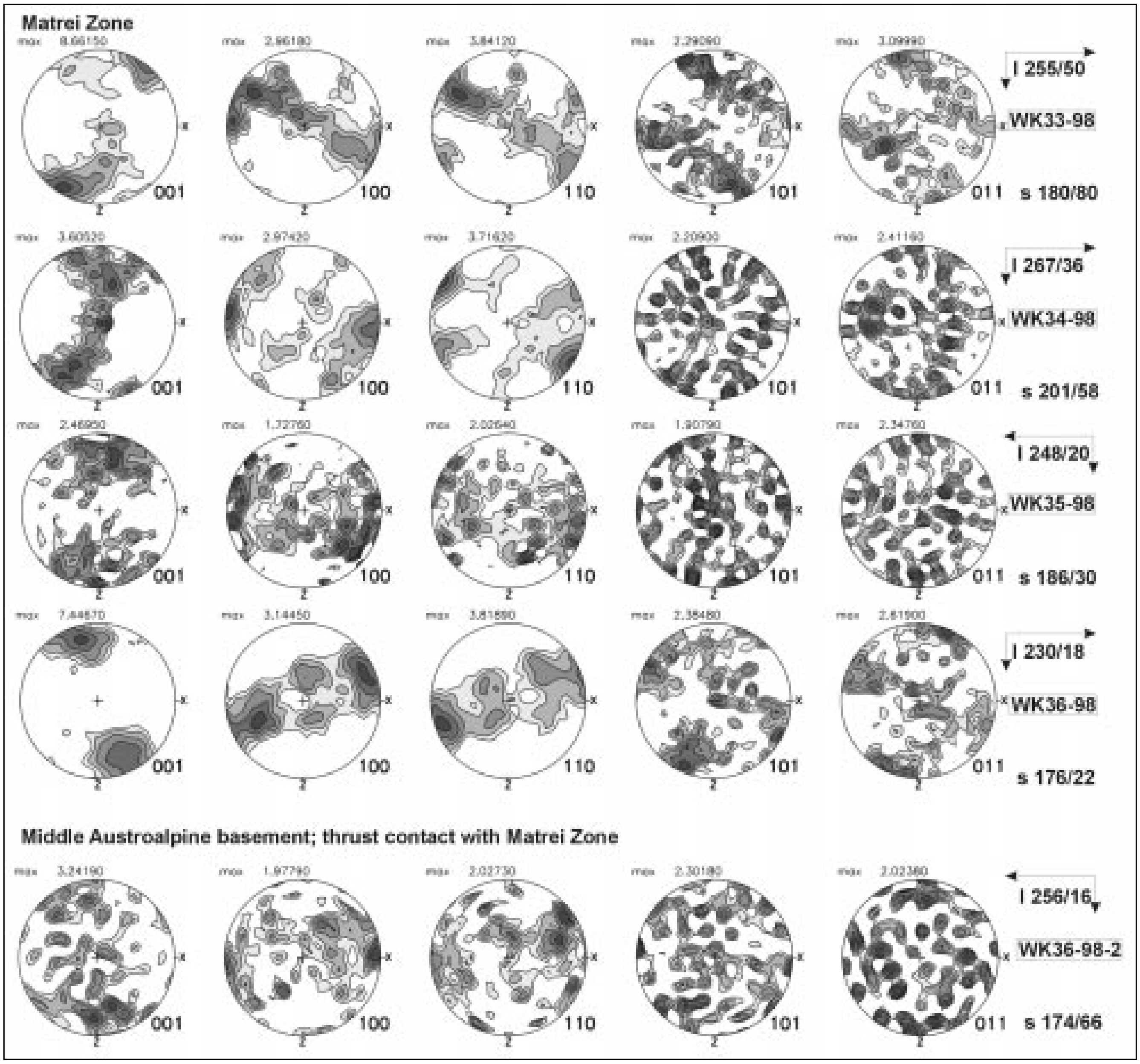


Text-Fig. 16a (previous page) and b.
Representative quartz CPOs that are related to deformation phase D_2, southwestern Tauern Window.
For explanation see Text-Figs. 5, 6.

0.05–0.1 mm) developed along the grain boundaries and within the ribbon grains. Along the shear zones that are bordering the Tauern Window, a dramatic decrease of the grain size is documented due to secondary grain size reduction. The main mechanism of dynamic recrystallization is assumed to be subgrain rotation.

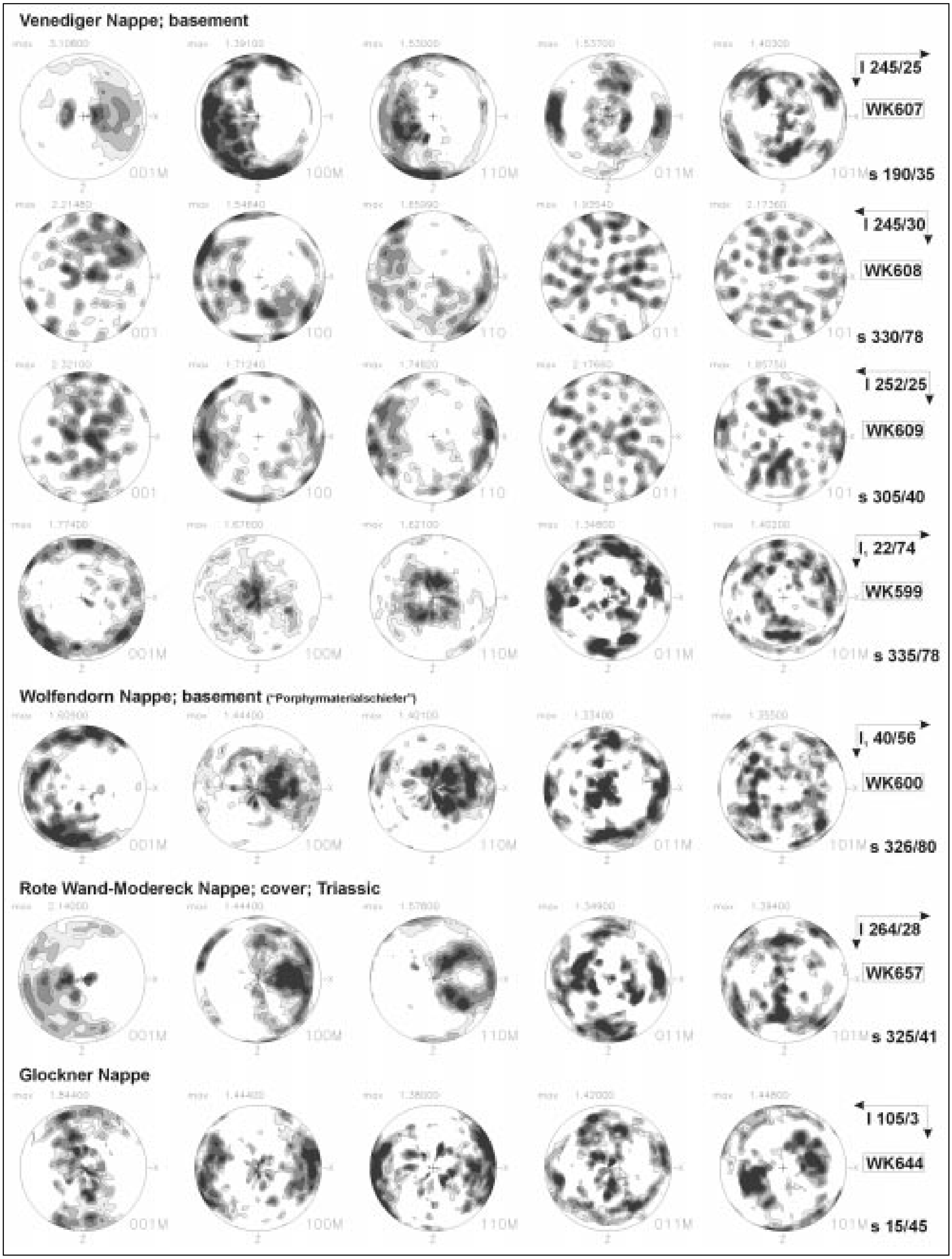
At decreasing temperatures, the plastic deformation of quartz grains ceases. Along the shear zones confining the dome structure a continuous transition from plastic to brittle fabrics including the development of cataclasites within quartz- and feldspar-rich rocks, is documented. Quartz grains are affected by extensional cracks, which are filled mainly with calcite (Text-Fig. 24b). Generally, the extensional cracks are oriented obliquely to the penetrative foliation, indicating a simple shear component.

8.2. Dolomite

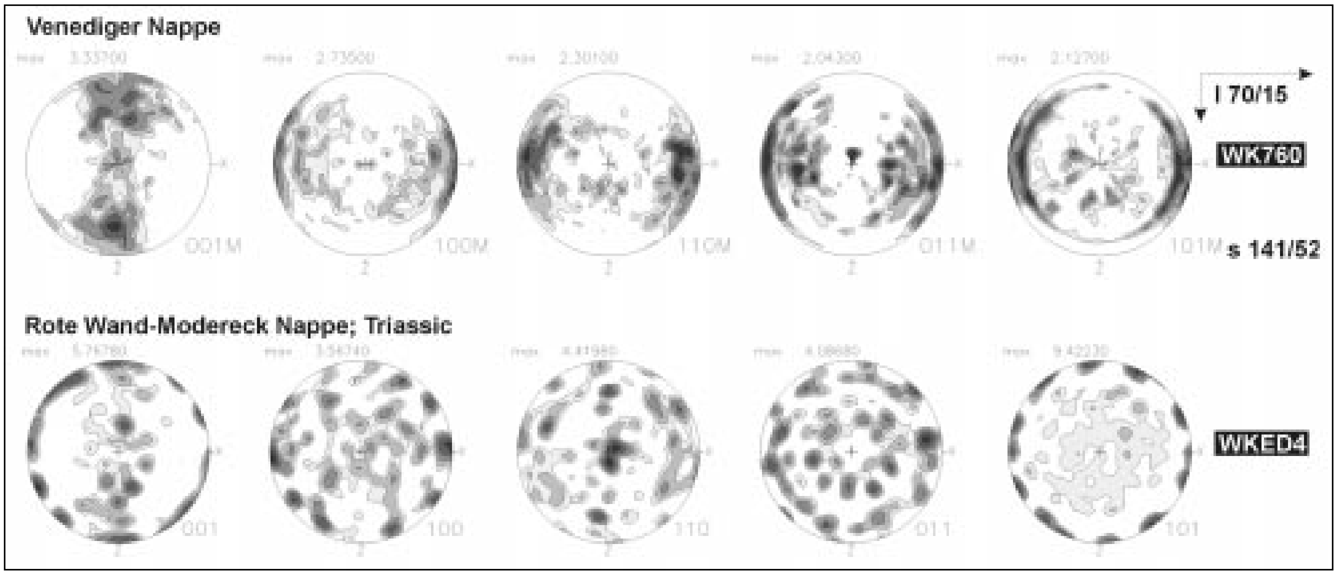
Dolomite marbles occur as banded, fine-grained marble mylonites. Several dolomite layers are separated by bands of sericitic white mica (Text-Fig. 24c). Furthermore, distinct, ultramylonitic layers can be separated from layers of coarse-grained dolomite (Text-Fig. 24c). Within the coarse-grained layers dolomite generally forms either isometric or slightly elongated grains with highly serrated and lobate grain boundaries (Text-Fig. 24d). The grain size equals 0.1–0.2 mm. Very often solution seams occur that are oriented subparallel to the foliation plane. Therefore, the dominating deformation mechanism is assumed to be pressure solution.

8.3. Calcite

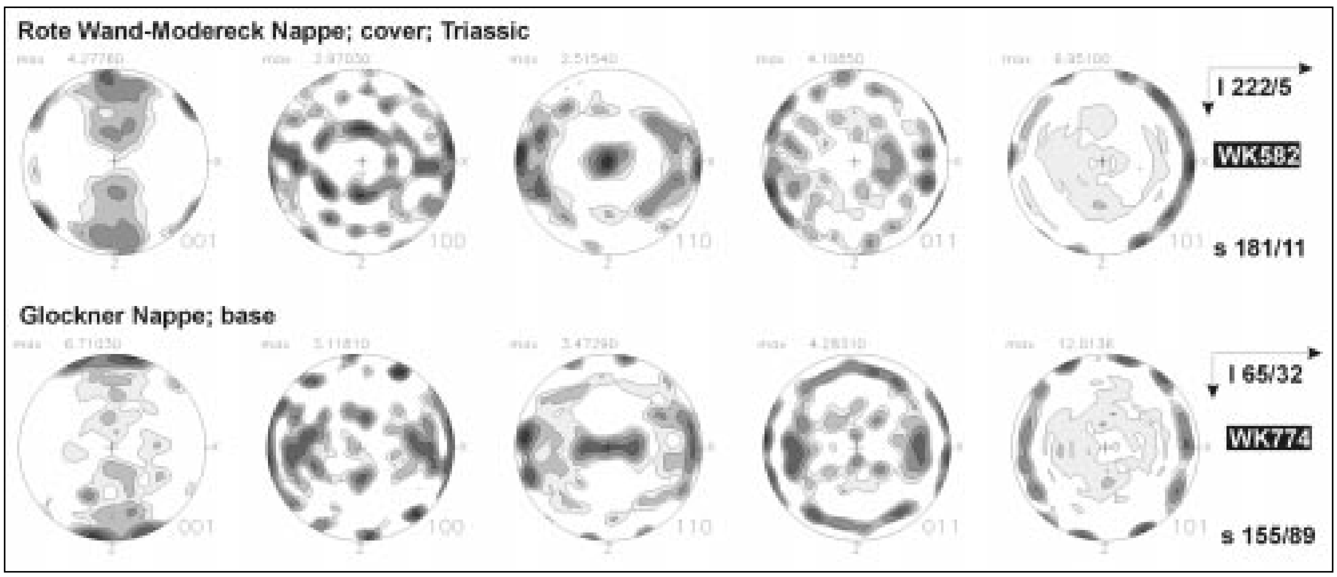
In mylonites within the shear zones bordering the Tauern Window that contain less than 5% quartz and mica, calcite displays uniform grain size between 0.3 and 1 mm. It is homogeneously twinned with conjugate sets of twins developed (Text-Fig. 24e). Twins are often bent due to intracrystalline plasticity of calcite within micro-scale shear zones, while domains between conjugate shear band sets are less deformed. Core-mantle textures are occasionally



Text-Fig. 17.
Representative quartz CPOs that are related to deformation phase D_2, northwestern Tauern Window.
For explanation see Text-Figs. 5, 6.



Text-Fig. 18.
Representative dolomite CPOs that are related to deformation phase D_2, central southern Tauern Window.
For explanation see Text-Figs. 5, 6.



Text-Fig. 19.
Representative dolomite CPOs that are related to deformation phase D_2, central southern Tauern Window.
For explanation see Text-Figs. 5, 6.

recognized. Approaching the Austroalpine units that are surrounding the Tauern Window, ultramylonites with optically not-discernable calcite grains are developed within the shear zones.

9. D_3 Crystallographic Preferred Orientations (CPOs)

9.1. Quartz

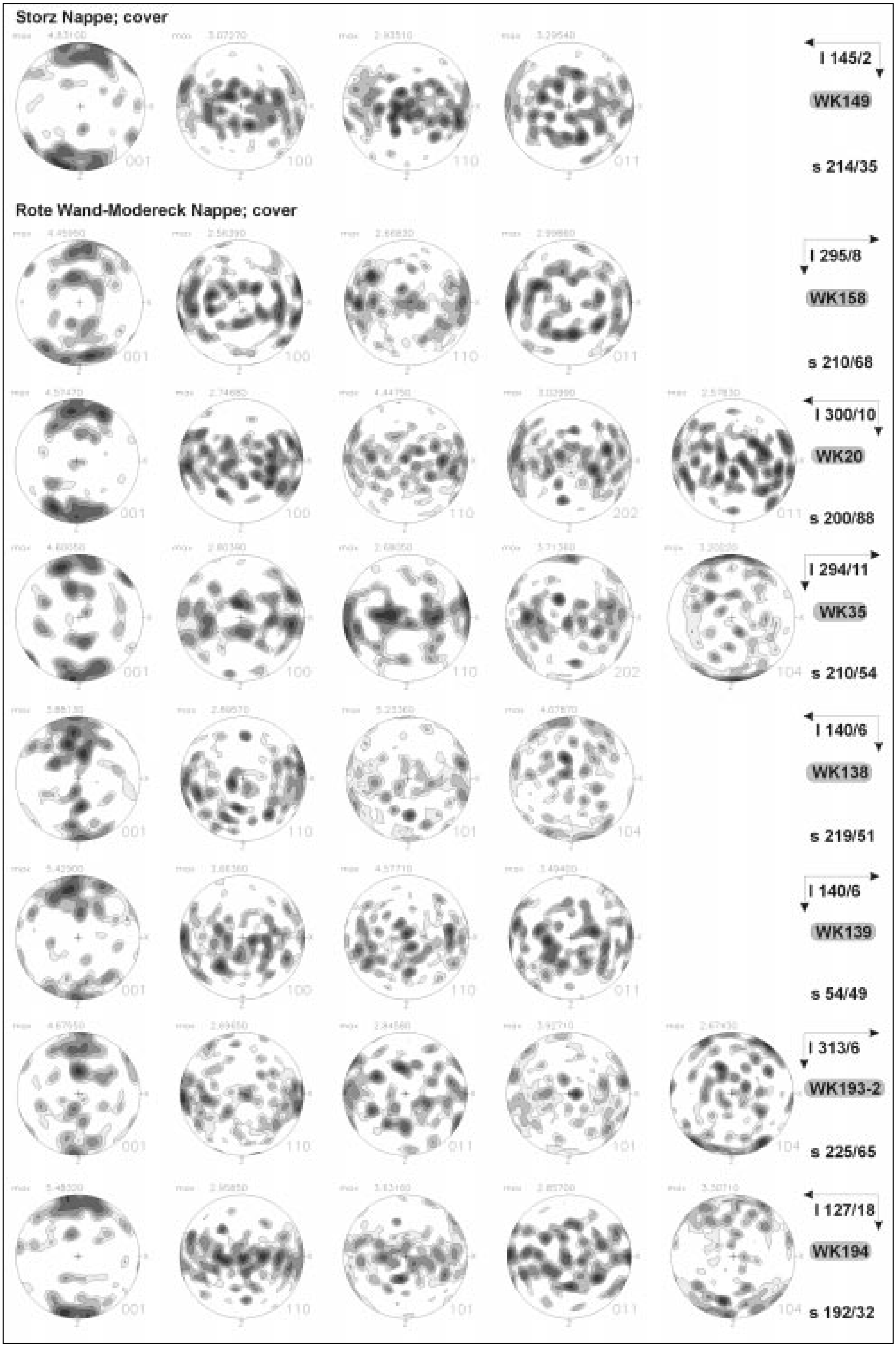
Quartz c-axis distributions of samples taken from shear zones bordering the Tauern Window (Text-Fig. 25) show two clusters that are asymmetrically arranged near the Z-axis (Text-Fig. 26). However, one cluster is less developed. Locally remnants of an asymmetric small circle distribution are observable. Along the Möll Valley Fault in the southeastern part of the Tauern Window type I crossed girdles progressively develop to small circle distributions (KURZ & NEUBAUER, 1996).

9.2. Dolomite

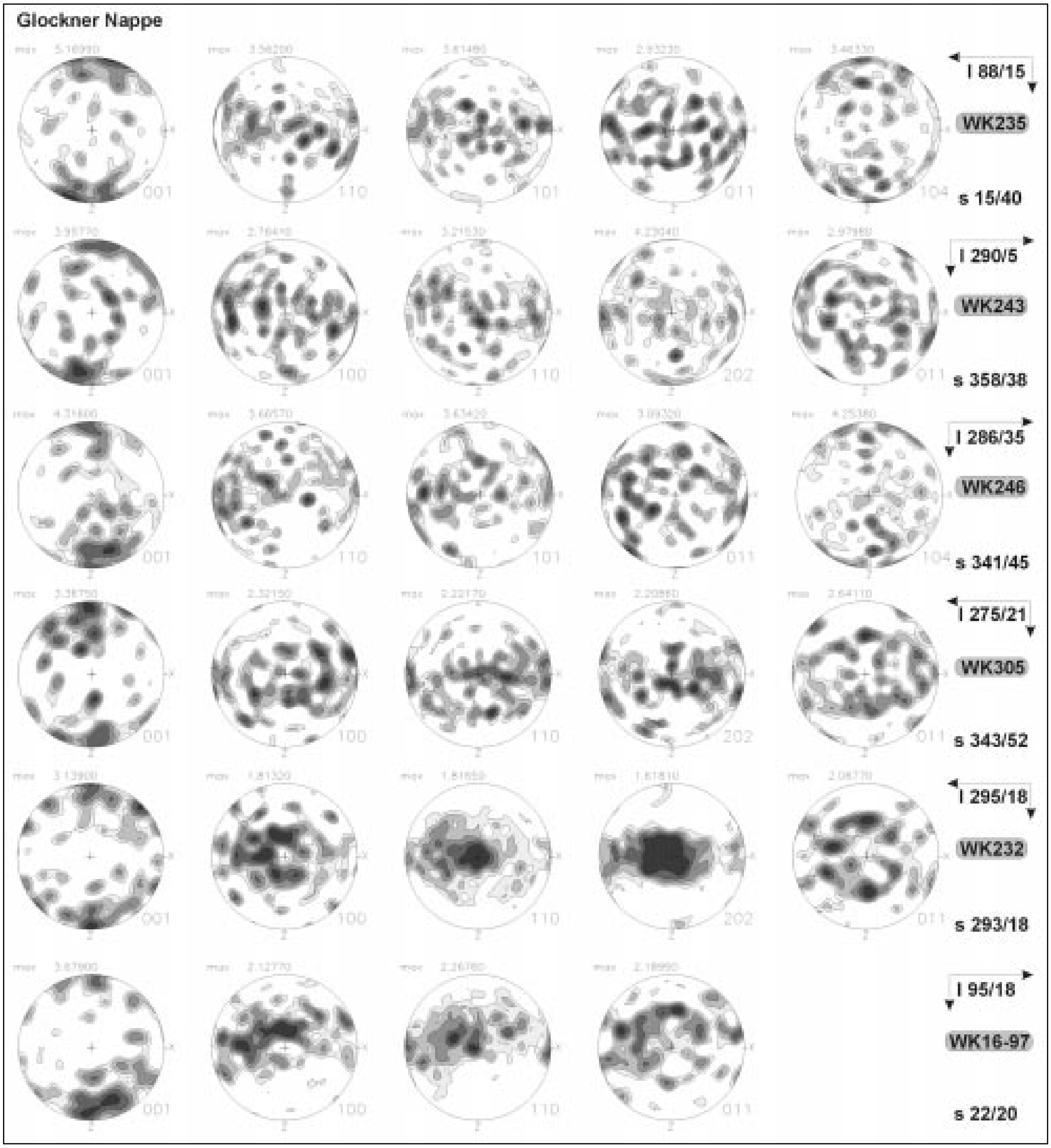
Dolomite c-axes [001] generally form single girdle distributions within the Y-Z-plane of the finite strain ellipsoid (Text-Fig. 27). One maximum is centered near the Z-axis. The a-axes [110] and the poles to the prism planes [100] are distributed along a girdle within the X-Y-plane, with one maximum near the X-axis. The poles to the rhombs [101] [011] plot along girdles subparallel to the Y-Z-plane.

9.3. Calcite

D_3-related calcite c-axes [001] fabrics are characterized by clusters close to the short axis of the finite strain ellipsoid (Z) (Text-Figs. 28, 29). Locally, especially along the northern margin of the Tauern Window (Salzach-Ennstal fault) (Text-Fig. 25), the c-axes are characterized by distributions that are typical for HT-fabrics according to WENK et al. (1987). Here the c-axes form single girdle distributions within the Y-Z-plane of the finite strain



Text-Fig. 20.
Representative calcite CPOs that are related to D_2.
Southeastern Tauern Window. For explanation see Text-Figs. 5, 6.



Text-Fig. 21.
Representative calcite CPOs that are related to D_2.
Northeastern Tauern Window. For explanation see Text-Figs. 5, 6.

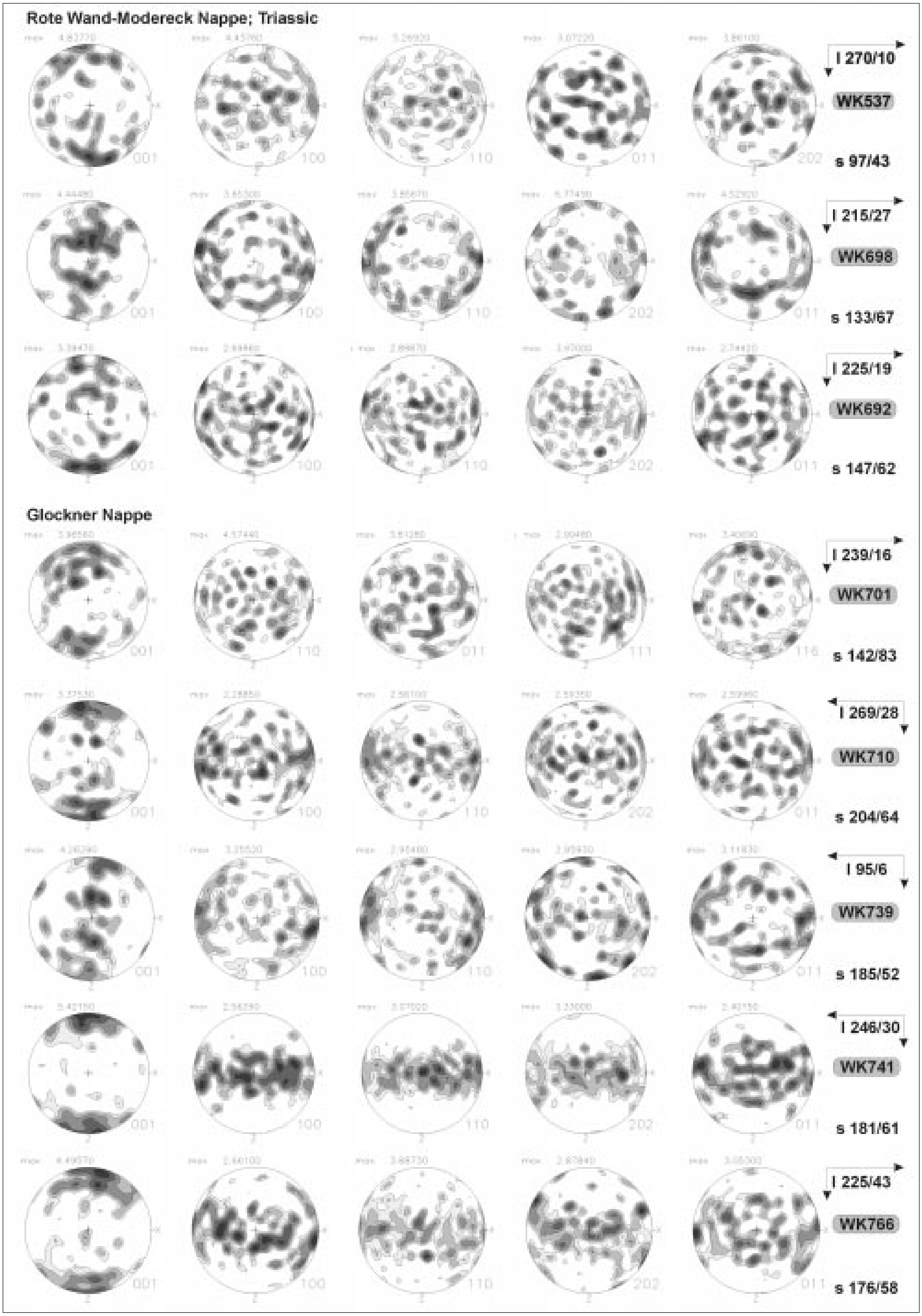
ellipsoid. One maximum is centered near the Z-axis, two maxima are situated between the Y- and Z-axis of the finite strain ellipsoid. The a-axes [110] and the poles to the prism planes [100] are distributed along a girdle within the X-Y-plane, with one maximum near the X-axis. The poles to the rhombs [101] [011] plot along girdles subparallel to the X-Y-plane, too.

10. Discussion

Generally, two types of quartz microstructures that are related to D_1 can be distinguished within the Tauern Window (Text-Fig. 30):

❶ Type 1 D_1-quartz microstructures are characterized by equilibrated and annealed fabrics without CPO. These microstructures have been only observed in the central part of the southeastern Tauern Window. The grain size of the recrystallized grains reaches 0.5–0.7 mm. The occurrence of these fabrics seems to coincide with the area of amphibolite facies metamorphic conditions (e.g., HÖCK, 1980), respectively within the staurolite-biotite isograde determined by DROOP (1985).

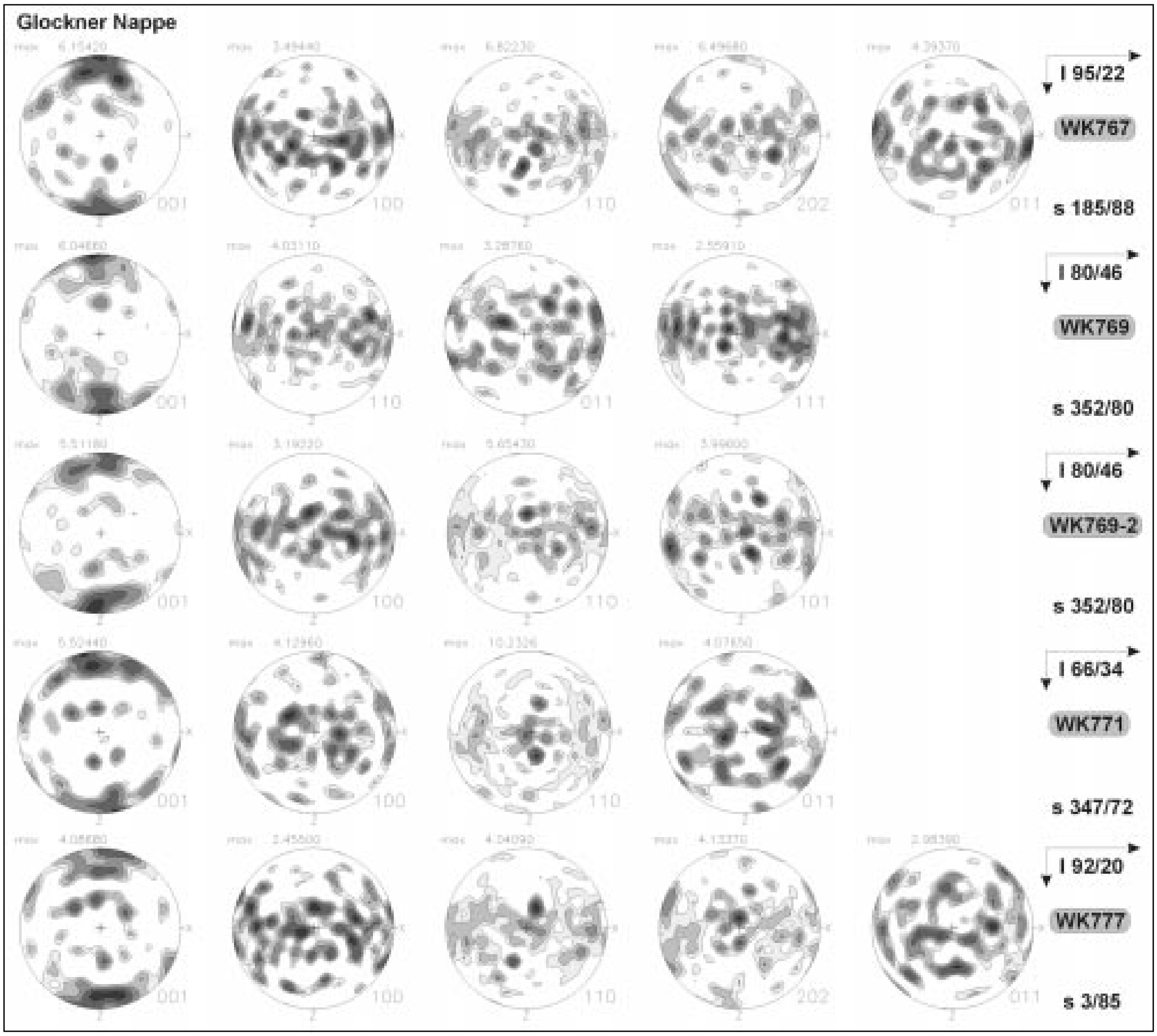
❷ Type 2 D_1-microstructures are characterized by quartz grains that show equilibrated fabrics (straight grain boundaries, triple junctions), but well preserved CPOs.



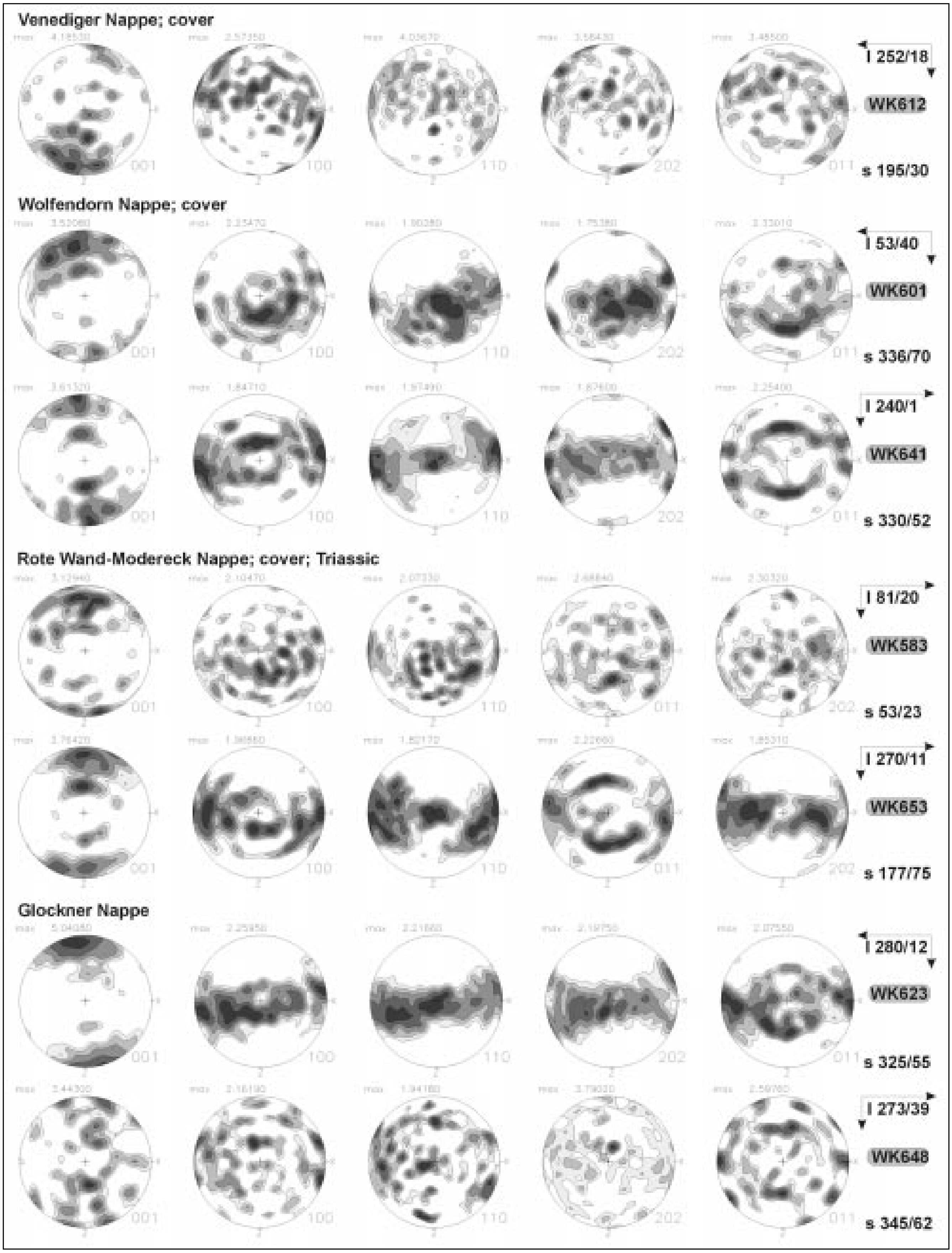
Text-Fig. 22.
Representative calcite CPOs that are related to D_2.
Central southern Tauern Window. For explanation see Text-Figs. 5, 6.

However, it is possible that the CPOs are preserved or strengthened during subsequent thermal equilibration (e.g., SCHMID & CASEY, 1986). The grain size is significantly smaller (0.2–0.4 mm) than that of type 1 microstructures (0.5–0.7 mm). Such fabrics have been observed in the central part of the Tauern Window, and locally in the northeastern and northwestern part of the Tauern Window. The occurrence of these fabrics seems to coincide with the area outside amphibolite facies metamorphic conditions (e.g., HÖCK, 1980), as well as with the staurolite-biotite isograde determined by DROOP (1985). The quartz c-axes generally form type I cross girdle distributions; very often, one girdle is less developed. The c-axis distributions indicate a deformation geometry close to plane strain (according to LISTER & PATERSON, 1979; LISTER & HOBBS, 1980). The CPOs indicate that especially the rhombs were the dominating active slip planes, as well as basal planes and prism planes. Slip occurred parallel to the a- and c-axis. The quartz c-axes at the base of the Rote Wand-Modereck Nappe show either two clusters or small circle distributions centered within Z, while within the central parts of this nappe type I cross girdles are continuously developed. It seems to be valid to assume that equilibration during subsequent amphibolite to greenschist facies metamorphism has equally affected several units. Therefore, these observations are interpreted in terms of an elevated component of flattening strain at the base of the Rote Wand-Modereck Nappe, while the deformation geometry in the central parts of the nappes is located closer to plane strain. Such features have already been observed by LAW (1987) and LAW et al. (1990). Furthermore, slip along the basal plane parallel <a> seems to dominate at the base of the Rote Wand-Modereck Nappe, while the dominance of slip along the rhombs continuously increases towards the central part of this nappe. This might be an indication of elevated strain rates and/or higher finite strain at the base of this nappe.

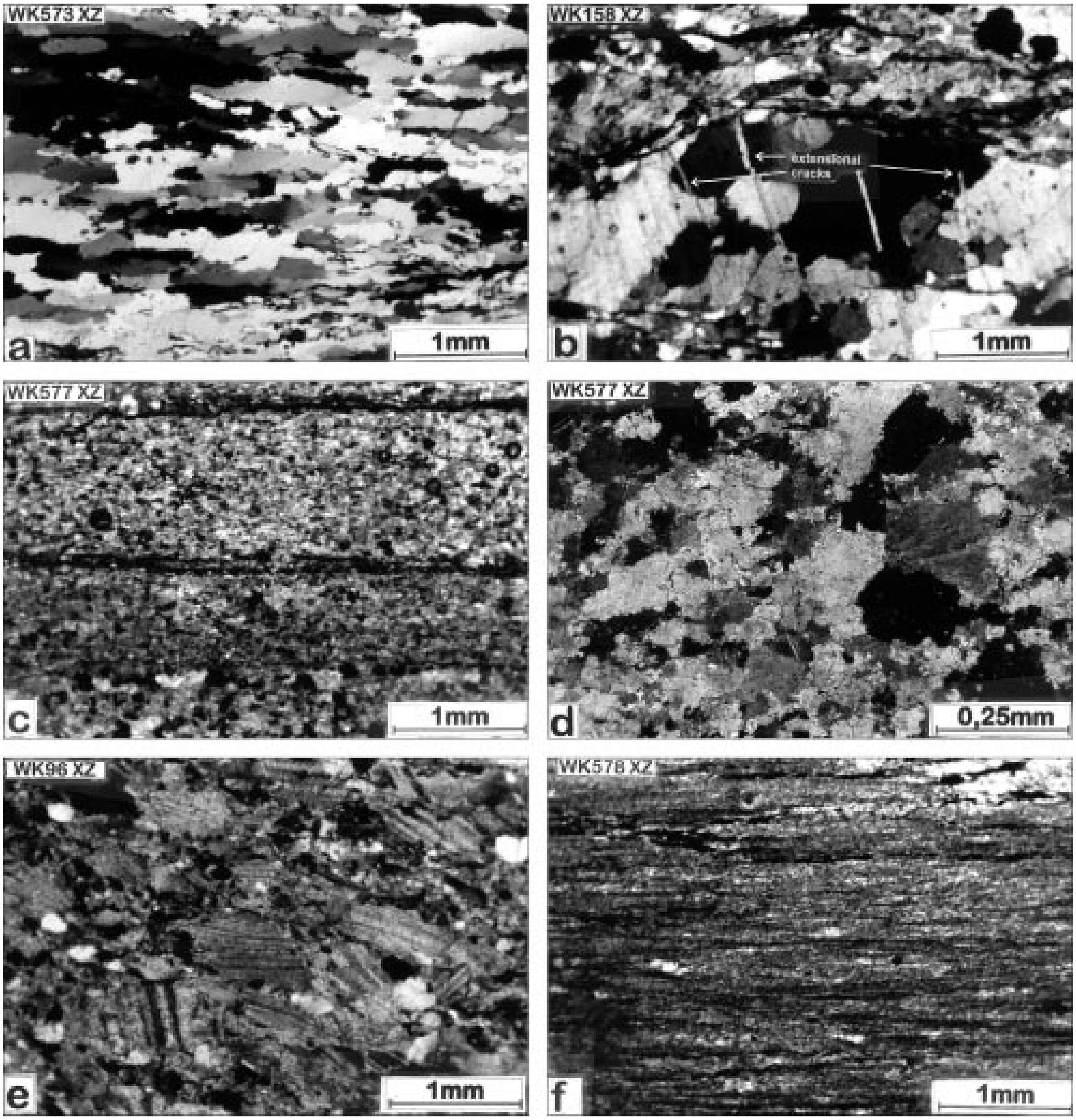
Two types of quartz microstructures related to D_2 can be distinguished within the Tauern Window (Text-Fig. 30):



Text-Fig. 23a (this page) and b (next page).
Representative calcite CPOs that are related to D_2,.
Southwestern (a) and northwestern (b) Tauern Window. For explanation see Text-Figs. 5, 6.



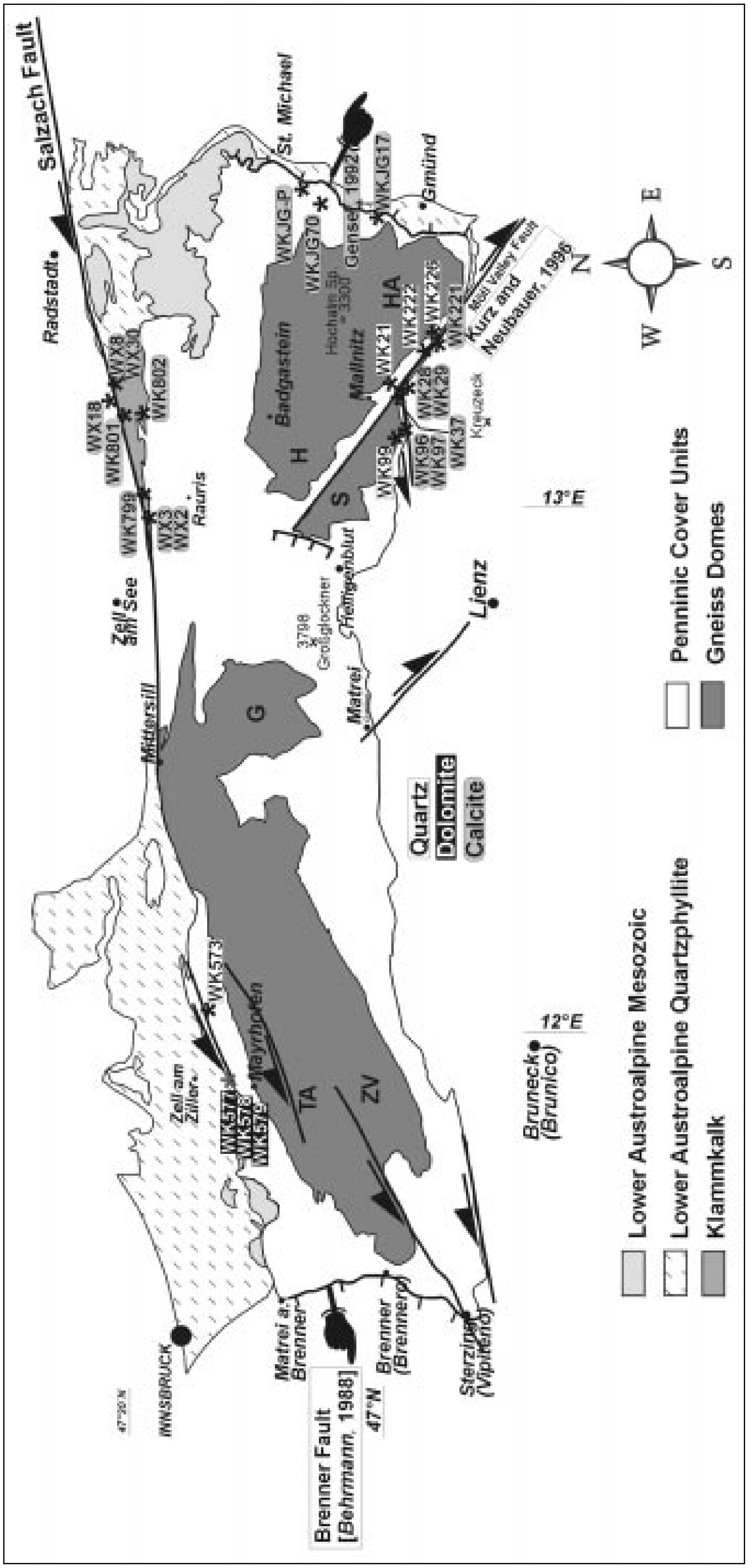
Text-Fig. 23b.
Continued from page 61; for explanation see Text-Figs. 5, 6.



Text-Fig. 24.
Representative microstructures that are related to D_3.
a) Quartz ribbon grains, northwestern margin of the Tauern Window.
b) Extensional cracks filled with calcite within quartz grains, Möll Valley Fault, southeastern Tauern Window.
c) Banded dolomite marble northwestern Tauern Window.
d) Dolomite microstructure, enlarged from Text-Fig. 14c.
e) Calcite microstructure, southeastern Tauern Window.
f) Calcite ultramylonite, northwestern Tauern Window.

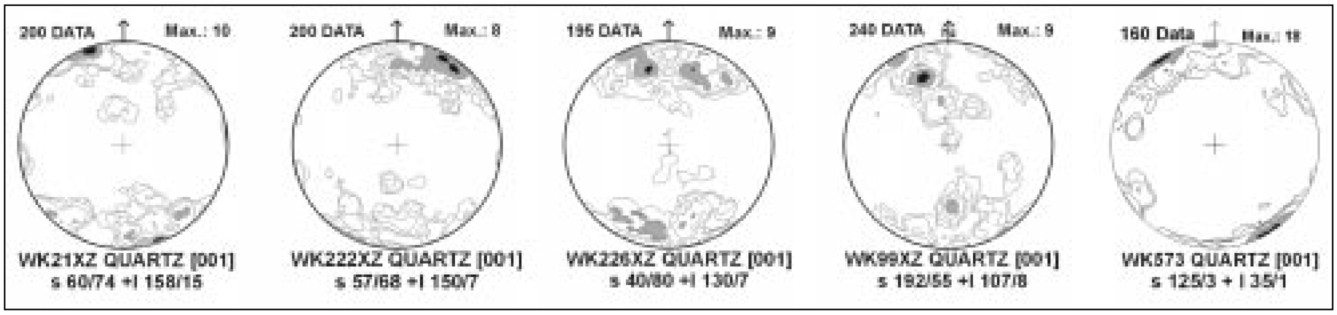
❶ Type 1: D_2 microstructures that are characterized by quartz grains that show equilibrated fabrics (straight grain boundaries, triple junctions), but well preserved CPOs. Such fabrics have been observed in the northeastern Tauern Window, in the northern and in the central southern part of the Tauern Window. In the southeastern part of the Tauern Window these fabrics only occur in the hanging-wall of the Venediger Nappe. The c-axis distributions are generally characterized by type I cross girdles, and in the southeastern part of the Tauern Window also locally by type II cross girdles. In places, oblique single girdle distributions have been recorded, e.g. within the Eclogite Zone.

❷ Type 2: D_2 microstructures that are characterized by highly elongated grains and fabrics typical for dislocation creep and grain boundary migration, and strongly developed CPOs. Such fabrics have been observed in the southeastern Tauern Window (Venediger Nappe and parautochthonous quartzites, Rote Wand-Modereck Nappe), and in the western Tauern Window. However, in the western section of the Tauern Window, a continuous transition from type 2 to type 1 fabrics from the south towards the north has been observed. The c-axes distributions show type I cross girdles in the western part of the Tauern Window and single girdles in the southeastern part of the Tauern Window.

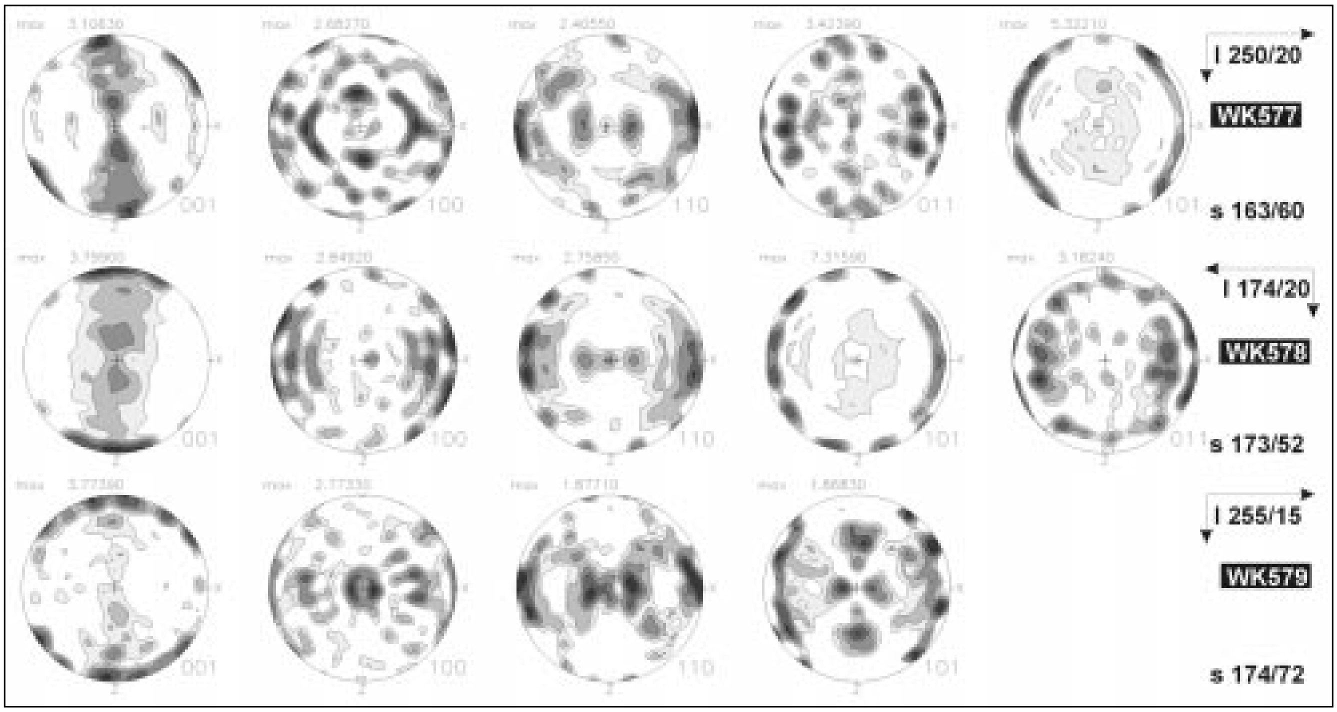


Text-Fig. 25.
Tectonic map of the Tauern Window, displaying sample locations presented in Text-Figs. 26–29.

However, these single girdle distributions continuously develop from cross girdle distributions. Therefore, the occurrence of single girdle distributions is interpreted in terms of higher finite strains. It is already clearly visible at the map-scale, that the Sonnblick Dome in the southeastern Tauern Window and the Tuxer and Zillertal Dome in the western Tauern Window (Text-Fig. 30) are characterized by an NW–SE, resp. W–E, elongated shape, and that these two areas show the highest amounts of finite strain with a subhorizontal direction of maximum elongation, while other parts have either not or only slightly been affected by this deformation. Therefore, it is not surprising that this feature is reflected in the quartz microstructures, too. The fabric evolution also documents, that the dome formation in the southeastern and western Tauern Window has already started during D_2 and was continued subsequent to the equilibration during amphibolite to greenschist facies metamorphism. Generally, the pure shear component, that can be derived from the quartz-c- and a-axis patterns, increases from the E (Sonnblick Dome) to the W. This is in accordance with the higher amount of subhorizontal shortening in the western part of the Tauern Window (Tux and Zillertal Domes). In the northeastern part of the Tauern Window, D_2 was not continued subsequent to the amphibolite to greenschist facies metamorphic overprint. Assuming synchronous metamorphism in the northern and southern part, this suggests that the penetrative deformation during D_2 propagated towards the south and downwards with time. This is in accordance with a south-dipping ramp during the collision between the Penninic continental unit and the European foreland. Simple shear and subhorizontal stretching is documented in the southeastern part of the Tauern Window. The deformation geometry within the northeastern and



Text-Fig. 26.
Representative quartz CPOs that are related to deformation phase D_3.
The quartz CPOs are U-stage measurements. Equal area projection; for explanation see Text-Figs. 5, 6.



Text-Fig. 27.
Representative dolomite CPOs that are related to deformation phase D_3.
For explanation see Text-Figs. 5, 6.

western sections of the Tauern Window is closer to plane strain, associated with a higher pure shear component during D_2.

Quartz microstructures that are related to D_3 are very homogeneous along various marginal sectors of the Tauern Window. Generally, they are characterized by ribbon grains. The c-axis distributions display small circles centered near Z indicating flattening strain.

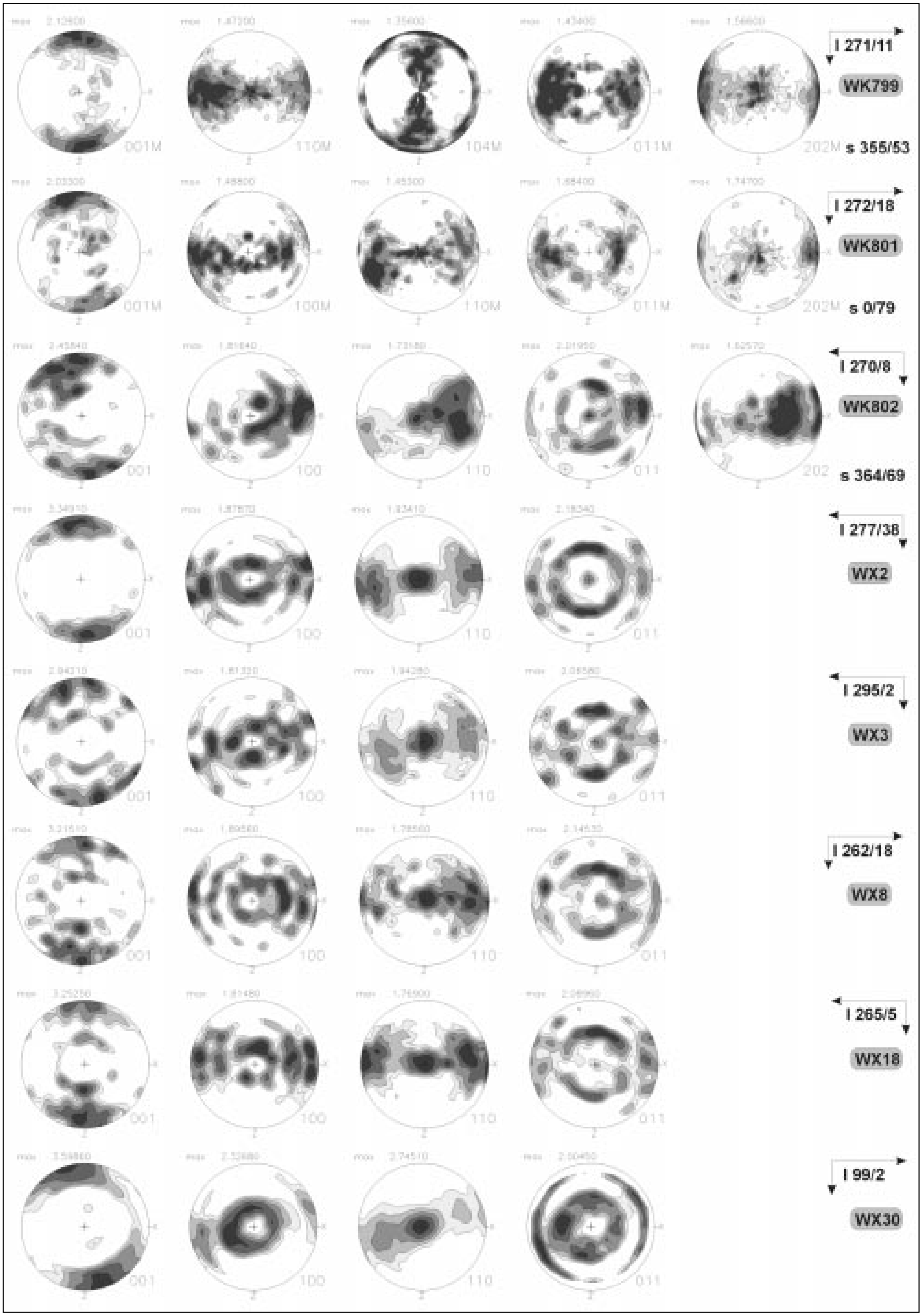
K-feldspar and plagioclase generally show undulatory extinction, which is characteristic for low-temperature plasticity. In the western and southeastern Tauern Window, K-feldspar shows the formation of subgrains. In the central part of the eastern Tauern Window plagioclase has dynamically recrystallized during D_1 (GENSER, 1992; KRUHL, 1993). The recrystallized grains show oligoclase composition.

The dolomite microstructures are very similar over the entire Tauern Window and for several phases of deformation. They indicate dynamic recrystallization and secondary grain size reduction.

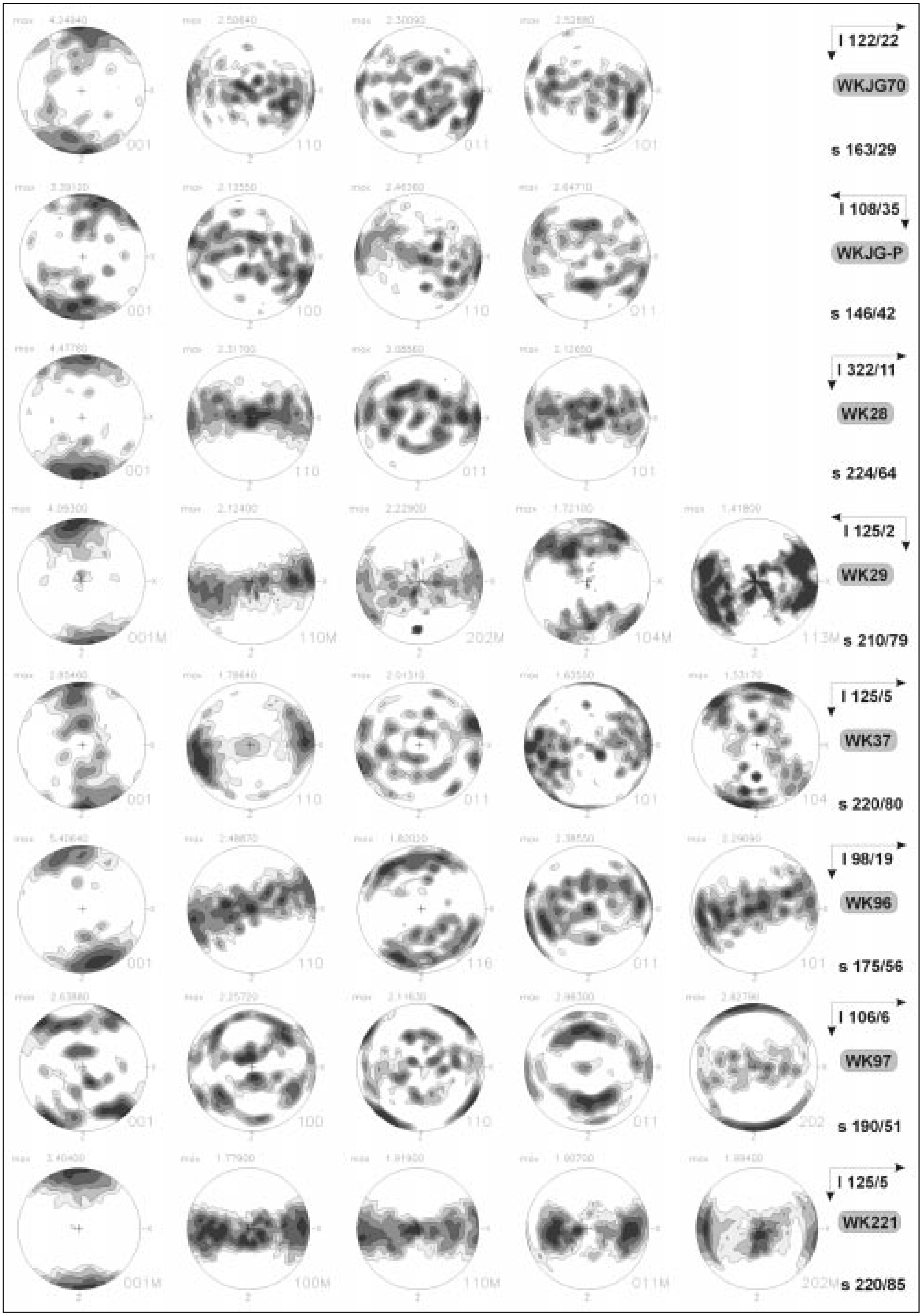
Only along the northeastern margin of the Tauern Window, dolomite is not affected by plastic deformation during D_1 and D_2, especially within the Matrei Zone.

The calcite microstructures are very similar in the interior parts of the Tauern Window. However, the fabrics do not seem to reflect the conditions of deformation during D_1 and D_2. D_1-related CPOs seem to have been strengthened during subsequent equilibration (e.g., SCHMID & CASEY, 1986). However, several CPOs are characterized by LT-fabrics according to WENK et al. (1987) and KURZ et al. (2000). D_2-related CPOs are dominated by HT-fabrics; however, these fabrics only indicate temperature conditions above 350°C (WENK et al., 1987).

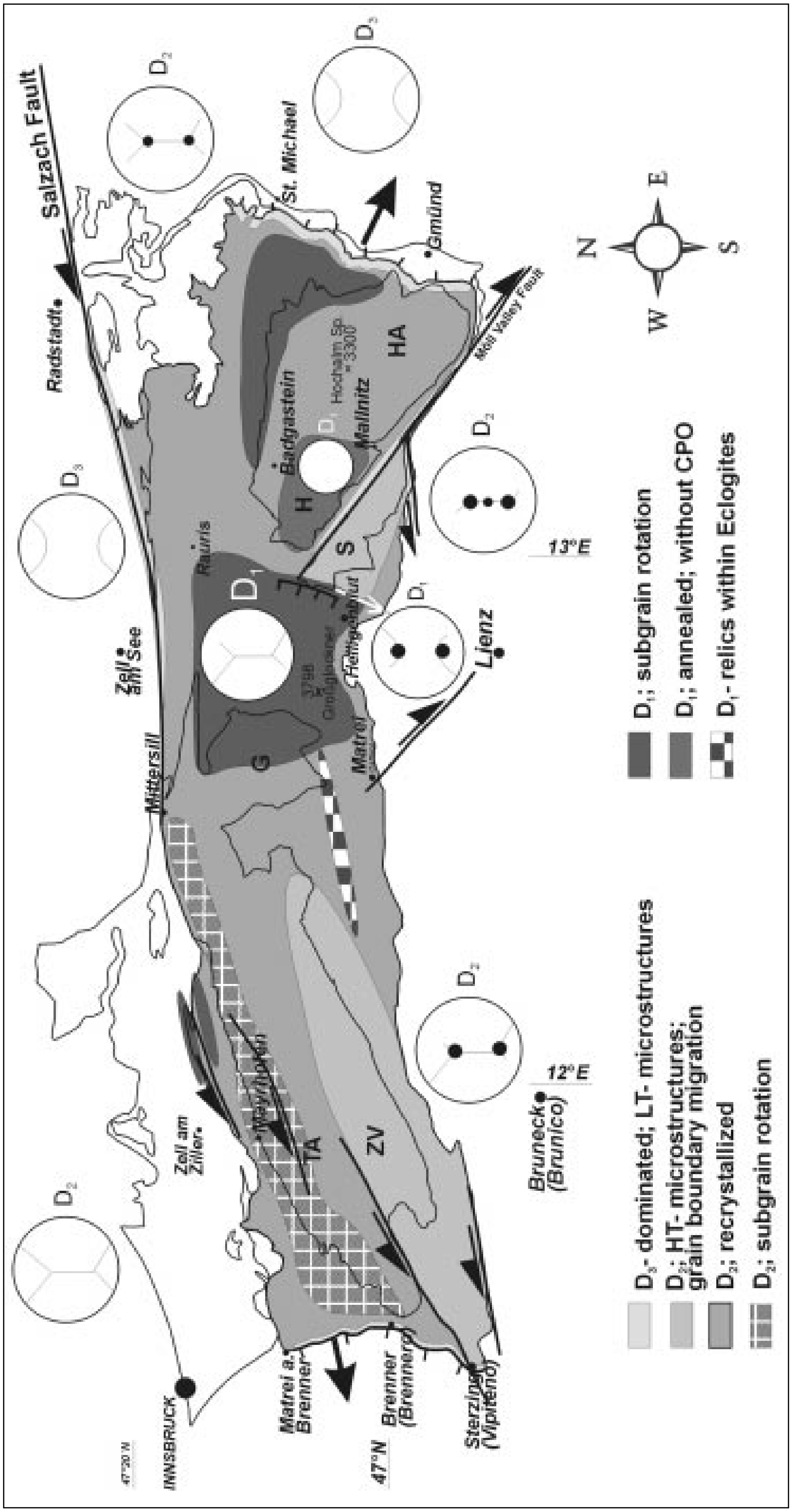
D_3 is restricted to distinct zones of semiductile and brittle deformation (e.g., GENSER & NEUBAUER, 1989; KURZ et al., 1994; KURZ & NEUBAUER, 1996, WANG & NEUBAUER, 1998) (Text-Fig. 30), and occurs within a regime of NNE–SSW-directed contraction. D_3-related calcite microstructures indicate dynamic recrystallization and secondary grain size reduction up to the formation of ultramylonites. The c-axes distributions show well defined clusters near the Z-axis of the finite strain ellipsoid. D_3 started at elevated temperatures, indicated by the plastic deformation of quartz along shear zones bordering the Tauern Window, but continued at decreasing temperatures. This is indicated by the brittle deformation of quartz, while calcite was still deformed plastically during this phase of D_3.



Text-Fig. 28.
Representative calcite CPOs that are related to deformation phase D_3.
Northern margin of the Tauern Window. For explanation see Text-Figs. 5, 6.



Text-Fig. 29.
Representative calcite CPOs that are related to deformation phase D_3.
Eastern and southeastern margins of the Tauern Window. For explanation see Text-Figs. 5, 6.



Text-Fig. 30.
Distribution of D_1-, D_2-, and D_3-related quartz microstructures (including characteristic quartz CPOs) within the Tauern Window.

11. Conclusions

The Tauern Window exposes underplated continental and obducted oceanic crust within the internal zones of the Eastern Alps. Exhumation occurred during the final stages of continent-continent collision, in a extensional regime.

Although the macro- and map-scale structures mainly document the uplift- and exhumation history, they only document the final stages of the orogenic evolution. Information on the pre-exhumation history can be obtained from meso- and microstructures, too. These microfabrics and textures bear therefore important information on the structural and metamorphic evolution of continental lithosphere that was in a lower plate position during continent-continent collision.

The deformational fabrics in the inner parts of the exhumed domes very often document the evolution related to the underthrusting history. These fabrics give furthermore information on the rheological behaviour of the lithosphere during several phases of crustal deformation. During underplating and nappe stacking (D_1), and subsequent continent-continent collision (D_2) several tectonic units were homogenously deformed.

Deformation was generally not concentrated along distinct shear zones, which is interpreted in terms of low competence contrast between various lithotectonic units. Conditions for the plastic deformation of the main rock-forming mineral phases (quartz, feldspar, dolomite, calcite) have been reached during these phases of crustal deformation. During exhumation and doming (D_3) deformation occurred at continuously decreasing temperatures. Therefore deformation was continuously transferred into rheologically weak lithologies, especially carbonates. While the plastic deformation of quartz, feldspar and dolomite ceased continuously and diminished with decreasing temperatures, calcite was deformed plastically until the final phases of crustal deformation. Competence contrasts had been elevated due to decreasing temperatures, and probably due to elevated strain rates, too.

Acknowledgements

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