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Early to Middle Miocene tectonics of the eastern part of the Northern Calcareous Alps

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ABSTRACT

Three deviatoric paleostress tensor groups describe the upper crustal dynamics of the Northern Calcareous Alps during Oligo-Miocene continental collision and eastward lateral extrusion of the central Eastern Alps. Paleostresses are correlated to three kinematic stages.

(1) Early to Middle Miocene N-directed strike-slip compression during the onset of eastward lateral extrusion led to the formation of (N)NE-striking sinistral faults. N-directed compression in the Calcareous Alps paralleled the N-directed translation of the Adriatic plate.

(2) Middle Miocene NE-directed compression of thrust- and strike-slip type during the subsequent stage of extrusion caused sinistral movements along NE-striking faults which were partially linked with NE-directed thrusts. Locally, thrust distances exceeded 6 km (Warscheneck nappe), sinistral offsets at strike-slip faults reached up 30 km (Pyhrn fault). Most of the sinistral displacement along the Salzach-Ennstal fault occured during this stage. NE-directed compression in the Calcareous Alps resulted from the drag of the eastward extruding central Eastern Alps. Sinistral shear stress was transmitted across the ENE-trending Salzach-Ennstal fault. NE-oriented $\sigma 1$-axes include 45° with the E-W-striking zone of distributed sinistral shear in the Calcareous Alps.

(3) Middle Miocene E-directed extension was associated with orogen-parallel normal faulting of the central Eastern Alps. E-directed extension paralleled the direction of mass transfer towards the Pannonian Basin during lateral extrusion. Normal faulting was induced by reduced lateral confinement east of the Alps due to the eastward motion of the Pannonian lithospheric fragments. On the large scale, eastward motion was enabled by the E-directed retreat of the Eastern Carpathian subduction zone.

Key words: Northern Calcareous Alps, Miocene tectonics, lateral extrusion, paleostress

Introduction

The Tertiary tectonic evolution of the Eastern Alps was characterized by generally N-S directed postcollisional shortening between the Adriatic upper plate and the European lower plate, and by N-directed folding and thrusting (e.g., Tollmann, 1976; Ring et al., 1989; Decker et al., 1993; Fig.1). The onset of continental collision is dated by the extinction and overthrust of the Penninic ocean which separated the two continental plates up to the Early Eocene. The youngest Flysch deposits of these deep water Flysch basins are dated with c. 53 Ma (Fig. 2; Egger, 1990; Schnabel, 1992). Continued post-collisional convergence caused overthrusting of the passive ("Helvetic") margin of the European plate which was eliminated during the Late Eocene (37 Ma; Hagn et al., 1981; Rögl, pers. com.) and overthrusting of the Molasse during the Miocene (24-17 Ma; Kröll and Wessely, 1967). Postcollisional convergence lasted for about 36 Ma years and gave rise to extensive deformation within the Calcareous Alps, the Flysch- and Helvetic nappes, and the overthrust Molasse which formed the leading edge of the upper plate. Total thrust shortening is estimated to excede 200 km with a minimum of 35 km Late Oligocene to Early Miocene shortening (compare sections by Wessely in Brix and Schultz, 1993; Wessely, 1987). The latter thrust distance is constrained from overthrust Molasse sediments drilled below the Calcareous Alps (Wessely, 1987).

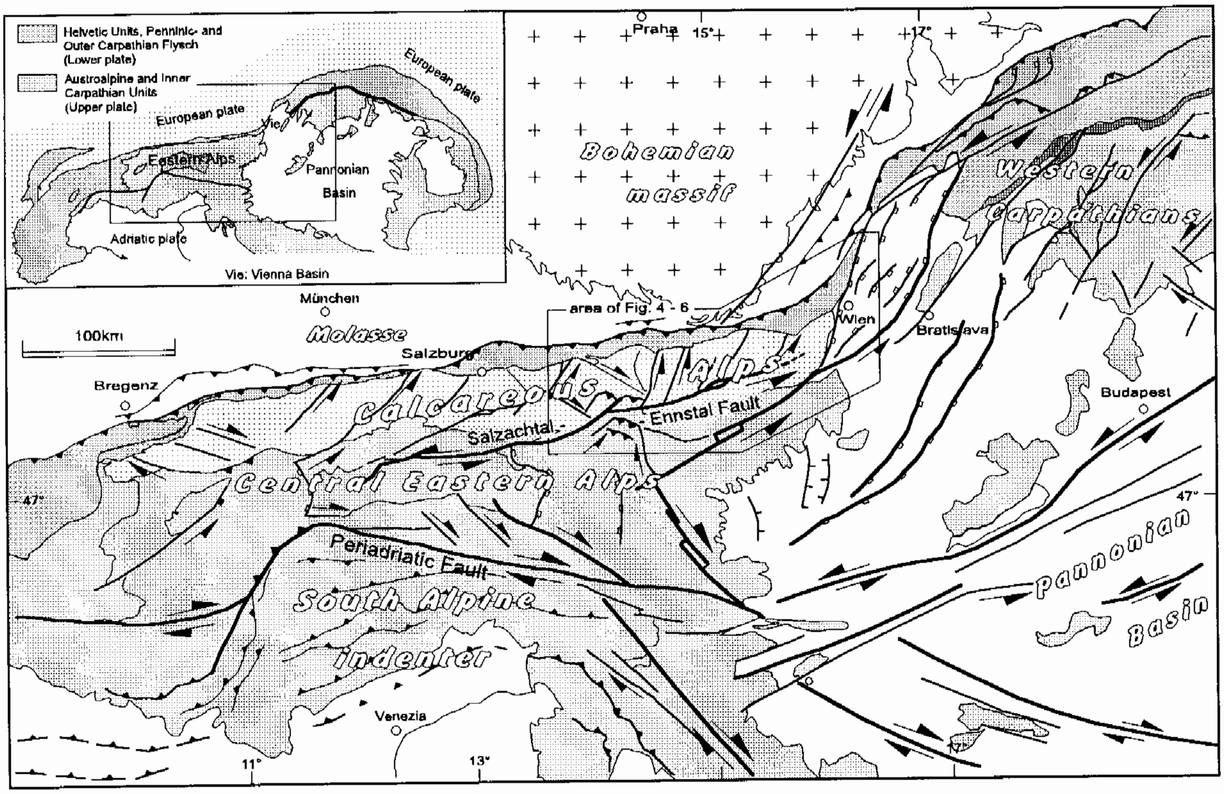

Fig. 1. Miocene tectonic map of the Eastern Alps and surrounding areas. Compiled from Doglioni and Siorpaes, 1990; Ratschbacher et al., 1991; Horvath, 1993; Decker et al., 1994.

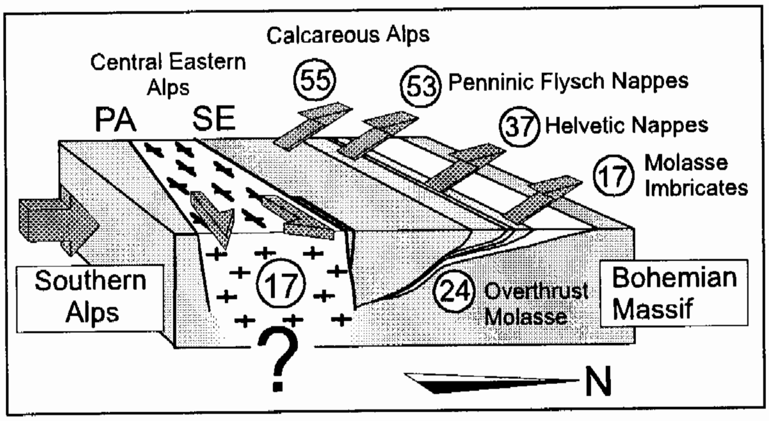

Fig. 2. Schematic block diagram illustrating the timing of foreland propagating thrusting in the northern Eastern Alps and lateral extrusion of the central Eastern Alps. Numbers in circles refer to thrust ages determined by the stratigraphic ages of the youngest overthrust sediments.

Thrusting at the northern margin of the Eastern Alps terminated in the Early Miocene (Kröll and Wessely, 1967). At about the same time, deformation which accounted for continued N-S shortening changed from thrusting and crustal thickening to lateral extrusion and orogen-parallel extension (Ratschbacher et al., 1991a, b). Wedges of the central Eastern Alps moved out of the convergent zone towards the Pannonian region (Royden et al., 1983; Royden, 1988; Neubauer and Genser, 1990). Eastward motion occured between sets of ENE-striking sinistral faults like the Salzachtal-Ennstal fault in the north and ESE-striking dextral faults in the south (Fig. 1). Miocene E- and W-directed detachment

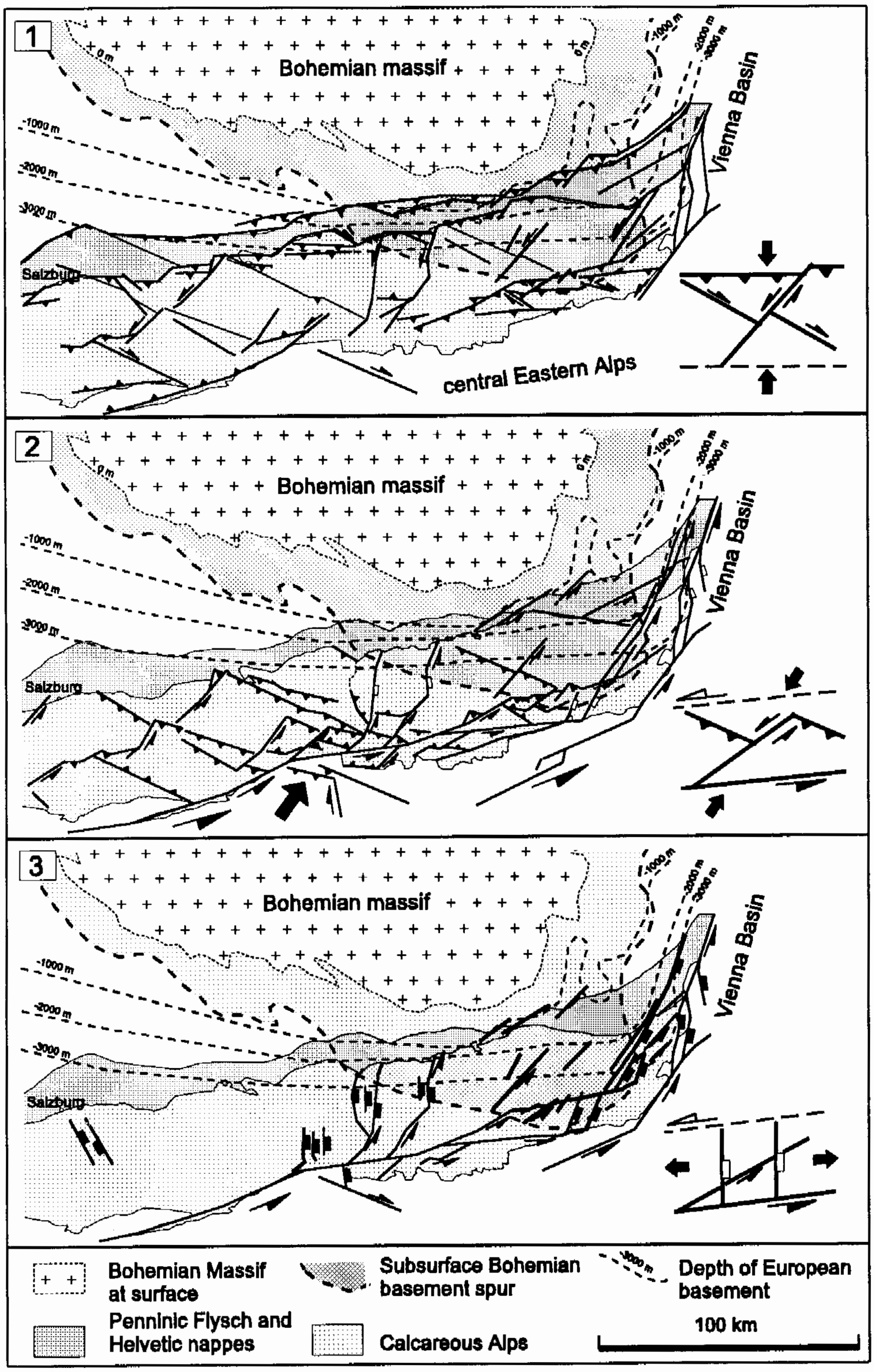

Fig. 3. Simplified kinematic maps of the northern Eastern Alps during the three discerned stages of eastward extrusion (after Peresson and Decker, in press). (1) N-directed compression during the ?Oligocene - Early Miocene. Sinistral NE-striking faults which branch off from the Salzachtal-Ennstal fault formed during the onset of lateral extrusion. (2) NE-directed reverse faults and kinematically linked sinistral ENE-trending faults accommodated NE-directed compression during the second stage of lateral extrusion in the Middle Miocene. The subsurface extent of the Bohemian spur (Wessely, 1987) and the present depth of the basement (Brix and Schulz, 1993) are shown. (3) Middle Miocene E-directed extension generated conjugate normal faults and reactivated strike-slip faults with oblique normal-sinistral slip.

faults in the central Eastern Alps exhuming the metamorphic Tauern dome and the Rechnitz core (review by Decker and Peresson, in press; Dunkl and Grasemann, this vol.; Tari, this vol.) reflect the gravitational instability of the Alpine nappe stack. Analogue experiments by Ratschbacher et al. (1991a) indicate that gravitational forces together with the indentation of the Southern Alps (Fig. 1) caused the Miocene east-directed extrusion of crustal wedges from the Eastern Alps into the Pannonian region. In the Early and Middle Miocene, the Salzach-Ennstal fault zone separated the Calcareous Alps from the eastward moving central Eastern Alps (Fig. 1; Linzer et al., 1995; 1996). In the Calcareous Alps, a set of sinistral NE- to ENE-trending strike-slip faults formed which cut and offset Cretaceous to Paleogene structures (Fig. 1; Ratschbacher et al., 1991b; Linzer et al., 1996). These faults branched off from the Salzach-Ennstal shear zone in the southern Calcareous Alps (Linzer et al., 1991). Several of these major faults were kinematically linked with NE-directed thrusts, acting like tear faults during NE-directed shortening (Decker et al., 1994). At the eastern margin of the Calcareous Alps the Vienna Basin opened along NE-trending sinistral faults during Miocene extrusion (see Decker, this vol.).

Miocene dynamics of the Calcareous Alps

Comprehensive analysis of the Tertiary tectonic evolution of the Northern Eastern Alps have been given by Ratschbacher et al. (1991b), Linzer et al. (1995; 1996), and Peresson and Decker (in press). The following chapter focuses on paleostresses and related kinematics during Miocene lateral extrusion. Miocene deformations in the Calcareous Alps were distinguished from older, Cretaceous and Paleogene tectonics by concentrating on structures in Late Cretaceous to Early Eocene sediments of the Gosau group (Faupl et al., 1987; Wagreich and Faupl, 1994). Additional age constraints derived from deformed Miocene sediments of the Vienna Basin and from remnant Miocene deposits in the Calcareous Alps close to the Salzachtal-Ennstal fault (e.g., the Hieflau Basin; Fig. 6). Consequently, three Oligocene (?) to Middle Miocene deformations were discerned. These are (1) N-directed compression associated with strike-slip faulting; (2) NE-directed compression associated with both thrust- and strike-slip faults; and (3) E-directed extension. The stages (2) and (3) are dated as post-Karpatian (< 17 Ma). Figure 3 summarizes schematic tectonic maps which show fault kinematics in the Calcareous Alps associated with the three tectonic stages.

(1) N-directed compression

N-S compression is indicated by conjugate dextral and sinistral slickensides which trend NW and NE, respectively (Fig. 4). The mean direction of 86 computed $\sigma 1$-orientations trends N (358/01), mean $\sigma 3$ is oriented W (268/00). The recognition of such microfaults in most stations indicates that this stress event was associated with significant strain. In contrast to the outcrop-scale microfault patterns (plots in Fig. 4), map-scale fault patterns show a strong assymetry with sinistral faults dominating. NNE to NE striking sinistral faults which cut both Paleogene thrust faults and NW-striking dextral faults (Fig. 3-1) formed during the onset of eastward lateral extrusion (Ratschbacher et al., 1991b; Linzer et al., 1995; 1996). These faults transferred part of the eastward motion of the central Eastern Alps into the Calcareous Alps. Initial slip along the ENE-trending Salzach-Ennstal fault in the southern Calcareous Alps, which formed the boundary to the extruding units, was sinistral-transpressive (Fig. 1 and 3). The early stage of extrusion during the (?)Oligocene to Early Miocene therefore was characterized by N-directed compression within the Calcareous Alps. N-directed compression paralleled the convergence direction between the Adriatic and European plates (Dewey et al., 1989) and traced the northward indentation of the Southern Alps into the central Eastern Alps (Fig. 1).

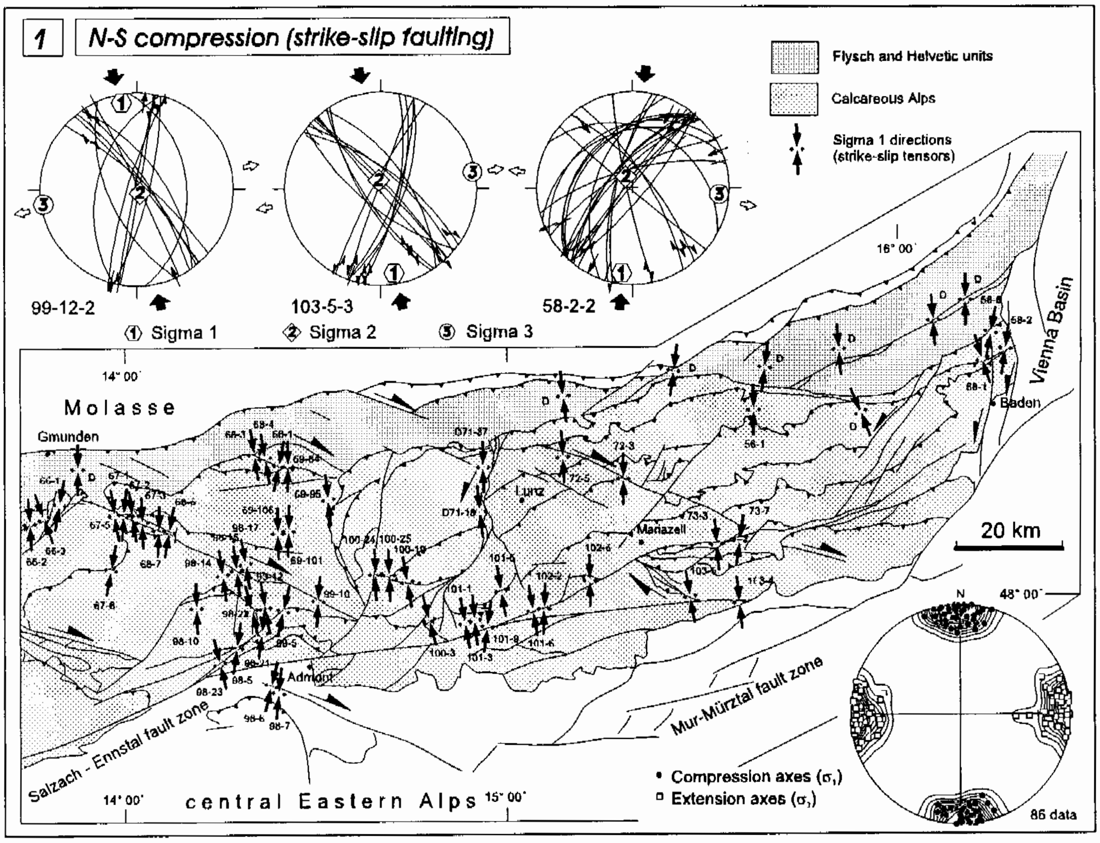

Fig. 4. Orientations of σ1 (black arrows) of paleostress tensors related to the early stage of lateral extrusion (N-directed strike-slip compression). See Decker at al. (1993) and Peresson and Decker (in press) for data base. Plot on right bottom: orientation of σ1 (filled circles) and σ3 (open squares) of the complete data set (86 tensors); Plots on top: Typical sets of mesoscale slickensides used for paleostress computation.

(2) NE-directed compression (Middle Miocene)

Paleostresses related to NE-directed compression were computed from both, conjugate reverse and strike-slip faults. Reverse faults trend NW with dip-slip slickenlines on fault surfaces. Mean σ_1 computed from sets dominated by reverse faults is oriented 038/02, σ_3 is subvertical (Fig. 5). Fault sets with conjugate N-trending dextral and ENE-trending sinistral strike-slip faults give a mean compression direction σ_1 oriented 042/03, σ_3 is trending 312/03 (Fig. 5). The occurrence of reverse and strike-slip faults indicates local variations of the stress field due to stress partitioning at structural boundaries. NE-compressional structures were found in Early Miocene (Karpatian, 17 Ma) conglomerates of the Hieflau Basin suggesting a Middle Miocene deformational age (Fig. 6). Close to the Vienna Basin, NE-directed compression is substituted by NW-directed extension as shown by vertical σ_1- and NW-trending σ_3-axes.

Middle Miocene NE-directed compression correlated the formation of sinistral (E)NE-striking faults which branched off from the Salzach-Ennstal fault and which were partially linked to NE-directed thrusts. Deformation along the Salzach-Ennstal fault was characterized by the formation of convergent flower structures (Fig. 7). The Bärengraben-flower (comp. Nemes et al., 1995) shows symetric fault patterns with NE-directed sinistral-reverse faults north of the main fault and SW-directed sinistral-reverse faults south of the main fault (Fig. 7). Close to the Bärengraben locality, in the Hieflau Basin south of the Salzach-Ennstal fault, Early Miocene sediments (Wagreich et al., 1996) were deformed and thrust towards SW (Fig. 6).

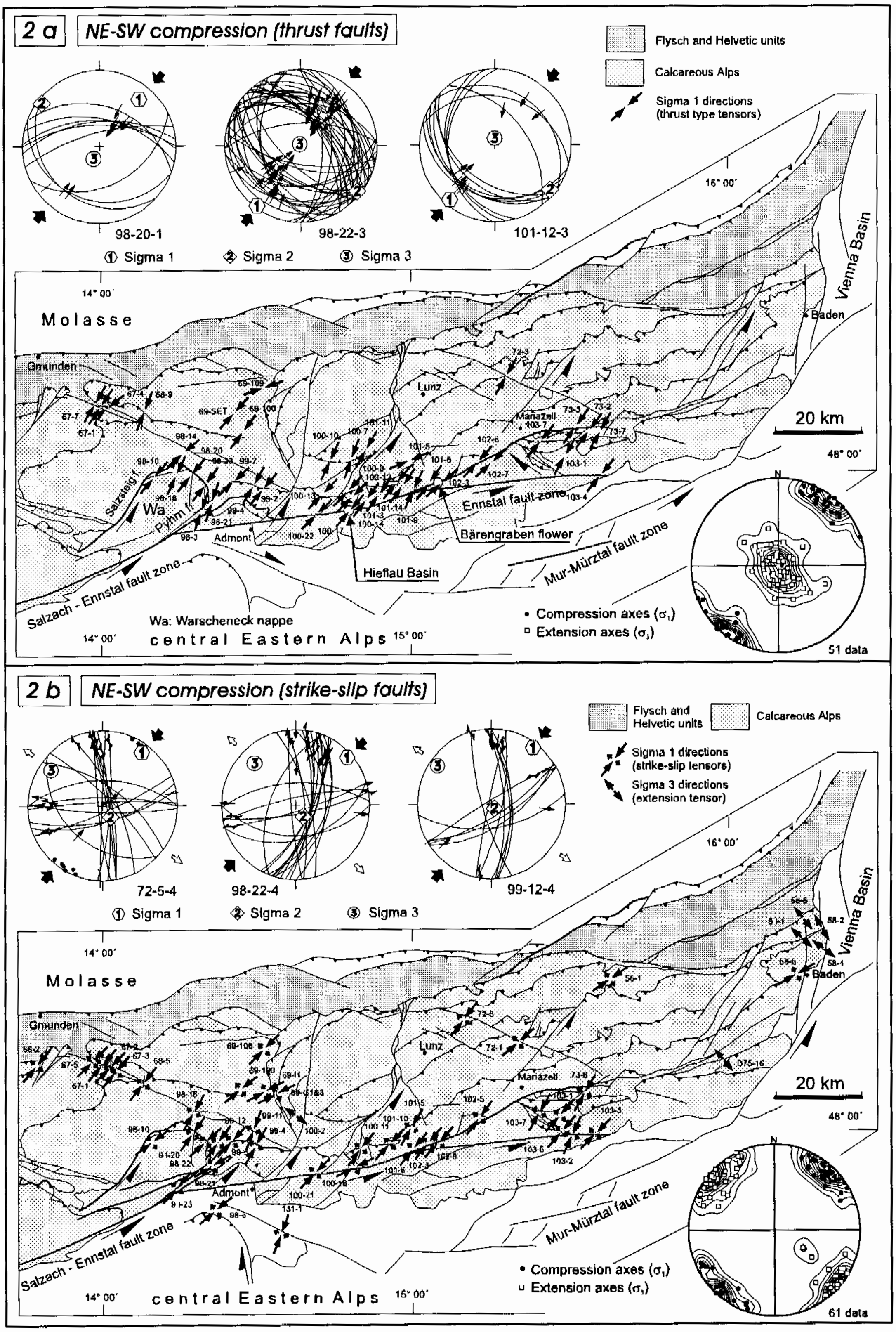

Fig. 5. Orientations of σ1 (black arrows) of paleostress tensors related to the second stage of lateral extrusion in the Middle Miocene. See Decker at al. (1993) and Peresson and Decker (in press) for data base. (2a) Thrust type NE-directed compression. Plot on right bottom: orientation of σ1 (filled circles) and σ3 (open squares) of the complete data set (51 tensors). (2b) Strike-slip-type NE-directed compression. Plot on right bottom: orientation of σ1 (filled circles) and σ3 (open squares) of the complete data set (61 tensors). Plots on top: Typical sets of mesoscale slickensides used for paleostress computation.

(61 tensors). Plots on top: Typical sets of mesoscale slickensides used for paleostress computation.

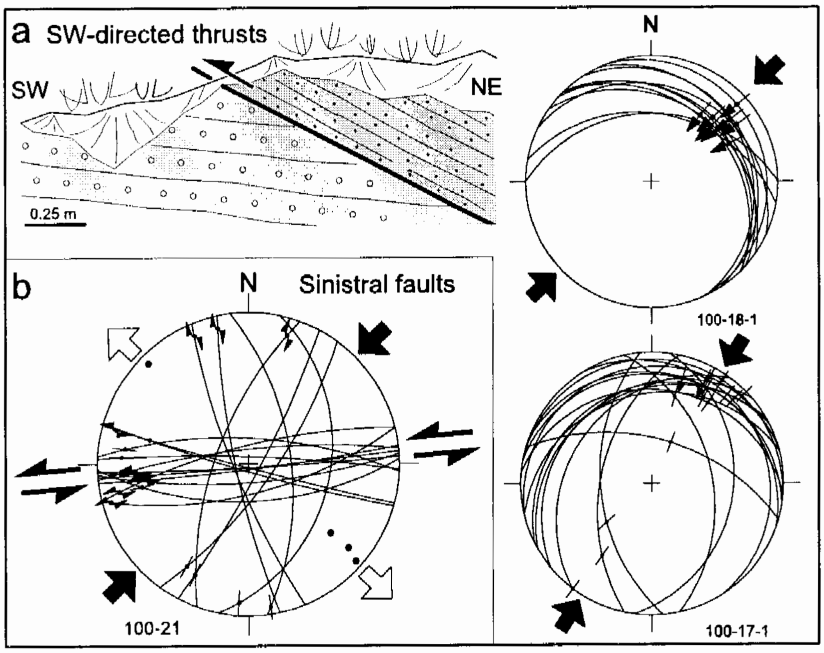

Fig. 6. Deformation structures in Early Miocene sediments of Hieflau. (a) Ramp-flat geometry in conglomerates and sandstones related to SW-directed thrusting. (b) E-W striking sinistral faults paralleling the main trend of the Salzach-Ennstal fault.

In the western part of the study area, transpressional faults which are linked to NE-directed thrusts prevail. Such faults include transpressional segments with convergent strike-slip duplexes and flower structures. Quantification of uplift and transpression of such duplexes constrains a basal detachment level at the base of the Calcareous Alps (Decker and Peresson, 1996). Up to 30 km of sinistral offsets are documented for individual faults (e.g. the Pyhrn fault). Thrust distances of connected NE-directed thrusts are in the order of several kilometers. The sole thrust of the Warscheneck nappe which is connected with the Salzsteig fault shows a minimum displacement of 6 km over the Gosau sediments of Windischgarsten (Fig. 5). NE-directed shortening also reactivated Eocene WNW-striking faults as high-angle reverse faults (Fig. 3-2).

NE-directed thrusts are most abundant close to the Salzach-Ennstal shear zone in the south of the Calcareous Alps and in the area SW of the Bohemian basement spur. This basement spur formed a morphologic high of the overthrust lower plate below the Calcareous Alps which extended more than 50 km behind the alpine deformation front (Wessely, 1987). We suggest that it acted as a frontal ramp during NE-directed thrusting. Accordingly, basement morphology was responsible for compressional deformation at the advancing (SW) side of the basement high and for extensional deformation at its retreating (SE) side (Fig. 3-2). SE of the Bohemian basement spur, large Early- to Middle Miocene extensional strike-slip faults formed adjacent to the Vienna Basin.

Stress orientations during NE-compression are interpreted as the sum of regional N-directed compression due to continued northward translation of the Adriatic plate and sinistral shear which was exerted by the eastward moving central Eastern Alps during lateral extrusion. According to this model, the eastward extruding central Eastern Alps were not completely decoupled from the Calcareous Alps by the sinistral Salzach-Ennstal fault. The drag of the extruding units induced sinistral shear in the Calcareous Alps north of the fault in which $\sigma 1$ was deflected from N to NE (Peresson et al., 1993). Sinistral faults and NE-directed thrusts defined a broad sinistral shear zone and indicate that the Calcareous Alps were detached from the underlying units.

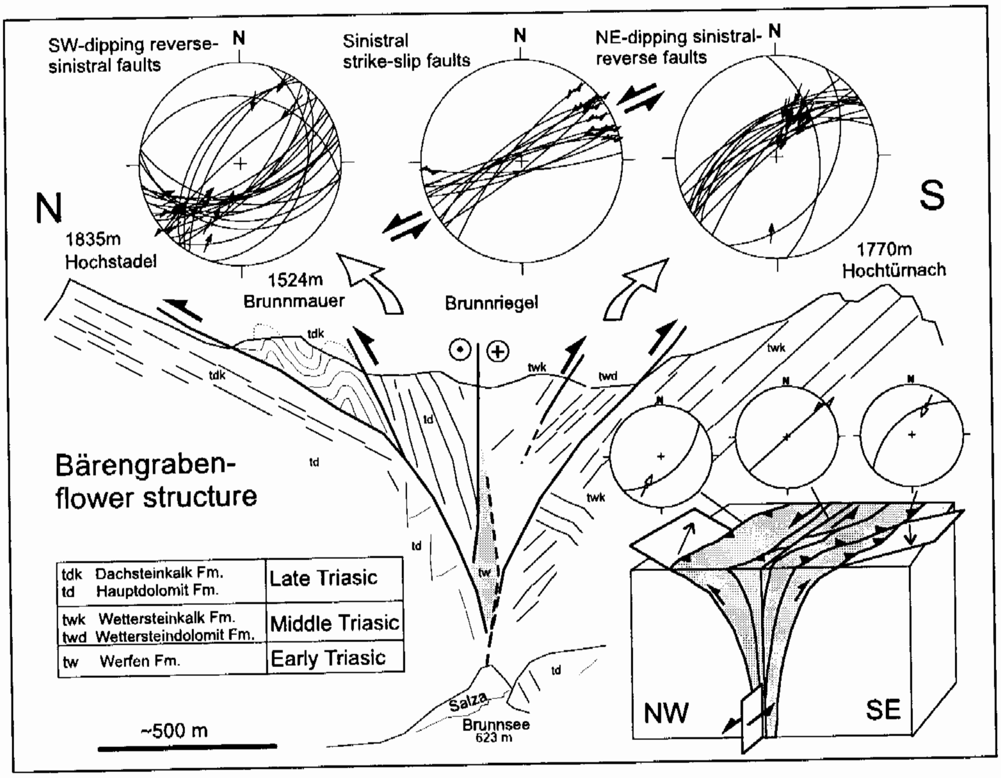

Fig. 7. Tectonic sketch of the Bärengraben-flower structure at the Salzachtal-Ennstal fault (E of Wildalpen; comp. Nemes et al., 1995). Sinistral strike-slip motion in the central part of the symetric positive flower structure is accompanied by NE-directed oblique thrusting N of the master fault and by SW-directed thrusting S of it.

(3) E-directed extension (Middle Miocene)

Significant E-directed extension overprinted all former compressional structures. Overprinting included the normal-slip reactivation of older strike-slip and thrust faults (Fig. 3-3) as well as the formation of cross-cutting N-striking normal faults. Normal and oblique-normal slip striations are generally dipping E or W and the computed extension direction $\sigma 3$ is oriented E-W (269/04), $\sigma 1$ is oriented vertically (Fig. 8). Deviations from generally E-W directed Extension occured near the Salzach-Ennstal fault where $\sigma 3$-trajectories were oriented NW and near the Vienna Basin where variable extension directions were found (Fig. 8; see Decker, this vol.).

Middle Miocene extensional structures include map-scale E-directed normal faults, minor W-dipping conjugate faults, and (E)NE-trending faults which were reactivated with normal-sinistral slip. Movements at the Salzach-Ennstal fault zone were characterized by sinistral transtension. Large-scale extensional structures marked the region S and SE of the overthrust Bohemian basement spur (Fig. 3-3) where increasing extensional strain marked the transition to the extensional basins of the Miocene Vienna- and Pannonian Basin system (Fig. 1). The Vienna Basin evolved E of the basement spur, indicating that the location of the basin was controlled by the geometry of the overthrust lower plate (Fig. 1).

Normal faulting in the Calcareous Alps was generally directed towards the east. Top-to-E extension conformed with the synchronous unroofing of metamorphic domes and E-directed detachment faulting in the central Eastern Alps which culminated in the Middle Miocene (Genser and Neubauer, 1989; Tari et al., 1992). E-directed normal faulting responded to the Miocene plate tectonic evolution in the Pannonian-Carpathian region. There, E-directed subduction roll back initiated upper plate extension of the Pannonian area (Royden, 1993a) and caused eastward shift of material east of the Alps. Extension in the Eastern

Alps thus parallels the E-directed mass flow during lateral extrusion from the Central Alps towards the Pannonian Basin. During extrusion, material was both squeezed out by N-S directed shortening across the Eastern Alps and "pulled" out of the convergent zone by trench suction along the retreating Carpathian plate boundary (Royden, 1993b).

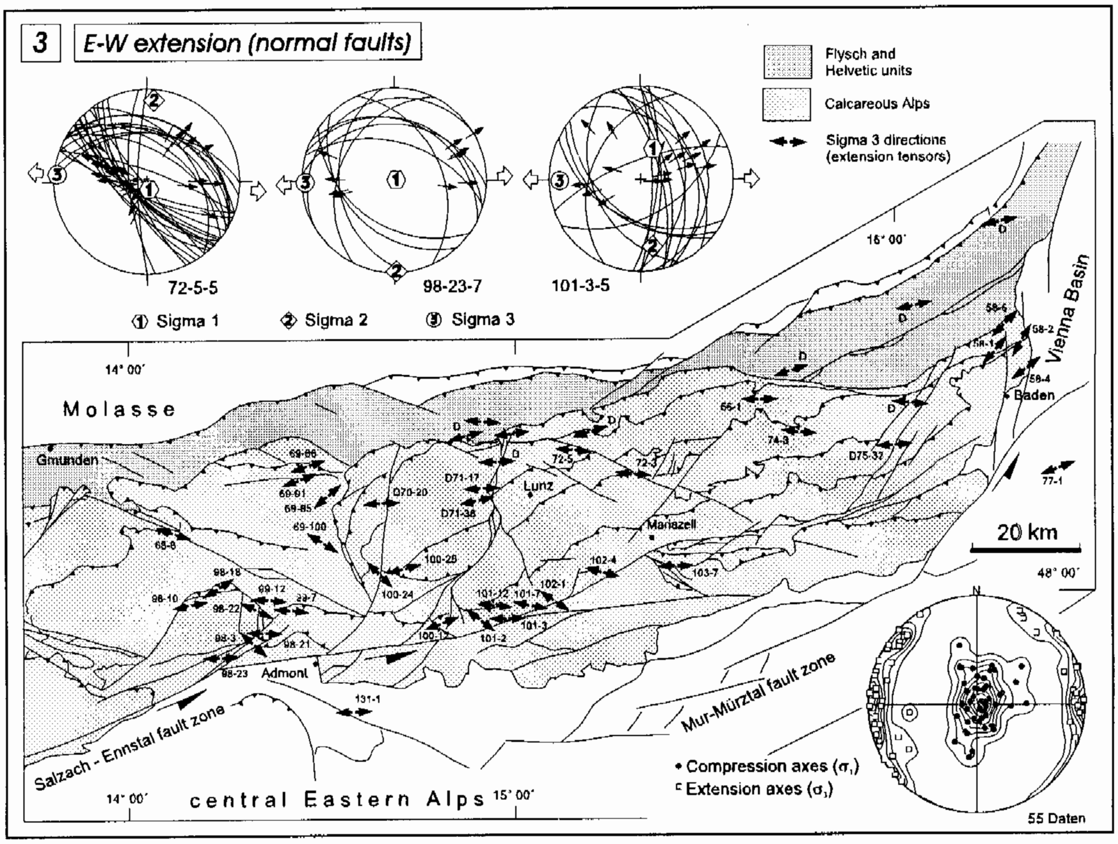

Fig. 8. Orientations of σ3 (black arrows) of paleostress tensors during the third stage of lateral extrusion in the Middle Miocene (E-directed extension). See Decker at al. (1993) and Peresson and Decker (in press) for data base. Plot on right bottom: orientation of σ1 (filled circles) and σ3 (open squares) of the complete data set (55 tensors); Plots on top: Typical sets of mesoscale normal faults used for paleostress computation.

Conclusion

Miocene paleostresses in the Calcareous Alps correlate to three kinematic stages during lateral extrusion. These stages are (1) Oligocene(?) to Early Miocene N-directed compression which is accomodated by NE-striking sinistral faults; (2) Middle Miocene NE-directed compression of both thrust- and strike-slip type during lateral extrusion; (3) Middle Miocene E-directed extension related to orogen-parallel extension. Paleostress orientations are found to be very consistent in the study area. Sets of small-scale slickensides, from which paleostress results were obtained, include new-formed conjugate shear planes and reactivated pre-existing faults. Changing paleostresses caused repeated slip on the faults with different directions and senses of shear. Kinematics of small scale slickensides mirror that of prominent map scale faults. Deformation of the sinistral ENE-trending Salzach-Ennstal fault changed gradually from transpression (stage 2) to transtension (stage 3).

The paleostress tensors describe the dynamics of the Calcareous Alps during final continental collision and eastward lateral extrusion. Paleostresses and related kinematics of the Calcareous Alps are explained by the complex interactions of three main processes:

(1) Shortening during northward motion of the Adriatic plate. ?Oligocene to Early Miocene distributed deformation in the Calcareous Alps under N-directed compression can be related to the northward translation of the Adriatic plate. Kinematic directions in the northern Eastern Alps therefore approximated the Adriatic translation vector and the N-directed indentation of the Southern Alps.

(2) Drag effects during the east-directed motion of the extruding central Eastern Alps. The stress change from N-directed to NE-directed compression is interpreted as the result of drag forces exerted by the eastward moving central Eastern Alps south of the Salzachtal-Ennstal fault which deflected the regional maximum compression direction from N to NE (Peresson et al., 1993). Their eastward extrusion was forced by continued northward indentation of the Southern Alps (Ratschbacher et al., 1991a, b). We argue that sinistral shear stress was transmitted into the Calcareous Alps north of the Salzachtal-Ennstal fault which caused strain partitioning into NE-directed out-of-sequence thrusts partly linked with NE-striking strike-slip faults and transpressional ENE-trending strike-slip faults.

(3) The remote effect of subduction in the Eastern Carpathians. Lateral extrusion of the central Eastern Alps continued as long as free space was created by the eastward-retreating subduction boundary in the outer Eastern Carpathians (Royden, 1993a). The existence of this free lateral interface E of the Eastern Alps resulted in Middle Miocene E-directed tensional stresses. After the locking of subduction in the Eastern Carpathians no more space was created by the roll back to account for E-directed motion of the extruding wedges. This Late Miocene event terminated the lateral extrusion process and was responsible for a complete dynamic change in the Alpine-Carpathian-Pannonian area (see Peresson and Decker, this volume).

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