Tectonic evolution of Penninic Units in the Tauern Window during the Paleogene: constraints from structural and metamorphic geology

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Abstract: Based on structural, lithological, and metamorphic evidence, the continental and oceanic nappes in the Tauern Window of Austria are paleogeographically restored in space and time. Special emphasis is given on the structural and metamorphic evolution of the Eclogite Zone in the central southern part of the Tauern Window. We infer that the units within the Tauern Window were incorporated into a nappe stack that was formed during the collision between a northern Penninic Zentralgneis Terrane and a southern Austroalpine block. In a late stage of Alpine orogeny (Late Eocene?), postdating the closure of the Penninic oceanic basin, the European continental margin including the Zentralgneis Terrane, was subducted southward beneath the Penninic ophiolite nappes (Glockner Nappe) and the Lower Austroalpine nappe stack. The Eclogite Zone and external parts of the Zentralgneis Terrane, predominantely represented in the Rote Wand-Modereck Nappe, reached depths sufficient for eclogites facies metamorphism. From there, the Eclogite Zone was emplaced towards an internal (southern) position. South over north nappe stacking postdated subduction-related (high-pressure) eclogite and blueschist facies metamorphism. Emplacement of the Eclogite Zone and the Glockner Nappe onto Penninic continental units that derived from the Zentralgneis Terrane (Storz Nappe, Venediger Nappe Complex) occurred subsequent to eclogite facies metamorphism. The Eclogite Zone, a former extended continental margin, is overridden by a pile of basement-cover nappes along a ductile out-of-sequence thrust. Low-angle normal faults that have developed during the Jurassic extensional phase might have been inverted during nappe emplacement.

Zusammenfassung: Basierend auf strukturellen, lithologischen und metamorph-petrologischen Hinweisen wird eine Lösung für die paläogeographische Rekonstruktion und den Zeitpunkt der Platznahme penninischer kontinentaler und ozeanischer Decken im Tauernfenster vorgeschlagen. Besondere Berücksichtigung findet die strukturelle und metamorphe Entwicklung der Eklogitzone im zentralen südlichen Tauernfenster. Die Einheiten des Tauernfensters sind in einen Deckenstapel

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einbezogen, der während der Kollision zwischen einem nördlichen penninischen Zentralgneisterran und einem südlichen ostalpinen Block gebildet wurde. In einer Spätphase der Alpidischen Orogenese (Spätes Eozän?), nach der Schliessung des Penninischen ozeanischen Beckens, wurde der europäische passive Kontinentalrand inklusive des Zentralgneisterrans nach Süden unter die Penninischen Ophiolitdecken (Glockner Decke) und den Unterostalpinen Deckenstapel subduziert. Die Eklogitzone und externe Teile des Zentralgneisterrans, großteils repräsentiert in der Rote Wand-Modereck Decke, wurden dabei in Tiefen subduziert, die für eine eklogitfazielle metamorphe Überprägung ausreichen. Von dort wurde die Eklogitzone relativ rasch in Richtung Oberfläche in eine interne (südliche) Position zurücktransportiert. Die nordgerichtete Deckenstapelung erfolgte nach einer eklogit- und gleichzeitig mit blauschieferfazieller Hochdruckmetamorphose. Die Platznahme der eklogitführenden Einheiten (Eklogitzone und Glockner Decke) auf penninischen kontinentalen Einheiten (Storz Decke, Venediger Deckenkomplex) erfolgte nach der eklogitfaziellen Metamorphose. Die Eklogitzone, die einen ehemaligen ausgedünnten externen Kontinentalrandbereich darstellt, wird von einem Grund-Deckgebirgsdeckenstapel entlang einer duktilen, durchbrechenden Überschiebung überfahren. Flache Abschiebungen, die während der jurassischen Riftingphase gebildet wurden, dürften dabei invertiert worden sein.

Keywords: Tauern Window, Penninic Units, Structural Geology, Metamorphism, Tectonics, Collision.

Contents

1. Introduction 348
2. Study area 352
   2.1. Tectonic units of the Tauern Window 354
3. Material and methods 356
4. Data and results 356
   4.1. The Eclogite Zone: lithofacies and tectonostratigraphic position 356
   4.2. Structures and kinematics 358
   4.3. Tectonometamorphic evolution of the Eclogite Zone and surrounding units 362
5. Discussion and interpretation 364
   5.1. Evolution of Penninic nappes in space and time 366
6. Conclusions 369
References 369

1. INTRODUCTION

The tectonometamorphic evolution and the paleogeographic reconstruction of Penninic Nappes in the Eastern Alps (Fig. 1), that are particularly exposed in the Tauern Window (Fig. 2), represents a crucial problem of tectonics of the Eastern Alps and was controversially discussed for many years. The Eastern Alps are generally subdivided into (1) the Austroalpine nappe complex, and the (2) Penninic nappe complex. Both include pre-Alpine basement units that are covered by Permian to Mesozoic, and partly Cenozoic, sequences (e.g., TOLLMANN, 1977). During the Alpine orogenesis these units have been incorporated into several Austroalpine and Penninic nappes. For a very long time, mainly according to correlations and comparative interpretations with models developed for the Western Alps, this orogenic event has been interpreted to be related to the collision between the European continental block s.l. and its outliers to the north, and the Adriatic

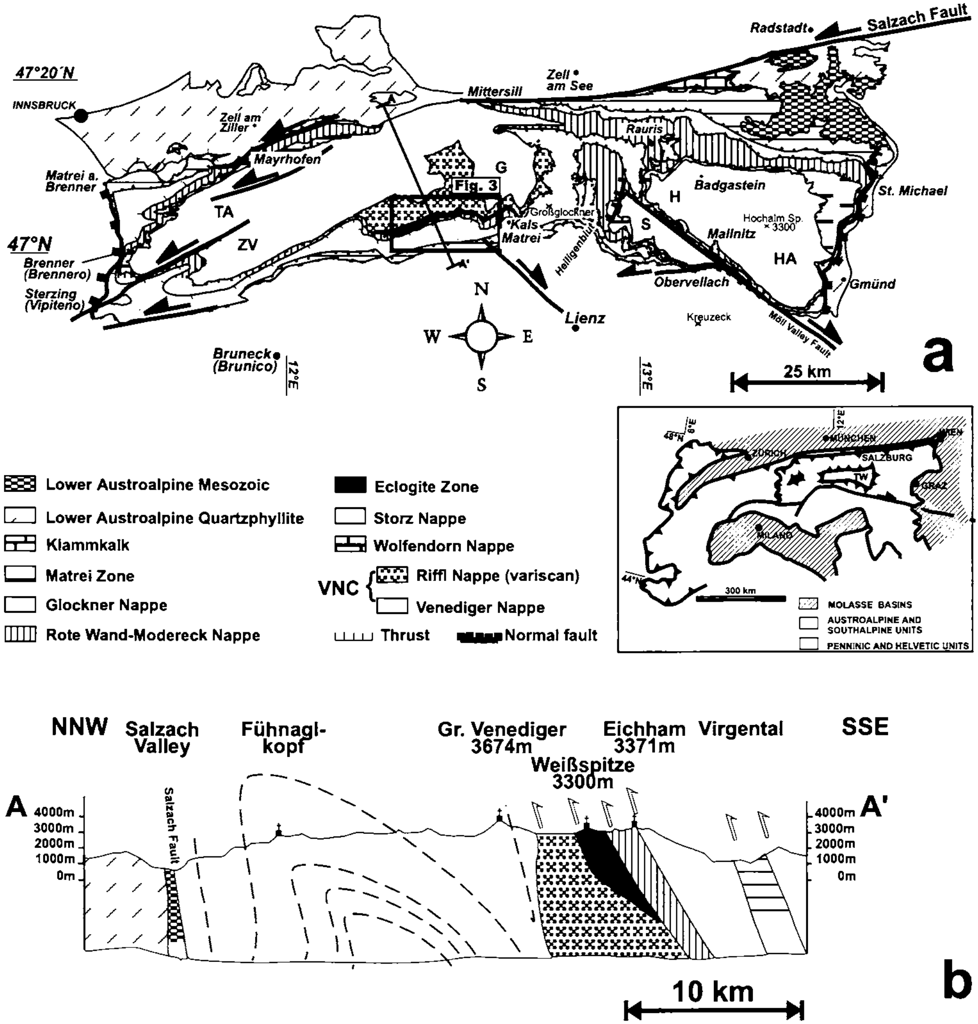

Fig. 1: a – Tectonic sketch map of the Tauern Window; S- Sonnblick Dome; HA- Hochalm-Ankogel Dome; H-Hölltor-Rotgülden Dome; G- Granatspitz Dome; ZV- Zillertal-Venediger Domes; TA- Tux-Ahorn Domes; VNC- Venediger Nappe Complex; A–A´-Location of cross section in Figure 1b (modified after KURZ et al., 1998b); the insert shows the tectonic position of the Tauern Window (TW) within the Alps. b – Section across the central part of the Tauern Window (for location see Figure 1a).

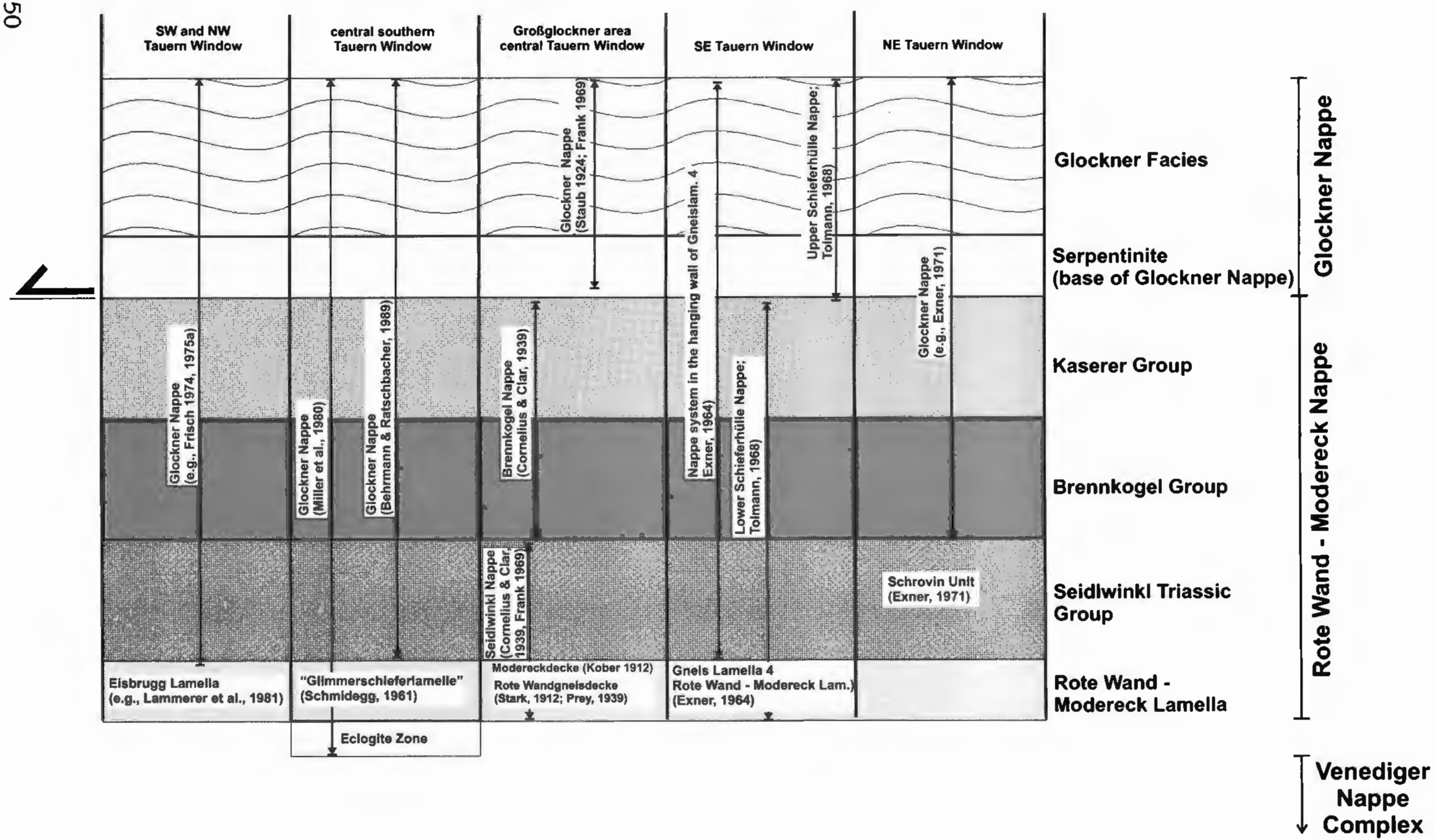

Fig. 2: Scheme documenting former structural subdivisions and interpretations of tectonic units within the Tauern Window.

continental plate to the south. The northern plate was in a footwall position (e.g., FRANK et al., 1987; FRANK, 1987). These continental units were separated by the Southpenninic oceanic domain, that had been subducted prior to the collisional event. Remnants of this oceanic domain are exposed within the Tauern Window and form the suture between the Austroalpine nappe complex in the hanging wall, and the continental Penninic nappe complex in the footwall. For these remnants of oceanic crust the term "Glockner Nappe" was introduced by STAUB (1924). The Tauern Window exposes many different lithostratigraphic and lithotectonic units that have multiply been affected by subsequent tectonometamorphic events. Due to the polymetamorphic and polydeformational evolution of these units the reconstruction of major and minor thrusts, that separate the different tectonostratigraphic units, was difficult (e.g., KOBER, 1921; PREY, 1939; EXNER, 1964; TOLLMANN, 1975; BICKLE & HAWKESWORTH, 1978). However, it was very easy to separate different lithofacial units (CORNELIUS & CLAR, 1939; FRASL, 1958; FRASL & FRANK, 1964, 1969; TOLLMANN, 1977). Therefore, in the course of time, lithofacial boundaries became tectonic boundaries in terms of "thrusts". In particular, concerning the separation of the Glockner Nappe it seemed to be reliable, that this nappe contains former oceanic lithosphere and the lithologies that are associated within an oceanic lithofacies (the "Glockner Facies"). Yet it is possible, that terrigenous sediments have been deposited on oceanic lithosphere, derived from former continental crust.

One of the major points of discussion in previous decades was the separation of the Glockner Nappe from the footwall units. Depending on several presumptions, different and controversial structural and paleogeographic interpretations have been suggested. A summary of former descriptions is documented in Fig. 2. For example, in the southeastern Tauern Window, EXNER (1964) established the "nappe system in the hanging wall of Gneiss Lamella 4" (the Rote Wand-Modereck Lamella, which corresponds to the "Modereckdecke" of KOBER, 1912, 1921, 1933; the "Rote Wandgneisdecke" of STARK, 1912 and WINKLER, 1923, 1926; and the "Rote-Wand-Gneisdecke" of PREY, 1939). The meta-sediments in the hanging wall of this gneiss lamella have been separated by TOLLMANN (1968, 1975, 1977, 1980) into a "Lower Schieferhülle Nappe" in the footwall, and the "Upper Schieferhülle Nappe" in the hanging wall. Serpentinite slices were used as criteria for this separation. However, the term "Lower Schieferhülle" was originally introduced for pre-Variscan units that have been intruded by Variscan granitoids, and for the Permian to Mesozoic cover sequences deposited on these units (e.g., FRASL, 1958). Accordingly, the "Lower Schieferhülle" would have occurred in the footwall of the "Lower Schieferhülle Nappe". FRISCH (1975a) used a similar separation, but later established one major nappe, the Glockner Nappe, in the hanging wall of the former unit. According to FRISCH (1976, 1980a, b) and FRISCH et al. (1987), the Glockner Nappe comprises the "Bündner Schiefer" and the "Tauernflysch Formation", that have been deposited within a rather small oceanic basin and subsequently stacked within an accretionary wedge. In places, slices of Permian to Triassic rocks occur along the base of this unit. Continental basement rocks are usually missing.

On the other hand, the Gneiss Lamella 4 (Rote Wand-Modereck Lamella) was very often interpreted to form the base of the Glockner Nappe, but this suggestion was highly under debate. Therefore, FRANK (1969, 1972) established the Seidlwinkl Nappe (corresponding to CORNELIUS & CLAR, 1939; HOTTINGER, 1934, 1935), which occurs in the structural position of the "Lower Schieferhülle Nappe". The Rote Wand-Modereck

Lamella formed the base of this unit. Slices of Triassic rocks separate this unit from the Glockner Nappe in the hanging wall.

In the southern part of the Tauern Window SCHMIDEGG (1961) established an independent tectonic basement lamella (the "Glimmerschiefer Lamella"), that appears to represent an equivalent to the Gneiss Lamella 4 (Rote Wand-Modereck Lamella) (KURZ et al., 1998b). According to SCHMIDEGG (1961) and BEHRMANN & RATSCHBACHER (1989), the base of the Glockner Nappe is formed by Triassic meta-carbonates directly in the hanging wall of this gneiss lamella. However, in the Glockner area, these meta-sediments are part of the Seidlwinkl Nappe established by FRANK (1969).

In the reviews by TOLLMANN (1975, 1977) the problem of the separation of the Glockner Nappe from the footwall units is well documented. In the northeastern part of the Tauern Window the base of the Glockner Nappe was interpreted to follow the top of the Permian to Triassic quartzites and carbonates of the Schrovin Unit. In the southeastern part of the Tauern Window, the base of the Glockner Nappe was formed by the Permian to Triassic quartzites and meta-carbonates in the hanging wall of the Rote Wand – Modereck Lamella; controversially, the Rote Wand – Modereck Lamella was often interpreted to form base of the Glockner Nappe. In the central part of the Tauern Window, the Permian to Triassic quartzites and carbonates (Wustkogel Quartzite, Seidlwinkl Triassic Group), and the Jurassic Brennkogel Facies assemblage formed the Rote Wand-Modereck Nappe, the base of the Glockner Nappe in this area was defined by the first occurrence of Glockner Facies assemblages (e.g., BEHRMANN, 1990).

In the central southern Tauern Window the base of the Glockner Nappe was interpreted to be formed by Triassic meta-carbonates in the hanging wall of the "Glimmerschieferlamelle" (compare BEHRMANN & RATSCHBACHER, 1989). However, referring to MILLER et al. (1980) and FRANK et al. (1987), the tectonic base of the Glockner Nappe in this area is formed by the Eclogite Zone (Fig. 1a, b). On the other side, it was clearly shown by RAITH et al. (1980) that the Eclogite Zone forms a coherent, independent tectonic unit (DROOP et al., 1990; KURZ et al., 1996, 1998a, b).

In the southwestern and northwestern Tauern Window the base of the Glockner Nappe followed the top of Permian to Triassic quartzites and meta-carbonates in the hanging wall of the Eisbrugg Lamella (LAMMERER et al., 1981; FRISCH, 1974, 1975a), which correlated with "Gneiss Lamella 4" of EXNER (1964) (the Rote Wand – Modereck Lamella).

Referring to the discussions described above, it seems necessary to clarify the tectonostratigraphic subdivision within the Tauern Window and to re-define it prior to the establishment of paleogeographic models and geodynamic-tectonic interpretations.

2. STUDY AREA

The study area comprises the Tauern Window (Austria) (Fig. 1a) which is bordered by the Brenner normal fault in the W, the Katschberg normal fault in the E, the Salzach fault in the N, and an Alpine thrust, which emplaced Middle Austroalpine basement units onto Penninic units, in the S. The Tauern Window exposes Penninic units in the footwall of the Austroalpine nappe complex (Fig. 1). For a tectonic overview of the Eastern Alps, see Fig. 1 in KURZ et al. (this volume).

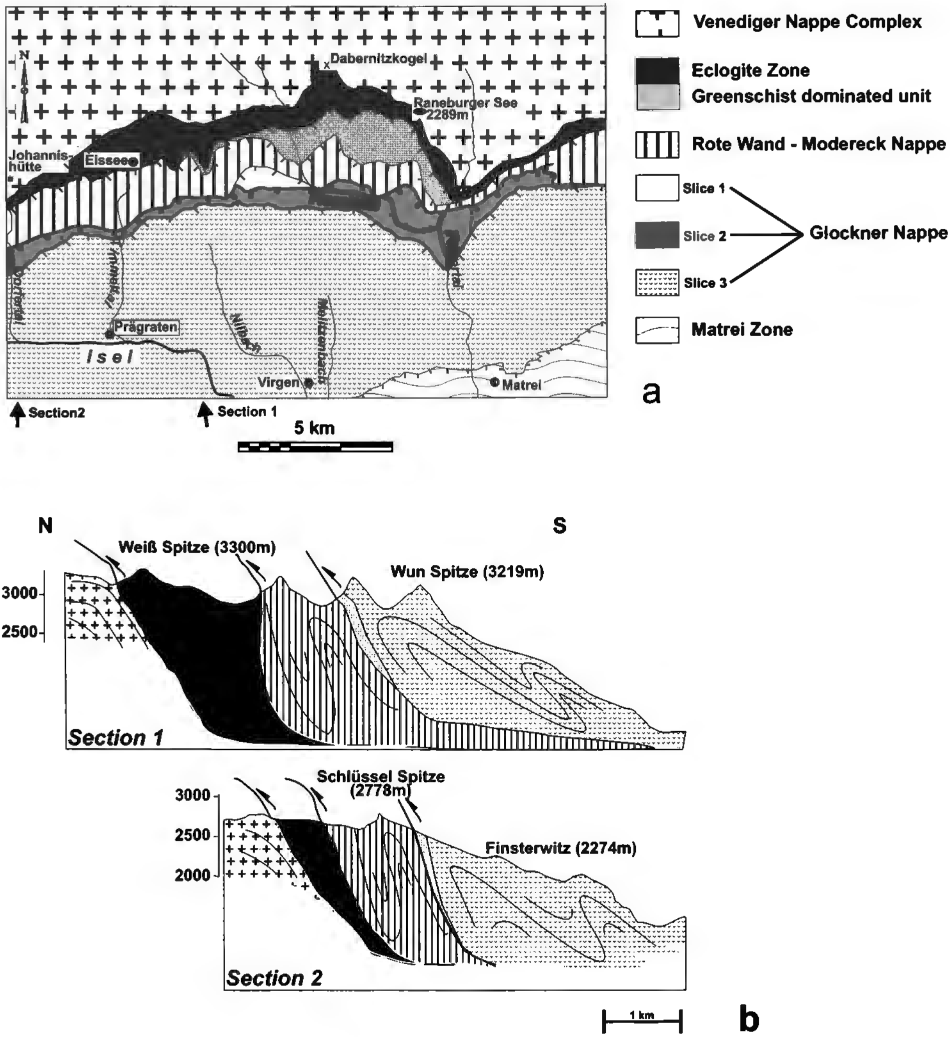

Fig. 3: a – Tectonic map of the central southern part of the Tauern Window, including the Eclogite Zone. b – Sections across the central southern part of the Tauern Window, documenting the tectonostratigraphic position of the Eclogite Zone (for location see Figure 2a).

Based on lithological, lithostratigraphic, structural and petrological arguments, the tectonostratigraphy of Penninic Nappes within the Tauern Window had been revised and re-defined by KURZ et al. (1998b). The subdivision is based on the occurrence of slices of continental/oceanic basement between packages of meta-sediments. These slices form the base of several nappes.

2.1. Tectonic units of the Tauern Window

From the footwall to the hanging wall, the Penninic nappe stack includes: (1) The Venediger Nappe and the Wolfendorn Nappe; these nappes comprise a pre-Variscan basement intruded by Variscan granitoids (the Zentralgneis) and a cover sequence of Jurassic metacarbonates (Hochstegen Marble Formation), and Cretaceous metapelites and metapsammites (Kaserer Group) (FRISCH, 1980b, 1984). Referring to LAMMERER (1988), sedimentation within the Kaserer Group reached up until the Eocene. The Wolfendorn Nappe mainly forms a duplex of the cover sequences of the Hochstegen Marble Formation and the Kaserer Group, underlain by thin slices of former continental basement. (2) The Storz and Riffl Nappes comprise Variscan and Alpidic polymetamorphic basement rocks covered by metapelites and graphitic quartzites of the Murtörl Group, which was supposed to be of either late Paleozoic (EXNER, 1971, 1982, 1983, 1990) or Cretaceous (KURZ et al., 1998b) age; referring to lithofacial similarities to the Kaserer Group of the Venediger Nappe, a Cretaceous age of the Murtörl Group is preferred (KURZ et al., 1998b). The tectonic contact between the Venediger Nappe and the Riffl Nappe (Fig. 1) was highly under debate and is interpreted to be related to the Variscan orogeny by FRISCH (1977a, 1980b). (3) The Eclogite Zone (see below) is restricted to the central southern Tauern Window and is characterized by a Mesozoic volcano-sedimentary sequence of a distal continental slope. The Eclogite Zone is tectonically positioned in the hanging wall of the Venediger Nappe Complex (Figs. 1, 3), and is overlain by the Rote Wand-Modereck Nappe (Figs. 1, 3, 4a). However, where the Eclogite Zone is missing, the Rote Wand-Modereck Nappe is directly thrusted onto the Venediger Nappe (Fig. 4b). (4) The Rote Wand-Modereck Nappe is formed by basement rocks of the Rote Wand-Modereck Lamella that are covered by Permian to Triassic quartzites and Triassic metacarbonates, Jurassic breccias, calcareous micaschists and metatuffs as well as Cretaceous metapelites and metapsammites. (5) The Glockner Nappe comprises an oceanic basement (serpentinites and ultramafic rocks) and a partly incomplete ophiolitic sequence. Locally, terrigenous sequences have been observed, for example in the central part and the western part of the Tauern Window. It is very important to note that the base of the Glockner Nappe is built up of former oceanic lithosphere, while the cover sequences of several other nappes within the Tauern Window are underlain by continental basement. Hence, the separation of the Glockner Nappe from the Rote Wand-Modereck Nappe in the footwall is only possible, if serpentinites and other remnants of former oceanic lithosphere are intercalated between meta-sediments (Fig. 4c). Additionally, for these reasons it is not proven that the Eclogite Zone may form the base of the Glockner Nappe, as suggested by MILLER et al. (1980). Accordingly, the same has to be stated for the Triassic metacarbonates, which have been suggested to form the base of the Glockner Nappe by BEHRMANN & RATSCHBACHER (1989). (6) The Matrei Zone is interpreted to represent an accretionary wedge that is character-

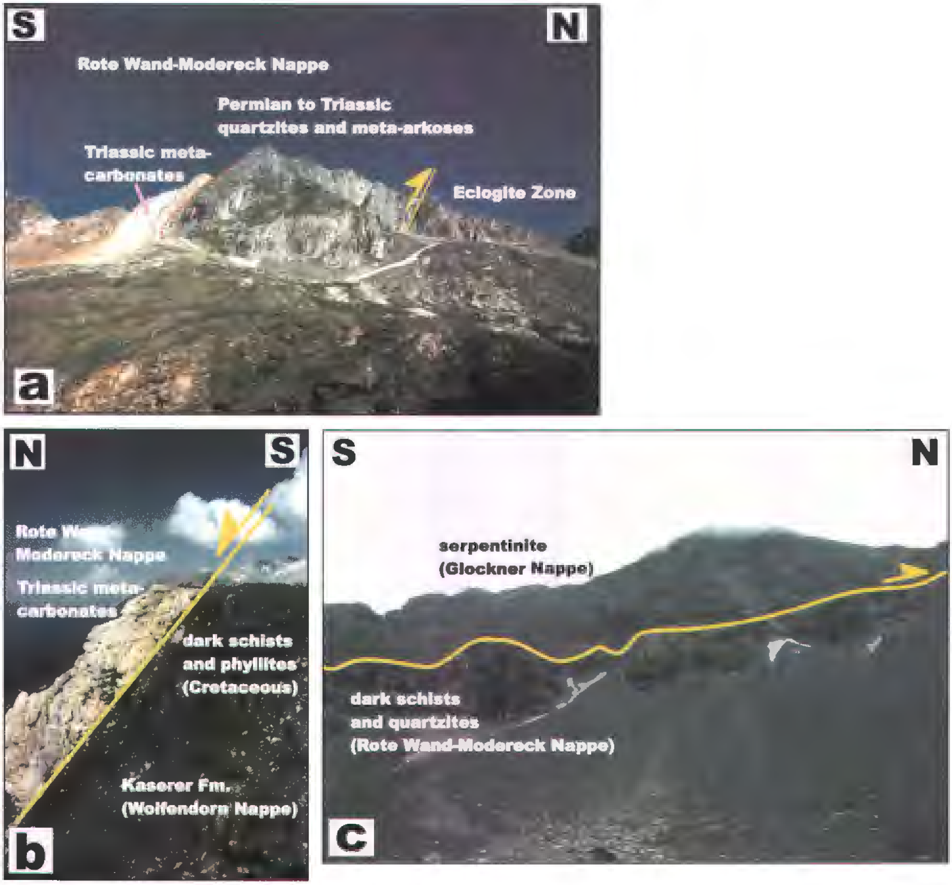

Fig. 4: a – Thrust contact between the Eclogite Zone (footwall) and the Rote Wand-Modereck Nappe (hanging wall). Central southern Tauern Window, Timmel Valley, Zopetscharte, Osttirol. b – Thrust contact between the Wolfendorn Nappe (footwall) and the Rote Wand-Modereck Nappe (hanging wall). Northwestern Tauern Window, ca. 250m south of Tuxer Joch Haus, altitude 2350m, Tirol. c – Thrust contact between the Rote Wand-Modereck Nappe (footwall) and the Glockner Nappe (hanging wall). Central Tauern Window, Großglockner Hochalpenstraße, Elendgrube, altitude 2420m, Salzburg.

ized by metamorphic flysch sediments (mainly calcareous and carbonate-free micaschists), breccias and olistolites mainly of Austroalpine derivation (Frisch et al., 1987). (7) The Klammkalk Zone comprises calc-schists, massive marbles and thin-bedded green phyllites, and forms a low-grade metamorphic eqivalent to the "Bündnerschiefer" of the Glockner Nappe. (8) The Lower Austroalpine nappe stack in the hanging wall of the Penninic nappe stack, which comprises pre-Alpine continental basement units and Permian to Mesozoic cover sequences, predominantely derived from a rifted, passive continental margin. Most of the lithofacial assemblages (TOLLMANN, 1963, 1965b, 1977; HÄUSLER, 1987, 1988; HANDY, 1996) are quite similar to the sequences that can be observed within the Rote Wand-Modereck Nappe. A detailed lithostratigraphic description of several nappes is given by KURZ et al. (1998b).

3. MATERIAL AND METHODS

We have investigated several sections across the Eclogite Zone and the surrounding tectonic units. In particular, special emphasis was given on the identification of macro-, meso-, and microscale shear criteria in order to establish the sense of nappe emplacement, on the lithofacies and age of several lithological units, and their metamorphic evolution. 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. Additionally, the metamorphic conditions during nappe stacking have been investigated in detail for several nappes. Quartz CPOs have been measured by X-ray texture measurements with a Siemens D500 X-ray goniometer at the University of Graz (Austria) in reflexion mode. The apparative and methodical limitations restrict samples to a size of 2.5 x 1.5 cm. The X-ray beam is reflected from an area of about 5 x 5 mm. Generally we used a 0.6° diaphragm for the detector. This allows the detection of single peaks that are spaced at a 2θ of at least 1.2°. The evaluation of pole figures was done with the program TexAT v. 2.2c/ODF AT v.1.1a provided by Siemens Co. which includes corrections for background and beam defocussing.

The structure of this area is well documented by an enormous amount of structural field data (CLIFF et al., 1971; BICKLE & HAWKESWORTH, 1978; DROOP, 1981, 1985; LEDOUX, 1984; FRANK et al., 1987; LAMMERER, 1988; BEHRMANN & RATSCHACHER, 1989; BEHRMANN, 1990; KRUHL, 1993; OEHLKE et al., 1993; WALLIS et al., 1993; KURZ et al., 1996; WALLIS & BEHRMANN, 1996). Microfabric 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). Concerning the studies in this contribution, the reader is referred to the structural data published by KURZ et al. (1996, 1998a, b, 1999, 2000).

4. DATA AND RESULTS

4.1. The Eclogite Zone: lithofacies and tectonostratigraphic Position

The *Eclogite Zone* (Fig. 3) comprises mafic eclogites of tholeiitic basaltic and, in places, tuffitic chemical composition as well as eclogite facies meta-gabbroic rocks (MILLER, 1974, 1977). The meta-gabbros are generally located at the base of the lithostratigraphic sequence. Eclogitic lenses and boudins of a thickness of a few metres to several hundred metres are intercalated within metasediments, especially within quartzites (Fig. 5a), and calcareous micaschists (Fig. 5b). The eclogites, in places, contain relics of

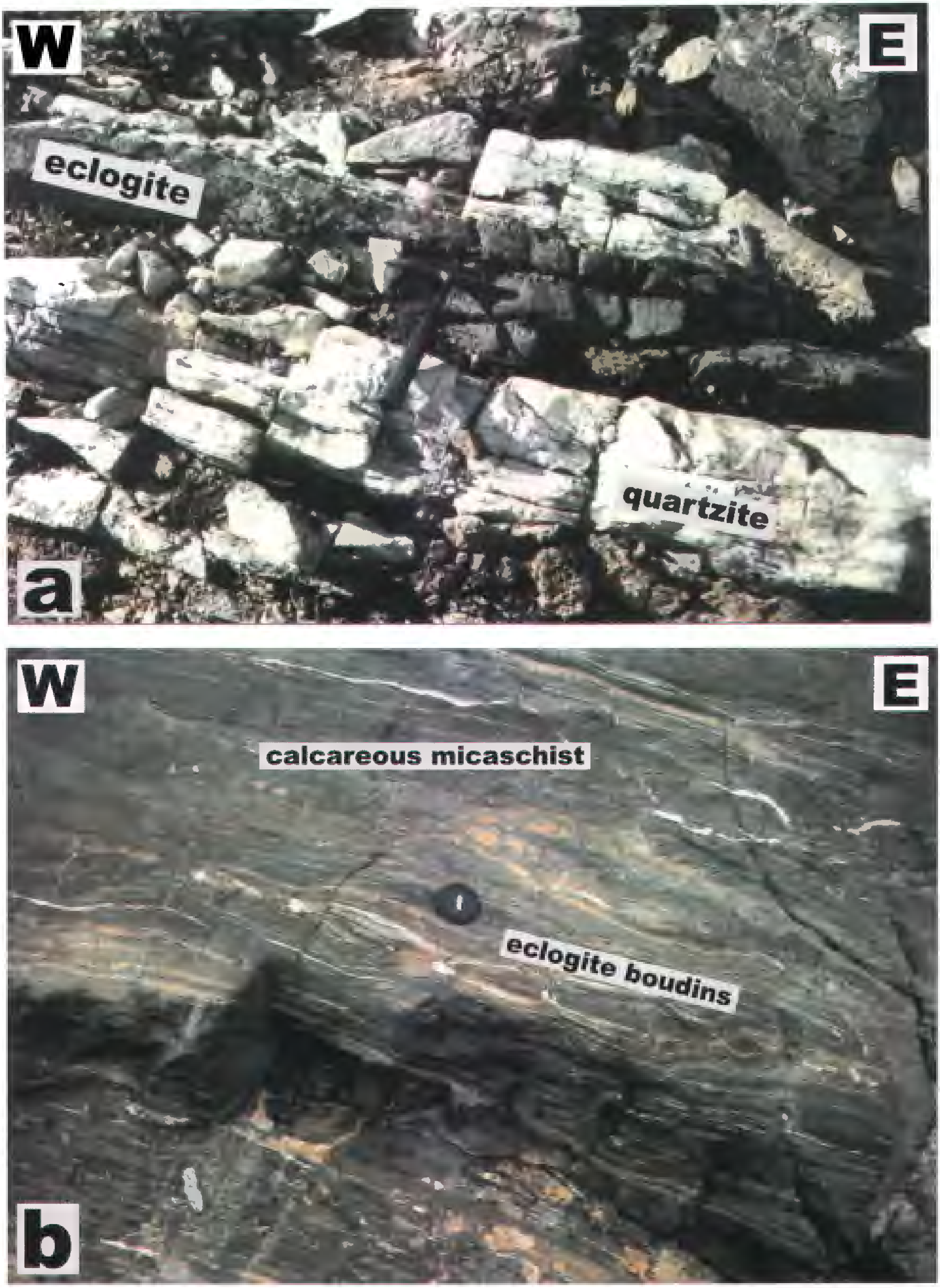

Fig. 5: Outcrop-scale structures from the Eclogite Zone. a – Eclogitic layer intercalated between layers of quartzite. b – Eclogite boudins in a matrix of marble mylonite, calcareous micaschists and metapelites; eastern shore of Eissee (2550m); Timmeltal.

pillow structures (MILLER et al., 1980). They are often retrogressed to garnet-amphibolites and garnet-bearing greenschists. The degree of retrogression varies laterally and vertically. Generally, retrogression increases to the hanging wall (Greenschist dominated unit in Fig. 3). The eclogites and their retrogressed derivates occur together with metagabbros and metasediments like pure quartzites, paragneisses, metaarkosic rocks, garnet-micaschists, calcareous micaschists, and calcitic and dolomitic marbles which are intercalated at decimeter- to meter-scale. The eclogites are mainly associated with the metapelites and quartzites, but in places also with the calcareous micaschists. The rock association within the Eclogite Zone is interpreted to indicate an initial rift stage (MILLER et al., 1980), and a depositional environment along the continental slope of a passive continental margin, strongly influenced by terrigeneous sedimentation as represented by metapsammites (KURZ et al., 1998b). The occurrence of meta-gabbros seems to indicate the intrusion of basic melts into continental lithosphere. A small slice of eclogites is also exposed in the Dorfertal north of Kals am Großglockner in the same tectonic position as the Eclogite Zone (Fig. 2). The co-facial nature of the high pressure assemblages in metasediments and metabasic rocks also suggests that the Eclogite Zone behaved as a coherent unit during eclogite facies metamorphism and its emplacement onto the Venediger Nappe (RAITH et al., 1980; DROOP et al., 1990). This is supported by the apparent stratigraphic continuity of continental margin sequences on a scale of tens of metres to kilometres (RAITH et al. 1980; KURZ et al. 1996), and on the independent high pressure metamorphic evolution prior to the amphibolite to greenschist facies metamorphic overprint (HOLLAND, 1979; FRANZ & SPEAR, 1983; SPEAR & FRANZ, 1986; DACHS, 1986, 1990). Furthermore, this is corroborated by the fact that the tectonic units in the footwall and the hanging wall have not been affected by eclogite facies metamorphism (e.g., FRANK et al. 1987; SELVERSTONE, 1993).

Lithofacial similarities exist in particular between the Rote Wand-Modereck Nappe and the Eclogite Zone. Both units comprise similar Permian to Triassic and Jurassic lithofacial sequences. However, Jurassic breccias are missing within the Eclogite Zone. Additionally, the Permian to Triassic sequences of the Rote Wand-Modereck Nappe have been deposited on continental basement. This and the occurrence of gabbroic rocks at the base of the Eclogite Zone argue for a more distal (southern) paleogeographic position of the Eclogite Zone with respect to the Rote Wand-Modereck Nappe. Furthermore, lithologies that can be derived from former continental basement are nearly entirely missing within the Eclogite Zone. Lithofacial similarities to the footwall units are hard to observe, because the sedimentary sequence of the Venediger Nappe does not start before the Jurassic (TOLLMANN, 1975a, b; FRISCH, 1980a, 1984; LAMMERER, 1988; KURZ et al., 1998b).

4.2. Structures and kinematics

For the structural and paleogeographic restoration of the Penninic nappes in the Tauern Window it is of great importance to get knowledge on the direction of nappe emplacement. In particular, the direction of emplacement of the Rote Wand-Modereck Nappe on top of the Eclogite Zone is the question concerned most. Nappe stacking resulted in the formation of a penetrative foliation (S_1) and a N- trending stretching lineation (L_1). Stretching lineations, sheath folds, and isoclinal orthorhombic folds with axes parallel to

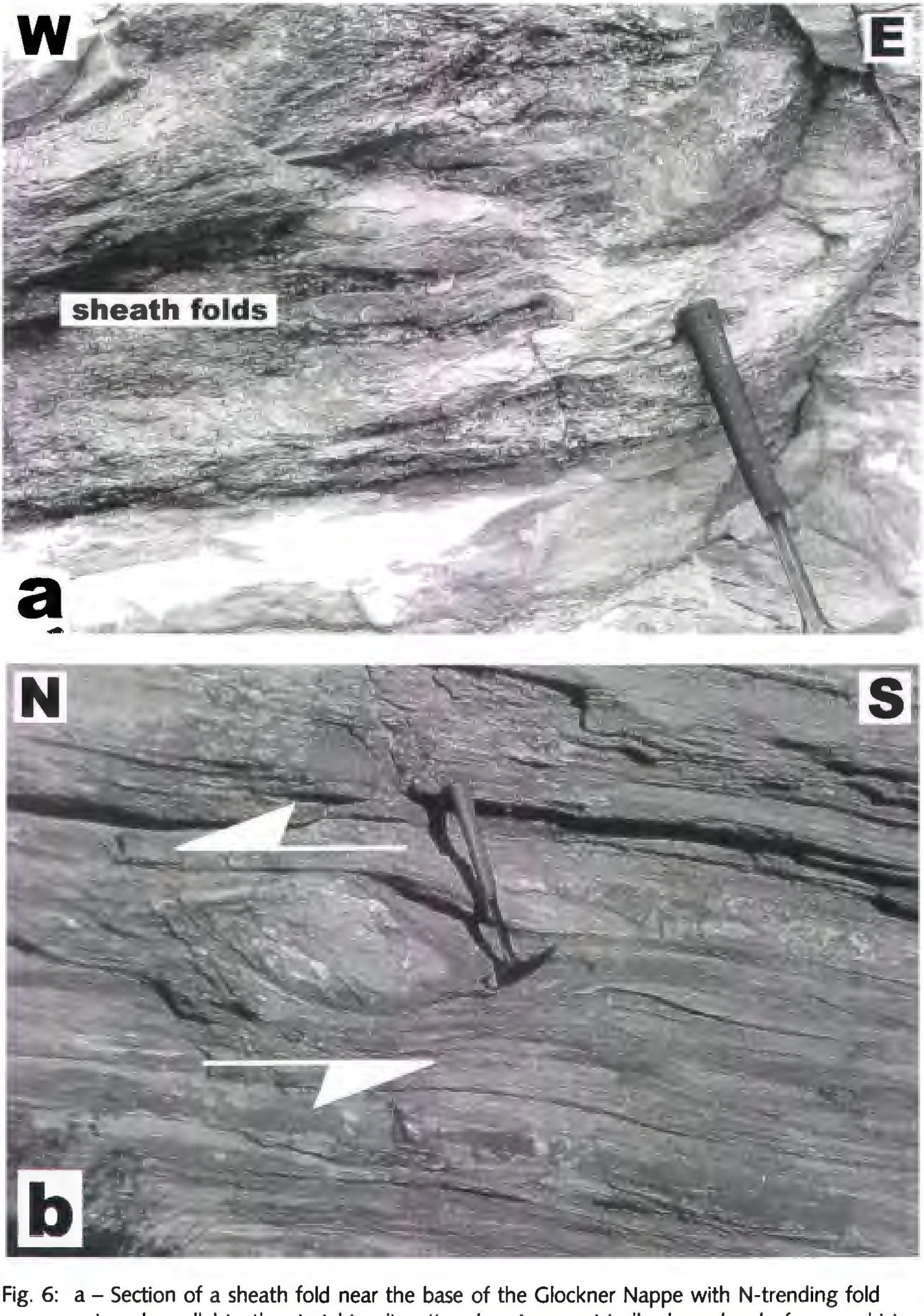

Fig. 6: a – Section of a sheath fold near the base of the Glockner Nappe with N-trending fold axis, subparallel to the stretching lineation. b – Asymmetrically shoped rod of greenschist in a matrix of calcareous micaschist near the base of the Glockner Nappe, Glockner area.

the stretching lineation consistently trend NNW to N over the entire area (Fig. 6a) (KURZ et al., 1996). This consistency is generally related to the high finite shear strain. These structures occur within incompetent metasediments like marbles and calcareous micaschists as well as within more competent units like garnet amphibolites. In the central part of the Tauern Window relics of meso-scale duplexes near the base of the Glockner Nappe, and near competence boundaries within the Glockner Nappe indicate top-to-the N sense of shearing. Similar kinematics is documented by asymmetric rods of greenschist within a ductile matrix of marble mylonites (KURZ et al., 1996) (Fig. 6b), showing a σ-type geometry. Within the Rote Wand-Modereck Nappe σ-type porphyroclasts of albite and asymmetric strain shadows filled with annealed quartz further indicate top-to-the N simple shear (see Fig. 11a in KURZ et al., 1996). Asymmetric strain shadows around relictic garnets (σ-type porphyroclasts) in garnet amphibolites of the Glockner Nappe indicate top-to-the-N ductile shearing. Top-to-the N shearing is indicated by asymmetric crystallographic preferred orientations of quartz, too (KURZ et al., 2000). The c-axes [001] distributions (Fig. 7) at the base of the Rote Wand-Modereck Nappe are characterized by two clusters that are positioned between the Y- and Z- axes of the finite strain ellipsoid (Fig. 7; sample WK369, WK371). Relics of a small circle distribution are observable. The asymmetric arrangement of the clusters indicates top-to-the N sense of shear during D_1 and might therefore be used as sense of shear indicators for nappe emplacement. 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 (Fig. 7; sample WK358). Towards the hanging wall, symmetrical or slightly asymmetrical small circle distributions of quartz c-axes are developed. Relics of a cluster within Y can locally be observed, but this gradually diminishes to the hanging wall (Fig. 7; sample WK359). In the central part of the Rote Wand-Modereck Nappe (cover sequences) the c-axis distributions develop gradually from oblique type I cross girdles (Fig. 7; sample WK444, WK472, WK474, WK482) to clusters within Y (WK423). The asymmetry of these fabrics indicates a south over north sense of shear. While the clusters between Y and Z diminish, the cluster within Y is getting stronger. The quartz c-axes distributions within the Riffl Nappe, and along the base of the Glockner Nappe are very similar (Fig. 7, WK512, WK349, WK521). They show symmetrical type I cross girdles, indicating a top-to-the N sense of shear. In the central part of the Glockner Nappe, small circle c-axis distributions are observed (Fig. 7, WK522).

These observations indicate a stronger component of flattening strain at the base of the Rote Wand-Modereck Nappe. The deformation geometry in the central parts of the nappe is located closer to plane strain, documented by the predominance of type I crossed girdles. In the footwall of the Rote Wand-Modereck Nappe type I cross girdle distributions dominate (Fig. 7, WK512), similar as within the central parts of the Rote Wand-Modereck Nappe (Fig. 7, WK444, WK472, WK474, WK482). This indicates strain localization along the base of the Rote Wand–Modereck Nappe during nappe stacking (D_1) within the Penninic continental units of the Tauern Window (KURZ et al., 2001, in press). Summarizing, this may document higher finite strain at the base of the Rote Wand–Modereck Nappe, which is related to shear localization within this zone (KURZ et al., 2000, 2001).

In the Venediger Nappe and the Eclogite Zone a penetrative mylonitic foliation and a NE-trending stretching and mineral lineation are developed. Related asymmetric

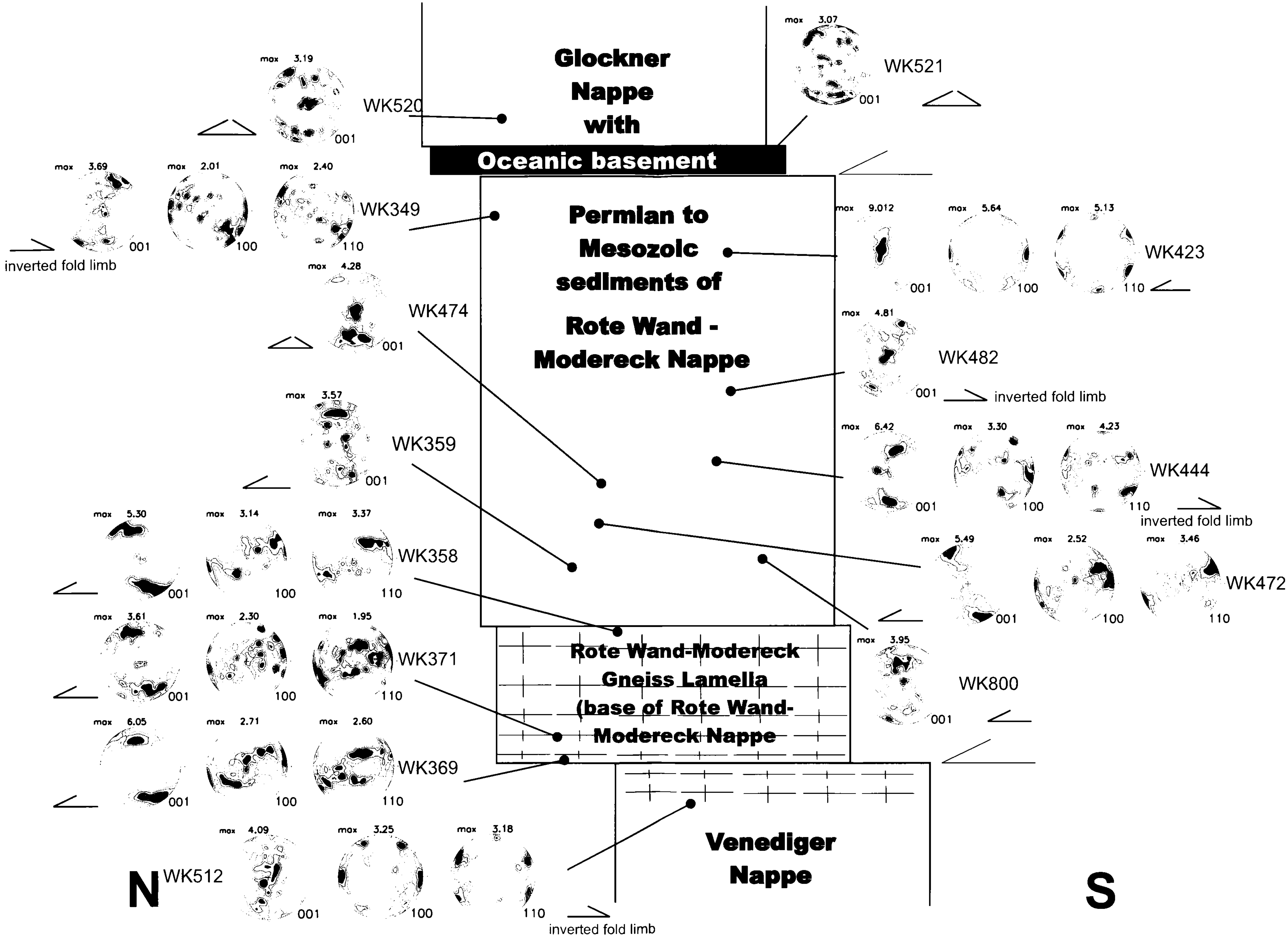

Fig. 7: Simplified columnar section across the Rote Wand – Modereck Nappe (including footwall and hanging wall units), including representative quartz CPOs of D_1 deformation stage. Equal area projections; logarithmic gradation of isolines; first isoline: uniform distribution; fifth isoline: 85% of maximum. Top to the S sense of shear indicated by some pole figures results from sampling within inverted fold limbs.

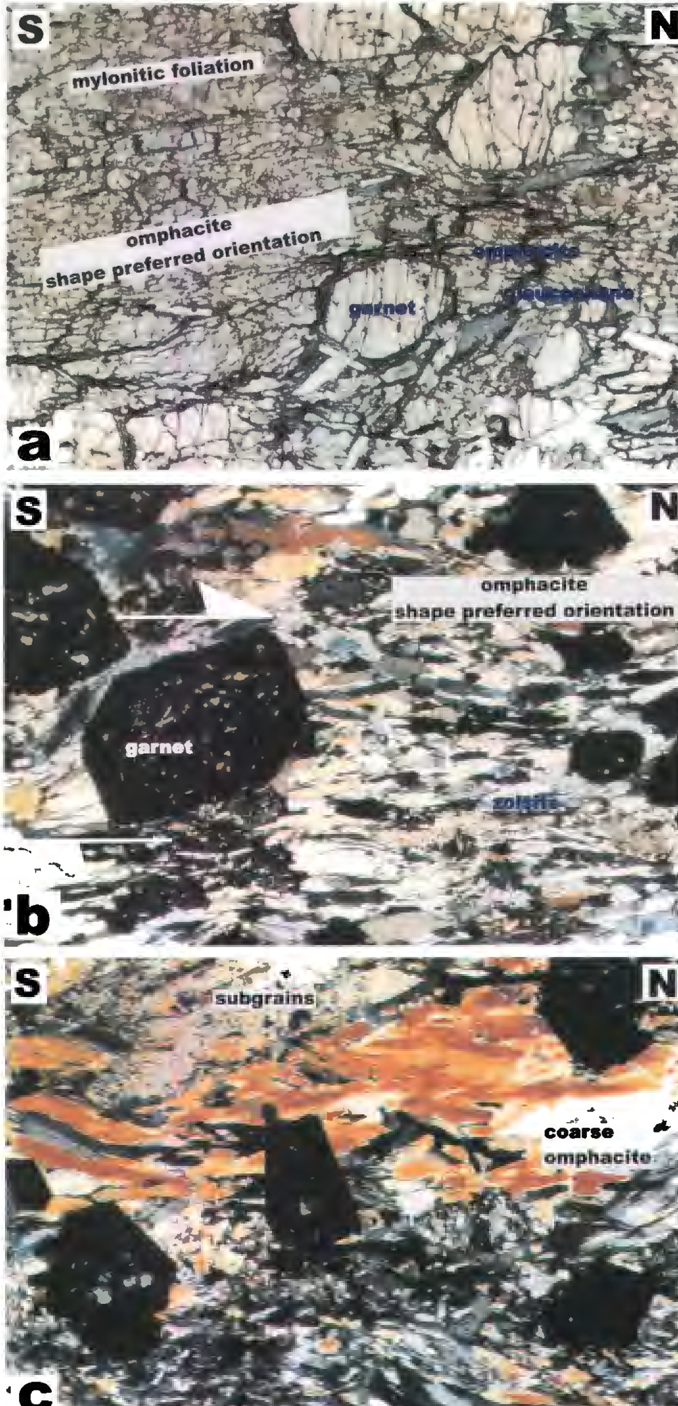

Fig. 8:
Microfabrics of eclogites from the Eclogite Zone of the Tauern Window. a – Photomicrograph of fine-grained eclogitic mylonite, showing a shape preferred orientation of omphacite, zoisite, and glaucophane; between garnet and omphacite new glaucophane is developed during subsequent blueschist facies metamorphic overprint.
b – Coarse-grained elongated garnet asymmetric strain shadows indicating a top-to-the N sense of shear during eclogite facies metamorphism.
c – Photomicrograph of plastically deformed coarse omphacite, showing the formation of subgrains; subgrain boundaries are preferably oriented parallel to the prism planes, and parallel to the foliation. a–c: Width is 4 mm, crossed polarizing filters.

ductile structures document top-to-the-NE shearing. Only in lower parts of the Venediger Nappe these fabrics are obliterated by W- directed ductile shear structures.

The microfabric of eclogites in the Eclogite Zone is characterized by a shape-preferred orientation of omphacite and zoisite defining the penetrative foliation (Fig. 8a, b). Oblique alignment of omphacite with respect to the shear plane is missing. Garnets partly show an elongated shape; asymmetric strain shadows around garnet are mainly filled with recrystallized omphacite, crossitic hornblende, zoisite, and phengite. The asymmetric arrangement of strain shadows documents top-to-the-NE ductile shearing (Fig. 8b). δ-porphyroblasts of garnet are rather scarce and document top-to-the-NE ductile shear. Some garnets are surrounded by a rim of blue amphibole (Fig. 8a). The garnets are sometimes fractured or asymmetrically boudinaged. Tension gashes and fractures as well as necks between boudinaged garnets are filled with phengite, epidote, quartz, and rare blue amphibole. The penetrative foliation is overgrown during decompression by zoisite/epidote, amphibole, chlorite, and phengite. Deformation already started at eclogite facies conditions. A sub-phase of deformation can be observed at approx. 19–20 MPa and 550–570° C (KURZ et al., 1998a). This deformational event resulted in dislocation glide, and the formation of subgrains within omphacite (Figs. 8c, 9). A second sub-phase of deformation resulted in dynamic recrystallisation of omphacite and the formation of fine grained eclogitic mylonites, showing a shape preferred orientation of garnet, zoisite and omphacite (Figs. 8a, 9). This sub-phase of deformation can be observed at approx. 21–23 MPa and 600–620° C (KURZ et al., 1998a) (Fig. 9). Subsequently, deformation was continued at blueschist facies conditions at approx. 10–11 MPa and 450° C (KURZ et al., 1998a) (Fig. 9).

4.3. Tectonometamorphic evolution of the Eclogite Zone and surrounding units

The rocks exposed within the Eclogite Zone have been affected by a multiphase tectonometamorphic evolution. Inclusions in garnets, which are sometimes interpreted as pseudomorphs after lawsonite, document a first stage of metamorphism at ca. 400° C (MILLER, 1977; FRANK et al., 1981, 1987). Eclogite facies metamorphism is only observed clearly within the Eclogite Zone. The eclogite facies rocks were buried to a depth of at least 65 km (20 MPa, ± 600° C; HOLLAND, 1979; DACHS, 1986, 1990; DROOP et al., 1990; FRANK et al., 1987; SELVERSTONE et al., 1992; ZIMMERMANN et al., 1994; GETTY & SELVERSTONE, 1994) (Fig. 9). Within the Glockner Nappe and the Rote Wand-Modereck Nappe eclogite facies metamorphism is just locally recorded (KURZ et al., 1996; STURM et al., 1997; PROYER et al., 1999). Only within garnets, if they are preserved, rare inclusions of blue amphiboles (glaucophane) are recognizable. Locally relics of pyroxene (possibly omphacite) are preserved (PROYER et al., 1999). Generally, eclogite facies assemblages can only be observed in the southern sections of these nappes, which would be related to a more distal (southern) paleogeographic position. The tectonic units that were derived from the Zentralgneiss Terrane were subsequently affected by blueschist facies metamorphism (Fig. 9). Within the Glockner nappe this phase of metamorphic overprint has not been observed (PROYER et al., 1999). Within the Eclogite Zone pressures of 7–9 MPa and temperatures of *ca.* 450° C are estimated by RAITH et al. (1980); 450° C and 10–15 MPa are estimated by HOLLAND (1979) and ZIMMERMANN et al. (1994), but the P-T data are not well constrained due to the subsequent strong overprint by Barrovian-

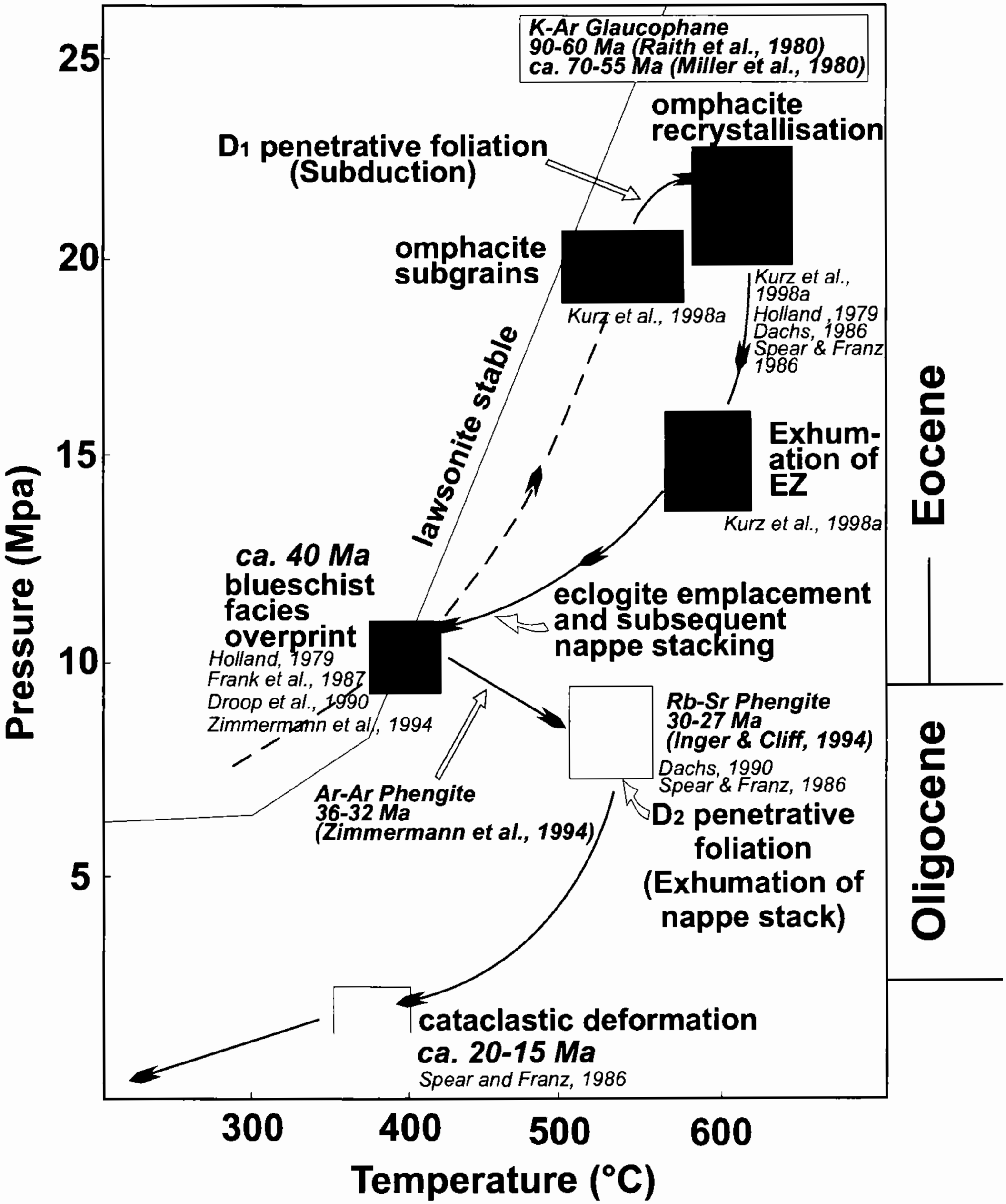

Fig. 9: Temperature-pressure-time path including several phases of deformation for the Eclogite Zone, based on data of own investigation and P-T-paths published by ZIMMERMANN et al. (1994); EZ: Eclogite Zone.

type metamorphism. Within the other tectonic units peak pressures of up to 10–12 MPa have been evaluated (SELVERSTONE et al., 1984, 1992; CLIFF et al., 1985; DROOP, 1985; HOLLAND & RAY, 1985; FRANK et al., 1987; BEHRMANN & RATSCHBACHER, 1989; BEHRMANN, 1990; SELVERSTONE, 1993). Finally, the entire nappe pile was affected by Barrovian-type upper greenschist to lower amphibolite facies metamorphism (e.g., FRANK et al., 1987; SELVERSTONE, 1993) (Fig. 9). In contrast to supposed Cretaceous ages, phengite ^{40}Ar-^{39}Ar mineral ages of ca. 36–32 Ma (ZIMMERMANN et al., 1994) and 38 Ma (RATSCHBACHER, pers. comm.; KURZ, unpublished data) from the Eclogite Zone are interpreted to represent cooling ages subsequent to Eocene blueschist facies metamorphism (ZIMMERMANN et al., 1994) (Fig. 9). The possibility of a younger age of high pressure metamorphism is elucidated by INGER & CLIFF (1994), too.

The Austroalpine units surrounding the Tauern Window show a partly different chronological evolution in contrast to the Penninic units within the Tauern Window. Whole rock ^{40}Ar-^{39}Ar plateau ages from the Lower Austroalpine NW of the Tauern Window (Reckner Nappe and Hippold Nappe) as well as the Glockner Nappe in the footwall, which all have been affected by high-pressure, blueschist facies metamorphism, record ages around 50 Ma (Reckner Nappe) and 44–37 Ma (Hippold Nappe and Glockner Nappe) (DINGELDEY et al., 1997). These ages are interpreted to date the high-pressure metamorphism. The Zircon fission track ages from the uppermost Lower Austroalpine nappe (Innsbrucker Quartzphyllite; Lower Austroalpine Quartz Phyllite in Fig. 1) range from 67 Ma to 35 Ma (FÜGENSCHUH et al., 1997).

5. DISCUSSION AND INTERPRETATION

From the descriptions above a paleogeographic interpretation will be suggested, as well as timing of emplacement of continental and oceanic nappes in the Tauern Window of the Eastern Alps. Special emphasis is given on the structural and metamorphic evolution of the Eclogite Zone. The structural deepest units in the area are the Venediger Nappe, the Wolfendorn Nappe, and the Storz Nappe, which were originally part of the European continental margin until the formation of the Rhenodanubian Flysch basin in the Late Cretaceous (e.g., FAUPL & WAGREICH, 1992), and part of the Helvetic paleogeographic realm in the Jurassic and Cretaceous (e.g., FRISCH, 1975b). The next higher structural unit is represented by the Eclogite Zone, which is restricted to the central southern part of the Tauern Window (Fig. 2). It is overlain by the Rote Wand-Modereck Nappe. Geobarometric data document a pressure-gap of approximately 10 MPa between the Eclogite Zone (with pressures in the range of 20–23 MPa) and the Venediger Nappe (10–12 MPa) in the footwall as well as the Rote Wand-Modereck Nappe (9–11 MPa) in the hanging wall (KURZ et al., 1998b). Hence, this gap justifies the separation of the Vendiger Nappe and the Rote Wand – Modereck Nappe into two major structural units, with the Eclogite Zone sandwiched between these two units.

The structural and paleogeographic restoration of these units is based on both lithostratigraphic, structural and petrological data. Metagabbroic rocks, which may predominantely be observed along the base of the Eclogite Zone, indicate the intrusion of gabbroic melts into continental lithosphere. The lithofacies of the Rote Wand-Modereck Nappe and the Eclogite Zone indicate a depositional environment along the

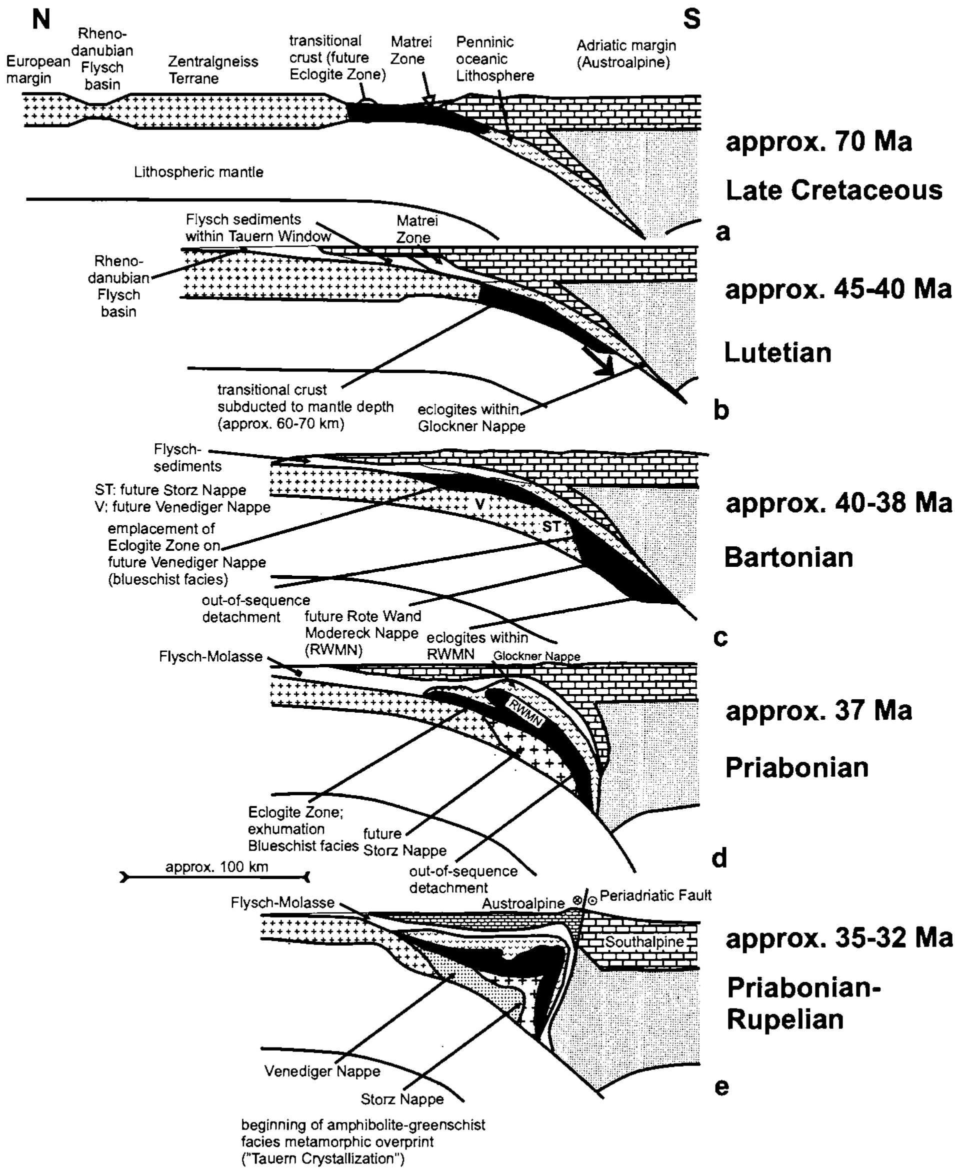

Fig. 10: Plate tectonic evolution of the Penninic units of the Eastern Alps during the Late Cretaceous and the Paleogene (based on Schmid et al., 1996; Froitzheim et al., 1996; Kurz et al., 1998b); not to scale.

continental slope of a passive continental margin, strongly influenced by terrigenous sedimentation. Hence, the Eclogite Zone is interpreted as a more distal (southern) depositional environment compared to the lithofacies exposed within Rote Wand-Modereck Nappe. This suggests an original position of the Eclogite Zone south of the future Rote Wand-Modereck Nappe (Fig. 10a–c). The lithofacial distribution seems to indicate that the Eclogite Zone consists of the remnants of the ocean-continent transition between the European continental lithosphere to the N, and the Penninic oceanic lithosphere to the south (Fig. 10a). However, referring to the tectonostratigraphy described above, the tectonic position of the Eclogite Zone is in the footwall of the Rote Wand-Modereck Nappe. This is already obvious at map scale. Additionally, several kinematic indicators from the Eclogite Zone and from the base of the Rote Wand-Modereck Nappe document a south-over-north sense of shear during nappe emplacement. This implies, that the Eclogite Zone must have already been emplaced on top of the Venediger Nappe before it had been overthrusted by the Rote Wand-Modereck Nappe (Fig. 10c). Hence, this is only possible by the development of a south-dipping out-of-sequence thrust in an internal position, south of the Eclogite Zone and the European continental margin (preserved in the future Venediger Nappe and Storz Nappe). During this phase the Glockner Nappe was already part of the upper plate, mainly represented by the Austroalpine nappe stack. Along this major detachment the Glockner Nappe, the Matrei Zone, and the Austroalpine are only passively transported (Fig. 10d, e). According to KURZ et al. (1998b), the Rote Wand – Modereck Nappe was emplaced together with the Penninic units in the hanging wall and with the Austroalpine unit along an out-of-sequence thrust onto the Venediger Nappe. Therefore, the base of the Rote Wand–Modereck Nappe was the main thrust that has been activated during the Penninic–Austroalpine continental collision. Footwall propagation of thrusts resulted in the subsequent detachment of the Storz Nappe and the Venediger Nappe (Fig. 10e). Low-angle normal faults, that have developed during the Jurassic extensional phase might have been reactivated and inverted during nappe emplacement (KURZ et al., 1998b).

5.1. Evolution of Penninic nappes in space and time

The model developed above is compatible with southward subduction of a single lithospheric slab comprising, from south to north, the Penninic ocean and the European margin. The Zentralgneis Terrane formed an outlier of the European lithospheric plate since the formation of the Rhenodanubian Flysch basin in the Late Cretaceous. It is represented by the Venediger Nappe, the Storz Nappe, and the Rote Wand-Modereck Nappe (Fig. 10). The Venediger Nappe was often supposed to be of Middlepenninic paleogeographic origin because of the subsidence of the Rhenodanubian Flysch basin to the N, which separated this unit from the main European margin (e.g., FRISCH, 1976, 1977b, 1979; KURZ et al., 1998b). This is similar to reconstructions of SCHMID et al. (1996) for the Alps of Eastern Switzerland, of STAMPFLI et al. (1998) for Western Switzerland, and of FROITZHEIM et al. (1996) and FROITZHEIM (2001) for the Western Alps in general. However, referring to these models, the Northpenninic Valais ocean had been subducted prior to the accretion of the European margin. Transferring this model to the Eastern Alps, the Glockner Nappe must have been of Northpenninic Paleogeographic origin. On the other side, the Glockner Nappe is situated directly in the footwall of the Lower Austroalpine nappe pile (e.g., DINGELDEY et al., 1997), which would propose its Southpenninic paleogeographic origin. However, the subdivision of South-, Middle- and Northpenninic in the Western Alps is related to the occurrence of the Brianconnais microcontinent, which can be directly traced to the Iberian plate (e.g., OBERHÄNSLI, 1994; STAMPFLI, 1993; STAMPFLI & MARCHANT, 1997). Referring to these models, the Brianconnais terminated to the east and can not be traced to the Eastern Alps (TOLLMANN, 1965a). Hence, the South- and Northpenninic oceanic basins (Ligurian or Piemontais, and Valais) merge into one oceanic basin to the east. Additionally, east of the area of the actual Tauern Window, both the Penninic oceanic basin and the Rhenodanubian Flysch basin merged into a single basin (EGGER, 1990, 1992). This, for example, is documented in the Ybbsitz ophiolite, which forms the base of turbiditic deposits (e.g., DECKER, 1990). Distinct outliers of the European margin may still be observed as extensional allochthons in an internal (southern) position, due to asymmetric rifting during continental breakup from the Triassic to the Jurassic (e.g., FROITZHEIM & MANATSCHAL, 1996). One of these allochthons may be represented by the Zentralgneis Terrane, predominantely formed by the Venediger Nappe of the Tauern Window, others by the continental Margna-, Hippold-, and the Sesia extensional allochthons in the Lower Austroalpine unit (FROITZHEIM & MANATSCHAL, 1996; FROITZHEIM et al., 1996, 1997; HEIDORN, 1998), which have been part of the opposite, southern passive continental margin. These allochthons have been formed during a rifting phase during the Jurassic, which created the Southpenninic (Piemontais oceanic) basin by rifting off the stable European continent and a north-facing passive continental margin (Lower Austroalpine unit) south of this basin. Resulting structures along this passive margin are halfgrabens filled with escarpment breccias, for example represented in the Brennkogel facies of the Rote Wand – Modereck Nappe. Asymmetric simple shear is supposed to result in exhumation of the subcontinental mantle lithosphere and the formation of these extensional allochthons (NEUBAUER et al., 1998).

The southward subduction of the lithospheric slab described above is indicated by south-over-north sense of nappe emplacement, and by the remnants of eclogite facies assemblages in the southern parts of the Glockner Nappe and the Rote Wand-Modereck Nappe (STURM et al., 1997; PROYER et al., 1999) (Fig.10). These remnants are not documented in the northern parts. Additionally, a general decrease of metamorphic pressures can be observed from the south towards the north (KURZ et al., 1998b). The exact timing of subduction and collision has been discussed controversially during the last decades. In the Western Alps radiometric data for the peak of high pressure metamorphism show decreasing ages from the internal (Southpenninic) to the external zones (the European margin) (GEBAUER, 1999; FROITZHEIM, 2001). Alpine high-pressure metamorphism within the Penninic units is now supposed as Paleogene by a great majority of authors (TILTON et al., 1991; HENRY et al., 1993; BOWTELL et al., 1994; RUBATTO et al., 1998; CLIFF et al., 1998). This is in contrast to earlier assumptions of Late Cretaceous to Early Paleogene ages of high-pressure metamorphism, which was mostly based on K-Ar dating (e.g., MILLER et al., 1980) (Fig. 9). The high-pressure metamorphic assemblages within the Eclogite Zone were suspected to form a "paired metamorphic belt" together with Cretaceous middle pressure metamorphic sequences within Austroalpine units, according to ERNST (1971, 1975) (e.g., FRANK 1987; FRANK et al., 1987;

WALLIS et al., 1993). However, no direct evidence of a Cretaceous high-pressure metamorphism age within the Penninic realm is documented by these authors. In contrast to these supposed Cretaceous ages, phengite 40Ar–39Ar mineral ages of ca. 36–32 Ma (ZIMMERMANN et al., 1994) from the Eclogite Zone are interpreted to represent cooling ages after the blueschist facies metamorphic event (ZIMMERMANN et al., 1994). The possibility of a younger age of high pressure metamorphism was already discussed by INGER & CLIFF (1994). Sm-Nd garnet ages of ca. 42 Ma from the Eclogite Zone are cited by DROOP et al. (1990), INGER & CLIFF (1994). Sm-Nd dating of garnet peridodites and an eclogite from the Upper Penninic Cima Lunga Nappe (Lepontine Dome, Swiss Alps) yielded consistent mineral ages of ca. 40 Ma (BECKER, 1993). 52±18 Ma are reported from the Zermatt-Saas ophiolite (BOWTELL et al., 1994; AMATO et al., 1999; RUBATTO et al., 1998), which is in a similar tectonic position as the Glockner Nappe, approx. 60 Ma are reported from the Monviso ophiolite (CLIFF et al., 1998). Garnet Rb-Sr ages of ca. 65 Ma are documented within the Venediger Nappe in the western part of the Tauern Window by CHRISTENSEN et al. (1994). This implies that the Venediger Nappe was already subducted at the end of the Late Cretaceous, and that growth of metamorphic garnets was initiated. In the Western Alps, ultra-high pressure metamorphism is dated at about 38 Ma (HENRY et al., 1993) and 35 Ma (GEBAUER et al., 1997) in the Dora Maira Massif, which is in a similar tectonic position as the Venediger Nappe (Middle Penninic unit). As the future Eclogite Zone was positioned south of the Zentralgneis block, this implies, that the Eclogite Zone was already subducted. At which time the lithospheric level of eclogite facies conditions was reached is poorly constrained. The geothermometric calculations of eclogite facies metamorphism (ca. 600° C) suggest, that the Sm-Nd data indicate the age of garnet formation, because the temperature conditions are either equal, or beneath the closure temperature of ca. 600±30° C (MEZGER et al., 1992) for garnet.

Additionally, subduction and accretion of the Lower Austroalpine unit is documented by blueschist facies metamorphism within this unit (ENZENBERG, 1967; ENZENBERG-PRAEHAUSER, 1976; DINGELDEY & KOLLER, 1994; DINGELDEY et al., 1997). However, blueschist facies metamorphism is documented between approx. 50 and 40 Ma (DINGELDEY et al., 1997). The Lower Austroalpine Innsbruck Quartzphyllite has already been exhumed and was cooled below temperatures in the range of 200° C from 67 Ma to 35 Ma (FÜGENSCHUH et al., 1997). Therefore, these data may be better interpreted to record the deformation and associated metamorphic imprint during the final emplacement of the Austroalpine nappe complex onto the Penninic nappe complex, and its subsequent exhumation.

According to these data, the Penninic oceanic lithosphere was already subducted in the Late Cretaceous, and the Danian (about 50 Ma) (Fig. 10a), with the southern parts of it reaching eclogite facies metamorphism (Fig. 10b). Subsequently, the European margin descended into the subduction zone, which resulted in eclogite facies metamorphism in the Eclogite Zone at the end of the Lutetian (about 45–40 Ma) (Fig. 10b). The Eclogite Zone ascended towards the surface either in a corner flow mode (CLOOS, 1982, 1985), or along a south-dipping ramp according to HYNES et al. (1996), while subduction was still active and, hence, heating was prevented (KURZ et al., 1998). This is evidenced by a blueschist facies metamorphic overprint. After emplacement of the Eclogite Zone on the future Venediger Nappe, both units have been overridden by the Rote Wand-Modereck Nappe along a major out-of-sequence detachment (see above) (Fig. 10c, d).

High-pressure metamorphic conditions within the Rote Wand-Modereck Nappe, and subsequently in the Venediger Nappe should have been reached in the Bartonian (about 40–38 Ma) to Priabonian (approx. 37 Ma) (Fig. 10c–e), according to the evolution in the Dora Maira Massif (Henry et al., 1993). The Venediger Nappe was cooled below 300° C already at the end of the Oligocene at about 23 Ma (e.g., Cliff et al., 1985; Droop, 1985; Reddy et al., 1993).

6. CONCLUSIONS

The southward subduction of a single lithospheric slab comprising the Penninic ocean in the south and the European margin in the north (represented by the Venediger Nappe Complex) resulted in nappe stacking within the Penninic units of the Tauern Window. After the consumption of the Penninic oceanic basin, the European margin was incorporated into the subduction zone, which resulted in eclogite facies metamorphism in the Eclogite Zone and the southern structural sections of the Rote Wand – Modereck Nappe. The Eclogite Zone ascended towards the surface and was emplaced on the Zentralgneis Terrane, which is mainly exposed in the Venediger Nappe Complex and the Storz Nappe. Both units have been overridden subsequently by the Rote Wand-Modereck Nappe along a major out-of-sequence detachment. Referring to recently published geochronological data, this phase of continental collision, and related Alpine high-pressure metamorphism and nappe stacking within the Penninic units is supposed to having occurred in the Paleogene. The main deformational phase related to nappe stacking occurred during the Eocene.

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References

Amato, J. M., Johnson, C. M., Baumgartner, L. P. & Beard, B. L., 1999: Rapid exhumation of the Zermatt-Saas ophiolite deduced from high-precision Sm-Nd and Rb-Sr geochronology. – Earth Planet. Sci. Lett. **171**: 425–438, Amsterdam.

Becker, H., 1993: Garnet peridodite and eclogite Sm-Nd mineral ages from the Lepontine dome (Swiss Alps): New evidence for Eocene high-pressure metamorphism in the central Alps. – Geology **21**: 599–602, Boulder.

Behrmann, J. H., 1990: Zur Kinematik der Kontinentkollision in den Ostalpen. – Geotekt. Forsch. **76**: 1–180, Göttingen.

Behrmann, J. H. & Ratschbacher, L., 1989: Archimedes revisited: a structural test of eclogite emplacement models in the Austrian Alps. – Terra Nova **1**: 242–252, Oxford.

Behrmann, J. H. & Frisch, W., 1990: Sinistral ductile shearing associated with metamorphic decompression in the Tauern Window, Eastern Alps. – Jahrb. Geol. Bundesanst. **133**: 135–146, Vienna.

BELL, T. H. & JOHNSON, S. E., 1992: Shear sense: a new approach that resolves conflicts between criteria in metamorphic rocks. – J. metamorphic Geol. **10**: 99–124, London.

BICKLE, M. J. & HAWKESWORTH. C. J., 1978: Deformation phases and tectonic history of the eastern Alps. – Geol. Soc. Am. Bull. **89**: 293–306, Boulder.

BOWTELL, S. A., CLIFF, R. A. & BARNICOAT, A. C., 1994: Sm-Nd isotopic evidence on the age of eclogitization in the Zermatt-Saas ophiolite. – J. metamorphic Geol. **12**: 187–196, London.

CHANNEL, J. E. T. & KOZUR, H. W. 1997: How many oceans? Meliata, Vardar, and Pindos oceans in Mesozoic Alpine paleogeography. – Geology **25**: 183–186, Boulder.

CHRISTENSEN, J. N., SELVERSTONE, J., ROSENFELD, J. L. & DEPAOLO, D. J., 1994: Correlation by Rb-Sr geochronology of garnet growth histories from different structural levels within the Tauern window, Eastern Alps. – Contrib. Mineral. Petrol. **118**: 1–12, Berlin.

CLAR, E., 1932: Modereckdecke oder Rote Wandgneisdecke ? – Verh. Geol. Bundesanst. 153–157, Vienna.

CLIFF, R. A., DROOP, G. T. R. & REX, D. C., 1985: Alpine metamorphism in the south-east Tauern Window, Austria: II. heating, cooling and uplift rates. – J. metamorphic Geol. **3**: 403–415, London.

CLIFF, R. A., BARNICOAT, A. C. & INGER, S., 1998: Early Tertiary eclogite facies metamorphism in the Monviso Ophiolite. – J. metamorphic Geol. **16**: 447–455, London.

CLIFF, R. A., NORRIS, R. J., OXBURGH, E. R. & WRIGHT, R. C., 1971: Structural, metamorphic and geochronological studies in the Reisseck and southern Ankogel Group. – Jahrb. Geol. Bundesanst. **114**: 121–272, Vienna.

CLOOS, M., 1982: Flow melanges: numerical modeling and geologic constraints on their origin in the Franciscan subduction complex. – Geol. Soc. Amer. Bull. **93**: 330–345, Boulder.

CLOOS, M., 1985: Thermal evolution of convergent plate margins: thermal modeling and reevaluation of isotopic Ar-ages for blueschists in the Franciscan Complex, California. – Tectonics **4**: 421–433, Washington.

CORNELIUS, H. P. & CLAR, E., 1939: Geologie des Großglocknergebietes (I.Teil). – Abh. Zweigst. Wien Reichsst. f. Bodenforsch. (Geol. Bundesanst.) **25**: 1–305, Vienna.

DACHS, E., 1986: High-pressure mineral assemblages and their breakdown products in metasediments South of the Grossvenediger, Tauern Window, Austria. – Schweiz. mineral. petrogr. Mitt. **66**: 145–161, Zürich.

DACHS, E., 1990: Geothermobarometry in metasediments of the southern Grossvenediger area (Tauern Window, Austria). – J. metamorphic Geol. **8**: 217–230, London.

DECKER, K., 1990: Plate tectonics and pelagic facies: Late Jurassic to Early Cretaceous deep-sea sediments of the Ybbsitz ophiolite unit (Eastern Alps, Austria). – Sedimentary Geology **67**: 85–99, Amsterdam.

DINGELDEY, Ch. & KOLLER, F., 1994: Zusammensetzung von Hellglimmern in Gesteinen des Reckner Komplexes und seiner Nebengesteine (Tarntaler Berge, Tirol). – Mitt. Österr. Mineral. Ges. **139**: 287–289, Vienna.

DINGELDEY, Ch., DALLMEYER, R. D., KOLLER, F. & MASSONE, H. J., 1997: P-T-t history of the Lower Austroalpine Nappe Complex in the "Tarntaler Berge" NW of the Tauern Window: implications for the ggeotectonic evolution of the central Eastern Alps. – Contrib. Mineral. Petrol. **129**: 1–19, Berlin.

DROOP, G. T. R., 1981: Alpine metamorphism of pelitic schists in the south-east Tauern Window, Austria. – Schweiz. Mineral. Petrogr. Mitt. **61**: 237–273, Zürich.

DROOP, G. T. R., 1985: Alpine metamorphism in the south-east Tauern Window, Austria: I. P-T variations in space and time. – J. metamorphic Geol. **3**: 371–402, London.

DROOP, G. T. R., LOMBARDO, B. & POGNATE, U., 1990: Formation and distribution of eclogite facies rocks in the Alps. – In: CARSWELL, D. A.(ed.): Eclogite Facies Rocks. – 225–259, Glasgow (Blackie).

EGGER, H., 1990: Zur paläogeographischen Stellung des Rhenodanubischen Flysches (Neokom-Eozän) der Ostalpen. – Jahrb. Geol. Bundesanst. **133**: 147–155, Vienna.

EGGER, H., 1992: Zur Geodynamik und Paläogeographie des Rhenodanubischen Flysches (Neokom – Eozän) der Ostalpen. – Z. dt. geol. Ges. **143**: 51–65, Hamburg.

ENZENBERG, M., 1967: Die Geologie der Tarntaler Berge (Wattener Lizum), Tirol. – Mitt. Ges. Geol. Bergbaustud. Österr. **17**: 5–50, Vienna.

ENZENBERG-PRAEHAUSER, M., 1976: Zur Geologie der Tarntaler Breccie und ihrer Umgebung im Kamm Hippold-Kalkwand (Tuxer Voralpen, Tirol). – Mitt. Ges. Geol. Bergbaustud. Österr. **23**: 163–180, Vienna.

ERNST, W. G., 1971: Metamorphic Zonations on Presumably Subducted Lithospheric Plates from Japan, California and the Alps. – Contrib. Mineral. Petrol. **34**: 43–59, Berlin.

ERNST, W. G., 1975: Systematics of large-scale tectonics and age progressions in Alpine and Circum-Pacific blueschist belts. – Tectonophysics **26**: 229–246, Amsterdam.

EXNER, Ch., 1964: Erläuterungen zur Geologischen Karte der Sonnblickgruppe 1 : 50.000. – Geol. Bundesanst., Wien 170 S, Vienna.

EXNER, Ch., 1971: Geologie der peripheren Hafnergruppe (Hohe Tauern). – Jahrb.Geol.Bundesanst. **114**: 1–119, Vienna.

EXNER, Ch., 1982: Geologie der zentralen Hafnergruppe (Hohe Tauern). – Jahrb.Geol.Bundesanst. **125**: 51–154, Vienna.

EXNER, Ch., 1983: Erläuterungen zur geologischen Karte der Hafnergruppe (Blatt Muhr, Ö.K.156 – Südteil, 1:25 000). – Mitt. Ges. Geol. Bergbaustud. Österr. **29**: 41–74, Vienna.

EXNER, Ch., 1990: Erläuterungen zur Geologischen Karte des mittleren Lungaus. – Mitt. Ges. Geol. Bergbaustud.Österr. **36**: 1–38, Vienna.

FAUPL, P. & WAGREICH, M., 1992: Cretaceous flysch and pelagic sequences of the Eastern Alps: correlations, heavy minerals, and paleogeographic implications. – Cretaceous Research **13**: 387–403, London.

FRANK, W., 1969: Geologie der Glocknergruppe. – Wissensch. Alpenvereinsh. **21**: 95–111, München.

FRANK, W., 1972: Permoskyth im Pennin der Hohen TTauern (Seidlwinkldecke östlich der Großglockner-Hochalpenstraße). – Verh. Geol. Bundesanst. **1972**: 151–153, Vienna.

FRANK, W., 1987: Evolution of the Austroalpine Elements in the Cretaceous. – In: FLÜGEL, H. W. & FAUPL, P. (Eds.): Geodynamics of the Eastern Alps. – 379–406, Vienna (Deuticke).

FRANK, W., HÖCK, V. & MILLER, CH., 1987: Metamorphic and tectonic history of the central Tauern Window. – In: FLÜGEL, H. W. & FAUPL, P. (Eds.): Geodynamics of the Eastern Alps. – 34–54, Vienna (Deuticke).

FRANK, W., MILLER, CH., PETRAKAKIS, K., PROCHASKA, K. & RICHTER, W., 1981: Das penninische Kristallin im Mittelabschnitt des Tauernfensters und die Rieserferner Intrusion mit ihrem Kontakthof. – Fortschr. Mineral. (ÖMG– Tagung 1981) 59: 97–128, Vienna.

FRANZ, G. & SPEAR, F. S., 1983: High pressure metamorphism of siliceous dolomites from the central Tauern Window, Austria. – Amer. J. Sci. 283–A: 396–413, Washington.

FRASL, G., 1958: Zur Seriengliederung der Schieferhülle in den mittleren Hohen Tauern. – Jahrb. Geol. Bundesanst. **101**: 323–472, Vienna.

FRASL, G. & FRANK, W., 1964: Exkursion I/2: Mittlere Hohe Tauern. – Mitt. Österr. Geol. Ges. **57**: 17–31, Vienna.

FRASL, G. & FRANK, W., 1969: Bemerkungen zum zweiteiligen geologischen Panorama von der Edelweißspitze (Großglockner-Hochalpenstraße). – Wissenschaftliche Alpenvereinshefte **21**: 112–117, München.

FRISCH, W., 1974: Die stratigraphisch-tektonische Gliederung der Schieferhülle und die Entwicklung des penninischen Raumes im westlichen Tauernfenster (Gebiet Brenner-Gerlospaß). – Mitt. geol. Ges. Wien **66–67 (1973/74)**: 9–20, Vienna.

FRISCH, W., 1975a: Ein Typ-Profil durch die Schieferhülle des Tauernfensters: Das Profil am Wolfendorn (westlicher Tuxer Hauptkamm, Tirol). – Verh. Geol. Bundesanst. **1974/2–3**: 201–221, Vienna.

FRISCH, W., 1975b: Hochstegen-Facies und Grestener-Facies – ein Vergleich des Jura. – N. Jb. Geol. Paläont. Mh. **1975/2**: 82–90, Stuttgart.

FRISCH, W., 1976: Ein Modell zur Alpidischen Evolution und Orogenese des Tauernfensters. – Geol. Rundschau **65**: 375–393, Berlin.

FRISCH, W., 1977a: Der alpidische Internbau der Venedigerdecke im westlichen Tauernfenster (Ostalpen). – N. Jb. Geol. Paläont. Mh. **1977**: 675–696, Stuttgart.

FRISCH, W., 1977b: Die Alpen im westmediterranen Orogen – eine plattentektonische Rekonstruktion. – Mitt. Ges. Geol. Bergbaustud. Österr. **24**: 263–275, Vienna.

FRISCH, W., 1979: Tectonic progradation and plate tectonic evolution of the Alps. – Tectonophysics **60**: 121–139, Amsterdam.

FRISCH, W., 1980a: Plate motions in the Alpine region and their correlation to the opening of the Atlantic ocean. – Mitt. Österr. Geol. Ges. **71/72**: 45–48, Vienna.

FRISCH, W., 1980b: Post-Hercynian formations of the western Tauern window: sedimentological features, depositional environment and age. – Mitt. Österr. Geol. Ges. **71/72**: 49–63, Vienna.

FRISCH, W., 1984: Sedimentological response to late Mesozoic subduction in the Penninic windows of the Eastern Alps. – Geol. Rdsch. **73**: 33–45, Berlin.

FRISCH, W., GOMMERINGER, K., KELM, U. & POPP, F., 1987: The Upper Bündner Schiefer of the Tauern Window – A Key to Understanding Eoalpine Orogenic Processes in the Eastern Alps. – In: FLÜGEL, H. W. & FAUPL, P. (Eds.): Geodynamics of the Eastern Alps.– 55–69, Vienna (Deuticke).

FROITZHEIM, N., 2001: Origin of the Monte Rosa nappe in the Pennine Alps – A new working hypothesis. – Geol. Soc. Amer. Bull.: **113**: 604–614, Boulder.

FROITZHEIM, N. & MANATSCHAL, G., 1996: Kinematics of Jurassic rifting, mantle exhumation, and passive margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). – Geol. Soc. Amer. Bull. **108**: 1120–1133, Boulder.

FROITZHEIM, N., SCHMID, St. M. & FREY, M., 1996: Mesozoic paleogeography and the timing of eclogite facies metamorphism in the Alps: A working hypothesis. – Eclogae geol. Helv. **89**: 81–110, Basel.

FROITZHEIM, N., CONTI, P. & VAN DAALEN, M., 1997: Late Cretaceous, synorogenic, low-angle normal faulting along the Schlinig fault (Switzerland, Italy, Austria) and its significance for the tectonics of the Eastern Alps. – Tectonophysics **280**: 267–293, Amsterdam.

FÜGENSCHUH, B., SEWARD, D. & MANCKTELOW, N., 1997: Exhumation in a convergent orogen: the western Tauern window. – Terra Nova **9**: 213–217, Oxford.

GEBAUER, D., 1999: Alpine geochronology of the Central and Western Alps: new constraints for a complex geodynamic evolution. – Schweiz. mineral. petrogr. Mitt. **79**: 191–208, Zürich.

GEBAUER, D., SCHERTL, H. P., B. M. & SCHREYER, W., 1997: 35 Ma old ultrahigh-pressure metamorphism and evidemce for rapid exhumation in the Dora Maira Massif, Western Alps. – Lithos **41**: 5–24, Amsterdam.

GETTY, S. R. & SELVERSTONE, J., 1994: Stable isotopic and trace element evidence for restricted fluid migration in 2 GPa eclogites. – J. metamorphic Geol. **12**: 747–760, London.

HÄUSLER, H., 1987: The northern Austroalpine margin during the Jurassic: Breccias from the Radstädter Tauern and Tarntaler Berge. – In: FLÜGEL, H. W. & FAUPL, P. (eds.): Geodynamics of the Eastern Alps. – 103–111, Vienna (Deuticke).

HÄUSLER, H., 1988: Unterostalpine Jurabreccien in Österreich. Versuch einer sedimentologischen und paläogeographischen Analyse nachtriadischer Breccienserien im unterostalpinen Rahmen des Tauernfensters (Salzburg–Tirol). – Jahrb. Geol. Bundesanst **131**: 21–125, Vienna.

HANDY, M. R., 1996: The transition from passive to active margin tectonics: a case study from the Zone of Samedan (eastern Switzerland). – Geol. Rdsch. **85**: 832–851, Berlin.

HANMER, S. & PASSCHIER, C., 1991: Shear sense indicators: a review. – Geological Survey of Canada **Paper 90–17**: 72 pp., Toronto.

HEIDORN, R., 1998: Structural evolution at the Penninic to Lower-Austroalpine boundary, northwestern margin of the Tauern Window (Tux Mountains/Eastern Alps). – 130 pp, Naturw. Fak., Unic. Salzburg (Diplomarbeit).

HENRY, C., MICHARD, A. & CHOPIN, C., 1993: Geometry and structural evolution of ultr-high-pressure and high-pressure rocks from the Dora-Maira massif, Western Alps, Italy. – J. Struct. Geol. **15**: 965–981, Oxford.

HOLLAND, T. J. B., 1979: High water activities in the generation of high pressure kyanite eclogites in the Tauern Window, Austria. – J. Geol. **87**: 1–27, Washington.

HOLLAND, T. J. B. & RAY, N. J., 1985: Glaucophane and pyroxene breakdown reactions in the Pennine units of the Eastern Alps. – J. metamorphic Geol. **3**: 417–438, London.

HOTTINGER, A., 1935: Geologie der Gebirge zwischen der Sonnblick-Hocharn-Gruppe und dem Salzachtal in den östlichen Hohen Tauern. – Eclogae geol. Helv. **28**: 349–368, Basel.

HOTTINGER, A., 1934: Zur Geologie des Nordrandes des Tauernfensters in den zentralen Hohen Tauern. – Eclogae geol. Helv. **27**: 11–23, Basel.

HYNES, A., ARKANI-HAMED, J. & GREILING, R., 1996: Subduction of continental margins and the uplift of high-pressure metamorphic rocks. – Earth Planet. Sci. Lett. **140**: 13–25, Amsterdam.

INGER, S. & CLIFF, R. A., 1994: Timing of Metamorphism in the Tauern Window, Eastern Alps: Rb-Sr- ages and fabric formation. – J. metamorphic Geol. **12**: 695–707, London.

KOBER, L., 1912: Bericht über geologische Untersuchungen in der Sonnblickgruppe und ihrer weiteren Umgebung. – Sitzber. d. kaiserl. Akad. d. Wiss., m.-n. Kl., Abt.I **CXXI**: 105–119, Vienna.

KOBER, L., 1921: Das Östliche Tauernfenster. – Denkschr. Akad. d. Wiss., m.-n. Kl. **98**: 201–245, Vienna.

KOBER, L., 1933: Modereckdecke oder Rote Wandgneisdecke? – Verh. Geol. Bundesanst. 131–132, Vienna.

KRUHL, J. H., 1993: The P-T-d development at the basement-cover boundary in the north-eastern Tauern Window (Eastern Alps): Alpine continental collision. – J. metamorphic Geol. **11**: 31–47, London.

KURZ, W. & UNZOG, W., 1999: Variation of Quartz Textures within the Plattengneiss of the Koralm Complex (Eastern Alps). – Mitt. naturwiss. Ver. Steiermark **129**: 33–42, Graz.

KURZ, W., NEUBAUER, F. & GENSER, J., 1996: Kinematics of Penninic nappes (Glockner Nappe and basement-cover nappes) in the Tauern Window (Eastern Alps, Austria) during subduction and Penninic-Austroalpine collision. – Eclogae geol. Helv. **89**: 573–605, Basel.

KURZ, W., NEUBAUER, F. & DACHS, E., 1998a: Eclogite meso- and microfabrics: implications for the burial and exhumation history of eclogites in the Tauern Window (Eastern Alps) from P-T-d paths. – Tectonophysics **285**: 183–209, Amsterdam.

KURZ, W., NEUBAUER, F. & UNZOG, W., 1999: Evolution of Alpine Eclogites in the Eastern Alps: Implications for Alpine Geodynamics. – Physics and Chemistry of the Earth **24**: 667–674, Amsterdam.

KURZ, W., NEUBAUER, F., GENSER, J. & DACHS, E., 1998b: Alpine geodynamic evolution of passive and active continental margin sequences in the Tauern Window (Eastern Alps, Austria, Italy): a review. – Geol. Rdsch. **87**: 225–242, Berlin.

KURZ, W., UNZOG, W., NEUBAUER, F. & GENSER, J., 2001: Evolution of quartz microstructures and textures during polyphase deformation within the Tauern Window (Eastern Alps). – Geol. Rdsch. **90**: 361–378, Berlin.

KURZ, W., NEUBAUER, F., UNZOG, W., GENSER, J. & WANG, X., 2000: Quartz, dolomite and calcite microstructures and textures within the Tauern Window (Eastern Alps, Austria, Italy). – Jahrb. Geol. Bundesanst. **142**: 33–71, Vienna.

LAMMERER, B., 1988: Thrust-regime and transpression-regime tectonics in the Tauern Window (Eastern Alps). – Geol. Rdsch. **77**: 143–156, Berlin.

LAMMERER, B., SCHMIDT, K. & STADLER, R., 1981: Zur Stratigraphie und Genese der Penninischen Gesteine des südwestlichen Tauernfensters. – N. Jb. Geol. Paläont. Mh. 678–696, Stuttgart.

LEDOUX, H., 1984: Paläogeographische und tektonische Entwicklung im Penninikum des Tauern-Nordwestrandes im oberen Tuxer Tal. – Jahrb. Geol. Bundesanst. **126**: 359–368, Vienna.

MEZGER, K., ESSENE, E. J. & HALLIDAY, A. N., 1992: Closure temperatures of the Sm-Nd system in metamorphic garnets. – Earth Planet. Sci. Lett. **113**: 397–409, Amsterdam.

MILLER, Ch., 1974: On the Metamorphism of the Eclogites and High-Grade Blueschists from the Penninic Terrane of the Tauern Window, Austria. – Schweiz. mineral. petrogr. Mitt. **54**: 371–384, Zürich.

MILLER, Ch., 1977: Chemismus und phasenpetrologische Untersuchungen der Gesteine aus der Eklogitzone des Tauernfensters, Österreich. – Tscherm. Min. Petr. Mitt. **24**: 221–277, Berlin.

MILLER, Ch., SATIR, M. & FRANK, W., 1980: High pressure metamorphism in the Tauern window. – Mitt. Österr. Geol. Ges. **71/72**: 89–97, Vienna.

NEUBAUER, F., GENSER, J. & HANDLER, R., 2000: The Eastern Alps: Result of a two-stage collision process. – Mitt. Österr. Geol. Ges. **92 (1999)**: 117–134, Vienna.

NEUBAUER, F., GENSER, J., HANDLER, R. & KURZ, W., 1998: The structure of the Alps: an overview. – Carpathian – Balkan Geological Association, XVI Congress, Field Guide ("Transect through the central Eastern Alps") 7–24, Salzburg.

OBERHÄNSLI, R., 1994: Subducted and obducted ophiolites in the Central Alps: Paleotectonic implications deduced by their distribution and metamorphic overprint. – Lithos **33**: 109–118, Amsterdam.

OEHLKE, M., WEGER, M. & LAMMERER, B., 1993: The "Hochfeiler Duplex" – Imbrication Tectonics in the SW Tauern Window. – Abh. Geol. Bundesanst. **49**: 107–124, Vienna.

PREY, S., 1939: Modereckdecke und Rote-Wand-Gneisdecke. – Verh. Geol. Bundesanst. **1938**: 190–192, Vienna.

PROYER, A., DACHS, E. & KURZ, W., 1999: Relics of high-pressure metamorphism from the Großglockner region, Hohe Tauern, Austria: Textures and mineral chemistry of retrogressed eclogites. – Mitt. Österr. Geol. Ges. **90**: 43–56, Vienna.

RAITH, M., MEHRENS, Ch. & THÖLE, W., 1980: Gliederung, tektonischer Bau und metamorphe Entwicklung der penninischen Serien im südlichen Venediger-Gebiet, Osttirol. – Jahrb. Geol. Bundesanst. **123**: 1–37, Vienna.

RAMSAY, J. G. & HUBER, M. I., 1983: The Techniques of Modern Structural Geology. – 1: Strain Analyses. – 307 S., London (Academic Press).

REDDY, S. M., CLIFF, R. A. & EAST, R., 1993: Thermal history of the Sonnblick Dome, south-east Tauern Window, Austria: Implications for heterogenous uplift within the Pennine basement. – Geol. Rdsch. **82**: 667–675, Berlin.

RUBATTO, D., GEBAUER, D. & FANNING, M., 1998: Jurassic formation and Eocene subduction of the Zermatt-Saas-Fee ophiolites: implications for the geodynamic evolution of the Central and Western Alps. – Contrib. Mineral. Petrol. **132**: 269–287, Berlin.

SCHMID, S. M., PFIFFNER, O. A., FROITZHEIM, N., SCHÖNBORN, G. & KISSLING, E., 1996: Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. – Tectonics **15**: 1036–1064, Washington.

SCHMIDEGG, O., 1961: Geologische Übersicht der Venediger-Gruppe. – Verh. Geol. Bundesanst. **1961, 1**: 34–55, Vienna.

SELVERSTONE, J., 1993: Micro- to macroscale interactions between deformational and metamorphic processes, Tauern Window, Eastern Alps. – Schweiz. mineral. petrogr. Mitt. **73**: 229–239, Zürich.

SELVERSTONE, J., FRANZ, G., THOMAS, S. & GETTY, S., 1992: Fluid variability in 2GPa eclogites as an

indicator of fluid behaviour during subduction. – Contrib. Mineral. Petrol. **112**: 341–357, Berlin.
SELVERSTONE, J., SPEAR, F. S., FRANZ, G. & MORTEANI, G., 1984: High- Pressure Metamorphism in the SW Tauern Window, Austria: P-T Paths from Hornblende- Kyanite- Staurolite Schists. – J. Petrol. **25**: 501–531, London.
SIMPSON, C. & SCHMID, S.M., 1983: An evaluation of criteria to deduce the sense of movements in sheared rocks. – Geol. Soc. Amer. Bull. **94**: 1281–1288, Boulder.
SPEAR, F. S. & FRANZ, G., 1986: P-T evolution of metasediments from the Eclogite Zone, south central Tauern Window, Austria. – Lithos **19**: 219–234, Amsterdam.
STAMPFLI, G. A., 1993: Le Brianconnais, terrain exotique dans les Alpes? – Eclogae geol. Helv. **86**: 1–45, Basel.
STAMPFLI, G. M. & MARCHANT, R. H., 1997: Geodynamic evolution of the Tethyan margins of the Western Alps. – In: PFIFFNER, A., LEHNER, P., HEITZMANN, P., MUELLER, St. & STECK, A. (Eds.): Deep Structure of the Swiss Alps: Results of NRP 20. – 223–239, Basel (Birkhäuser).
STAMPFLI, G. M., MOSAR, J., MARQUER, D., MARCHANT, R., BAUDIN, T. & BOREL, G., 1998: Subduction and obduction processes in the Swiss Alps. – Tectonophysics **296**: 159–204, Amsterdam.
STARK, M., 1912: Vorläufiger Bericht über geologische Aufnahmen im östlichen Sonnblickgebiet. – Sitzber. Akad. d. Wiss. Wien, m.-n. Kl., Abt.I **121**: 195–226, Vienna.
STAUB, R., 1924: Der Bau der Alpen. – Beitr. Geol. Karte Schweiz,**52**: 272 S., Bern.
STURM, R., DACHS, E. & KURZ, W., 1997: Untersuchung von Hochdruckrelikten in Grüngesteinen des Großglocknergebietes (zentrales Tauernfenster, Österreich): Erste Ergebnisse. – Zbl. Geol. Paläont. Teil I **1996**: 345–363, Stuttgart.
TILTON, G. R., SCHREYER, W. & SCHERTL, H. P., 1991: Pb-Sr-Nd isotopic behaviour of deeply subducted crustal rocks from the Dora Maira Massif, Western Alps, Italy-II: what is the age of the ultrahigh-pressure metamorphism? – Contrib. Mineral. Petrol. **108**: 22–33, Berlin.
TOLLMANN, A., 1963: Ostalpensynthese. – 256 S., Vienna (Deuticke).
TOLLMANN, A., 1965a: Die Fortsetzung des Brianconnais in den Ostalpen. – Mitt. Österr. Geol. Ges. **57(1964)**: 469–478, Vienna.
TOLLMANN, A., 1965b: Faziesanalyse der alpidischen Serien der Ostalpen. – Z. dt. Geol. Ges. **116(1964).**: 359–389, Hamburg.
TOLLMANN, A., 1968: Potenzierte Faltung in den Ostalpen. – Geotekt. Forsch. **29**: 60–80, Göttingen.
TOLLMANN, A., 1975: Ozeanische Kruste im Pennin des Tauernfensters und die Neugliederung des Deckenbaus der Hohen Tauern. – N. Jb. Geol. Paläont. Abh. **148**: 286–319, Stuttgart.
TOLLMANN, A., 1977: Die Geologie von Österreich (Band I): Die Zentralalpen. – 766 pp, Vienna (Deuticke).
TOLLMANN, A., 1980: Das östliche Tauernfenster. – Mitt. Österr. Geol. Ges. **71/72**: 73–79, Vienna.
WALLIS, S. R. & BEHRMANN, J. H., 1996: Translation, crustal stacking, and extension recorded along the Penninic – Austroalpine megathrust, eastern Alps: a case study from the S.E. Tauern, Austria. – J. Struct. Geol. **18**: 1455–1470, Oxford.
WALLIS, S. R., PLATT, J. P. & KNOTT, S. D., 1993: Recognition of syn-convergence extension in accretionary wedges with examples from the Calabrian Arc and the Eastern Alps. – Amer. J. Sci. **293**: 463–495, Washington.
WINKLER, A., 1926: Geologische Probleme in den östlichen Tauern (1. Teil). – Jahrb. Geol. Bundes-anst. **76**: 245–322, Vienna.
ZIMMERMANN, R., HAMMERSCHMIDT, K. & FRANZ, G., 1994: Eocene high pressure metamorphism in the Penninic units of the Tauern Window (Eastern Alps). Evidence from 40Ar–39Ar dating and petrological investigations. – Contrib. Mineral. Petrol. **117**: 175–186, Berlin.