Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 93 (2000)

Heft: 1

Artikel: On the edge of the extruding wedge : Neogene kinematics and geomorphology along the southern Niedere Tauern, Eastern Alps

Autor: Eder, Nikola / Neubauer, Franz

DOI: https://doi.org/10.5169/seals-168809

0012-9402/00/010081-12 $1.50 + 0.20/0
Birkhäuser Verlag, Basel, 2000

Eclogae geol. Helv. 93 (2000) 81–92

On the edge of the extruding wedge: Neogene kinematics and geomorphology along the southern Niedere Tauern, Eastern Alps

NIKOLA EDER & FRANZ NEUBAUER

Key words: fault kinematics, extrusion tectonics, relief, topography, peneplain, extensional allochthon

ABSTRACT

The Neogene structural and geomorphological evolution along the northwestern edge of an eastward extruding wedge within central Eastern Alps has been studied. There, the Karpatian Tamsweg basin formed at the releasing overstep between an ESE-directed normal fault exposing Lower Austroalpine units in the footwall, and an E-trending sinistral oblique-slip Prebersee fault. This fault separates deeper Middle Austroalpine units exposed in the Niedere Tauern from structurally higher Middle Austroalpine and Upper Austroalpine units (Gurktal nappe complex) adjacent to the south. Fault patterns along the Oberwölz-Tamsweg wrench corridor reflect complicate kinematics, from initial strike-slip displacement, subsequent N-S extension to late-stage, post-Karpatian faults and basin inversion due to transpression according to overall contraction within the Eastern Alps. The geomorphological evolution, including the Cenozoic formation of peneplain surfaces preserved within the extensional wedge, reflects the Neogene extrusion and surface subsidence of the extrusional wedge. This strongly contrasts with uplift of the Niedere Tauern footwall block that is characterized by a steep, immature relief.

ZUSAMMENFASSUNG

Die neogene strukturelle und geomorphologische Entwicklung längs des Nordwestrandes des ostwärts gerichteten Extrusionskeiles östlich des Tauernfensters innerhalb der zentralen Ostalpen wurde untersucht. Hier wurde das karpatische Tamswegbecken an einem distensiven Übertritt zwischen einer ESE-gerichteten Abschiebung, welche unterostalpine Einheiten im Liegenden aufschließt, und der E-W verlaufenden, sinistralen Preberseestörung gebildet. Die Preberseestörung trennt tiefere strukturelle Einheiten des Mittelostalpins der Niederen Tauern von höheren mittelostalpinen und auflagernden oberostalpinen Einheiten (Gurktaler Deckenkomplex). Die Störungskinematik entlang des östlich anschließenden Tamsweg-Oberwölz-Seitenverschiebungskorridors zeigt eine komplexe Kinematik von frühen Seitenverschiebungen über N-S-Dehnung zu späten, postkarpatischen Störungen und Beckeninversion gemäß genereller Kompression in den Ostalpen. Die geomorphologische Entwicklung einschließlich der känozoischen Bildung von Verebnungsflächen, die auf dem Extrusionskeil erhalten sind, spiegelt ebenfalls die neogene Extrusion und relative Oberflächenabsenkung des Extrusionskeiles wider. Dies kontrastiert mit der stärkeren Heraushebung des Niedere Tauern-Blockes, der durch ein steiles, unreifes Relief gekennzeichnet ist.

Introduction

The eastward extrusion of tectonic wedges plays an important role in the explanation of Late Cretaceous and Neogene kinematics of the Eastern Alps. Tectonic models of Balla (1985), Kázmér & Kovac (1985), Neubauer (1988) and Ratschbacher et al. (1989) proposed that the interior of the Carpathian orocline might have been filled by crustal blocks escaping from the Eastern Alps. The physical expression of escape is found in several sinistral wrench corridors in northern and central sectors of the Eastern Alps, which confine, together with the dextral Periadriatic fault, the extrusional wedge (Neubauer 1988; Ratschbacher et al. 1989, 1991). The northern sinistral wrench corridors were active during Late Cretaceous, Oligocene and Neogene times (Ratschbacher et al. 1989; 1991; Neubauer 1994; Neubauer et al. 1995, 2000; Linzer et al. 1997; Peresson & Decker 1997a, b; Wang & Neubauer, 1998). Previous studies (e.g. Wang & Neubauer 1998) also indicate that the northern, sinistral margin of the extruding wedge shifted in time from north (Salzach-Enns fault) to south-central (Mur-Mürz wrench corridor) sectors of the wrench corridor during Oligocene to Neogene extrusion (Fig. 1). During that time, tectonics were closely linked to surface movements, facilitating formation of a central high in the region of the future Tauern window, subsidence in eastern sectors of the extrusional wedge, and formation of various Neogene, extensional, pull-apart and flexural, basins (e.g. Neubauer 1988; Ratschbacher et al. 1991; Sachsenhofer et al. 1997; Nemes et al. 1997; Frisch et al. 1998; Neubauer et al. 2000). These basins are interpreted to reflect distinct stages of evolution within and along margins of the extrusional wedge. Pull-apart basins formed along northern wrench corridors and extensional basins within the extruding wedge during Early to Middle Miocene, the flexural Klagenfurt basin during the Late Miocene and Pliocene stages (Fig. 1;

Institut für Geologie und Paläontologie, Universität Salzburg, Hellbrunnerstr 34, 5020 Salzburg, Austria

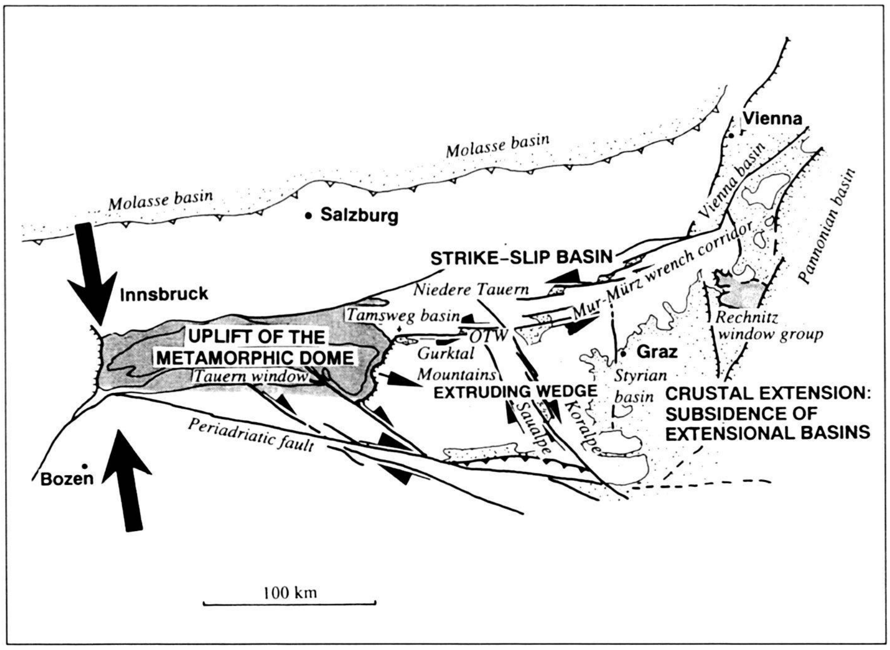

Fig. 1. Tectonic map of the Eastern Alps displaying major Neogene structures. OTW – Oberwölz-Tamsweg wrench corridor.

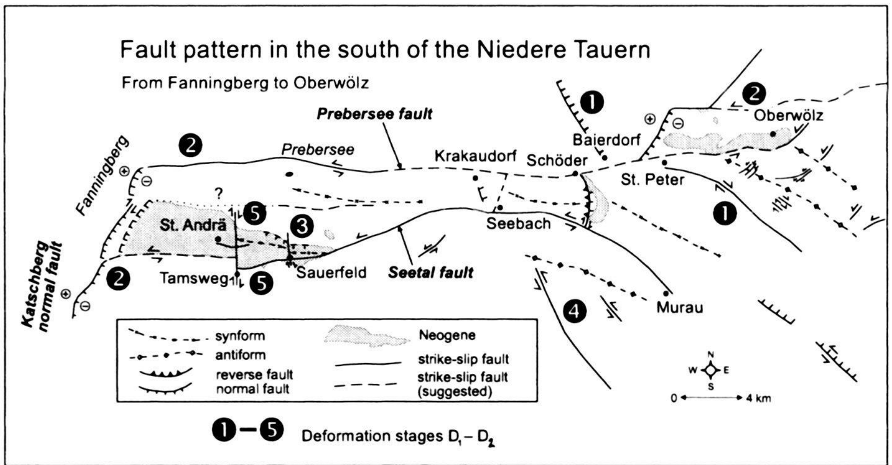

Fig. 2. Neogene fault patterns between the Niedere Tauern and the Gurktal nappe complex. Encircled numbers relate to deformation stages.

Nievoll 1985; Ratschbacher et al. 1991; Frisch et al. 1998; Neubauer et al. 2000).

The geomorphological evolution of the Eastern Alps during the Oligocene and Neogene and its relationship to extrusional tectonics received little attention although formation of peneplains as preserved in central and northern sectors within the eastern part of the Eastern Alps has been interpreted as related to tectonics (e.g. Frisch et al. 1998). Planation surfaces at elevations between 1,800 to 2,200 m in the western Gurktal mountains, known as „Nock peneplain" (e.g. Aigner 1923; Winkler-Hermaden 1951; Schneider 1988, 1995) and elsewhere in the Eastern Alps (e.g. Cornelius 1950) argues for specific, climate-depending conditions during their formation and for a later uplift to elevations of ca. 2,000 m and more. This contrasts with the Tauern window and Niedere Tauern regions where the morphology is dominated by a steep, immature landscape without relics of peneplains due to young to recent uplift (Exner 1949; Senftl and Exner 1973; Staufenberg 1987; Schneider 1988, 1995). We studied the transition zone between the area of the Niedere Tauern to the Gurktal mountains in order to compare their geomorphological and structural evolution (Figs. 1, 2). The presence of these Oligocene/Miocene elevated peneplains represents a major difference of eastern sectors of the Eastern Alps as compared to French/Swiss/Italian Western Alps where morphology is young. This confirms a different tectonic evolution of the Eastern Alps compared to Western Alps. The Paratethys time-scale calibration follows Rögl (1996).

Regional tectonic framework

The study area is located at the westernmost exposure of the Mur-Mürz wrench corridor (Fig. 1). Until now, no detailed knowldege of fault patterns, fault kinematics and dynamics was available. There, the Penninic units of the Tauern window are overlain by the Lower Austroalpine units of the Radstädter Tauern adjacent to the northeast. Genser & Neubauer (1989) and Elsner (1992) described a ductile low-angle normal fault (Katschberg normal fault) along the eastern margin of the Tauern metamorphic core complex (which largely corresponds to the Tauern window), which was exhumed during regional, post-metamorphic cooling from Late Oligocene to Recent times. Becker (1993) found the northern extension of this fault as an E-directed normal shear zone with a prominent distributed deformation along the upper margin of Penninic units and within the Lower Austroalpine units adjacent to the northeast. The Penninic and Lower Austroalpine units form high mountains (peak elevations are more than 3,000 m in the Penninic units, and more than 2,600 m in most sectors of the Lower Austroalpine units) which are dominated by a steep relief with only small, and subordinate planation relics along ridges. The Oberwölz-Tamsweg wrench corridor, the westernmost sector of the Mur-Mürz wrench corridor, separates Middle Austroalpine basement units in the north (exposed in the Radstädter Tauern/Niedere Tauern) from higher structural levels of Middle Austroalpine and the flat-overlying Upper Austro-Alpine units (Gurktal nappe complex) in the south (Murau and Gurktal mountains; Fig. 2). There is a marked geomorphological contrast between the Niedere Tauern with a steep relief and acute crests at average elevations of ca. 2,400 m (peaks to 2,683 m) and the Murau-Gurktal mountains with broad, flat, peneplain-like elevations between 1,800 and 2,200 m. Only a few elevations with flat, peneplained mountains („Nocks") are above these surfaces (Aigner 1923, 1925a, b; Spreitzer 1951a-c; Schneider 1988, 1995). The wrench corridor itself is located between these two domains and comprises east-trending valleys, the wide Tamsweg basin, and the Neogene Schöder and Oberwölz basins further to the east (Oestreich 1899; Aigner 1925a; Schwinner 1925; Petrascheck 1926/1929; Thurner 1958; Heinrich 1977). Sachsenhofer (1989) showed a variable, partly high coalification within eastern sectors of the Tamsweg basin.

Neogene fault pattern along the southern margin of the Niedere Tauern

A map of post-metamorphic faults (Fig. 2) was compiled from all available detailed geological maps of the region (Thurner 1958; Heinrich 1977; Neubauer 1980; von Gosen 1982; Exner 1989) and own investigations. The sense of displacement along faults has been deduced from geological maps and comprises the sum of all superposed relative movements. Note that the internal structure of the entire region is dominated by Late Cretaceous ductile fabrics with a generally flat-lying foliation. These fabrics imply a maximum Late Cretaceous age (<80 Ma) of formation of brittle faults. Previous studies along the thrust surfaces at the base of Upper Austroalpine units indicated that ductile fabrics were formed during Late Cretaceous nappe assembly and subsequent ductile extensional reactivation of these surfaces (Ratschbacher 1986; Handler 1994; Neubauer et al. 1995; Dallmeyer et al. 1998, Koroknai et al. 1999 and references cited therein)

The fault pattern is dominated by the several kilometres wide, E-trending Oberwölz-Tamsweg wrench corridor (OTW) between Mauterndorf and Oberwölz, which extends further to the east into the Mur-Mürz wrench corridor. The OTW corridor is dominated by the steep, E-trending Prebersee fault which can be continuously traced from S of Oberwölz to the northwestern edge of the Tamsweg basin. The Prebersee fault appears to have a major sinistral strike-slip component and a subordinate normal, S down component of displacement. A releasing overstep at Oberwölz is occupied by the Neogene Oberwölz basin (Thurner 1958), which opened along NE-trending normal faults as a pull-apart basin. At Fanningberg, the Prebersee fault turns into a SW-trending normal fault (as mapped by Exner 1989) which separates Lower Austroalpine and Middle Austroalpine tectonic units. Becker (1993) gave some indications of ESE-directed ductile shear within Lower Austroalpine units which he related to Neogene kinematics. Another regional fault is the curvilinear Seetal fault, which starts along the southern margin of the Neogene Tamsweg basin and can be traced to Murau (Fig. 2). This fault configuration indicates that releasing oversteps are responsible for the formation of the pull-apart-type basins of Oberwölz and Tamsweg. Furthermore, subordinate fault structures can be found. These include: (1) a NW-trending, normal, NE down fault northwest of Baierdorf, which is obviously cut by the Prebersee fault; (2) several minor NE-trending sinistral strike-slip faults; (3) a N-trending reverse fault at the western margin of the Neogene Schöder basin; and (4) a N-trending dextral strike-slip fault cutting through the Tamsweg basin. The N-trending strike-slip and reverse faults postdate depositional sequences within the Neogene basins. These relationships allow to infer a relative succession of faulting stages which include (Table 1): Deformation stage D_1, which is deduced from NW-trending normal faults, indicates NE-SW extension, and dextral strike-slip along E-trending faults, which are related to NW-SE compression. Deformation stage D_2 is characterized by reactivation of E-trending strike-slip zones as sinistral faults and associated SW-trending normal faults, which opened the Neogene Oberwölz and Tamsweg pull-apart basins. Deformation stage D_3 is related to N-S extension as can be seen along northern margins of the Tamsweg basin and dip-slip reactivation of E-trending, sinistral strike-slip faults. The deformation stage D_4 is not expressed by map-scale faults within the working area, but well expressed in outcrop-scale where ca. N-trending normal faults can be observed (see below). Deformation stage D_5 is related to NE-SW contraction due to reverse, oblique displacement along N- and NW-trending faults, forma-

Deform--action stage	Oberwölz-Tamsweg corridor	Palaeostress analysis	Tamsweg basin	Kinematic interpretation
D_1	E-trending dextral strike-slip and NE-trending normal faults	NNW-SSE to NW-SE compression, transpressional		? related to Palaeogene, dextral transpressive, collision (?) of Austroalpine units with foreland-related units
D_2	E-trending sinistral strike-slip faults, ca. NNE-trending normal faults	NE-SW compression, continuously changing to trans-tensional strike-slip	basin formation along fault overstep	intra-Karpatian formation of the sinistral, E-trending wrench corridor
D_3	E-trending normal faults	N-S to NNW-SSE extension	E-trending normal faults	N-S stretching of the extrusional wedge due to widening of the extrusional wedge
? D_4	mainly meso-scale faults	E-W extension		E-W stretching of the extrusional wedge
D_5	ESE-trending, low-amplitude folds with large fold lengths	NE-SW compression	ESE-trending synforms and mesoscale faults, N-trending reverse faults	inversion of structures due to c. NE-SW contraction within the extrusional wedge

Table 1. Overview of structures and kinematics of the Oberwölz-Tamsweg wrench corridor.

tion of conjugate N-trending dextral and ca. E-trending sinistral faults. Furthermore, open low-amplitude, large-scale folds with ESE-trending fold axes are kinematically related to these D_5 faults. Gentle ESE-trending antiforms and synforms dominate the structure of basement sequences to the S of the Prebersee fault (Fig. 3). These folds are similar in style and orientation to folds exposed within the Tamsweg basin (see below) and therefore can easily be related to D_5 kinematics because of similar orientation of kinematic (strain and displacement) and dynamic (principal palaeostress axes) conditions of their formation (NNE-SSW shortening/compression).

Structure of the Tamsweg basin

The Tamsweg basin is divided by a N-trending strike-slip fault into two sectors. The Tamsweg basin exposes a thick basal conglomerate, associated sandstones and coal seams in eastern sectors of the basin, and less consolidated coarse conglomerate, gravel, and sand in western sectors. A cumulative thickness of 350 metres was estimated by Heinrich (1977) and Zeilinger et al. (1999). A Karpatian age is suggested by plant fossils.

Because of poor outcrop conditions, no unequivocal evidence for synsedimentary faulting, e.g., strike-slip or normal faults, was found. However, there is ample evidence for post-depositional deformation, especially in eastern sectors of the basin. Based on the detailed geological map by Heinrich (1977) and own observations, three types of faults can be recognized within and along the basin margins (Fig. 3). (1) An E-trending normal, S down fault separates the basement from the southerly adjacent eastern Tamsweg basin, (2) a N-trending, dextral strike-slip fault separates the eastern from the western sector, and (3) the ca. WSW- to W-trending Seetal strike-slip fault separates the basin from the Middle Austroalpine basement adjacent to the south.

In eastern sectors of the basin, a well-consolidated conglomerate with intercalated thin coal seams and sandstones displays a wide-spaced, rough, flat-lying stylolitic schistosity due to pressure solution during advanced stages of compaction. This sequence is also folded and faulted. A broad, ca. E- to ESE-trending syncline dominates the eastern subbasin. The distribution of bedding planes displays a broad great circle due to folding with an ESE trending axis (Fig. 3). This trend is consistent with decimetre- to metre-scaled, WNW-trending open folds with a subvertical axial surface, which can be found in some outcrops. This phase of folding indicates a post-Karpatian age of NNE-SSW shortening and basin inversion. The amplitude and fold length of the syncline within the Tamsweg basin is similar in orientation and style to low-amplitude folds within the basement to the south of the Oberwölz-Tamsweg wrench corridor. This relationship suggests a similar, post-Karpatian age of these folds.

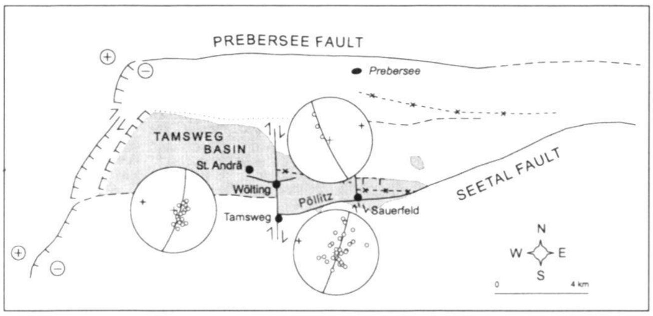

Fig. 3. Structure and orientation data related to c. NNE-SSW compression and folding from the Tamsweg basin. Poles to bedding planes (open circles) and fold axes (crosses) are shown in the lower hemisphere projection.

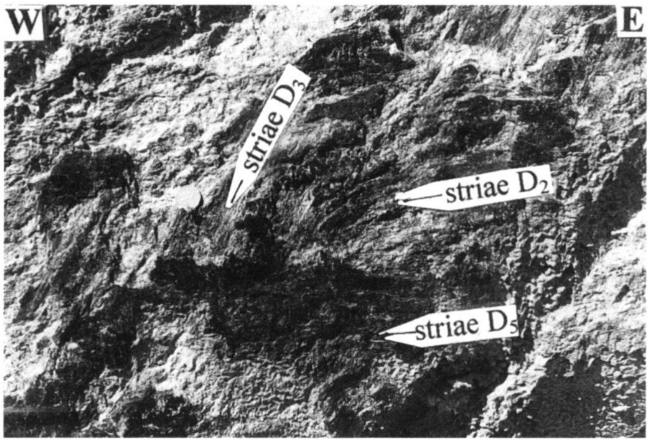

Fig. 4. Succession of deformation events at site 26, an outcrop along the Seetal fault. For location, see Fig. 5.

The composition of clasts is dominated by medium-grade metamorphic orthogneisses, quartz-rich micaschists and paragneisses similar to rocks exposed within northerly adjacent Middle Austroalpine units of the Niedere Tauern. Among these, abundant fine-grained orthogneisses are representative for the Schladming Tauern, by contrast Penninic and Lower Austroalpine clasts are missing (e.g., Exner 1949; Heinrich 1977 and references therein) as well as such from Middle Austroalpine units exposed to the south. Consequently, most clasts came from the north and/or northeast.

Palaeostress patterns

Slickenside and striation data were collected at 77 stations between Mauterndorf and Schöder in order to evaluate fault kinematics (Fig. 2). In many outcrops, superimposed sets of slickensides and striations indicate a polyphase reactivation of these faults. Note that along fault traces outcrop conditions are poor and therefore only a few reasonably large exposures have been found on major faults. The determination of the succession of faulting and of displacement followed criteria proposed by, e.g., Petit (1987) and Gamond (1983, 1987). Palaeostress orientation patterns were evaluated from these fault and slickenside data using numerical and graphical inversion methods proposed by Angelier & Méchler (1977), Angelier (1979, 1989), Armijo et al. (1982) and Marret & Almendinger (1990). These inversion methods indicate strain rate rather than palaeostress patterns with relative magnitudes of principal stress axes (Twiss & Unruh 1998). Because the rocks are generally anisotropic, we do not report the R-value of the palaeostress tensor because present versions of palaeostress inversion techniques calculate the R-value only for isotropic material. Because of the dominance of metamorphic, foliated rocks this prerequisite is not given in the study area.

Only results from those sites are reported where measurements are related to a significant (more than six) number of fault-striae pairs after separation of data. Results of palaeostress analysis are presented in Figures 5 and 6. Sinistral E-trending, generally steeply S-dipping faults dominate the mesoscale structures along the wrench corridor (Figs. 5, 6). As an example for polyphase fault activation we discuss an outcrop along the easternmost Seetal fault (site 26). On a single large, ca. E-trending and steeply S-dipping fault surface marked changes of orientations of striae and senses of displacement were observed that suggest a succession of activation stages due to changing orientations of palaeostress (Table 1). These stages include an initial dextral transpressional activation of the fault (D_{1a}), which changes to a transtensional regime (D_{1b}: dextral NE-SW transtension). After a D_2 sinistral strike-slip activation, representing the main phase, follows D_3 ca. N-S directed extension, which is followed by D_4 WNW-ESE extension, both represented by normal faults. These faults are overprinted by D_5 sinistral strike-slip fault faults (Fig. 4).

The distinction between D_2 and D_5 sinistral strike-slip faults is often difficult, because overprint criteria are often missing. Consequently, we included all palaeostress patterns with strike-slip patterns along E-trending faults with similar NE-SW orientation of the deduced maximum principal stress axis (σ_1) in one pattern (Fig. 5b). The following succession of deformation stages can be deduced from slickenside and striation data:

(1) D_1 palaeostress patterns deduced from dextral E-trending and sinistral, ca. N-trending strike-slip faults are common along the Seetal fault (Fig. 5a).

(2) D_2 palaeostress patterns indicating sinistral strike-slip along E-trending faults are common all over the area and dominate the palaeostress patterns (Fig. 5b). We suppose that most of the mesoscale E-trending sinistral strike-slip faults are formed during deformation stage D_2, because many of them are overprinted by normal faults on the same, E-trending fault surface.

(3) D_3 palaeostress patterns indicating ca. N-S extension are widespread, but are often concentrated at distinct zones

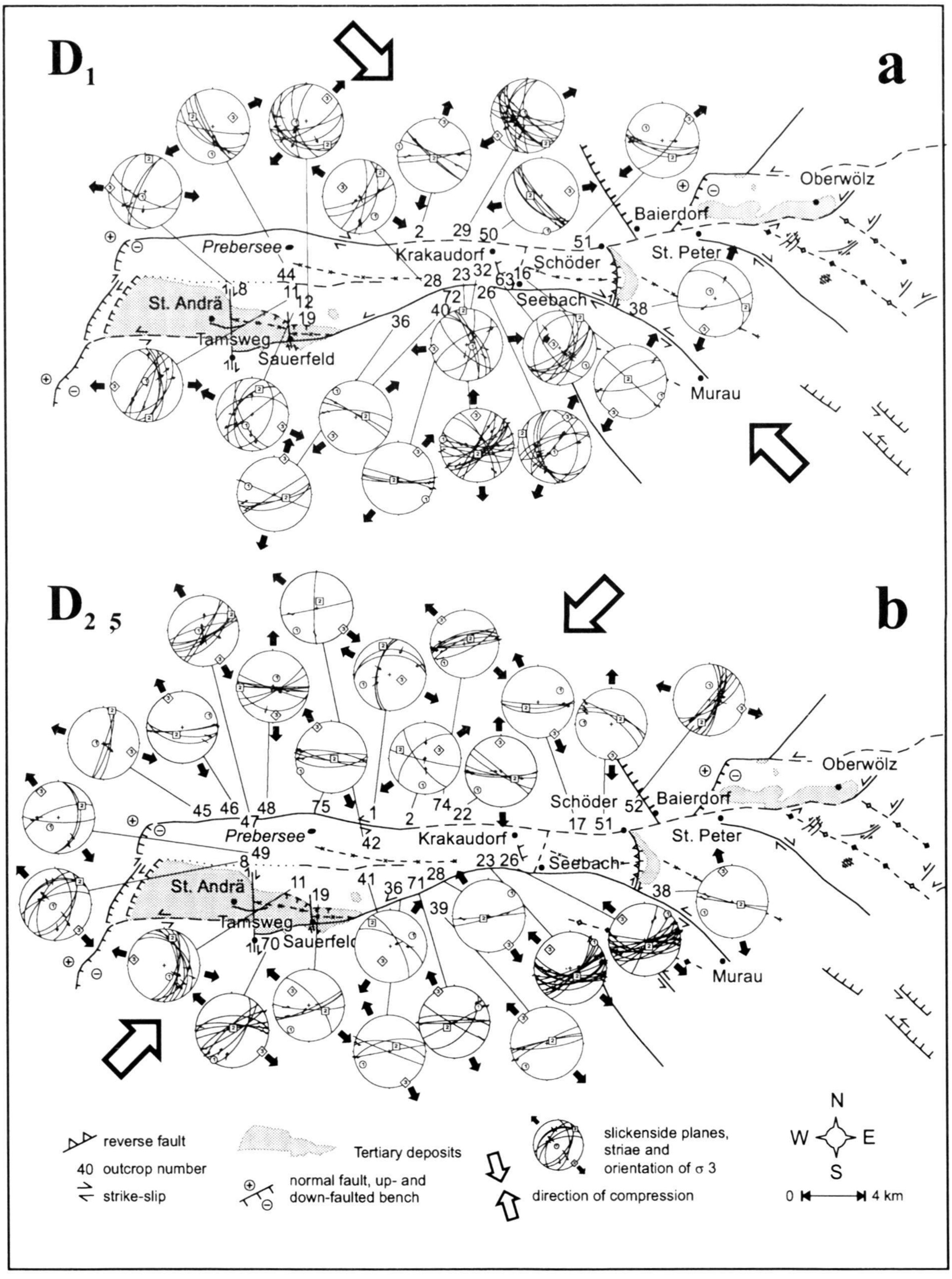

Fig. 5. Palaeostress patterns of deformation stages (a) D_1 dextral strike-slip regime with NW-SE orientation of the maximum principle stress axis, and (b) combined D_2/D_5 sinistral strike-slip with NE-SW orientation of the maximum principal stress axis.

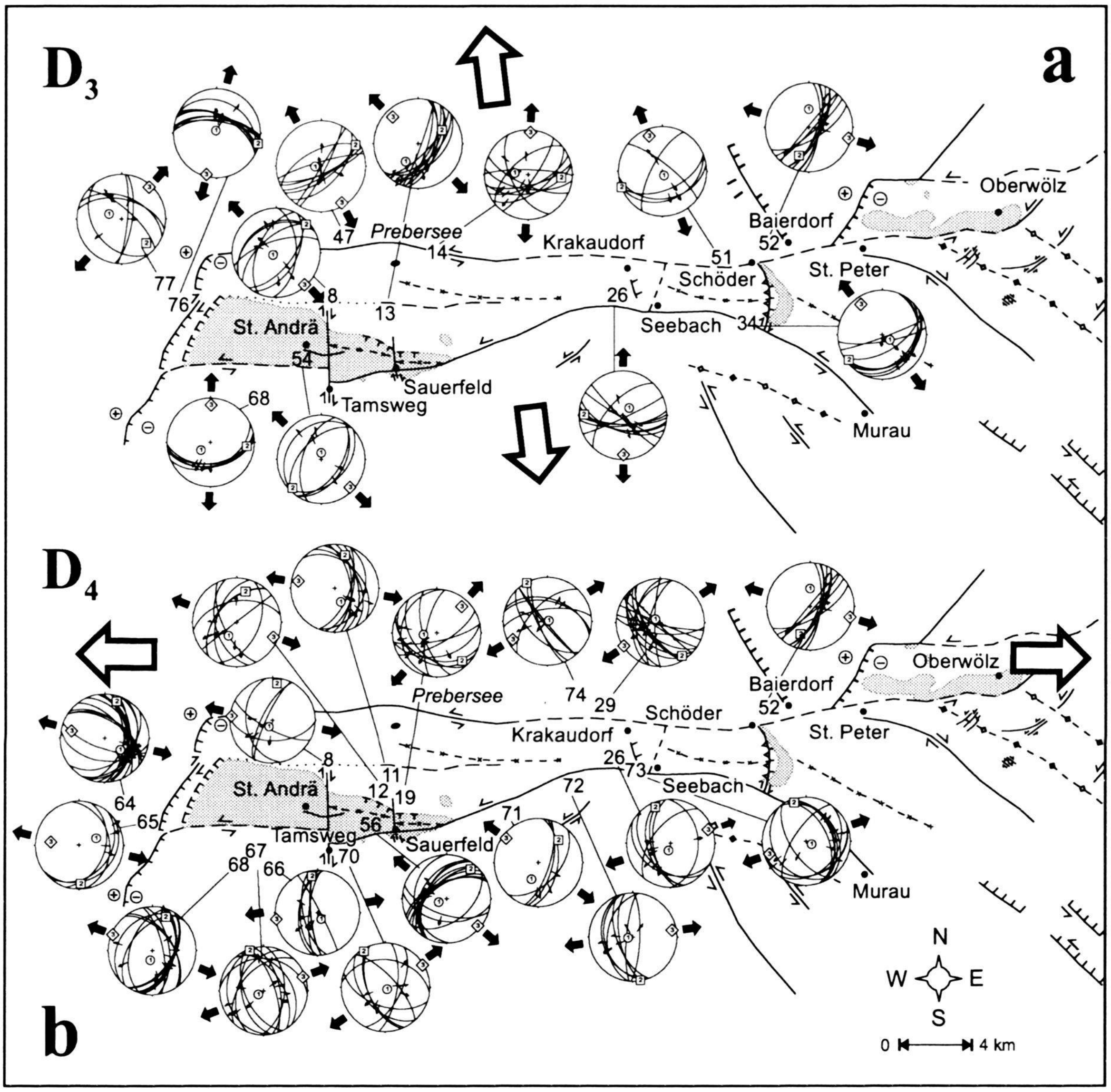

Fig. 6. Palaeostress patterns of deformation stages (a) D_3 and (b) D_4. For legend, see Fig. 5.

like the Prebersee and Seetal fault (Fig. 6a). These generally reactivated E-trending, steeply S-dipping faults and resulted in southward, normal displacement of the southern, hangingwall block.

(4) D_4 c. E-W (varying between WNW-ESE and WSW-ENE) tensional palaeostress patterns overprint and interfer with $D_{2,3}$ patterns (Fig. 6b). D_2 to D_4 palaeostress patterns represent a continuous succession of faults which relates to one developing process, an initial transpressive, later transtensive development within a wrench corridor.

(5) In some outcrops, there is evidence for some minor sinistral reactivation of E-trending sinistral faults by D_5 palaeostress patterns (Fig. 5b).

Geomorphology

The geomorphologic evolution is closely related to Oligocene-Neogene tectonics. Most obvious are morphological differences between the Gurktal and Murau mountains in the south and the Niedere Tauern in the north, which are separated by an E-trending valley system (Figs. 7, 8).

The Niedere Tauern represent a high, mountainous region with steep slopes and crests at elevations between 2,300 and 2,600 m (Fig. 7a). No planation relics are present, except some small surfaces at altitudes of ca. 1,800 to 2,000 m along the southern margin, facing towards the Tamsweg-Oberwölz depression (Schneider 1988). Slopes are generally continuous

Fig. 7. a - Geomorphology of the western Tamsweg basin and the Niedere Tauern, the latter with a steep, immature landscape. View towards north. b – Western Gurktal mountains with planation surfaces at an elevation of ca. 2,000 to 2,100 metres. View towards north. Note the peaks of Niedere Tauern to the north.

from crests to valleys (Fig. 7a). Deep and long valleys with N-S- to NNW-trending directions are common (Fig. 8a). Rapid and strong uplift caused intense linear erosion. In addition, glacial erosion shaped the surface of these valleys and mountains (e.g., Seefeldner 1961; Morawetz 1986) and may have destroyed some formerly existing, small planation surfaces.

The Gurktal and Murau mountains show a lower altitude, extended remnants of former peneplains (Fig. 7b) and short and steep valley systems with various directions (Fig. 8). Lower rates of uplift and a smaller difference in relief caused less intense erosion and denudation and, therefore, the remains of peneplains are still well preserved.

In the eastern Gurktal Mountains, red palaeosoil occurs on peneplains postdating Eocene deposits, and predating Neogene (Karpatian?) gravel (Thiedig 1970, 1975). Therefore, the development of the peneplains began after the Late Eocene under a warm and humid climate and ends during Middle/Late Miocene (Thiedig 1970). It is believed that peneplains formed at low elevations (e.g., Gellert 1971; Schwarzbach 1993). Hejl (1995, 1997) found Oligocene (35–29 Ma) apatite fission track ages within the western Gurktal mountains indicating formation of the Nock planation surfaces after 29 Ma. Furthermore, the entire region was uplifted and tilted eastwards after Middle/Late Miocene. Incision of recent valleys is a result of this block uplift. The difference in the elevation between the peneplains (ca. 2,200 to 2,000 m altitude) and the present level of

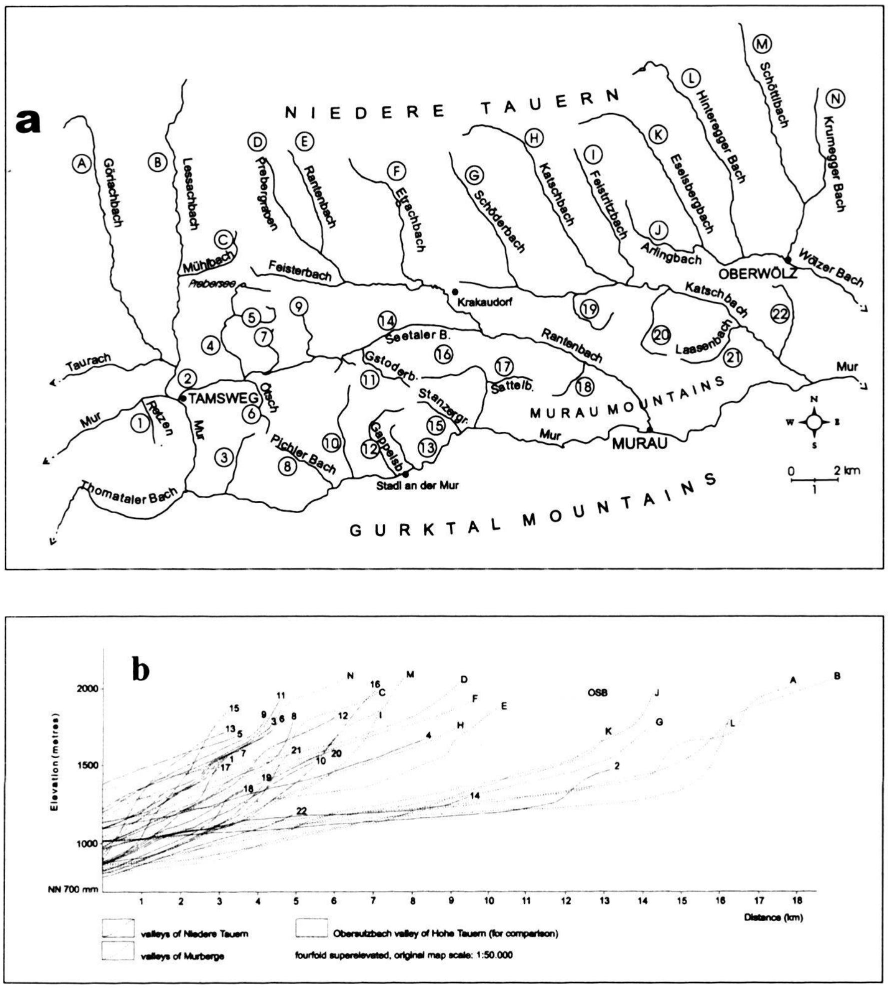

Fig. 8. Valley systems (a) and valley gradients (b). Note the short, steep valley gradients from the northern Gurktal-Murau Mountains due to the bulk uplift.

the valleys (ca. 800 m altitude) in the western Gurktal mountains is therefore a reasonable estimate (ca. 1,200 to 1,400 m) for the amount of block uplift.

The small fossil peneplains in the Hohe Tauern mentioned above cannot be correlated to the peneplains in the Gurktal mountains, because the Penninic rocks were not exposed prior to the Pliocene (Staufenberg 1987). At that time the change of climate from tropic/subtropic (Eocene to Miocene) to a moderate humid climate (Pliocene) resulted in formation of pediment plains or valley grounds, but no longer peneplains (Winkler-Hermaden 1957; Frisch et al. 1998).

Between the Gurktal-Murau Mountains and the Niedere Tauern the valleys show an atypical pattern (Fig. 8a). In this region the valleys strike in W-E- to NW-SE-direction. This feature is interpreted as caused by the strike-slip fault system at the northern edge of the extruding wedge. These fault zones could easily be eroded by rivers, so the present valley system is a result of tectonic and erosive events (e.g. Winkler-Hermaden 1957; Frisch et al. 1998).

Discussion

The presented data suggest that the Mur-Mürz wrench corridor extends to the northwestern corner of the Tamsweg basin, where it ends in an ESE-dipping normal fault forming the basal detachment plane (Katschberg normal fault) of the extruding wedge. Consistent with structural data, this implies a normal displacement component along the northern lateral, sinistral wrench corridor. A minimum vertical offset of ca. 1,600 m near Oberwölz can be estimated using maximum heights (ca. 2,400 m) within Middle Austroalpine units exposed to the north and the lowest exposures of the Gurktal nappe complex at ca. 800 m to the south. The most obvious effect of the normal displacement is the preservation of the Gurktal nappe complex in a wide graben-like structure and the preservation of pre-Karpatian peneplains and red soils on it (Fig. 9). These peneplains are in contrast to the Niedere Tauern area which is characterized by a steep, immature relief suggesting young surface uplift in the order of several 100 me-

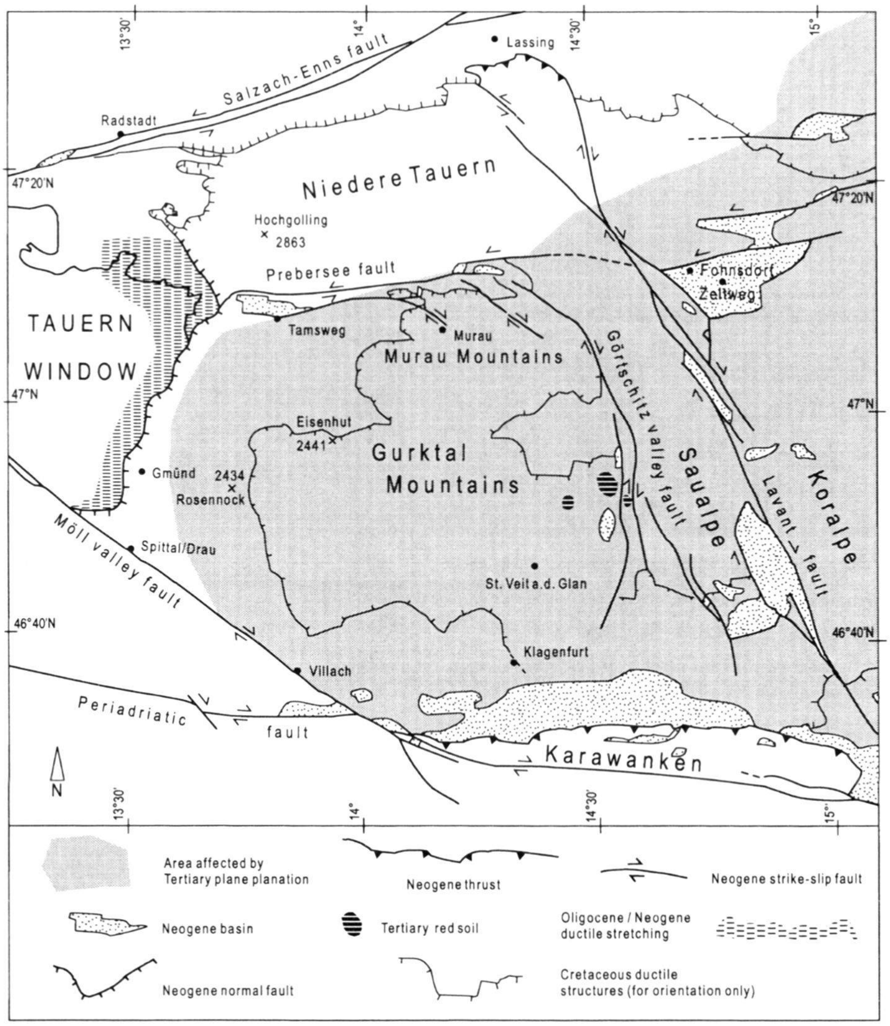

Fig. 9. Distribution of Neogene deposits, Tertiary red soils and planation surfaces to the east of the Tauern window.

tres relative to the Gurktal and Murau mountains. Apatite fission track data (Hejl 1997, 1999) have shown that the western Gurktal-Murau block was originally exhumed and cooled through ca. 100 °C, the approximate fission track closing temperature, during the Oligocene (ca. 35–29 Ma). This is in contrast to the western Niedere Tauern block which cooled through ca. 100 °C between 24 and 15 Ma, at the time of formation of the Tamsweg basin and activity along the OTW corridor. The southeasternmost Niedere Tauern block (east of Oberwölz) cooled earlier, ca. at 40 Ma. Assuming a normal geothermal gradient of 30 °C/km, this implies that the post-Palaeogene denudation there was less than 2,000 m, which is similar to the estimate for vertical structural offset. Vitrinite reflectance data from the Tamsweg basin (Sachsenhofer 1989) suggest an even higher geothermal gradient along the Oberwölz-Tamsweg wrench corridor (Sachsenhofer 1992). This would imply a reduction of the estimate of maximum vertical offset.

The structural data are similar to those from detailed studies in other regions, including the Northern Calcareous Alps (Peresson & Decker 1997a, b; Linzer et al. 1997), the Tauern window (Kurz et al. 1994; Kurz & Neubauer 1996; Amann et al. 1997; Wang and Neubauer 1998) and the Periadriatic fault (Nemes 1996). Equivalents include the Karpatian sinistral wrenching and opening of sedimentary basins along releasing oversteps (Neubauer 1988; Ratschbacher et al. 1991), followed by N-S extension along former strike-slip faults (Neubauer et al. 1999). An open question is the age and significance of the initial dextral strike-slip activation of E-trending faults. No similar dextral brittle faults are known in the central Eastern Alps. However, such faults would well fit with Palaeogene WNW-directed emplacement of the Austroalpine nappe complex onto Penninic units (Ring et al. 1991).

Syn- to postdepositional N-S extension within the Miocene basins along the sinistral wrench corridors, postdating lateral displacement, within the eastwards moving extruding wedge was proposed to result from widening of the wedge perpendicular to the motion direction (Neubauer et al. 1999). Evidence for subsequent E-W compression was found by Peresson & Decker (1997a), who explained this feature by collision within the Carpathian arc. Final NNE-SSW shortening and sinistral displacement are in line with the post-Sarmatian closure of the Klagenfurt basin to the north of the Periadriatic fault (Nemes et al. 1997), and with the crustal-scale, low-amplitude folding of the entire extruding wedge to the east of the Tauern window (Neubauer et al. 1999). Furthermore, the presence of planation surfaces at higher elevation argues for block uplift of the central Eastern Alps similarly to that postulated from subsidence analysis of the Molasse basin (Genser et al. 1998). Recent earthquakes indicate that the Mur-Mürz wrench corridor is still seismically active (e.g., Hammerl & Lenhardt 1997). One of the largest historical earthquakes of the central Eastern Alps occurred in the study area (Murau-Katschberg earthquake on May 4, 1201, with an EMS epicentral intensity of 9). Consequently, eastward extrusion is still active as already shown by Gutdeutsch et al. (1987).

Conclusions

The structural and geomorphological data constrain the following major features:

(1) The Gurktal nappe complex is preserved within a graben-like structural unit on top of the subsided extrusion block. This block also carries widespread, flat-lying, Late Oligocene (?) to Early Miocene peneplains. In contrast, the morphology of the Niedere Tauern block is young due to ongoing surface denudation.

(2) The Mur-Mürz wrench corridor extends to the northwestern edge of the Neogene extrusional wedge where it is linked to the N-trending normal fault at the structural base of the extrusional wedge.

(3) Fault kinematics along western sectors of the Mur-Mürz wrench corridor is complex and changes from strike-slip to N-S extension and late-stage, post-Karpatian NE-SW contraction as recently also found by Zeilinger et al. (1999).

Acknowledgments:

We gratefully acknowledge support and discussions by Gsi Amann, Hans Genser and Hans-Peter Steyrer. Hans Genser, Ewald Hejl, John Reinecker and Reinhard Sachsenhofer read earlier versions of the manuscript and improved consistency and linguistics. We acknowledge careful reading and suggestions by Wolfgang Frisch, Silvana Martin and Jürgen Remane. Work has been supported by grant no. P9918-GEO of the Austrian Research Foundation.

REFERENCES

AIGNER, A. 1923: Geomorphologische Beobachtungen in den Gurktaler Alpen. Sitzber. Akad. Wiss. Wien, math.-naturwiss. Kl. Abt. I 131.

AIGNER, A. 1925a: Über Talbildung am Südrand der Niederen Tauern. Sitzber. Akad. Wiss. Wien, math.-naturwiss. Kl. Abt. I 134, 67–100.

AIGNER, A. 1925b: Über tertiäre und diluviale Ablagerungen am Südfuße der Niederen Tauern. Jb. Geol. Bundesanst. Wien 74, 179–196.

AMANN, G., DAXNER, G., NEUBAUER, F., PAAR, W.H. & STEYRER, H.P. 1997: Structural evolution of the Schellgaden gold district, eastern Tauern window, Austria – a preliminary report. Zbl. Geol. Paläont., Teil II 1997, 215–228.

ANGELIER, J., 1979: Determination of the mean principal directions of stresses for a given fault population. Tectonophysics 56, T17–T26.

ANGELIER, J. 1989: From orientation to magnitudes in paleostress determination using fault slip data. J. Struct. Geol., 11, 37–50.

ANGELIER, J. & MECHLER, P. 1977: Sur une methode de recherche des contraintes principales egalement utilisable en tectonique et en seismologie: la methode de dièdres droits. Bull. Soc. Geol. France (7) 19/6, 1309–1318.

ARMIJO, R., CAREY, E. & CISTERNAS, A., 1982: The inverse problem in microtectonics and the separation of tectonic phases. Tectonophysics 82, 145–160.

BALLA, Z. 1985: The Carpathian loop and the Pannonian basin: a kinematic analysis. Geophys. Transactions 30, 313–353.

BECKER, B. 1993: The structural evolution of the Radstadt thrust system, Eastern Alps, Austria – kinematics, thrust geometries, strain analysis. Tübinger Geowiss. Arb. Reihe A 92: 1–83.

CORNELIUS, H. P. 1950: Zum Beitrag der jugendlichen Hebung der Alpen. Mitt. Geogr. Ges. Wien 92, 161–171.

DALLMEYER, R.D., HANDLER, R., NEUBAUER, F. & FRITZ, H. 1998: Sequence of thrusting within a thick-skinned tectonic wedge: Evidence from $^{40}Ar/^{39}Ar$ ages from the Austroalpine nappe complex of the Eastern Alps. J. Geol. 106, 71–86.

ELSNER, R., 1992: Geologie des Tauern-Südostrandes und geotektonische Konsequenzen. Jb. Geol. Bundesanst. Wien 134, 561–645.

EXNER, CH. 1949: Beitrag zur Kenntnis der jungen Hebung der östlichen Hohen Tauern. Mitt. Österr. Geogr. Ges. 91, 186–196.

EXNER, CH. 1989: Geologie des mittleren Lungaues. Jb. Geol. Bundesanst. Wien 132, 7–103.

FRISCH, W., KUHLEMANN, J., DUNKL, I. & BRÜGEL, A. 1998: Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion. Tectonophysics 297, 1–16.

GAMOND, J.F. 1983: Displacement features associated with fault zones: a comparison between observed and experimental models. J. Struct. Geol. 5, 33–45.

GAMOND, J.F. 1987: Bridge structures as sense of displacement in brittle fault zones. J. Struct. Geol. 9, 609–620.

GELLERT, J. F. 1971: Das System der Entstehung und Gestaltung der Rumpfflächen, Inselberge samt Pedimenten und Rumpftreppen in Afrika. Petermanns geogr. Mitt. 115, 172–182.

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., CLOETINGH, S. & NEUBAUER, F. (1998): Late orogenic rebound and oblique Alpine convergence: new constraints from subsidence analysis of the Austrian Molasse basin. In: XVI Carpathian-Balkan Geological Congress, Field Trip Pre 1 Transsect through the central Eastern Alps, Geological Survey of Austria, Vienna, 33–43.

GOSEN, W. VON 1982: Geologie und Tektonik am Nordostrand der Gurktaler Decke (Steiermark/Kärnten – Österreich). Mitt. Geol.-Paläont. Inst. Univ. Hamburg 53, 33–149.

GUTDEUTSCH, R. & ARIC, K. 1987: Geophysical Aspects of the Crustal Structures of the Eastern Alps. In: Geodynamics of the Eastern Alps (Ed. by FLÜGEL, H.W. & FAUPL, P.). Deuticke, Wien, 309–324.

HANDLER, R. 1994: $^{40}Ar/^{39}Ar$ and Rb-Sr mineral dating within a complex polymetamorphic terrain. The northeastern Alps, Austria. Unpubl. PhD thesis, Faculty of Sciences University of Graz, 143 p.

HAMMERL, C. & LENHARDT, W. 1997: Erdbeben in Österreich. 191 p., Leykam, Graz.

HEINRICH, M. 1977: Zur Geologie des Jungtertiärbeckens von Tamsweg mit kristalliner Umrahmung. Jahrb. Geol. Bundesanst. Wien 120, 295–341.

HEJL, E. 1997: 'Cold spots' during the Cenozoic evolution of the Eastern Alps: thermochronological interpretation of apatite fission-track data. Tectonophysics 272, 159–172.

HEJL, E. 1998: Über die känozoische Abkühlung und Denudation der Zentralapen östlich der Hohen Tauern – eine Apatit-Spaltspuranalyse. Mitt. Österr. Geol. Ges. 89(1996), 179–199.

KÁZMÉR, M. & KOVAC, S. 1985: Permian-Paleogene paleogeography along the eastern part of the Insubric-Periadriatic lineament system: evidence for continental escape of the Bakony-Drauzug unit. Acta Geologica Hungarica 28, 71–84.

KOROKNAI, B., NEUBAUER, F., GENSER, J. & TOPA, D. 1999: Metamorphic and tectonic evolution of the Austroalpine units at the western margin of the Gurktal nappe complex, Eastern Alps. – Schweiz. Mineral. Petrogr. Mitt. 79, 277–295.

KURZ, W. & NEUBAUER, F. 1996: Strain Partitioning during Formation of the Sonnblick Dome (southeastern Tauern Window, Austria). J. Struct. Geol. 18, 1327–1343.

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

LINZER, H.G., MOSER, F., NEMES, F., RATSCHBACHER, L. & SPERNER, B. 1997: Build-up and dismembering of the eastern Northern Calcareous Alps. Tectonophysics 272, 97–124.

MARRET, R. & ALMENDINGER, R.W. 1990: Kinematic analysis of fault slip data. J. Struct. Geol. 12, 596–612.

MORAWETZ, S. 1986: Talanordnung und Talformung ein rhythmisches Phänomen und der glaziale Einfluß am Beispiel der Niederen Tauern. Arb. Inst. Geogr. Karl-Franzens-Univ. Graz 27, 133–140.

NEMES, F. 1996: Kinematics of the Periadriatic fault in the Eastern Alps. Evidence from structural analysis, fission track dating and basin modelling. PhD thesis University of Salzburg, 225 p.

NEMES, F., NEUBAUER., F., CLOETINGH, S. & GENSER, J. 1997: The Klagenfurt Basin in the Eastern Alps: a decoupled intra-orogenic flexural basin? Tectonophysics 282, 189-204.

NEUBAUER, F.R. 1980: Die Geologie des Murauer Raumes - Forschungsstand und Probleme. Mitt. Abt. Geol. Paläont. Bergbau Landesmus. Joanneum 41, 67-79.

NEUBAUER, F. 1988: Bau und Entwicklungsgeschichte des Rennfeld-, Mugel- und des Gleinalmkristallins (Ostalpen). Abh. Geol. Bundesanst. Wien 42, 1–137.

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

NEUBAUER, F., DALLMEYER, R.D., DUNKL, I. & SCHIRNIK, D. 1995. Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics 242, 181–199.

NEUBAUER, F., FRITZ, H., GENSER, J., KURZ, W., NEMES, F., WALLBRECHER, E., WANG, X. & WILLINGSHOFER, E. 2000: Structural evolution within an extruding wedge: model and application to the Alpine-Pannonian system. In: Aspects of tectonic faulting. (Georg Mandl Volume) (Ed. by LEHNER, F. & URAI, J.). 141-153. Springer, Berlin – Heidelberg – New York.

NIEVOLL, J. 1985. Die bruchhafte Tektonik entlang der Trofaiachlinie (Östliche Zentralalpen, Österreich). Jb. Geol. Bundesanst., Wien 127, 643–671.

OESTREICH, K., 1899: Ein alpines Längstal zur Tertiärzeit. Jb. k. k. Geol. Reichs-Anst. Wien 49, 165–212.

PERESSON, H. & DECKER, K. 1997a: Far-field effects of Late Miocene subduction in the Eastern Carpathians: E-W compression and inversion of structures in the Alpine-Carpathian-Pannonian region. Tectonics 16, 38–56.

PERESSON, H. & DECKER, K. 1997b: The Tertiary dynamics of the northern Eastern Alps (Austria): changing palaeostress in a collisional plate boundary. Tectonophysics 272, 125–157.

PETIT, J.P. 1987: Criteria for the sense of movement on fault surfaces in brittle rocks. J. Struct. Geol. 9, 597–608.

PETRASCHECK, W. 1926/1929: Kohlengeologie der österreichischen Teilstaaten. 484 p., Kottowitzer Verlag, Katowice.

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

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

RATSCHBACHER, L., FRISCH, W., LINZER, G. & MERLE, O. 1991: Lateral Extrusion in the Eastern Alps, part 2: Structural Analysis, Tectonics 10, 257–271.

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.

RÖGL, F. 1996: Stratigraphic correlation of the Paratethys Oligocene and Miocene. Mitt. Ges. Geol. Bergbaustud. 41, 65–73.

SACHSENHOFER, R. F. 1989: Das Inkohlungsbild im Jungtertiär der Norischen Senke (Östliche Zentralalpen, Österreich) und seine paläogeothermische Deutung. Jb. Geol. Bundesanst. Wien 132, 489–505.

SACHSENHOFER, R.F. 1992: Coalification and thermal histories of Tertiary basins in relation to late Alpidic evolution of the Eastern Alps. Geol. Rundschau 81, 291–308.

SACHSENHOFER, R.F., LANKREIJER, A., CLOETINGH, S. & EBNER, F. 1997. Subsidence analysis and quantitative basin modelling in the Styrian Basin (Pannonian Basin System, Austria). Tectonophysics 272, 175–196.

SCHNEIDER, T. 1988: Die geomorphologische Entwicklung des Lungau im Jungtertiär. Augsburger geogr. Hefte 7, 1–267.

SCHNEIDER, T. 1995: The development of the valley knot and basic landscape in the Lungau – a contribution to upper Tertiary relief evolution in the Eastern Central Alps. Regensburger Geogr. Schriften, 25, 165–183.

SCHWARZBACH, M. 1993: Das Klima der Vorzeit. Eine Einführung in die Paläoklimatologie. Enke-Verlag, Stuttgart.

SCHWINNER, R. 1925: Über das Tertiär im Lungau. Verh. Geol. Bundesanst. Wien 1925, 192–195.

SEEFELDNER, E. 1961: Salzburg und seine Landschaften. Eine geographische Landeskunde. Mitt. Ges. Salzburger Landeskunde, 2. Erg.-Bd. 573 p., Salzburg – Stuttgart.

SENFTL, E. & EXNER, CH. 1973: Rezente Hebung der Hohen Tauern und geologische Interpretation. Verh. geol. Bundesanst. Wien 1973, 209–234.

SPREITZER, H. 1951a: Die Großformung im oberen steirischen Murgebiet. Geograph. Studien (Wien), Festschrift J. Sölch, 132–144.

SPREITZER, H. 1951b: Die Piedmonttreppen in der regionalen Geomorphologie. Erdkunde 5, 294–305.

SPREITZER, H. 1951c: Über die Entstehung der Großformen der hohen Gurktaler Alpen. Carinthia II 141/61, 65–77.

STAUFENBERG, H. 1987: Apatite Fission-Track Evidence for Postmetamorphic Uplift and Cooling History of the Eastern Tauern Window and the Surrounding Austroalpine (Central Eastern Alps, Austria), Jb. Geol. Bundesanst. Wien 130, 571–586.

THIEDIG, F. 1970: Verbreitung, Ausbildung und stratigraphische Einstufung neogener Rotlehme und Grobschotter in Ostkärnten (Österreich). Mitt. Geol.Paläont. Inst. Univ. Hamburg 38, 97–116.

THIEDIG, F. 1975: Die junge Bruchtektonik im Bereich der Saualpe. Clausthaler Geol. Abh., Sonderband 1, 155–174.

THURNER, A. 1958: Erläuterungen zur Geologischen Karte Stadl-Murau 1:50.000. 106 p., Geol. Bundesanst., Wien.

TWISS, R.J. & UNRUH, J.R. 1998: Analysis of fault slip inversions: Do they constrain stress or strain rate? J. Geophys. Res. 103, 12.205–12.222.

WANG, X. & NEUBAUER, F. 1998: Orogen-parallel strike-slip faults bordering metamorphic core complexes: the Salzach-Enns fault zone in the Eastern Alps, Austria. J. Struct. Geol. 20, 799–818.

WINKLER-HERMADEN, A. 1951: Die jungtertiären Ablagerungen an der O-Abdachung der Zentralalpen und das inneralpine Tertiär. In: Geologie von Österreich (Ed. by SCHAFFER, F.X.). Deuticke, Wien, 414–524.

WINKLER-HERMADEN, A. 1957: Geologisches Kräftespiel und Landformung. XX + 822 p., Wien, Springer.

ZEILINGER, G., KUHLEMANN, J., REINECKER, J., KÁZMER, M. & FRISCH, W. 1999: Das Tamsweger Tertiär im Lungau (Österreich): Fazies und Deformation eines intramontanen Beckens. N. Jb. Geol. Paläont. Abh. 214, 537–569.

Manuscript received April 14, 1999
Revision accepted January 18, 2000