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Kinematics of Penninic nappes (Glockner Nappe and basement-cover nappes) in the Tauern Window (Eastern Alps, Austria) during subduction and Penninic-Austroalpine collision

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Key words: Eastern Alps, Penninic nappes, Glockner Nappe, suture, basement-cover nappes, Tertiary continent collision, subduction, Eclogite Zone, Eclogites, kinematics, nappe stacking

ABSTRACT

The succession of deformation events within the Penninic oceanic sequence of the Glockner Nappe and the underlying Penninic continental margin sequences within the Tauern Window has been investigated in order to constrain the kinematics of subduction and subsequent collision with the Austroalpine upper plate within this suture zone. Top-to-the-N- to NE-shear (D_1) within the Penninic lower plate was contemporaneous to, and postdated, high pressure eclogite and blueschist facies metamorphism, and predated the thermal peak of Barrovian type metamorphism within the Penninic units. An eclogitic mylonitic foliation within the Eclogite Zone of the southern Tauern Window was probably synchronous with respect to the peak pressure event or slightly postdates the pressure peak. Emplacement of the eclogite-bearing units onto Penninic units with continental basement (Venediger Nappe Complex, VNC) occurred subsequent to eclogite facies metamorphism. The Eclogite Zone was overridden by a pile of basement-cover nappes (Rote Wand – Modereck Nappe) and the Glockner Nappe which forms the main Penninic-Austroalpine suture zone. The Penninic nappe pile was affected by blueschist facies metamorphism afterwards. Thus progressive top-to-the-N shear was related to internal Penninic nappe stacking driven by the subduction of Penninic continental basement (VNC), and emplacement of the ophiolitic Glockner Nappe after consumption of the South Penninic oceanic domain. Later, top-to-the-W shear (D_2) was related to crustal thinning and decompression of the Penninic lower plate including the Glockner Nappe and developed at, or slightly previous to, peak thermal conditions (ca. 30 Ma); thrusts were partly reactivated during exhumation, especially within the northeastern part of the Tauern Window. Top-to-the-W shear started at higher structural levels and is continuously transferred to deeper structural levels within the VNC. Especially within the continental basement units in the central and eastern part of the Tauern Window D_2 became penetrative, while the Penninic nappe pile including the Glockner Nappe was affected penetratively only in local domains within the Tauern Window. Afterwards, the structure of the Tauern Window was highly modified during exhumation and doming (D_3). An Alpine indenter in the southern central part caused the kinked shape of the window and the rotation of several previous structures and kinematic indicators.

The entire kinematic development that is preserved in the Tauern Window is younger and, therefore, independent from the development in the Austroalpine nappe pile that has only been transported as a rigid block over the Penninic units during the documented deformation sequence. The Eastern Alps are, therefore, the result of two collisional events during the Alpine orogenic cycle.

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ZUSAMMENFASSUNG

Innerhalb des Tauernfensters wurde die Abfolge von Deformationsereignissen in den ozeanischen Sequenzen der Glockner-Decke und den darunterliegenden Kontinentalrandsequenzen untersucht, um die Kinematik der Subduktion und die darauffolgende Kollision mit der ostalpinen Oberplatte innerhalb dieser Suturzone herauszuarbeiten. Eine nord- bis nordostgerichtete Scherbewegung des Hangenden (D_1) innerhalb der penninischen Unterplatte erfolgt gleichzeitig mit oder kurz nach der eklogitfaziellen Hochdruckmetamorphose und vor dem thermischen Höhepunkt der Regionalmetamorphose innerhalb der penninischen Einheiten. Eine mylonitische Schieferung innerhalb der Eklogitzone im südlichen Tauernfenster wurde höchstwahrscheinlich gleichzeitig mit oder kurz nach dem Druckmaximum gebildet. Die Platznahme der eklogitführenden Einheiten auf penninischen kontinentalen Einheiten (Venediger Deckenkomplex) erfolgte nach der eklogitfaziellen Metamorphose, während die Eklogitzone selbst von einem Grund-Deckgebirgsdeckenstapel (Rote Wand-Modereck-Decke) und der Glockner-Decke überfahren wird, welche die penninisch-ostalpine plattentektonische Sutur bildet. Der penninische Deckenstapel wird danach von einer blauschieferfaziellen Metamorphose erfaßt. Die progressive nordgerichtete Scherbewegung hängt damit ursächlich mit der internen penninischen Deckenstapelung zusammen, die durch die Subduktion penninischer kontinentaler Grundgebirgseinheiten (Venediger-Decke) und in weiterer Folge durch die Platznahme der ophiolithischen Glockner-Decke ausgelöst wurde. Eine spätere westgerichtete Scherung des Hangenden (D_2) hängt mit vertikaler krustaler Ausdünnung und Dekompression innerhalb der penninischen Unterplatte einschließlich der Glockner-Decke zusammen und erfolgte gleichzeitig oder kurz vor dem thermischen Höhepunkt der Metamorphose (um ca. 30 Ma). Überschiebungsflächen wurden dabei teilweise reaktiviert, vor allem innerhalb des nordöstlichen Abschnittes des Tauernfensters. Die westgerichtete Scherung beginnt in den höheren strukturellen Abschnitten und wird kontinuierlich in tiefere Krustenabschnitte innerhalb des Venediger Deckenkomplexes verlegt. Vor allem innerhalb der kontinentalen Grundgebirgseinheiten im zentralen und östlichen Teil des Tauernfensters wird D_2 penetrativ, während der penninische Deckenstapel einschließlich der Glockner-Decke im Tauernfenster nur lokal penetrativ erfaßt wird. Danach wurde die Struktur des Tauernfensters während der Exhumierung und Dombildung stark modifiziert (D_3). Ein Alpiner Indenter im südlichen zentralen Teil verursachte die geknickte Form des Fensters und die Rotation sämtlicher präexistenter Strukturen und kinematischer Indikatoren.

Die gesamte kinematische Entwicklung, die innerhalb des Tauernfensters erhalten ist, ist vollkommen unabhängig von der duktilen Deformation und Deckenstapelung innerhalb der ostalpinen Einheit, die während der dokumentierten Deformationsabfolge nur noch passiv auf den penninischen Einheiten transportiert wurde. Die Ostalpen sind deshalb das Ergebnis zweier Kollisionsereignisse während des alpidischen orogenen Zyklus.

Introduction

Orogenesis of the (Eastern) Alps is generally interpreted to result from collision of a (Middle) Penninic lower continental plate and an Austroalpine upper continental plate (e.g., Frisch 1979a; Pfiffner 1992; Kruhl 1993) after consumption of the South Penninic oceanic domain. There are many different and controversial data and models about the exact time and the kinematics of continent collision. Especially about the time of collision many different statements exist, ranging from the middle Cretaceous (e.g. Frisch 1979a; Tollmann 1980, 1987; Frank 1987; Ratschbacher et al. 1989; Ring et al. 1989) to early Tertiary (e.g. Behrmann & Wallis 1987; Neubauer 1994). Based on older K-Ar mineral ages (Raith et al. 1980; Frank 1987; Frank et al. 1987a) Penninic high pressure metamorphic assemblages that are mainly exposed within the so-called Eclogite Zone at the southern margin of the Tauern Window, are suspected to form a paired metamorphic belt together with Cretaceous middle pressure metamorphic sequences in the Austroalpine units (e.g. Frank et al. 1987a; Wallis et al. 1993). But no direct evidence for a Cretaceous age of the high pressure metamorphism within the Penninic realm is documented by these authors.

The Cretaceous age of internal nappe stacking and subsequent extension within the

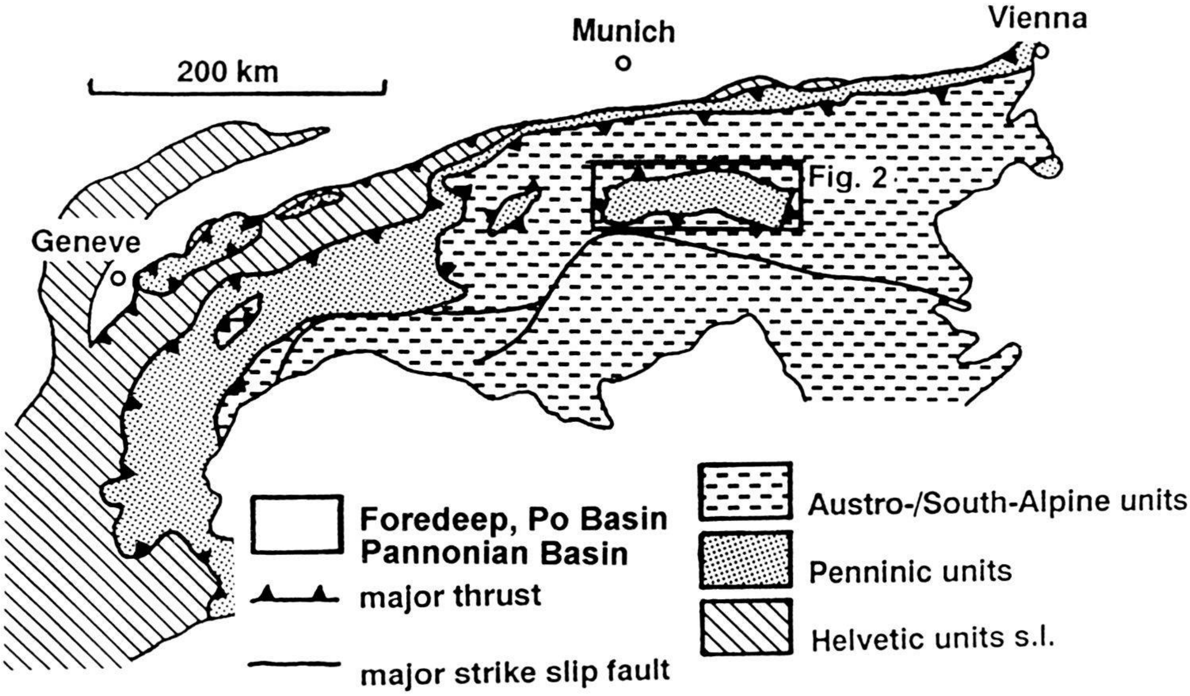


Fig. 1. Position of the Tauern Window within the Alps.

Austroalpine is well documented due to stratigraphic and geochronologic age data (Frank 1987; Krohe 1987; Neubauer & Genser 1990; Neubauer et al. 1993, 1995a, b; Handler et al. 1994, 1995; Dallmeyer et al. 1992, 1995), although problems occur in the interpretation of geochronologic data regarding the high pressure metamorphism within the Austroalpine (Neubauer 1991 and references therein; Thöni & Jagoutz 1992, 1993). The kinematics of internal Cretaceous nappe stacking within the Austroalpine are well documented, too. The succession of deformation events include: (1) top-to-the-W to WNW nappe emplacement and a footwall propagating master fault towards the foreland within the Austroalpine Nappe Complex (Ratschbacher 1986, 1987; Krohe 1987; Ratschbacher & Neubauer 1989; Dallmeyer et al. 1992; Genser 1992; Neubauer et al. 1993, 1995a, b; Handler et al. 1994, 1995), (2) followed by E-W extension and formation of the Gosau basins in the Late Cretaceous (Neubauer & Genser 1990; Neubauer et al. 1995b).

Geological setting

Within the Tauern Window (Fig. 1, 2), Penninic units are exposed below the Austroalpine Nappe Complex which forms the hangingwall continental plate during Tertiary plate collision. The Tauern Window exposes from footwall to hangingwall: (1) the parautochthonous (regarding the allochthonous hangingwall units of the Penninic and Austroalpine nappe stack) continental basement and parautochthonous cover sequences, which are locally imbricated, in the lower Venediger Nappe Complex (VNC) (Tab. 1) (Frisch 1975a, 1976, 1977, 1979b); (2) an imbrication zone of basement-cover nappes with the Rote

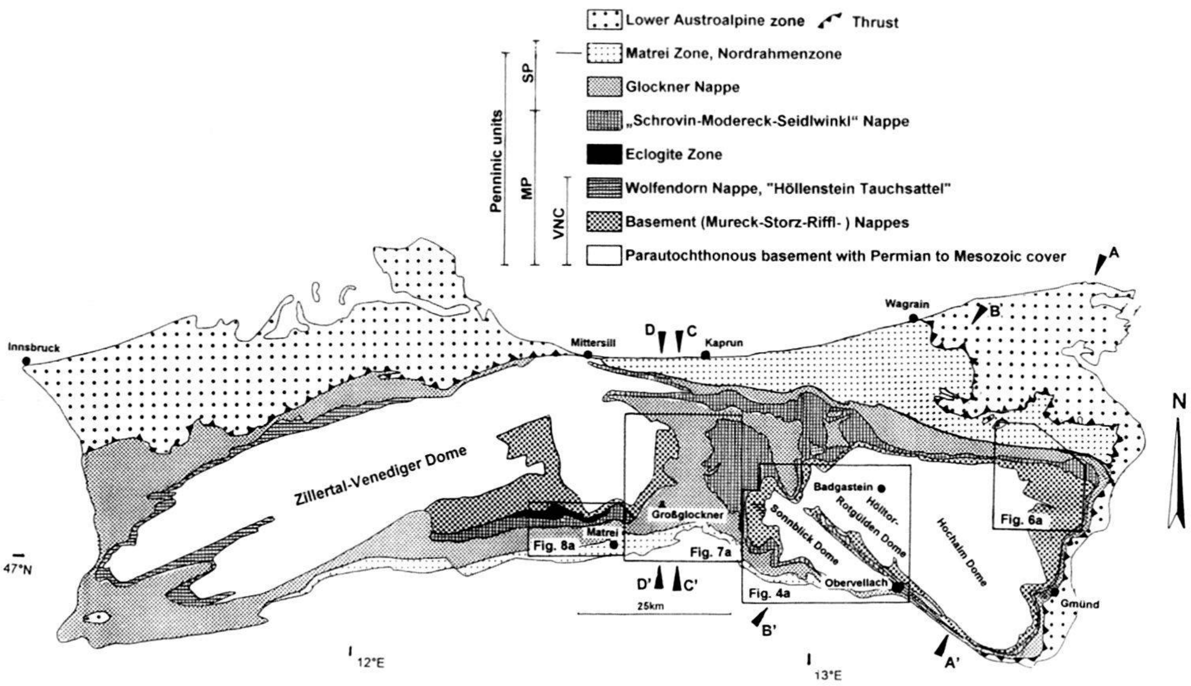


Fig. 2. Tectonic map of the Tauern Window (modified after Tollmann 1977) with areas of detailed investigation; VNC: Venediger Nappe Complex, MP: Middle Penninic paleogeographic origin, SP: South Penninic paleogeographic origin. A-A', B-B', C-C', D-D': positions of sections in Fig. 3.

Wand-Modereck Nappe (Tab. 1) as the largest nappe of this pile in the Tauern Window; both the VNC and the Rote Wand-Modereck Nappe are of Middle Penninic paleogeographic origin; Middle Penninic tectonic unit: MPU; (3) the Eclogite Zone is tectonically intercalated between the parautochthonous VNC and the basement-cover nappe stack (Tab. 1); (4) the oceanic sequences of the Glockner Nappe, which are of South Penninic paleogeographic origin; [and (5) the Lower Austroalpine nappe complex in the northeastern and northwestern corner, forming the hangingwall of the Tauern Window units]. Remnants of the oceanic crust between the MPU and the Austroalpine block are preserved in the units of the Glockner Nappe (South Penninic unit), which is emplaced onto the parautochthonous basement with its Permian to Mesozoic cover and onto the basement-cover units, while the Glockner Nappe itself is overthrusted by the Austroalpine nappe complex. Thus the Glockner Nappe forms the main plate tectonic suture zone within the Eastern Alps.

The VNC is exposed in a series of domes distributed over the entire length of the Tauern Window (Fig. 2). These domes include polymetamorphic basement sequences consisting of mainly amphibolites, migmatites, orthogneisses, dark micaschists and locally pre-Mesozoic ultramafic to mafic sequences intruded by Carboniferous granitoids. These granitoids were transformed to the Zentralgneis during Alpine deformation; an autochthonous metasedimentary cover ranging from the upper Permian (?) to the lower Cretaceous (?) (Lammerer 1986) consists of calcitic and dolomitic marbles, calcareous mica-

Tab. 1: Correlation of names of Penninic nappes in the Tauern Window.

		REGION	SOUTHEAST	NORTHEAST	GLOCKNER	CENTRAL SOUTH	(NORTH)WEST
Glockner Nappe (cf. Frisch 1974, 1975a)	Upper (Periperal) Schieferhülle		Matrei Zone	Nordrahmenzone	Matrei Zone	Matrei Zone	Nordrahmenzone
			Glockner Nappe	Glockner Nappe	Glockner Nappe	Glockner Nappe	Glockner Nappe
		Basement-cover nappes	Rote Wand-Modereck Nappe	Schrovin Unit	Seidlwinkl Nappe	Rote Wand-Modereck Nappe; „Glimmerschieferlamelle"	
			—	—	—	Eclogite Zone	—
Venediger Nappe (cf. Frisch 1977) Venediger Nappe Complex (VNC)	Lower (Inner) Schieferhülle	Basement (-cover) nappes					Wolfendorn Nappe Höllenstein-Tauchdecke
			Grieswies-Lonza Nappe	Storz Nappe	—	—	—
			Sandkopf-Neubau Nappe	Mureck-Gneiss Nappe	Riffl Nappe	Riffl Nappe	
		Basement with parautochthonous Permian to Mesozoic cover	Intruded basement and parautochthonous Permian to Mesozoic cover	Intruded basement and parautochthonous Permian to Mesozoic cover	Intruded basement and parautochthonous Permian to Mesozoic cover	Intruded basement and parautochthonous Permian to Mesozoic cover	Intruded basement and parautochthonous Permian to Mesozoic cover
	Zentralgneis		Sonnblick Dome	Hochalm and Hölltor-Rotgülden Domes		Granatspitz Dome	Tux- and Ahorn Domes

schists, quartzites and meta-conglomerates and very subordinate greenschists. Important members of this parautochthonous cover sequence are the Jurassic Hochstegen Marble and the mainly clastic sequences of the Cretaceous Kaserer Formation (Thiele 1970, 1974, 1976; Frisch 1974, 1975a, b, 1977). Permian to Triassic sequences are restricted to local domains and are otherwise completely missing within the VNC. The polymetamorphic basement sequences of the MPU, that are intruded by the late Variscan Granitoids of the Zentralgneis, the parautochthonous Permian to Mesozoic units and the basement-cover nappes of the VNC are often summarized as the Lower or Inner Schieferhülle (LSH) by some authors (Exner 1957, 1964, 1971, 1983; Cliff et al. 1971; Tollmann 1980; Selverstone 1993). Detailed correlation of these portions of the VNC is provided in Table 1.

The Eclogite Zone forms a tectonic slice between the VNC and the Rote Wand-Modereck Nappe within the central southern part of the Tauern Window. The Eclogite Zone comprises mafic eclogites of MORB chemical composition (Miller 1977). The eclogites are often retrogressed during decompression subsequent to the pressure peak to garnet-amphibolites and garnet bearing greenschists. Retrogression of the eclogites is irregular laterally and vertically. The eclogites and retrogressed derivates are intercalated with metasediments like quartzites, paragneisses, garnet-micaschists, calcareous micaschists and with calcitic and dolomitic marbles. The metasediments experienced the same high-pressure metamorphism (Dachs 1986, 1990). The eclogite facies rocks were buried to a depth of at least 55 km (20 kbar, 550–600 °C) (Holland 1979; Holland & Ray 1985; Dachs 1986, 1990; Frank et al. 1987a; Selverstone et al. 1992; Zimmermann et al. 1994; Inger & Cliff 1994; Getty & Selverstone 1994). Eclogite facies metamorphism is restricted to the Eclogite Zone, while the entire nappe pile, including the VNC, the Rote Wand-Modereck Nappe and the Glockner Nappe, is affected by high pressure blueschist facies metamorphism afterwards (7–9 kbar, ca. 450 °C; Raith et al. 1980) with peak pressures of up to 15 kbar (Selverstone et al. 1984, 1992; Selverstone 1985, 1993; Cliff et al. 1985; Droop 1985; Holland & Ray 1985; Frank et al. 1987a; Behrmann & Ratschbacher 1989; Behrmann 1990) and yet later by Barrovian-type upper greenschist to lower amphibolite facies metamorphism (e.g. Frank et al. 1987a; Selverstone 1993).

The base of the higher portions of the MPU basement-cover nappes is built up of so-called gneiss lamellae (Exner 1957, 1964; Cliff et al. 1971; Behrmann 1990; Bickle & Hawkesworth 1978). They are in part basement slices and/or slices of paragneisses derived from cover units that detached from the basement during internal nappe stacking, forming basement-cover duplexes (see Tab. 1). The Penninic basement-cover nappes consist of the gneiss lamellae and a metasedimentary/metavolcanic cover. The metasedimentary cover sequences of these nappes consist of quartzites, calcitic and dolomitic marbles, micaceous marbles, calcareous micaschists and subordinate greenschists with supposed stratigraphic ages from the Permian to the lower Cretaceous (Exner 1957, 1964, 1971, 1980, 1982, 1989, 1990; Frasl 1958; Tollmann 1977 p. 28, 1980). The typical Permian to Triassic sequence consists of quartzites ("Wustkogelquarzit") and meta-conglomerates at the base, covered by calcitic and dolomitic marbles, the so-called Seidlwinkl-Triassic (Frasl 1958; Frasl & Frank 1964; Frank 1969). The metacarbonates are interpreted to represent metamorphic platform-carbonate sequences and lagoonal deposits. The typical Jurassic sequence consists of carbonate-breccias near its base that are intercalated with paragneisses, dark micaschists, garnet-micaschists, carbonate quartzites, quartzites, calcareous micaschists, marbles and subordinate (sometimes garnet-bearing) greenschists (the so-called Brennkogel facies; e.g. Cornelius & Clar 1939; Tollmann 1977, p. 28). The Cretaceous is dominated by clastic sequences (paragneisses, carbonate-quartzites and dark micaschists). Detailed correlation of the distinct regionally distributed nappes of the higher MPU is given in Table 1.

The highest Penninic nappe is the Glockner Nappe. The base of the Glockner Nappe is built up of metabasites and serpentinites covered by a sequence of metamorphic cherts, quartzites, micaceous calcitic marbles and calcareous schists intercalated with MORB-type metabasic rocks (greenschists and amphibolites) (Bickle & Pearce 1975; Höck & Miller 1980, 1987) of supposed Jurassic to Cretaceous age. Where serpentinites and other ultrabasites are missing, however, the separation of the Glockner Nappe from footwall units becomes difficult because lithological similarities exist especially between rocks of the Rote Wand-Modereck Nappe and the Glockner Nappe. As a rule, MORB-type greenschists are restricted to the Glockner Nappe. In the hangingwall of the Glockner Nappe in the southern part of the Tauern Window the Matrei Zone (Fig. 2) is exposed. It is interpreted to reflect the trench-slope situation of the Penninic-Austroalpine active continental margin during the Cretaceous (Frisch et al. 1987), assuming that the collision between the MPU and the Austroalpine block occurred during the Cretaceous. The Matrei Zone is characterized by metamorphic flysch sediments (mainly calcareous and carbonate-free micaschists), breccias and olistholites mainly of Austroalpine derivation. However, again the separation from the Glockner Nappe s.str. in the footwall becomes difficult where these tectonic slices are missing. In some places there is no clear evidence of a thrust contact between the Glockner Nappe and the Matrei Zone, but a continuous sedimentary transition is documented. Following Frisch et al. (1987) the Matrei Zone forms the uppermost part of the "Bündner Schiefer" of the Glockner Nappe. The Matrei Zone is interpreted to correlate with the "Nordrahmenzone" in the northern part of the Tauern Window (Tollmann 1975).

The Rote Wand-Modereck Nappe and equivalent units, and the Glockner Nappe including the Matrei Zone are often summarized as the Upper (or Peripheral) Schieferhülle (USH) (Tab. 1) (Exner 1957, 1964, 1971; Selverstone 1993). The Rote Wand-Modereck Nappe and equivalent units are often missing beneath the base of the Glockner Nappe. So the term "Upper Schieferhülle" is often used and interpreted to be equivalent to the Glockner Nappe alone. Thus generally the terms "Upper and Lower Schieferhülle" should be omitted to avoid misunderstandings and misinterpretations, especially concerning structure.

Previous kinematic and geodynamic interpretations

The basement-cover units of the Venediger Nappe Complex as well as the Glockner Nappe were buried beneath the Austroalpine nappe complex to depths of at least 35 km (based on peak pressure conditions of ≥ 10 kbar) during subduction (Selverstone et al. 1984, 1991; Selverstone 1985, 1988, 1993; Selverstone & Spear 1985; Genser et al., in press). Eclogite facies metamorphism (550–600 °C, 20 kbar; Holland 1979; Selverstone et al. 1992) within the Tauern Window is restricted to the Eclogite Zone, while the entire nappe pile is affected by HP blueschist facies metamorphism afterwards and yet later by

Barrovian-type upper greenschist to lower amphibolite facies metamorphism (see above, Geological setting). Based on these pressure (and temperature) paths combined with structural data we want to reconstruct the kinematic path of the oceanic lithosphere within the Glockner Nappe and of the continental basement.

Because of the low temperatures in the lower plate during subduction (e.g., Peacock 1993) and the rigid behaviour of cool oceanic lithosphere we should expect brittle to semibrittle deformation along distinct thrusts during early stacking within the accretionary wedge between the Penninic lower plate and the Austroalpine upper plate. There are many different and controversial data and models about the exact time and the kinematics of continent collision in the Eastern Alps, especially within the Penninic lower plate. Particularly about the time of collision and about the correlation of structures between the Austroalpine and the Penninic units many different statements exist.

Ledoux (1984) argued for internal Penninic nappe stacking during N-S shortening in the middle to upper Cretaceous due to southward subduction. Behrmann & Wallis (1987) documented NE-directed emplacement and sinistral transpressive movement between (Middle-)Austroalpine basement units (Altkristallin) and the Penninic units. These data have been evaluated from tip lines of Austroalpine slices within the Matrei Zone. They supposed an upper Cretaceous to lower Tertiary age of emplacement of Austroalpine units onto Penninic units. Kruhl (1993) interpreted top-to-the-ENE- to NE imbrication at the basement-cover boundary of the Venediger Nappe in the NE part of the Tauern Window as a result of continental collision between a northern (European or Briançonnais) and a southern (Adriatic) plate. From the orientation of branch lines and cut-off-lines (Boyer & Elliot 1982), Behrmann (1990) deduced NW-directed nappe emplacement of the Penninic nappe pile over continental basement units (Venediger Nappe) within the western part of the Tauern Window. Behrmann (1990) correlated this deformation with top-to-the-W-directed nappe stacking within the Austroalpine nappe complex. Based on the same structural criteria in the central part of the Tauern Window, Behrmann (1990) documented NW- and N- to NNE-directed emplacement of basement-cover nappes over the Venediger Nappe. There the NNE orientation is interpreted as movement along a south dipping lateral ramp. Top-to-the-NW movement is correlated with the emplacement of the Glockner Nappe over the basement-cover units of the MPU. This movement is interpreted to correlate with the emplacement of Austroalpine units over the Penninic nappe pile because of the similar kinematics within the Austroalpine upper plate. Based on Rb/Sr geochronology by Hawkesworth (1976) from the Austroalpine nappe complex, the emplacement of the Glockner Nappe and Austroalpine units are assumed to be of Cretaceous age.

Oehlke et al. (1993) and Schön & Lammerer (1993) documented top-to-the-N nappe stacking and formation of thrust duplexes in the southwestern Tauern Window. These duplexes are interpreted to be early Alpine (Cretaceous) structures followed by top-to-the-W ductile shearing.

The timing of eclogite formation in the Eclogite Zone at the southern margin of the Tauern Window and of emplacement of the eclogite facies rocks (ca. 20 kbar, 550–600 °C) (Holland 1979) is discussed controversially. Generally, an early to middle Cretaceous age of eclogite formation is assumed (e.g., Behrmann & Ratschbacher 1989; Raith et al. 1980). The eclogite facies rocks are suspected to form a paired metamorphic belt together with Cretaceous middle pressure metamorphic sequences within Austroal-

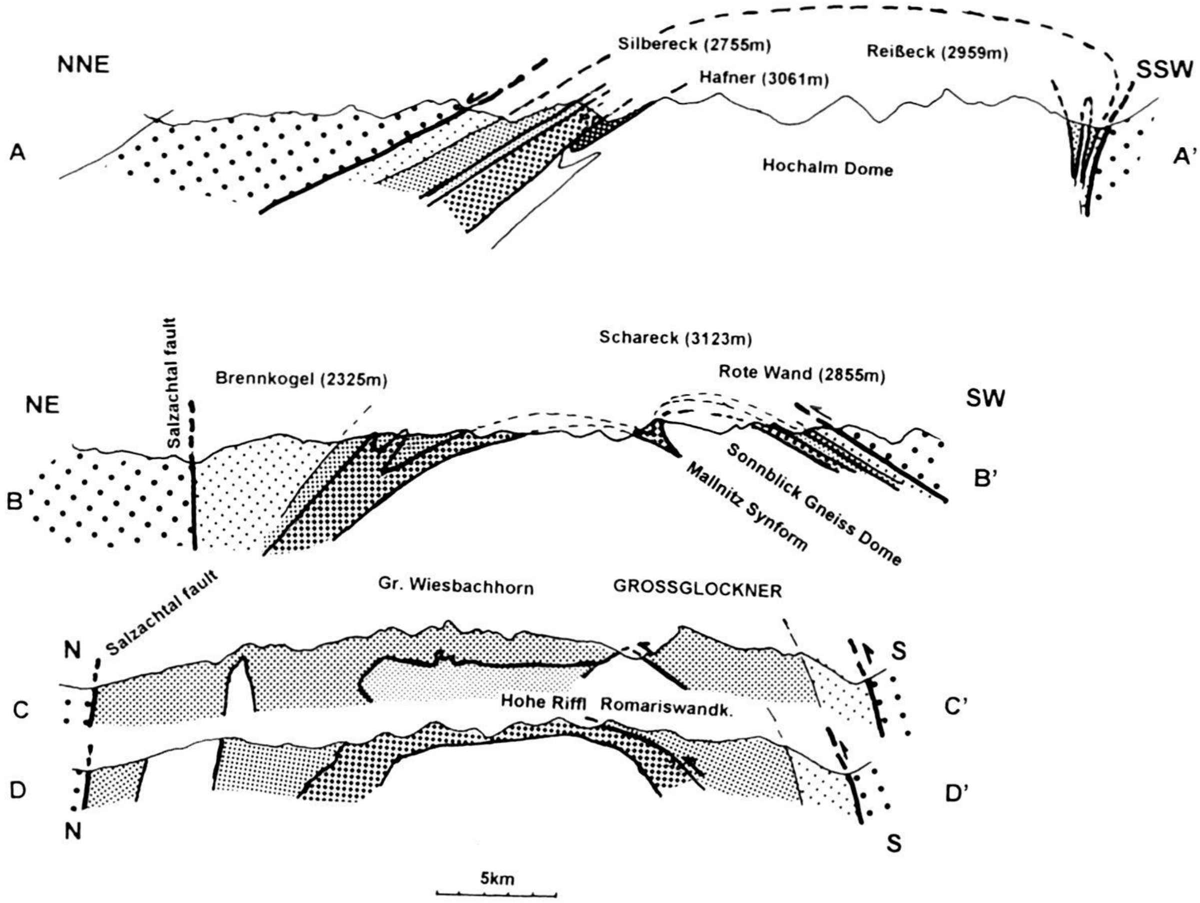


Fig. 3. Schematic sections across the eastern and central part of the Tauern Window (after Frank 1969), for position and legend see Figure 2.

pine units, but no direct evidence of Cretaceous eclogite facies metamorphism within the Tauern Window exists. Behrmann & Ratschbacher (1989) infer NE-directed emplacement of the Eclogite Zone upon the Penninic basement during the Cretaceous and subsequent exhumation and uplift due to extension of an overthickened accretionary wedge.

W- to NW-directed ductile shearing is well documented over the entire Tauern Window starting approximately at the thermal peak of Cenozoic Barrovian-type metamorphism (400–500 °C, 4–6 bar within the Rote Wand-Modereck Nappe and the Glockner Nappe, 450–550 °C, 7–8 kbar within the VNC) (Bickle & Hawkesworth 1978; Frank et al. 1987a; Lammerer 1988; Behrmann 1990; Behrmann & Frisch 1990; Selverstone 1993; Kruhl 1993; Oehlke et al. 1993; Wallis et al. 1993; Christensen et al. 1994; Kurz et al. 1995). This deformation is interpreted by Wallis et al. (1993) as syn-convergent extension within an accretionary wedge before Penninic-Austroalpine continental collision during N-S shortening. Again this is based on the assumption of similar kinematics and deformation geometry both within the Austroalpine and the Penninic plate.

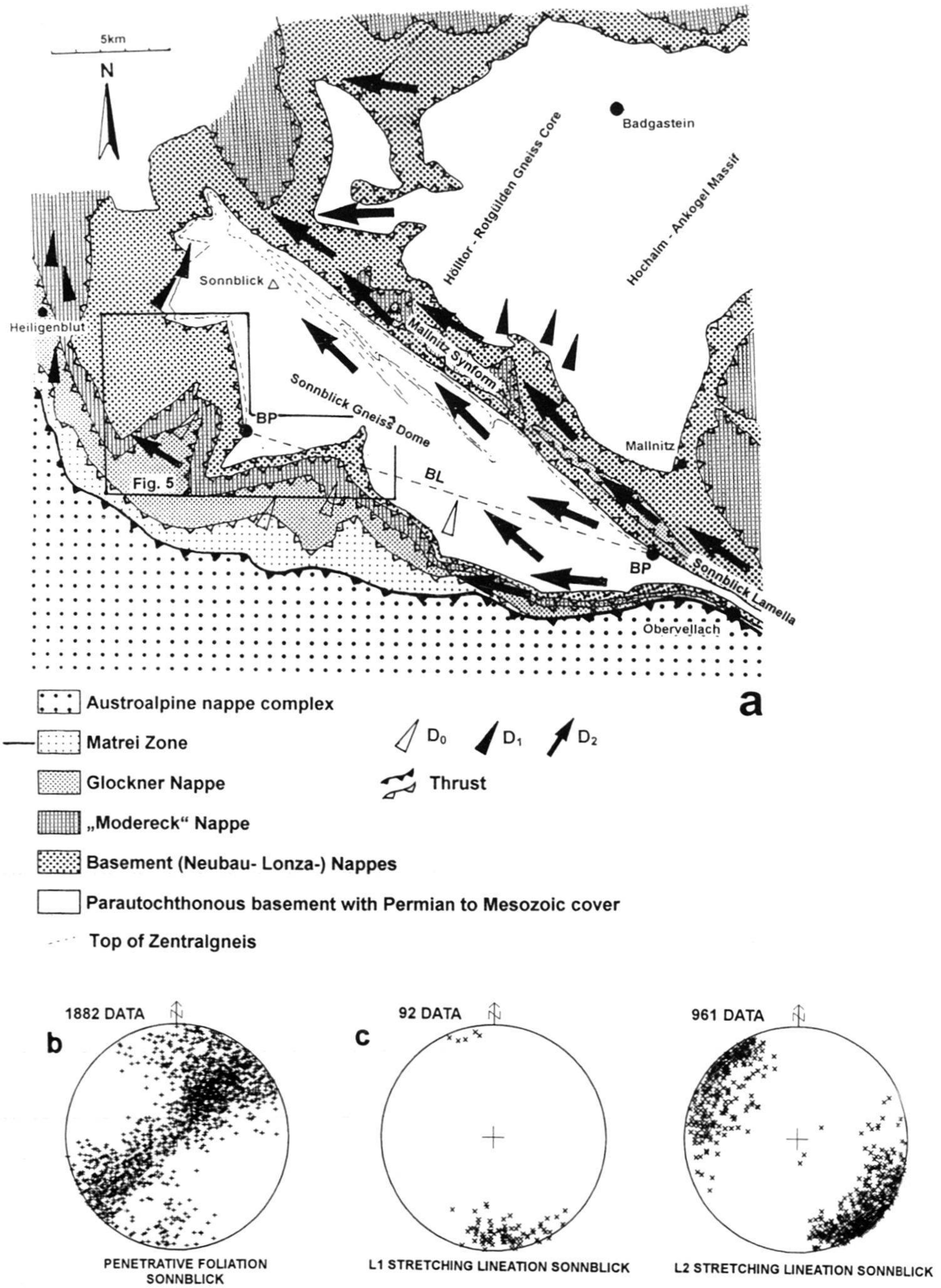


Fig. 4. a – Tectonic map of the Sonnblick area (southeastern Tauern Window) (after Exner 1964) with sense of shear during brittle and ductile nappe stacking (D_0, D_1) and subsequent decompression (D_2). **BP**: branch point; **BL**: branch line. b – Orientation data of the penetrative composite foliation (s_1, s_2). c – Stretching lineations (l_1, l_2) from the southeastern part of the Tauern Window.

The shape of the Tauern Window was highly modified during exhumation and doming after the penetrative deformation events that were related to nappe stacking. The Tauern Window is characterized by a kinked shape that might be the result of an Alpine indenter in the central part of the window. Indentation in the late Oligocene (slightly after peak thermal metamorphism) caused clockwise rotation of the eastern part of the Tauern Window and counterclockwise rotation of the western part (Kurz 1993). The rotation is proven by overprinting relationships of crosscutting NE-trending and younger NNE-trending subvertical mineralized extensional veins in the eastern part of the Tauern Window (Kurz et al. 1994). It resulted in the rotation of several previous structures and kinematic indicators and in the divergence of kinematic data over the entire Tauern Window.

Previous geochronological work: Rb-Sr white mica ages of ca. 27 Ma to 29 Ma (Reddy et al. 1993; Inger & Cliff 1994) in the southeastern part of the Tauern Window are interpreted as formation ages during the Cenozoic thermal peak of Barrovian type metamorphism. The ages are slightly decreasing approaching deeper structural levels. K-Ar and $^{40}Ar/^{39}Ar$ muscovite, biotite and amphibole cooling ages of ca. 35 Ma (Lambert 1970; Oxburgh et al. 1966) are supposed to be too high due to excess argon (von Blanckenburg & Villa 1988; von Blanckenburg et al. 1989). Within the eastern Tauern Window, amphibole $^{40}Ar/^{39}Ar$ ages of ca. 24 Ma are thought to date the thermal peak of metamorphism (Cliff et al. 1985).

Phengite $^{40}Ar/^{39}Ar$ mineral ages of ca. 36-32 Ma (Zimmermann et al. 1994) and 38 Ma (Ratschbacher, pers. comm.) from the Eclogite Zone are interpreted to represent cooling ages after the blueschist facies metamorphism (Zimmermann et al. 1994). The possibility of a post-Cretaceous age of high pressure metamorphism is also elucidated by Inger & Cliff (1994). At the moment it is not clear if argon isotopic systems of high-pressure phengite survived later Barrovian type metamorphism (of ca. 500 °C), in excess of the argon retention temperature of ca. 410 °C (e.g., von Blanckenburg et al. 1989).

Investigated areas

In four areas in the eastern and central Tauern Window (Fig. 2) we studied the kinematics of nappe stacking to reconstruct the structural evolution of the Penninic realm in the Eastern Alps which is related to the subduction of this unit. Special interest was given to the Glockner Nappe as the main Alpine suture zone.

The *southeastern Tauern Window* (Fig. 2, 3, 4, 5) exposes a complete section through the Penninic units. The basement units of the VNC in the southeastern part of the Tauern Window can be subdivided into the Hölltor-Rotgülden Gneiss Dome (which forms the eastern extension of the Hochalm Gneiss Dome) and the Sonnblick Gneiss Dome. The Sonnblick Dome forms a large NE-vergent dome structure that is narrowing along its southeastern extension to the so-called Sonnblick Lamella (Exner 1962, Cliff et al. 1971) (Fig. 2, 3, 4). These two dome structures are separated by the Mallnitz Synform (Fig. 2, 3, 4), where almost the entire Mesozoic metasedimentary/metavolcanic nappe pile is exposed above the MPU. The so-called gneiss lamellae are well exposed within the Mallnitz Synform and around the Sonnblick Gneiss Dome (Fig. 4a).

The *northeastern Tauern Window* (Fig. 2, 6a) also exposes a complete section through Penninic units. There is a voluminous accumulation of Penninic cover nappes in the

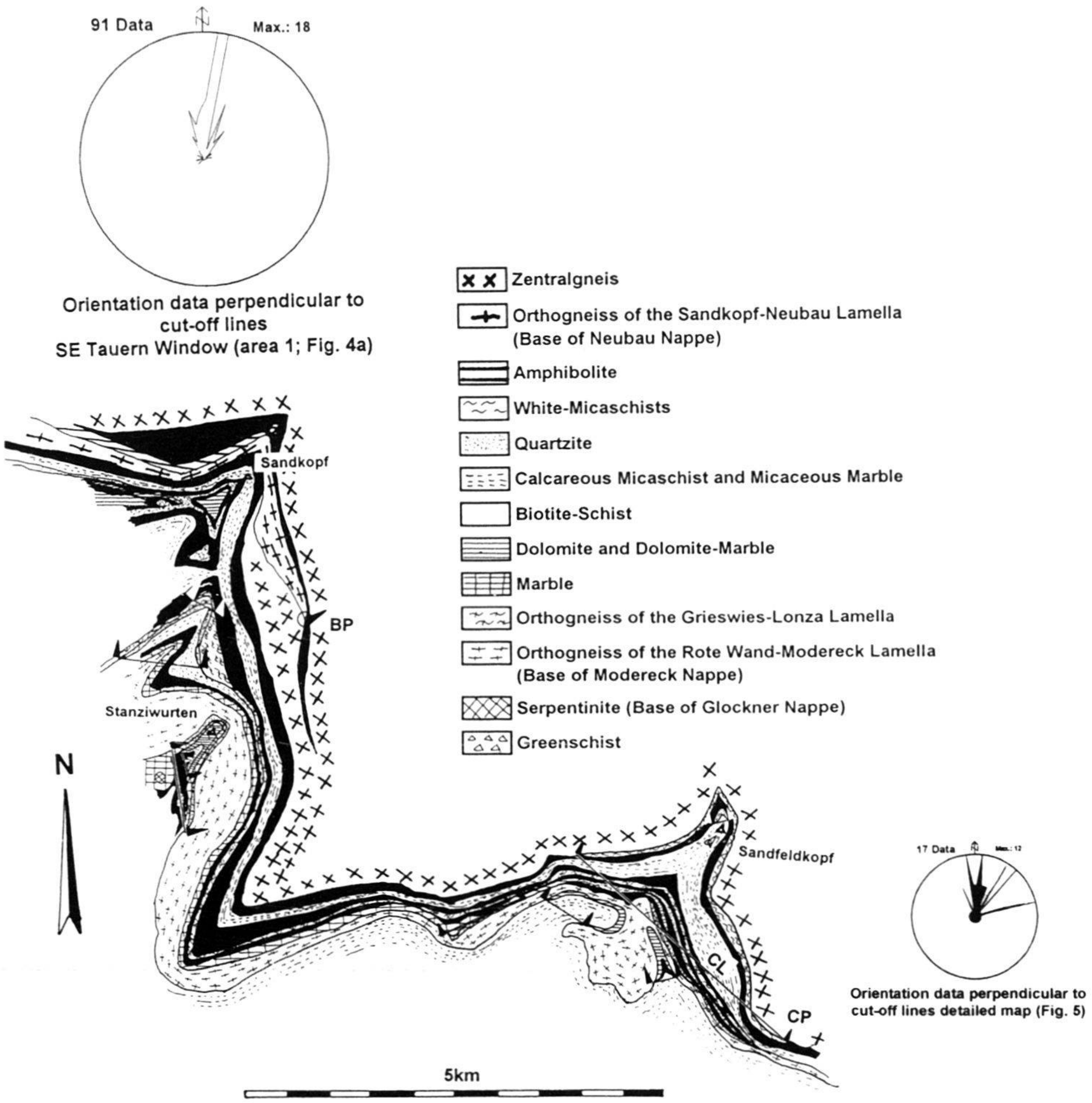
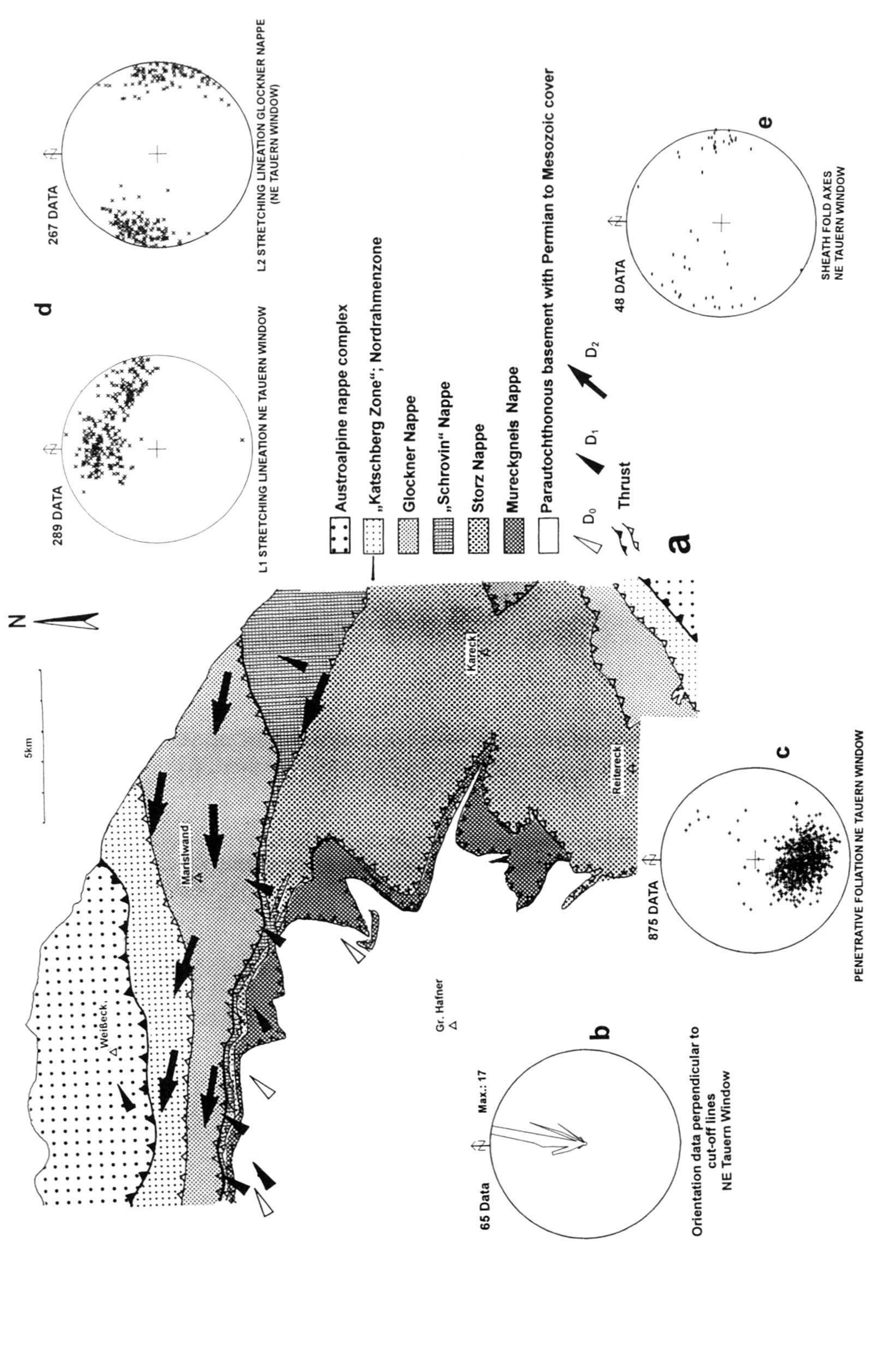


Fig. 5. Detailed map of the southwestern part of the Sonnblick area (after Exner 1964) documenting the orientation of cut-off lines, and orientation distribution diagram of displacement directions perpendicular to cut-off-lines; southeastern Tauern Window. **CP**: cut-off point, **CL**: cut-off line, **BP**: branch point.

Fig. 6. a – Tectonic map of the northeastern Tauern Window (after Exner 1983) with sense of shear during brittle and ductile nappe stacking (D_0, D_1) and following extension (D_2). b – Orientation data of displacement directions perpendicular to cut-off lines. c – Orientation data of the penetrative composite foliation (s_1, s_2). d – Orientation data of the stretching lineations (l_1, l_2). e – Orientation data of sheath fold axes and related isoclinal fold axes subparallel to stretching lineation (b_2); northeastern Tauern Window.


5km
N
289 DATA
L1 STRETCHING LINEATION NE TAUERN WINDOW
d
267 DATA
L2 STRETCHING LINEATION GLOCKNER NAPPE
(NE TAUERN WINDOW)
Austroalpine nappe complex
„Katschberg Zone"; Nordrahmenzone
Glockner Nappe
„Schrovin" Nappe
Storz Nappe
Mureckgneis Nappe
Parautochthonous basement with Permian to Mesozoic cover
D0
D1
D2
Thrust
a
48 DATA
e
SHEATH FOLD AXES
NE TAUERN WINDOW
Weißeck
Marislwand
Kareck
Reitereck
Gr. Hafner
c
875 DATA
PENETRATIVE FOLIATION NE TAUERN WINDOW
b
65 Data
Max.: 17
Orientation data perpendicular to
cut-off lines
NE Tauern Window

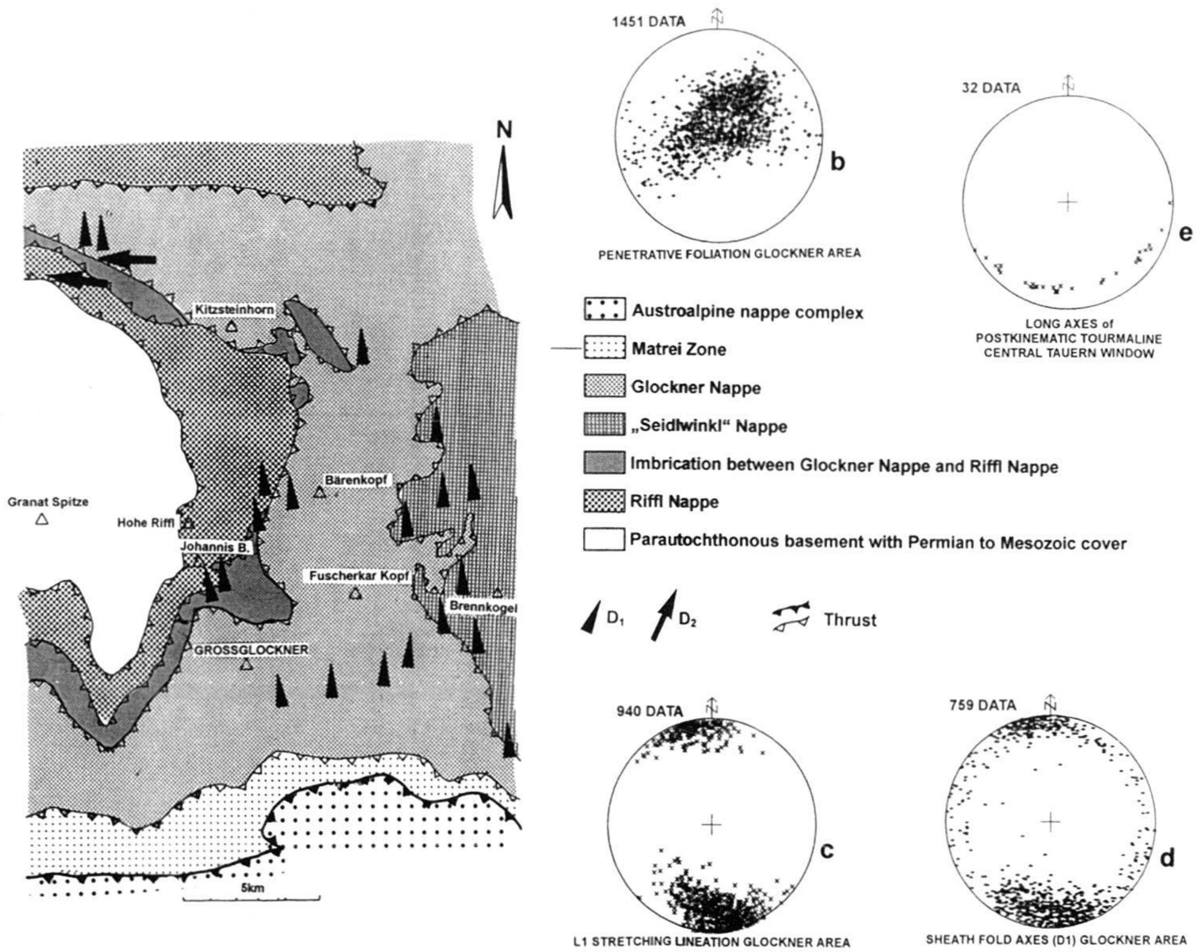


Fig. 7. a – Tectonic map of Glockner area (central Tauern Window) (modified after Frank et al. 1994) with sense of shear during ductile nappe stacking (D_1) and subsequent extension (D_2). b – Orientation data of the penetrative composite foliation (s_1, s_2). c – Orientation data of the stretching lineations (l_1, l_2). d – Orientation data of sheath fold axes and related isoclinal fold axes (b_1) subparallel to stretching lineation; central Tauern Window. e – Orientation data of the long axes of post-D_1 tourmaline which has overgrown s_1 and l_1 in basement rocks of the Riffl Nappe.

northeasternmost part of this area. Local imbrication of basement and parautochthonous units is documented in the western part of this area (Fig. 6a). The basement nappes of the VNC (Mureckgneis Nappe, Storz Nappe) and the Schrovin-Modereck Nappe (Tab. 1) are thinned out to the W, while the Glockner Nappe and the "Nordrahmenzone" (Tab. 1) are accumulated over the entire area. The Glockner Nappe is imbricated into at least three tectonic slices (Exner 1971). These are locally separated by serpentinites and by slices of a sequence of metaconglomerates, quartzites, marbles and dolomites (epicontinental sediments) of supposed Triassic age.

In the *Großglockner area* (Fig. 2, 7a), the Glockner Nappe and the Seidlwinkl Nappe, which is equivalent to the Rote Wand-Modereck Nappe (Tab. 1), represent the most voluminous exposure in the Tauern Window, while the basement nappes of the VNC show only subordinate occurrence. In the western part of this area the Glockner Nappe is di-

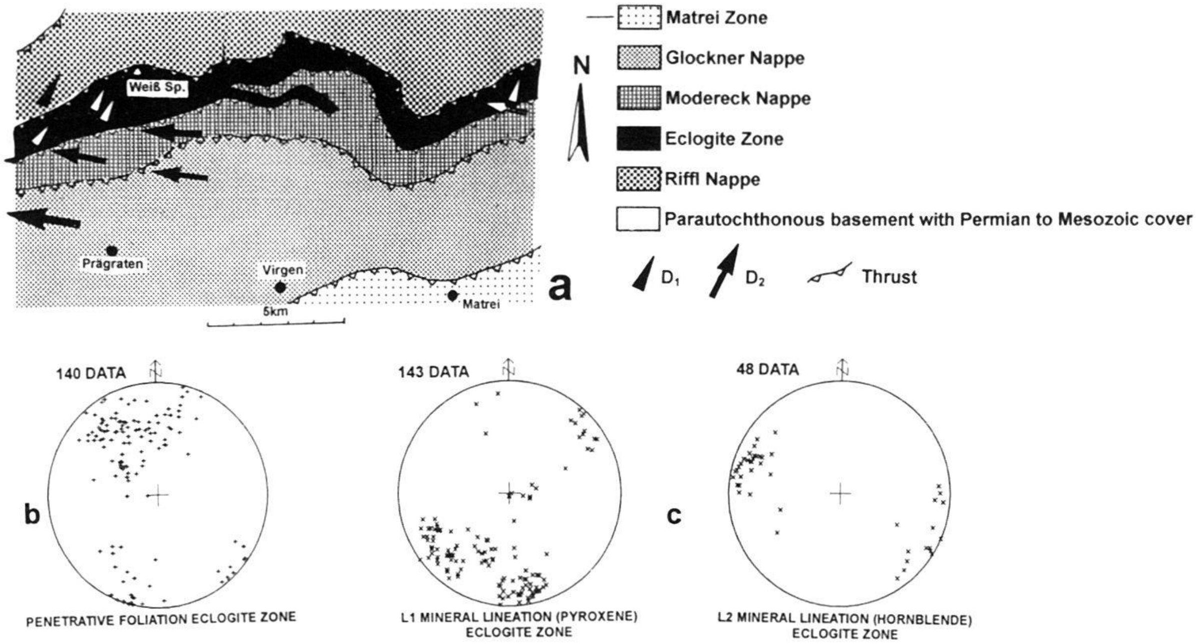


Fig. 8. a – Tectonic map of the southern central Tauern Window (Eclogite Zone) (modified after Frank et al. 1987b) with sense of shear during ductile nappe stacking (D_1) and following extension (D_2). b – Orientation data of the penetrative composite foliation (s_1, s_2). c – Orientation data of the stretching/mineral lineations (l_1, l_2); with separate data for eclogite mylonites and retrogressed eclogites.

rectly thrusted over the Riffl Nappe (part of the VNC), while the Seidlwinkl-Modereck Nappe is missing. The structural base of the Glockner Nappe is built up of slices and lenses of metabasites and meta-ultrabasites as well as of Triassic (?) carbonates. The Glockner Nappe itself is again subdivided into several tectonic slices which are separated by serpentinites and garnet-amphibolites. The latter are interpreted as relics of eclogites (Cornelius & Clar 1939; Dachs et al. 1991). However, no direct evidence of eclogite facies metamorphism of these rocks is known up to now. The eastern part of this area is dominated by accumulation of Permian to Triassic arkoses and quartzites, calcitic and dolomitic marbles containing cargneules and gypsum of the Seidlwinkl (Modereck-)Nappe. Following Frasl (1958), Frasl & Frank (1964) and Frank (1969) this unit forms a large flat-lying fold nappe with a NW- to N-trending fold axis and is thrusted over the basement and basement-cover nappes of the VNC (Fig. 3).

In the *central southern part of the Tauern Window* (Fig. 2, 8a) a slice of eclogites and associated high pressure metasediments is found between the VNC and the Rote Wand-Modereck Nappe. Both are overthrusted by the Glockner Nappe. Eclogite facies metamorphism is restricted to the Eclogite Zone, but the whole Penninic nappe pile was affected by blueschist facies metamorphism afterwards (see above). The mostly retrograde eclogites are intercalated within garnet-micaschists, calcareous micaschists and metacarbonates showing relics of high pressure metamorphism, too (Dachs 1986, 1990). Banded greenschists and amphibolites of the Rote Wand-Modereck Nappe and the Glockner Nappe contain relics of pillow structures in places (Holland & Norris 1979). The Glockner Nappe consists of voluminous calcareous micaschists, micaceous marbles and marble mylonites, greenschists and subordinate metapelites (garnet-micaschists) of supposed Jurassic to Cretaceous age, intercalated with serpentinite.

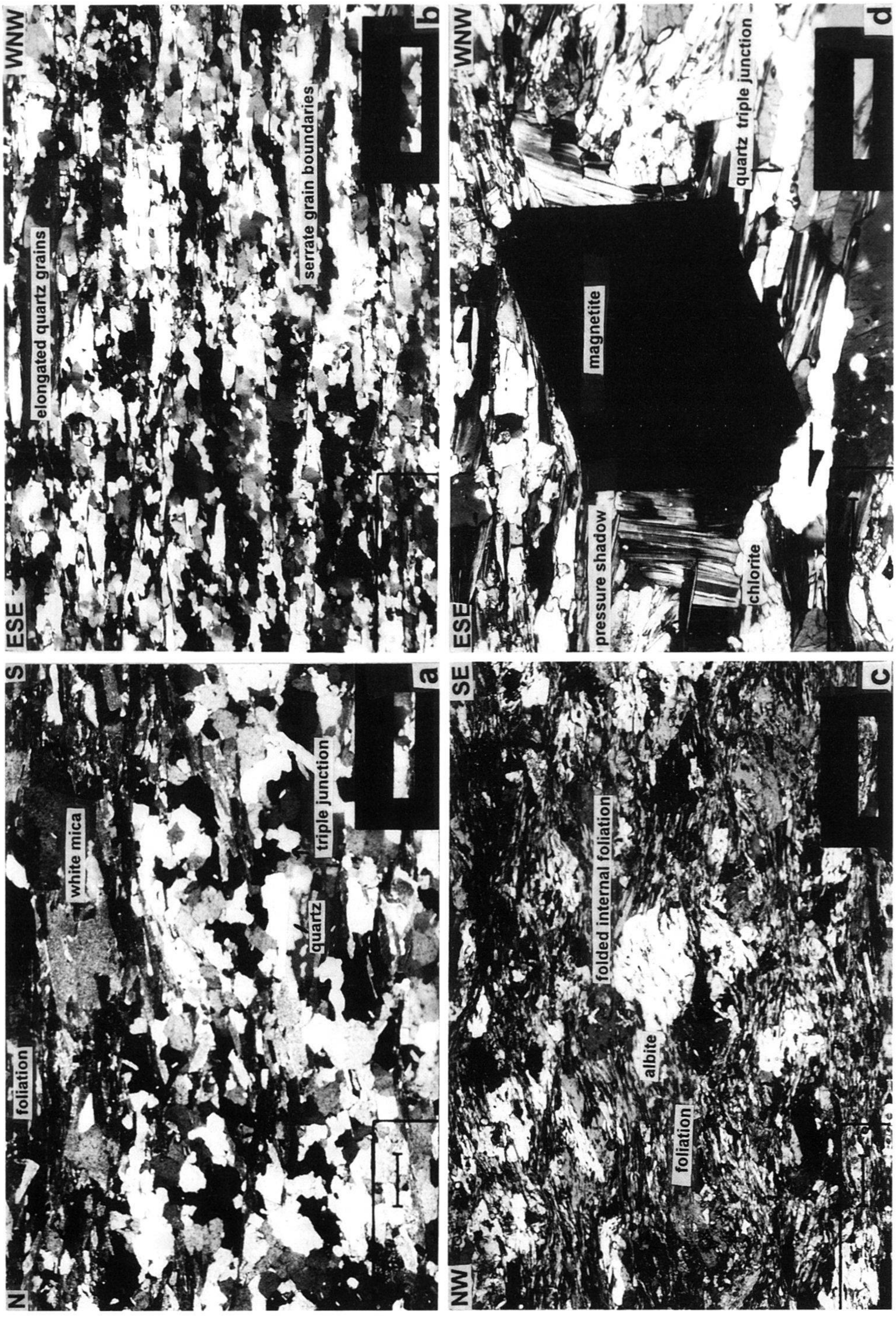
Structural evolution

Structures related to internal nappe stacking along distinct brittle thrust planes (D_0) are not developed at meso-scale within the *southeastern Tauern Window*, but can be elaborated at map-scale (Fig. 4a, 5). From the WNW-ESE orientation of branch lines (Fig. 4a) of the Sandkopf-Neubau-Gneiss Lamella and the Grieswies-Lonza Lamella (basement-cover nappes of the VNC; Tab. 1) NNE-directed detachment can be deduced (Fig. 4a). The orientation of cut-off lines and branch lines remains constant through the entire nappe pile up to Austroalpine units (Fig. 4a, 5).

The oldest distinct meso-scale structures resulted from N-directed ductile shearing (D_1). This deformation is penetratively developed only in the uppermost structural levels of the VNC (uppermost level of the Zentralgneis, the pre-Variscan basement and the parautochthonous Permian to Mesozoic cover). From D_0 to D_1 there is a continuous transition from brittle or semibrittle nappe stacking to penetrative deformation. There is no great difference between D_0 and D_1 concerning the kinematics. We have separated D_0 and D_1 to distinguish between detachment of basement-cover nappes during D_0 along distinct thrust surfaces, which are obvious from the map-scale, and penetrative deformation over the whole nappe pile during D_1. During D_1 a first penetrative foliation (s_1) (Fig. 4b) parallel to the thrust surfaces and a S- to SSE-plunging stretching lineation (l_1) (Fig. 4c) developed. Quartz displays partly, equilibrated fabrics with equigranular, polygonal grains and straight grain boundaries forming 120°-triple junctions. Preferred orientations of crystallographic axes are missing (Kurz 1993). These features suggest annealing during subsequent Cenozoic peak metamorphic temperatures (Fig. 9a). Static annealing is also documented by white mica overgrowing the penetrative foliation (Fig. 9a). The coexisting mineral assemblage hornblende + clinopyroxene + biotite + epidote + albite that formed during the thermal peak in syenitic gneisses of the VNC documents metamorphic conditions close to 500 °C and 6 kbar (Droop 1982).

Within the Sonnblick Gneiss Dome and the Mallnitz Synform, including the Glockner Nappe these structures are completely obliterated by a NW-SE striking penetrative foliation (s_2) subparallel to the lithotectonic boundaries and a subhorizontal, NW-trending stretching lineation l_2 (Fig. 4c). In some places relics of l_1, crosscut by l_2, can be recognized. s_1 and s_2 form a composite foliation. The basement units of the Sonnblick Dome

Fig. 9. Photomicrographs of representative microfabrics in several Penninic units of the southeastern and northeastern Tauern Window: a – Quartz of annealed mylonite in syenitic basement gneisses, southeastern Tauern Window. Width is 4 mm, crossed polarizing filters. b – Quartz fabric of a mylonite directly beneath the base of the Glockner Nappe, southeastern Tauern Window, with serrate grain boundaries and HT quartz microfabrics. Width is 4 mm, crossed polarizing filters. c – Greenschist of the Glockner Nappe, southeastern Tauern Window, showing synmetamorphically rotated albite blasts with folded internal foliation (consisting of actinolite, epidote and sphene) documenting synmetamorphic deformation during D_2 (top-NW shear). Width is 4 mm, crossed polarizing filters. d – Asymmetric pressure shadow around magnetite documenting top-to-the-W shear; annealed quartz microfabric. Width is 1.5 mm, crossed polarizing filters.

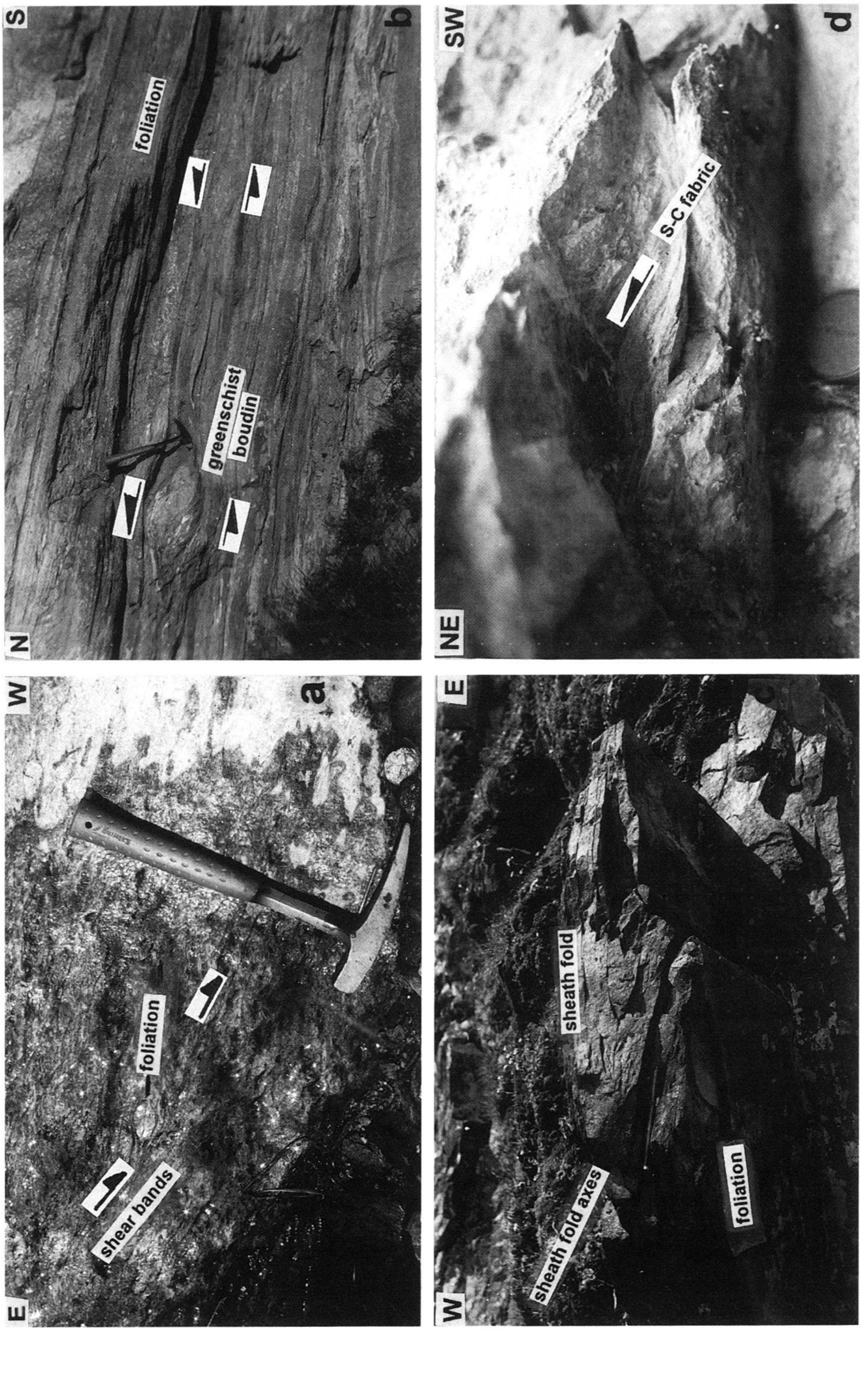

N
foliation
white mica
quartz
triple junction
S
a
ESE
elongated quartz grains
serrate grain boundaries
WNW
b
NW
foliation
albite
folded internal foliation
SE
c
ESE
pressure shadow
chlorite
magnetite
quartz triple junction
WNW
d

have possibly formed a large NW-trending fold structure during D_2 subparallel to the stretching lineation l_2 (Behrmann 1990). This structure is partly thrusted obliquely over the Penninic nappe pile of the Mallnitz Synform and over the Hochalm Gneiss Dome (Fig. 3, 4a). In the deepest structural levels that are affected by D_2 in the Zentralgneis of the Sonnblick Dome, the relictic magmatic layering within the orthogneisses is crosscut by s_2 and l_2. In basement units of the VNC 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 conditions in the units of VNC. Quartz also forms equigranular grains with straight grain boundaries and 120°-triple junctions in the basement-cover nappes of the VNC (Fig. 9a), but the quartz c-axes show a preferred orientation (type I and type II crossed girdles) (Kurz 1993). The characteristic mineral assemblage in the basement slices (gneiss lamellae) is biotite + albite + K-feldspar + quartz + actinolite + epidote + sphene. Plagioclase displays a continuous zonation with small oligoclase rims documenting peak temperatures of slightly more than 500 °C. Quartz microfabrics within the Modereck and the Glockner Nappes are characterized by high temperature structures like elongate grains, lobate and serrated grain boundaries (Fig. 9b), and a strong preferred orientation of a- and c-axes (Kurz 1993). Due to grain boundary migration white mica is overgrown by dynamically recrystallized quartz grains. Top-to-the-NW shearing within the Glockner Nappe occurred during the thermal peak within albite-epidote-amphibolite facies conditions. Synkinematically grown albite shows an internal foliation which is folded during deformation and is defined by epidote, actinolite and sphene (Fig. 9c). The matrix assemblage of greenschists is built up of actinolite, plagioclase, quartz, epidote, sphene and subordinate chlorite and biotite (Fig. 9c).

The nappe pile was refolded and modified during exhumation of the Hochalm Dome and development of the Sonnblick Dome (D_3), resulting in a girdle distribution of poles to foliation planes (Fig. 3, 4b).

In the *northeastern Tauern Window* (Fig. 2, 6a) map-scale cut-off lines (D_0) again document NE- to NNE-directed nappe emplacement within the VNC and basement-cover nappes of the entire MPU (Fig. 6b). D_1 in these units (ENE- to NE-trending stretching lineation, penetrative foliation) (Fig. 6c, d) documents ductile top-to-the-NE shearing (D_1). Within the basement-cover nappes (Schrovin-Modereck Nappe), stretching lineations trend N to NNE (Fig. 6d) with top-to-the-N shear pre-dating peak temperature of Barrovian-type metamorphism. This is indicated by kyanite, chloritoid, hornblende, and white mica that overgrew the penetrative foliation (s_1) and the stretching lineation (l_1).

Fig. 10. Examples of outcrop-scale structures within and directely beneath the Glockner Nappe. a – Extensional crenulation cleavage at the base of the Modereck-Schrovin Nappe overprinting the penetrative foliation (s_1) documenting top-W simple shear (D_2) and reactivation of the base of the nappe; northeastern Tauern Window. b – Asymmetric boudins of greenschist in a matrix of marble mylonite in the hangingwall of the thrust contact between the Glockner and Riffl Nappes, Glockner area. c – Sheath fold in the Seidlwinkl (Modereck) Nappe with N-trending fold axes. d – S-C fabrics indicating top-to-the-NE simple shear movement subparallel to the stretching lineation in meta-ultrabasic rocks of the Glockner Nappe, southern central Tauern Window.


N
S
foliation
greenschist
boudin
b
NE
SW
S-C fabric
d
E
W
shear bands
foliation
a
W
E
sheath fold axes
sheath fold
foliation
c

Microfabrics, especially of quartz, in the VNC and the basement-cover nappe stack of the higher MPU are similar to the fabrics in the southeastern part of the Tauern Window.

In the Glockner Nappe these structures are completely obliterated by a subhorizontal to N-dipping penetrative foliation subparallel to the lithotectonic boundaries and a W- to WNW-trending stretching lineation including the development of sheath folds (D_2) (Fig. 6c, d, e). Only in tectonic slices of Skythian (?) quartzites at the base of the Glockner Nappe some relics of a N-trending stretching lineation are preserved. s_1 and s_2 form a composite foliation. Meso-scale structures like symmetric and asymmetric quartzite boudins in calcareous micaschists and marble mylonites partly display top-to-the-W shear, but coaxial structures dominate. The bases of Penninic basement-cover nappes as well as lithological and competence boundaries were reactivated during D_2. This is documented by W-trending stretching lineations l_2 which are locally crosscutting l_1 and by top-to-the-W shear bands (Fig. 10a).

These structures are clearly distinguished from younger structures related to extension, exhumation and dome formation at the eastern margin of the Tauern Window, documented in brittle to ductile east-down low-angle normal faults and subvertical mineralized extensional veins (D_3) (Genser & Neubauer 1989).

In this area, quartz forms equigranular grains with straight grain boundaries and 120°-triple junctions also in the Glockner Nappe (Fig. 9d), differing from quartz microfabrics from the Glockner Nappe in SE part of the Tauern Window. Asymmetric pressure shadows around magnetite blasts filled with chlorite, quartz, white mica and epidote in greenschists of the Glockner Nappe as well as shear bands and extensional crenulation cleavage document top-to-the-W ductile shearing (Fig. 9d).

In the *Großglockner area* (Fig. 2, 7a) the Glockner Nappe and the Seidlwinkl-Modereck Nappe (Tab. 1) display the most voluminous exposure within the Tauern Window, the VNC is less exposed. Relics of meso-scale duplexes near the base of the Glockner Nappe and at competence boundaries within the Glockner Nappe as well as asymetrically boudinaged rods of greenschists within a ductile matrix of marble mylonites display N-directed thrusting (D_1) (Fig. 10b). Stretching lineations, sheath folds, and isoclinal orthorhombic folds with axes parallel to the stretching lineation (Fig. 7b, c, d; 10c) consistently trend NNW to N over the entire Glockner area. These structures occur within incompetent metasediments like marbles and calcareous micaschists as well as within more competent units like garnet amphibolites. In the sheath fold hinges, especially within pre-Alpine basement rocks, an older foliation affected by D_1 is locally discernible. Pegmatitic dykes of probably late Variscan age crosscut a planar fabric within the basement units of the Riffl Nappe (part of the VNC; Tab. 1), while the first deformation of the dykes is D_1.

Asymmetric meso-scale simple shear structures at the base of the Glockner Nappe document N- to NNW-directed shear (D_1) (Fig. 10b) predating peak temperatures of metamorphism. Decimeter-thick slices of metabasites, meta-ultrabasites and Triassic marbles at the thrust contact between the basement units of the Riffl Nappe and the Glockner Nappe are asymmetrically boudinaged, also documenting top-to-the-N ductile shearing (Fig. 10b). σ-type porphyroclasts of albite and asymmetric pressure shadows filled with annealed quartz further indicate top-to-the-N simple shear (Fig. 11a). Asymmetric pressure shadows around relictic garnets (σ-type porphyroclasts) in garnet amphibolites of the Glockner Nappe again indicate top-to-the-N ductile shearing. Because of the strong retrogressive overprint it is hard to decide whether these rocks were former

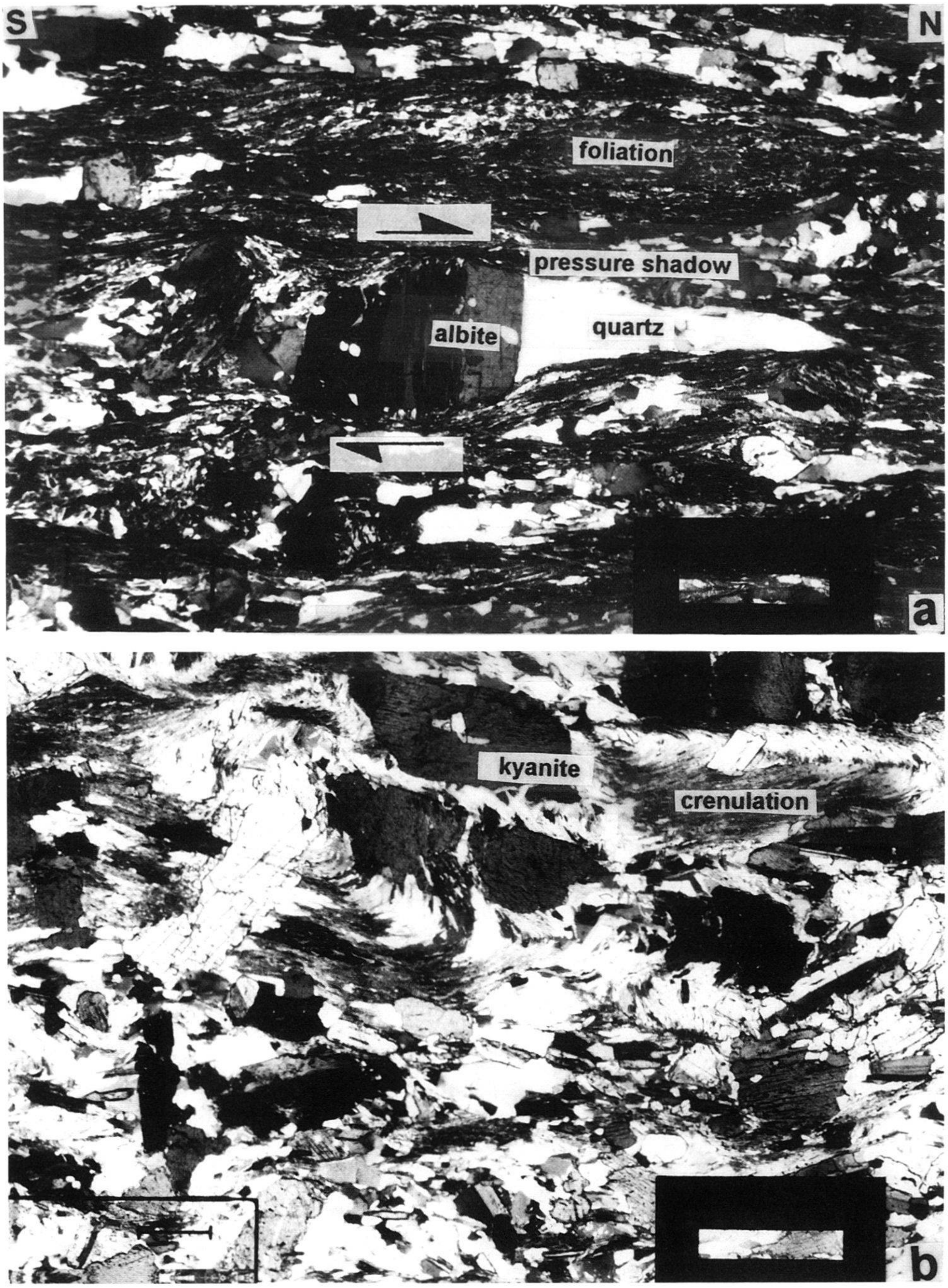


Fig. 11. a – Asymmetric pressure shadows around albite of a micaschist of the Modereck Nappe, central Tauern Window, documenting top-to-the-N simple shear. Quartz displays annealed microfabrics. Width is 4 mm, crossed polarizing filters. b – Crenulation of mica fabrics parallel to stretching lineation overgrown by kyanite, Glockner area. Width is 4 mm, crossed polarizing filters.

eclogites. Only within garnets, if they are preserved, rare inclusions of blue amphiboles (glaucophane) are recognizable. Locally relics of pyroxene (possibly omphacite) are preserved.

The penetrative foliation (s_1) and the correlated stretching lineation as well as sheath fold axes are overgrown by kyanite and chloritoid within Triassic quartzites of the Seidlwinkl-Modereck Nappe, by green and brown hornblende and biotite in greenschists of the Glockner Nappe, and by tourmaline within basement rocks of the Riffl Nappe (Fig. 11b). The long axes of these postkinematic minerals lack a preferred orientation (Fig. 7e). Only in deeper parts of the VNC these fabrics are obliterated by W-vergent ductile shear structures.

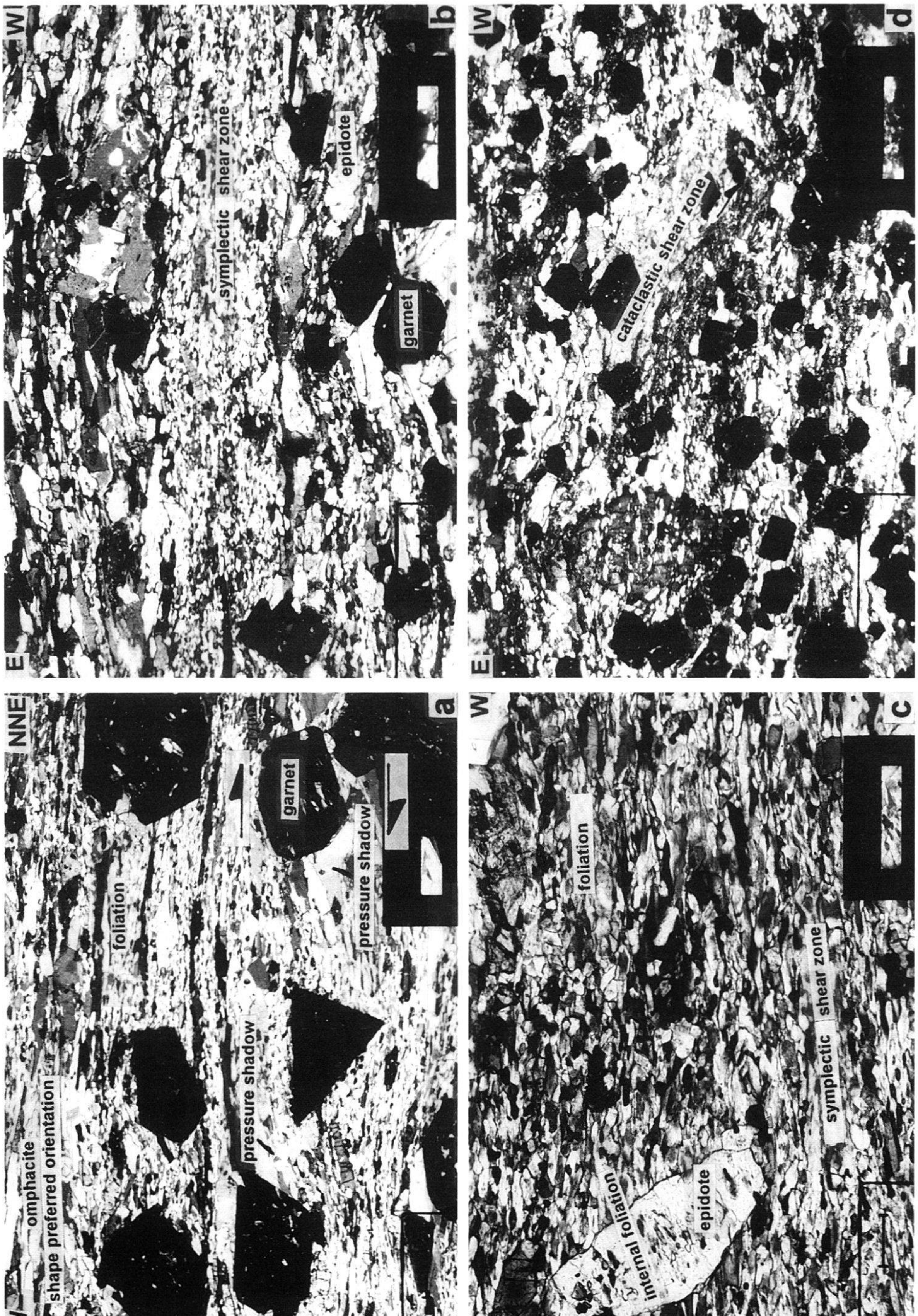
In the VNC and eclogite facies rocks of the *central southern part of the Tauern Window* (Eclogite Zone; Fig. 2, 8a) a penetrative mylonitic foliation (Fig. 8b) and a NE-trending stretching and mineral lineation are developed (D_1) (Fig. 8c). Related asymmetric ductile structures document top-to-the-NE shearing. NE-vergent structures like S-C fabrics are also developed in meta-ultrabasic rocks of the Glockner Nappe (Fig. 8d).

The microfabric of eclogites is characterized by a shape-preferred orientation of omphacite and epidote/zoisite defining the penetrative foliation (Fig. 12a). Oblique alignment of omphacite with respect to the shear plane is missing. Garnets partly show an elongated shape; asymmetric pressure shadows around garnet are mainly filled with recrystallized omphacite, crossitic hornblende, epidote/zoisite and phengite. The asymmetric arrangement of pressure shadows documents top-to-the-NE ductile shearing (Fig. 12a). The same is true for δ-porphyroblasts of garnet which are rather scarce (Fig. 12a). Some garnets are surrounded by a rim of blue amphibole and 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 (Fig. 12b, c). Retrogression of eclogites within the Eclogite Zone is very irregular laterally and vertically.

In strongly retrogressed portions of the Eclogite Zone and in incompetent rocks of the Glockner Nappe a W- to WSW-trending stretching lineation is developed (Fig. 8c). It correlates with W-vergent simple shear structures of the late extensional deformation event during decompression that obliterated the NE-vergent fabrics.

The microfabric of the retrogressed eclogites is characterised by symplectic aggregates of hornblende and plagioclase replacing pyroxenes and a shape-preferred orientation of hornblende and white mica (Fig. 12b, c), but the symplectic aggregates are hardly discernable microscopically. Epidote/zoisite overgrows the penetrative foliation. Phengite is unstable. Pressure shadows around garnet are often arranged symmetrically, within some domains asymmetric pressure shadows document a top-to-the-W simple shear

Fig. 12. a – Photomicrograph of foliated mylonitic eclogite showing shape-preferred orientation of omphacite and partly elongated garnets with asymmetric pressure shadows and δ-shaped garnet prophyroclasts documenting top-to-the-N simple shear. Width is 4 mm, crossed polarizing filters. b – Photomicrograph of fine-grained garnet-free retrogressive symplectic shear zones in eclogites. Width is 4 mm, crossed polarizing filters. c – Epidote overgrowing retrogressive symplectitic shear zones in eclogites. Width is 1.5 mm, crossed polarizing filters. d – Photomicrograph of top-to-the-W cataclastic shear zone in retrogressed eclogites. Width is 4 mm, crossed polarizing filters.


SSW
NNE
omphacite
shape preferred orientation
foliation
pressure shadow
garnet
pressure shadow
a
E
W
symplectic shear zone
epidote
garnet
b
E
W
internal foliation
epidote
foliation
symplectic shear zone
c
E
W
cataclastic shear zone
d

component. The pressure shadows are mainly filled with green hornblende; epidote/zoisite, quartz and chlorite are subordinate. The garnets show inclusions of epidote, amphibole and white mica. The penetrative foliation is again overgrown by a second generation of epidote/zoisite and white mica (Fig. 12b, c).

Shear zones with symplectic fabrics are developed as distinct domains within the eclogite facies rocks (Fig. 12b, c). The mineral assemblages in the shear zones are similar to the assemblages outside (see above) and document decompressional conditions. Garnet is generally missing within the shear zones.

Cataclastic top-to-the-W shear zones are found in places. They crosscut the penetrative foliation (Fig. 12d) and are often associated with extensional cracks subperpendicular to the penetrative foliation. The cracks are mainly filled with amphibole. They affected garnet, pyroxene and epidote. Some cracks are oriented at an angle between 60 to 85° to the foliation, indicating an orientation of σ_1 compatible with a west-directed sense of shear. This is consistent with the asymmetric pressure shadows around garnets and the top-to-the-W cataclastic shear zones described above.

Discussion and implications for Alpine orogeny

The Eastern Alps are the result of at least two collisional events during the Alpine cycle. The kinematics of internal Cretaceous nappe stacking and subsequent extension within the upper plate Austroalpine units are well documented (Ratschbacher 1986, 1987; Krohe 1987; Ratschbacher & Neubauer 1989), and the timing of events is well established by stratigraphic and radiometric age data. In contrast, the kinematics and exact timing of continental collision between the Penninic and the Austroalpine continental blocks remain unclear, or are highly controversial (Frank et al. 1987a; Lammerer 1988).

From the data presented above two distinct deformational phases can be distinguished within the Penninic units of the Tauern Window which, however, do not correlate with the events in the Austroalpine units by their different timing (Genser 1992; Kurz 1993, 1994; Kurz et al. 1995). The kinematic data for these deformational phases are summarized in Fig. 13a. In the southeastern part of the Tauern Window (Fig. 4a) top-N shear (D_1) is only developed in the uppermost sections of the Zentralgneis and at lower levels of the pre-Carboniferous basement and its parautochthonous cover. In the northeastern corner (Fig. 6a) and along the central southern margin (Eclogite zone) of the Tauern Window (Fig. 8a), N- to NE-directed simple shear deformation is preserved within all tectonic units in the footwall of the Glockner Nappe. The structural evolution of these units is similar to the evolution of the eastern part of the Tauern Window (Genser 1992). Only in the central part of the Tauern Window (Fig. 7a) D_1 is preserved penetratively over the entire nappe pile including the Glockner Nappe. This ductile deformational phase (D_1) with its brittle forerunner (D_0) correlates with the subduction and imbrication of the South Penninic ophiolites and the subsequent subduction of the MPU. The subduction results in internal Penninic nappe stacking and the development of the gneiss lamellae that detached from the basement along distinct thrusts (D_0). It includes the formation of basement-cover duplexes in the course of the collision between a northern plate (European or Briançonnais; Frisch 1979a) and a southern (Adriatic) plate (Kruhl 1993) as well as the emplacement of the ophiolitic Glockner Nappe. Continuous ductile top-to-the-N simple shear (D_1) is related to subduction of these units to deeper structural

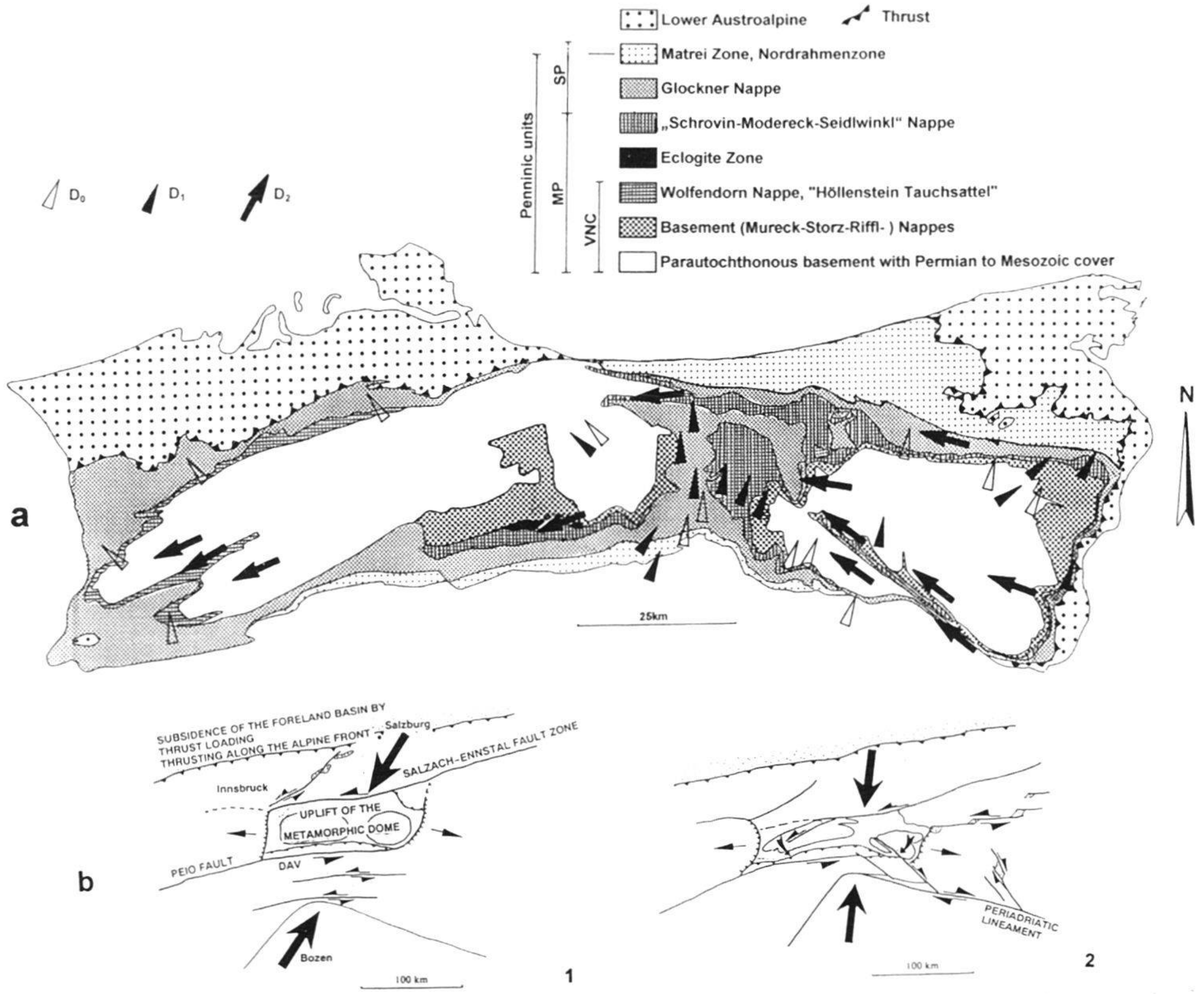


Fig. 13. a – Tectonic map of the Tauern Window with summarised kinematic data (D_0, D_1, D_2) including literature data (Lammerer 1988; Oehlke et al. 1993, Schön & Lammerer 1993; Behrmann & Frisch 1987; Genser 1992; Behrmann 1990; Behrmann & Ratschbacher 1989; Behrmann & Wallis 1987; Ledoux 1984; Kurz 1993); VNC: Venediger Nappe Complex, MP: Middle Penninic paleogeographic origin, SP: South Penninic paleogeographic origin. b – Sketch documenting the development of the kinked shape of the Tauern Window in the Neogene.

levels until they are ductilely deformed in their entity. The emplacement of the Eclogite Zone and the Glockner Nappe occurred during this phase of deformation. The whole nappe pile is subsequently affected by blueschist facies metamorphism. The formation of eclogite facies mylonites and a N- to NE-trending stretching lineation within the eclogites, therefore, predates the emplacement of eclogite facies rocks. The similar geometry of deformational structures suggests the same kinematic framework during mylonitization of the eclogites and subsequent emplacement. The lack of eclogite facies metamorphism in the footwall units (VNC), no clear evidence of eclogite facies rocks in the hangingwall units (Modereck and Glockner Nappes) of the Eclogite Zone and the fact that blueschist facies metamorphism affected the whole nappe pile are the most important arguments for tectonic emplacement of the eclogite unit after eclogite facies metamorphism. Therefore, the eclogite facies foliation predates the eclogite emplacement.

The fact that top-to-the-N to -NE plate convergence is followed by E-W extension at the central southern margin of the Tauern Window (including the Eclogite Zone) is used by Behrmann & Ratschbacher (1989) to establish the model of an overthickened accretionary complex which collapsed, leading to the exhumation of the HP metamorphic assemblages. This model implies pressures of at least 20 kbar in the eclogites and surrounding metasediments (Holland 1979; Dachs 1986, 1990; Miller 1986) in an accretionary wedge of at least 70 km thickness. In this model the pressure peak was followed by rapid heating during decompression shortly after the collapse. The fact that eclogite facies metamorphism is overprinted by blueschist facies (HP/LT) metamorphism rather argues for a mechanism of eclogite exhumation while heating was considerably delayed along a cooler P-T-path. Blueschist facies metamorphism further affects the footwall and hangingwall units of the Eclogite Zone (e.g. Selverstone 1993). Such a cool exhumation-path is only known from subduction zones and accretionary wedges. One possibility for eclogite emplacement is offered by the corner flow model developed by Cloos (1982). England & Holland (1979) argued for buoyant uprise of eclogites incorporated in low density matrix rocks of the accretionary wedge, but yet no clear evidence of eclogite emplacement exists. Eclogite emplacement onto the VNC must have occurred during the transition from eclogite facies to blueschist facies metamorphism.

Top-to-the-N nappe stacking and ductile simple shear deformation occurred before peak thermal conditions were reached in the Penninic units. The thermal peak is geochronologically dated at ca. 30 Ma (Cliff et al. 1985; Reddy et al. 1993; Inger & Cliff 1994; Christensen et al. 1994; etc.). The exact timing of internal nappe stacking and top-N-shear remains unclear as does the time-space relations between eclogite facies metamorphism in the Tauern Window, and the Cretaceous Barrovian-type metamorphism in the Austroalpine. The main problem is the stratigraphic correlation of Penninic metasedimentary units. The stratigraphy of the protoliths developed especially by Exner (1957, 1964, 1971, 1980, 1982, 1983, 1989, 1990), Frasl (1958), Frisch (1974, 1975a, b, 1977), Tollmann (1977) or Lammerer (1986) reaches up to the lower/middle Cretaceous and to the upper Cretaceous and Paleogene (Lammerer 1988). This resulted in the assumption that Penninic nappe stacking, emplacement of the Glockner Nappe and continent collision occurred during the Cretaceous. However, time constraints are unsufficient for these tectonic events. $^{40}Ar/^{39}Ar$ phengite ages of 36-32 Ma from the Eclogite Zone (Zimmermann et al. 1994) are interpreted to represent cooling ages after the blueschist facies metamorphism in the Penninic. Therefore, at least one HP-event subsequent to subduction of the Southpenninic oceanic domain (Glockner Nappe), the MPU and emplacement of the Eclogite Zone occurred in the Tertiary. Emplacement of the Austroalpine unit on top of the Penninic units of the Tauern Window may well have occurred after internal Penninic stacking. At the eastern margin of the Tauern Window the last penetrative deformation in the Austroalpine nappe complex, which is related to internal nappe stacking and top-to-the-W ductile shearing, is synmetamorphic and, therefore, of Cretaceous age (between 105 and 65 Ma within Lower Austroalpine units; Genser 1992). P-T modelling (Genser et al. 1994, in press) indicates that subduction of South Penninic oceanic lithosphere started at about 80 Ma and ceased at 70 Ma, followed by subduction of the MPU which ceased at about 60 to 50 Ma. Following Froitzheim et al. (1994), Cretaceous orogeny in the Austroalpine unit did not result from the subduction of the South Penninic oceanic lithosphere, but rather from a collision event to the east or southeast of the Austroalpine realm. During the Tertiary the Austroalpine unit was emplaced as a rigid block to the N to NNE on top of the lower Penninic nappe pile. In any case, progressive N- to NE-directed shearing is related to internal nappe stacking within the VNC, to the emplacement of the Eclogite Zone, the Rote Wand-Modereck Nappe and the Glockner Nappe, and finally continent collision with the development of the Penninic-Austroalpine suture including the metamorphic flysch series of the Matrei Zone.

Tertiary W- to NW-directed shear (D_2) in the Penninic occurred at peak thermal conditions at ca. 27 to 30 Ma (Reddy et al. 1993; Inger and Cliff 1994) in the eastern part of the Tauern Window; in the western window D_2 startet at about 35 Ma, already during decompression (Christensen et al. 1994; Selverstone, pers. comm.). The main deformational zone is continuously transferred to deeper structural levels. In the southeastern Tauern Window, for example, this is evidenced by the synmetamorphic D_2 deformation, which is the first penetrative deformation event in the lower structural levels of the Zentralgneis and by the slightly younger white mica formation ages in deeper structural levels. The structurally higher Penninic units are shortened subvertically. D_1 Penninic thrusts were probably reactivated as top-to-the-W shear zones (D_2), which was observed also by Amann (pers. comm.) in the northeastern part of the Tauern Window. Bearing in mind the Cretaceous age of top-to-the-W ductile shearing in the Austroalpine realm (Ratschbacher 1986; Genser 1992) and the Tertiary (Oligocene) age of top-to-the-W shear in the Penninic zone, the correlation of these deformational phases just on the base of the similar deformation geometry, as assumed by Wallis et al. (1993), Behrmann & Ratschbacher (1989) and Behrmann (1990) failed. These phases are separated by at least a considerable time interval of post-metamorphic cooling and formation of the extensional Gosau basins (e.g., Neubauer et al. 1995a, b) in the Austroalpine unit (see above).

But it still remains an unsolved problem that D_1 is completely obliterated in some portions of the Tauern Window, especially the southeastern part, during top-to-the-W ductile shearing (D_2) (Fig. 4a), whereas in other areas, like the central part (Fig. 7a), D_0 and D_1 structures are completely preserved, even within the highly incompetent metasediments of the Glockner Nappe.

Top-to-the-W shear deformation (D_2) happened after the subduction of the South Penninic domain and after the accretion of the MPU had ceased. A new subduction zone developed to the north. Therefore, D_2 may result from subduction of North Penninic units (Flysch zone) below the Penninic basement of the VNC. North Penninic subduction might be related to release of fluids from North Penninic flysch sediments and fluid channelling within the overriding MPU and South Penninic units (Selverstone et al. 1991). This is correlated with underplating of the MPU, extension, crustal thinning and decompression in the Penninic nappe pile. It might further correlate with dextral transpressive movement along the Periadriatic Lineament (Lammerer 1988) during the Oligocene (Polinski & Eisbacher 1992; Schmid et al. 1989; Sprenger & Heinisch 1992).

Further the shape of the Tauern Window was highly modified during exhumation and doming (D_3) after the penetrative deformation events ($D_{1,2}$). The Tauern Window is characterized by a kinked shape (Fig. 2, 13a) that might be the result of an Alpine indenter in the central part of the window. Indentation in the late Oligocene (slightly after peak thermal metamorphism) caused clockwise rotation of the eastern part of the Tauern

Window and counterclockwise rotation of the western part (Kurz 1993; Kurz et al. 1994). The rotation is proven by overprinting relationships of crosscutting NE-trending and younger NNE-trending subvertical mineralized extensional veins in the eastern part of the Tauern Window. It resulted in the rotation of several previous structures and kinematic indicators and in the divergence of D_0, D_1 and D_2 kinematic data over the entire Tauern Window (Fig. 13a, b). D_0 and D_1 tectonic transport was directed towards the NE to NNE in the eastern part of the window, towards the N in the central part, and towards NW to NNW in the western part. D_2 structures are trending NW to WNW in the eastern part and WSW in the western part (Fig. 13a). This and the fact that D_0 and D_1 are followed by a stage of Barrovian-type metamorphism makes it possible to distinguish several kinematic phases and to correlate these phases over the entire area of the Tauern Window. Many interpretations of internal Penninic nappe stacking correlated NW-trending D_0 simple shear structures from the western Tauern Window with NW-trending D_2 structures from the eastern part and even with W-trending (Cretaceous!) structures from Austroalpine units.

Conclusions

In the Penninic realm of the Tauern Window two stages of deformation are separated:

(1) Top-to-the-N to NNE-shear is possibly contemporaneous to, or postdates high pressure metamorphism and predates the thermal peak of regional metamorphism; a mylonitic foliation in the Eclogite Zone is synmetamorphic with respect to the high pressure event or slightly postdates the pressure peak. Eclogite facies metamorphism is restricted to the Eclogite Zone, but the Penninic nappe pile is affected by subsequent blueschist facies metamorphism. The eclogite facies mylonitic foliation in the Eclogite Zone formed prior to the emplacement of the eclogites between the VNC and Rote-Wand-Modereck Nappe and the Glockner Nappe. The ophiolitic Glockner Nappe represents the main suture zone between the MPU and the Austroalpine block. Top-to-the-N shear is related to subduction of the South Penninic oceanic lithosphere, followed by internal Penninic nappe stacking during subsequent subduction of Middle Penninic basement units. It also worked during emplacement of the Eclogite Zone onto the VNC.

(2) Later top-to-the-W shear is related to crustal thinning and further decompression of the Penninic lower plate including the Glockner Nappe. It developed at or slightly prior to the thermal peak of regional metamorphism (ca. 30 Ma). Thrusts are partly reactivated during extension, especially in the northeastern part of the window. The main deformation zone is transferred to deeper structural levels within the (Middle) Penninic basement units and the VNC, respectively. This phase might have been triggered by the subduction of North Penninic units beneath the Middle Penninic basement after the accretion of the MPU had ceased and a new subduction zone developed to the N. In the basement units of the central and eastern part of the Tauern Window deformation during top-W shear became penetrative, while higher parts show only locally penetrative deformation during this event.

(3) The kinematic evolution that is preserved in the Tauern Window is independent from the evolution in the Austroalpine block that has only been passively transported onto the Penninic units during the Cenozoic deformation sequence.

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REFERENCES

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

BEHRMANN, J.H. & FRISCH, W. 1990: Sinistral ductile shearing associated with metamorphic decompression in the Tauern Window, Eastern Alps. Jb. Geol. Bundesanst. 133, 135–146.

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

BEHRMANN, J.H. & WALLIS, S.R. 1987: Hangendverschuppung des Tauernfenster-Südrandes bei Kals (Osttirol) als Zeuge von eo-alpinem Underplating. Jb. Geol. Bundesanst. 130/2, 133–138.

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

BICKLE, M.J. & PEARCE, J.A. 1975: Oceanic Mafic Rocks in the Eastern Alps. Contrib. Mineral. Petrol. 49, 177–189.

BOYER, S.E. & ELLIOT, D. 1982: Thrust Systems. Mem. Amer. Assoc. Petroleum Geol. 66, 1196–1230.

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.

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.

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

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

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

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.

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

DACHS, E., FRASL, G. & HOINKES, G. 1991: Mineralogisch-Petrologische Exkursion ins Penninikum des Tauernfensters und in das Ötztalkristallin. Beihefte zum European J. Mineralogy 3, 79–110.

DALLMEYER, D., NEUBAUER, F., HANDLER, R., MÜLLER, W., FRITZ, H., ANTONITSCH, W. & HERMANN, S. 1992: $^{40}Ar/^{39}Ar$ and Rb-Sr mineral age control on pre-Alpine and Alpine tectonic evolution of the Austro-Alpine Nappe Complex, Eastern Alps. ALCAPA Field Guide IGP-KFU Graz 1992, 47–59.

DALLMEYER, R.D., NEUBAUER, F., FRITZ, H., HANDLER, R., MÜLLER, W., PANA, D. & PUTIS, M. 1995: Tectonothermal evolution of internal Alps and Carpathians: evidence from $^{40}Ar/^{39}Ar$ mineral data. Abstract volume Second Workshop on Alpine Geology Basel 1995, 26–27.

DROOP, G.T.R. 1982: A Clinopyroxene Paragenesis of Albit-Epidote-Amphibolite-Facies in Meta-Syenites from the South-East Tauern Window, Austria. J. Petrology 23/3, 163–185.

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

ENGLAND, P.C. & HOLLAND, T.J.B. 1979: Archimedes in the Tauern Eclogites: the role of bouyancy in the preservation of exotic eclogite blocks. Earth Planet. Sci. Lett. 44, 287–294.

EXNER, CH. 1957: Erläuterungen zur geologischen Karte der Umgebung von Gastein 1 : 50 000 (Ausgabe 1956); incl. geologische Karte 1 : 50 000. Geol. Bundesanst., Wien.
- 1962: Sonnblicklamelle und Mölltallinie. Jb. Geol. Bundesanst. 105, 273–286.
- 1964: Erläuterungen zur Geologischen Karte der Sonnblickgruppe 1 : 50 000; incl. geologische Karte 1 : 50 000. Jb. Geol. Bundesanst., Wien.
- 1971: Geologie der peripheren Hafnergruppe (Hohe Tauern). Jb. Geol. Bundesanst. 114, 1–119.
- 1980: Geologie der Hohen Tauern bei Gmünd in Kärnten. Jb. Geol. Bundesanst. 123, 343–410.
- 1982: Geologie der zentralen Hafnergruppe (Hohe Tauern). Jb. Geol. Bundesanst. 125, 51–154.
- 1983: Erläuterungen zur geologischen Karte der Hafnergruppe (Blatt Muhr, Ö.K. 156 – Südteil, 1 : 25 000); incl. geologische Karte 1 : 25 000. Mitt. Ges. Geol. Bergbaustud. Österr. 29, 41–74.
- 1989: Geologie des mittleren Lungaus. Jb. Geol. Bundesanst. 132, 7–103.
- 1990: Erläuterungen zur Geologischen Karte des mittleren Lungaus. Mitt. Ges. Geol. Bergbaustud. Österr. 36, 1–38.

FRANK, W. 1969: Geologie der Glocknergruppe. Wissensch. Alpenvereinsh. 21, 95–111.
- 1987: Evolution of the Austroalpine elements in the Cretaceous. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.). Deuticke/Vienna, 379–406.

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

FRANK, W., MILLER, CH. & PESTAL, G. (EDS.) 1987b: Geologische Karte der Republik Österreich 1 : 50 000, Blatt 152 (Matrei). Geol. Bundesanst.

FRANK, W., HÖCK, V. & PESTAL, G. (EDS.) 1994: Geologische Karte der Republik Österreich 1:50 000, Blatt 153 (Großglockner). Geol. Bundesanst.

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

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

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.
- 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.
- 1975b: Hochstegen-Fazies und Grestener-Fazies – ein Vergleich des Jura. N. Jb. Geol. Paläont. Mh. 1975/2, 82–90.
- 1976: Ein Modell zur Alpidischen Evolution und Orogenese des Tauernfensters. Geol. Rdsch. 65, 375–393.
- 1977: Der alpidische Internbau der Venedigerdecke im westlichen Tauernfenster (Ostalpen). N. Jb. Geol. Paläont. Mh. 1977, 675–696.
- 1979a: Tectonic progradation and plate tectonic evolution of the Alps. Tectonophysics 60, 121–139.
- 1979b: Tectonics of the Western Tauern Window. Mitt. Österr. Geol. Ges. 71/72, 65–71.

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: Geodynamics of the Eastern Alps (Ed. by FLÜGEL, H.W. & FAUPL, P.). DEUTICKE/VIENNA, 55–69.

FROITZHEIM, N., SCHMID, S.M. & CONTI, P. 1994: Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. Eclogae geol. Helv. 87, 559–615.

GENSER, J. 1992: Struktur-, Gefüge- und Metamorphoseentwicklung einer kollisionalen Plattengrenze: Das Beispiel des Tauernostrandes (Kärnten, Österreich). Unpublished PhD Thesis, Faculty of Sciences, University of Graz.

GENSER, J. & NEUBAUER, F. 1989: Low angle normal faults at the eastern margin of the Tauern Window (Eastern Alps). Mitt. Österr. geol. Ges. 81, 233–243.

GENSER, J., VAN WEES, J.D. & CLOETHING, S. 1994: Das jungalpidische Ereignis in den Ostalpen – Ausgangsmöglichkeiten einer thermischen Modellierung. Göttinger Arb. Geol. Paläont. Sb. 1, 149–151.

GENSER, J., VAN WEES, J.D., CLOETHING, S. & NEUBAUER, F. in press: Eastern Alpine tectonothermal evolution: constraints from two-dimensional P-T-t modelling. Tectonics.

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.

HANDLER, R., DALLMEYER, R.D. & NEUBAUER, F. 1994: Diachronous Alpine Thrusting Within Upper Levels of the Austro-Alpine Nappe Complex, Eastern Alps. Romanian Journal of Tectonics and Regional Geology, Alcapa II Abstract Volume (Voinesti-Covasna, Romania, October 21–22, 1994) 75, 22–23.

– 1995: Timing of Alpine ductile deformation in the Austro-Alpine Nappe Complex, Eastern Alps: Evidence from $^{40}Ar/^{39}Ar$ and Rb/Sr mineralogical data. Abstract volume Second Workshop on Alpine Geology, Basel 1995, 109–111.

HAWKESWORTH, C.J. 1976: Rb/Sr geochronology in the Eastern Alps. Contr. Mineral. Petrol. 54, 225–244.

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.

HOLLAND, T.J.B. & NORRIS, R.J. 1979: Deformed pillow lavas from the central Hohe Tauern, Austria, and their bearing on the origin of epidote-banded greenstones. Earth Planet. Sci. Lett. 43, 397–405.

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.

HÖCK, V. & MILLER, CH. 1980: Chemistry of mesozoic metabasites in the middle and eastern part of the Hohe Tauern. Mitt. Österr. Geol. Ges. 71/72 (1978/1979), 81–88.

– 1987: Mesozoic ophiolitic sequences and non-ophiolitic metabasites in the Hohe Tauern. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.). Deuticke/Vienna, 16–33.

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.

KROHE, A. 1987: Kinematics of Cretaceous nappe tectonics in the Austroalpine basement of the Koralpe region (eastern Austria). Tectonophysics 136, 171–196.

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.

KURZ, W. 1993: Strukturentwicklung längs der Mölltallinie (südöstliches Tauernfenster). Unpublished Ms Thesis, Faculty of Sciences/University of Graz.

– 1994: Struktur und Kinematik im Bereich des Sonnblickkernes und der Mallnitzer Mulde (südöstliches Tauernfenster, Österreich). Göttinger Arb. Geol. Paläont. Sb. 1, 144–145.

KURZ, W., NEUBAUER, F., GENSER, H. & HORNER, H. 1994: Sequence of Tertiary brittle deformations in the eastern Tauern Window (Eastern Alps). Mitt. Österr. Geol. Ges. 86 (1993), 153–164.

KURZ, W., NEUBAUER, F. & GENSER, J. 1995: Kinematics of the Penninic Glockner Nappe (Tauern Window, Eastern Alps, Austria) during continent collision and exhumation. 2nd Workshop on Alpine Geology Basel 1995, 118–120.

LAMBERT, R.ST.J. 1970: A Potassium-Argon Study of the Margin of the Tauernfenster at Döllach, Austria. Eclogae geol. Helv. 63, 197–205.

LAMMERER, B. 1986: Das Autochthon im westlichen Tauernfenster. Jb. Geol. Bundesanst. 128, 51–67.

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

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

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

– 1986: Alpine high-pressure metamorphism in the Eastern Alps. Schweiz. mineral. petrogr. Mitt. 66, 139–144.

NEUBAUER, F. 1991: Kinematic indicators in the Koralm and Saualm eclogites (Eastern Alps). Zbl. Geol. Paläont. Teil I H. 1, 139–155.

– 1994: Kontinentkollision in den Ostalpen. Geowissenschaften 12, 136–140.

NEUBAUER, F. & GENSER, J. 1990: Architektur und Kinematik der östlichen Zentralalpen – eine Übersicht. Mitt. naturwiss. Ver. Steiermark 120, 203–219.

NEUBAUER, F., GENSER, J., FRITZ, H. & WALLBRECHER, E. 1993: Alpine Kinematics of the Eastern Central Alps. Field Guide Structures and Tectonics at Different Lithospheric Levels Graz 1993, 17–26.

NEUBAUER, F., DALLMEYER, R.D. & FRITZ, H. 1995a: Who was Tethys? – Two rifts and two continent-continent collisions explain the Alpine-Carpathian evolution. Abstract volume Second Workshop on Alpine Geology Basel 1995, 50–51.

NEUBAUER, F., DALLMEYER, D., DUNKL, I. & SCHIRNIK, D. 1995b: Late Cretaceous exhumation of the metamorphic Gleinalm Dome, Eastern Alps: Kinematics, cooling history, and sedimentary response in a sinistral wrench corridor. Tectonophysics 242, 79–98.

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

OXBURGH, E.R., LAMBERT, R.ST.J., BAADSGAARD, H. & SIMONS, J.G. 1966: Potassium-Argon age studies across the southeast margin of the Tauern Window, the Eastern Alps. Verh. Geol. Bundesanst. 1966, 17–33.

PEACOCK, S.M. 1993: The importance of blueschist – eclogite dehydration reactions in subducting oceanic crust. Geol. Soc. Amer. Bull. 105, 684–694.

PFIFFNER, A. 1992: Alpine orogeny. A continent revealed. In: The European Geotraverse. (Ed. by BLUNDELL, D., FREEMAN, S. & MUELLER, ST.). Cambridge University Press/Cambridge, 180–190.

POLINSKI, R.K. & EISBACHER, H. 1992: Deformation patitioning during polyphase oblique convergence in the Karawanken Mountains, southeastern Alps. J. Struct. Geol. 14, 1203–1213.

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

RATSCHBACHER, L. 1986: Kinematics of Austroalpine cover nappes: changing translation due to transpression. Tectonophysics 125, 335–356.

– 1987: Strain, rotation, and translation of Austroalpine nappes. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.). Deuticke/Vienna, 237–243.

RATSCHBACHER, L. & NEUBAUER, F. 1989: West-directed decollement of Austro-Alpine cover nappes in the eastern Alps: geometrical and rheological considerations. In: Alpine Tectonics. (Ed. by COWARD, M.P., DIETRICH, D., PARK, R.G.). Geological Society Special Publication 45, 243–262.

RATSCHBACHER, L., FRISCH, W., NEUBAUER, F., SCHMID, S.M. & NEUGEBAUER, J. 1989: Extension in compressional orogenic belts: The eastern Alps. Geology 17, 404–407.

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.

RING, U., RATSCHBACHER, L., FRISCH, W., BIEHLER, D. & KRALIK, M. 1989: Kinematics of the Alpine plate-margin: structural styles, strain and motion along the Penninic-Austroalpine boundary in the Swiss-Austrian Alps. J. Geol. Soc. London 146, 835–849.

SCHMID, S.M., AEBLI, H.R., HELLER, F. & ZINGG, A. 1989: The role of the Periadriatic Line in the tectonic evolution of the Alps. Alpine Tectonics. (Ed. by COWARD, M.P., DIETRICH, D. & PARK, R.G.). Geol. Soc. Spec. Publ. 45, 153–171.

SCHÖN, CH. & LAMMERER, B. 1993: Strainanalyse an grobklastischen Metasedimenten des westlichen Tauernfensters. Abh. Geol. Bundesanst. 49, 97–106.

SELVERSTONE, J. 1985: Petrologic constraints on imbrication, metamorphism, and uplift in the SW Tauern Window, Eastern Alps. Tectonics 4, 687–704.

– 1988: Evidence for east-west crustal extension in the Eastern Alps: implications for the unroofing history of the Tauern Window. Tectonics 7, 87–105.

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

SELVERSTONE, J. & SPEAR, F.S. 1985: Metamorphic PT-Paths from pelitic schists and greenstones from the south-west Tauern Window, Eastern Alps. J. metamorphic Geol. 3, 439–465.

SELVERSTONE, J., FRANZ, G., THOMAS, S. & GETTY, S. 1992: Fluid variability in 2 GPA eclogites as an indicator of fluid behaviour during subduction. Contrib. Mineral. Petrol. 112, 341–357.

SELVERSTONE, J., MORTEANI, G. & STAUDE, J.M. 1991: Fluid channeling during ductile shearing: transformation of granodiorite into aluminous schist in the Tauern Window, Eastern Alps. J. metamorphic Geol. 9, 419–431.

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.

SPRENGER, W. & HEINISCH, H. 1992: Late Oligocene to Recent brittle transpressive deformation along the Periadriatic Lineament in the Lesach Valley (Eastern Alps): remote sensing and paleostress analyses. Annales Tectonicae VI, 134–149.

THIELE, O. 1970: Zur Stratigraphie und Tektonik der Schieferhülle der westlichen Hohen Tauern (Zwischenbericht und Diskussion über Arbeiten auf Blatt Lanersbach, Tirol). Verh. Geol. Bundesanst. 1970/2, 230–244.

– 1974: Tektonische Gliederung der Tauernschieferhülle zwischen Krimml und Mayrhofen. Jb. Geol. Bundesanst. 117, 55–74.

– 1976: Der Nordrand des Tauernfensters zwischen Mayrhofen und Inner Schmirn (Tirol). Geol. Rdsch. 65, 410–421.

THÖNI, M. & JAGOUTZ, E. 1992: Some new aspects of dating eclogites in orogenic belts: Sm-Nd, Rb-Sr and Pb-Pb isotopic results from the Austroalpine Saualpe and Koralpe type-locality (Carinthia/Styria, SE Austria). Geochim. Cosmochim. Acta 56, 347–368.

– 1993: Isotopic constraints for eo-Alpine high-P metamorphism in the Austroalpine nappes of the Eastern alps: bearing on Alpine orogenesis. Schweiz. mineral. petrogr. Mitt. 73, 177–189.

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.

– 1977: Die Geologie von Österreich (Band I): Die Zentralalpen. Deuticke/Vienna.

– 1980: Das östliche Tauernfenster. Mitt. Österr. Geol. Ges. 71/72, 73–79.

– 1987: The Alpidic evolution of the Eastern Alps. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.). Deuticke/Vienna, 361–378.

VON BLANCKENBURG, F. & VILLA, I.M. 1988: Argon retentivity and argon excess in amphiboles from the garbenschists of the Western Tauern Window, Eastern Alps. Contrib. Mineral. Petrol. 100, 1–11.

VON BLANCKENBURG, F., VILLA, I.M., BAUR, H., MORTEANI, G. & STEIGER, R.H. 1989: Time Calibration of a PT-path from the Western Tauern Window, Eastern Alps: the problem of closure temperatures. Contrib. Mineral. Petrol. 101, 1–11.

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.

ZIMMERMANN, R., HAMMERSCHMIDT, K. & FRANZ, G. 1994: Eocene high pressure metamorphism in the Penninic units of the Tauern Window (Eastern Alps). Evidence from $^{40}Ar/^{39}Ar$ dating and petrological investigations. Contrib. Mineral. Petrol. 117, 175–186.

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