

Miocene tectonics of the Maramures area (Northern Romania): implications for the Mid-Hungarian fault zone

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Received: 20 May 2005 / Accepted: 10 June 2006 / Published online: 11 August 2006
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Abstract The interplay between the emplacement of crustal blocks (e.g. “ALCAPA”, “Tisza”, “Dacia”) and subduction retreat is a key issue for understanding the Miocene tectonic history of the Carpathians. Coeval thrusting and basin formation is linked by transfer zones, such as the Mid-Hungarian fault zone, which separates ALCAPA from Tisza-Dacia. The presented study provides new kinematic data from this transfer zone. Early Burdigalian (20.5 to ~18.5 Ma) SE-directed thrusting of the easternmost tip of ALCAPA (Pienides), over Tisza-Dacia is linked to movements along the Mid-Hungarian fault zone and the Periadriatic line, accommodating the lateral extrusion of ALCAPA. Minor Late Burdigalian (~18.5 to 16 Ma) NE-SW extension is interpreted as related to back-arc extension. Post Burdigalian (post-16 Ma) NE-SW shortening and NW-SE extension correlate with “soft collision” of Tisza-Dacia with the European foreland coupled with southward migration of active subduction. During this stage the Bogdan-Voda and Dragos-Voda faults were kinematically linked to the Mid-Hungarian fault zone. Sinistral transpression (16 to 12 Ma) at the Bogdan-Voda fault was followed by sinistral transtension (12–10 Ma) along the coupled

Bogdan-Dragos-Voda fault system. During the trans-tensional stage left-lateral offset was reduced eastwards by SW trending normal faults, the fault system finally terminating in an extensional horse-tail splay.

Keywords Kinematic analysis · Eastern Carpathians · Mid-Hungarian fault zone · Pienides · Miocene tectonics

Introduction

Miocene tectonics in the Carpathian region is characterised by the formation of an arcuate fold-and-thrust-belt and contemporaneous back arc extension in the Pannonian basin (e.g. Royden 1988). The European margin features a large-scale bight between the Moesian and Bohemian promontories (Fig. 1). According to most authors (e.g. Balla 1982; Mason et al. 1998) this Carpathian “embayment” was at least partly floored by oceanic crust. Slab retreat (e.g. Royden 1988; Wortel and Spakman 2000; Sperner et al. 2005) created the necessary space that allowed for the invasion of large continental blocks (ALCAPA, Tisza and Dacia; Balla 1987) and smaller displaced terranes (Fig. 1).

Invasion of the ALCAPA block lasted from the Late Oligocene to the Middle Miocene (Fodor et al. 1999), but initiated earlier in case of the Tisza and Dacia blocks (Fügenschuh and Schmid 2005). Emplacement was accompanied by substantial strike-slip movements, together with extension, shortening and rotations of rigid blocks (Ratschbacher et al. 1993; Fodor et al. 1999; Márton 2000; Márton and Fodor 2003; Csontos and Vörös 2004; Horváth et al. 2005). The major displaced units are, from NW to SE (Fig. 1):

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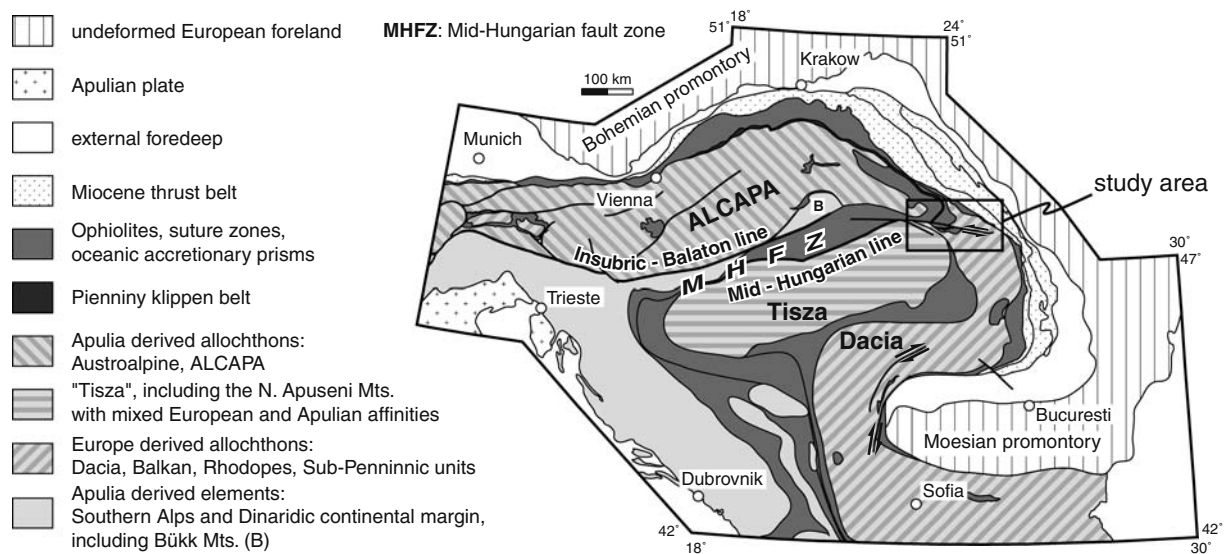


Fig. 1 Major tectonic units of the Alps, Carpathians, and Dinarides, simplified after an unpublished compilation by S. Schmid, B. Fügenschuh K. Ustaszewski, L. Matenco, R. Schuster and M. Tischler

1. Apulia-derived allochthons, such as the Austroalpine nappes of the Eastern Alps, that extend into the Central and Inner West-Carpathians (ALCAPA, e.g. Plasienka et al. 1997a, b).
2. A small stripe of units situated within the intensely deformed belt of the Mid-Hungarian fault zone (Fig. 1), whose Upper Paleozoic and Mesozoic cover (outcropping in the Bükk Mountains) has a marked affinity to the internal Dinarides (Kovács et al. 2000; Haas et al. 2000). These Dinaridic units also contain remnants of obducted ophiolites and oceanic accretionary prisms.
3. The Tisza block, located SE of the Mid-Hungarian fault zone and largely covered by the Neogene fill of the Pannonian basin, crops out in the North Apuseni mountains, as well as in a series of Hungarian and Croatian inselbergs. The paleogeographic position of the Tisza unit is much debated (e.g. Burchfiel 1980; Săndulescu 1984, 1994; Csontos et al. 1992; Balintoni 1995; Fodor et al. 1999; Haas and Pero 2004). Its Mesozoic cover with European as well as Apulian affinities suggests that it broke off Europe along an eastern extension of the Piedmont-Liguria basin in Mid-Jurassic times (Haas and Pero 2004; Stampfli and Borel 2004).
4. The Dacia block is a Europe-derived allochthon (or “Rhodopian” allochthon, Burchfiel 1980; Schmid et al. 1998; Fügenschuh and Schmid 2005), comprising the Balkan mountains, the Getides of the Southern Carpathians, as well as the Eastern Carpathian Bucovinian nappe system (Median

Dacides of Săndulescu et al. 1981; Săndulescu 1994). Some authors consider Tisza and Dacia as representing one single block (e.g. “Tisza-Dacia terrane” of Csontos and Vörös 2004) since the Late Cretaceous, but it is not yet sure as to how firmly Dacia remained attached to Tisza since the Mid-Cretaceous orogeny.

The development of the Carpathian orogen is also highly influenced by tectonic events within the Alps (Schmid et al. 2004a, b) and the Dinarides (Pamir 2000; Dimitrijevic 2001). Particularly the onset of “lateral extrusion”, a mechanism defined by Ratschbacher et al. (1991a, b) in the Eastern Alps, is of major importance: Indentation by the South Alpine block, coupled to retreat of the descending European lithosphere (Royden 1988; Wortel and Spakman 2000), led to the ENE-ward translation of the ALCAPA block along the Insubric-Balaton line.

However, since the emplacement of Tisza and Dacia is unrelated to indentation in the Alps, subduction retreat is considered to provide the principal driving force for the invasion of the various blocks into the Carpathian embayment (Royden 1988; Wortel and Spakman 2000; Sperner et al. 2005). Furthermore subduction and retreat of the European plate beneath the inner Carpathians led to the formation of a back-arc-type basin: the Pannonian basin (i.e. Horváth et al. 2005; Cloetingh et al. 2005). Net east-west extension in the Pannonian basin is realized by normal faulting connected via conjugate strike-slip dominated systems.

These strike-slip systems are also kinematically linked to synchronous thrusting in the external Miocene thrust belt (Royden 1988).

Field-based studies in the West Carpathians shed light on the interplay between subduction retreat and “lateral extrusion” (e.g. Nemčok 1993; Ratschbacher et al. 1993; Sperner et al. 2002). These authors documented NE-ward displacement and counter-clockwise rotation of the ALCAPA block, guided by strike-slip zones oriented sub-parallel to the collision suture. NNE–SSW shortening and ESE–WNW extension were the dominant modes of deformation during Late Oligocene to Mid-Miocene NE-ward movement of ALCAPA. After soft collision of ALCAPA with the European margin in the Western Carpathians at around 13 Ma ago, active subduction continued only further to the southeast, inducing NW–SE extension in the area of the Western Carpathians (Sperner et al. 2002).

The Mid-Hungarian fault zone played a key role during the emplacement of the various blocks in the Carpathian embayment. This major NE-trending strike-slip zone is thought to accommodate differential movements between ALCAPA and Tisza-Dacia (Fig. 1). It is bounded to the north by the Balaton line, the NE-wards continuation of the Periadriatic line (Fodor et al. 1998). The southern boundary of the Mid-Hungarian fault zone is termed Mid-Hungarian line, defined as “a major strike-slip fault along which the ALCAPA and Tisza–Dacia units of different provenance were juxtaposed” by Csontos and Nagymarosy (1998). ALCAPA, Tisza and Dacia feature contrasting Triassic and Jurassic sedimentary facies and fossil assemblages (Csontos and Vörös 2004, and references therein). The first important activity within the Mid-Hungarian fault zone occurred during the Oligocene (or earlier) (Csontos et al. 1992; Csontos and Nagymarosy 1998; Fodor et al. 1999). Thereby collision led to thrusting of the ALCAPA block over Tisza and Dacia in Late Oligocene times (Csontos and Nagymarosy 1998).

Corner effects at the Bohemian (Sperner et al. 2002) and Moesian (Ratschbacher et al. 1993; Schmid et al. 1998) promontories, respectively, led to opposed rotations well established by paleomagnetic studies (e.g. Márton and Fodor 1995, 2003; Márton 2000). While the timing of the emplacement of the ALCAPA block is fairly well constrained to have occurred between Late Oligocene and Middle Miocene times (Fodor et al. 1999; Sperner et al. 2002), emplacement of the Dacia (and Tisza?) block commenced earlier [during the Eocene according to Fügenschuh and Schmid (2005)], and ended later (in post-Middle

Miocene times, e.g. Matenco et al. 2003). During Mid–Late Miocene times (i.e. after 16 Ma) strike-slip deformation and extension dominated within the Mid-Hungarian fault zone, allowing for ongoing differential movements of the ALCAPA and Tisza-Dacia blocks (Csontos and Nagymarosy 1998). During this late stage the Mid-Hungarian fault zone may also have served as a transfer zone between the foreland thrust belt and the back-arc extension domain. In conclusion, diverging movement vectors as well as large opposed rotations call for important and complex tectonic movements within the Mid-Hungarian fault zone all the way from Oligocene to Miocene times.

This study covers the outcropping parts of the Mid-Hungarian fault zone at its NE termination in northern Romania (Fig. 1). The thrust contact of the so-called “Pienides” (Săndulescu et al. 1981), flysch nappes situated at the contact of the easternmost tip of ALCAPA with Tisza-Dacia, represents the Early Miocene Mid-Hungarian line sensu Csontos and Nagymarosy (1998) and is exposed in the study area. The Bogdan-Voda and Dragos-Voda strike-slip faults, as well as the Preluca fault near the northeastern rim of the Tisza block (Fig. 2), are first order candidates for representing surface exposures of the Mid-Hungarian fault zone that were active during Mid–Late Miocene times.

This study aims to provide further constraints on the timing and kinematics of movement along the Mid-Hungarian fault zone during back-arc extension and final emplacement of the ALCAPA, Tisza and Dacia blocks. With the aid of published and unpublished (Săndulescu personal communication.) maps of the Geological Survey of Romania, our field-work focussed on the analysis of kinematic data and was assisted by apatite fission track analyses. Stratigraphic ages are after Gradstein et al. (2004), Mediterranean and Parathetys stages are correlated according to Steininger and Wessely (2000).

Geological setting

The study area, located in the internal East Carpathians (Northern Romania) near the transition to the Western Carpathians (Fig. 1), comprises the northeastern tip of the Tisza block (Biharia unit) and the northernmost part of Dacia (Bucovinian nappes). Alpine-age deformation within the Bucovinian nappes and the Biharia unit started in Mid-Cretaceous times (“Austrian” phase) and continued until Late Cretaceous times (“Laramide” phase, Săndulescu et al. 1981; Săndulescu 1994). Upper Cretaceous–Paleocene sediments unconformably cover these Mid- and Late-Cretaceous

tectonic contacts, as well as contacts between Tisza, Dacia and intervening oceanic remnants (Fig. 1). Eocene–Burdigalian strata were deposited above a second unconformity. This mainly Tertiary cover is referred to as “autochthonous cover of Tisza-Dacia” in the following. During final closure of the Carpathian embayment, the Bucovinian nappes were emplaced onto Cretaceous–Miocene flysch deposits now forming the Miocene fold-and-thrust-belt of the East Carpathians.

Tisza and Dacia, together with their autochthonous cover, were overthrust by the Pienides during Burdigalian times (Săndulescu et al. 1981). According to Săndulescu et al. (1993) the Pienides, situated at the easternmost tip of ALCAPA, comprise an external (Petrova, Leordina and Wildflysch nappes) and an internal thrust sheet (Botiza nappe). Internal and external Pienides, mainly consisting of Eocene–Oligocene non-metamorphic flysch units, can be correlated with the Ivancovec-Krichevo units and the Magura flysch of the Western Carpathians, respectively (Săndulescu et al. 1981; Săndulescu 1994). Furthermore the internal Pienides feature frontal imbricates

containing phacoids of Pieniny Klippen type material embedded in Eocene flysch (Săndulescu et al. 1993). Note that these units and their equivalents form the innermost part of the Outer West Carpathians (Plasienska et al. 1997a, b), while they take a more internal position in our working area.

The post-Burdigalian infill of the Pannonian and Transylvanian basins in the working area starts with the deposition of the Mid-Miocene (Badenian) Dej tuff during a period of mainly acidic volcanism (Mason et al. 1998). Subduction-related calc-alkaline magmatism (Mason et al. 1998) started during Middle Miocene times in the working area (13.5 Ma, Pécskay et al. 1995). Magmatic activity led to the formation of a linear chain along the inner side of the East Carpathians decreasing in age from 12 Ma in the NW to 0.2 Ma in the SE.

From a tectonic point of view the most obvious structure is the E-striking, predominantly left-lateral, Bogdan-Drăgos-Voda fault system. The Bogdan-Voda fault to the west offsets the autochthonous cover of Tisza-Dacia, as well as the nappe pile of the Pienides,

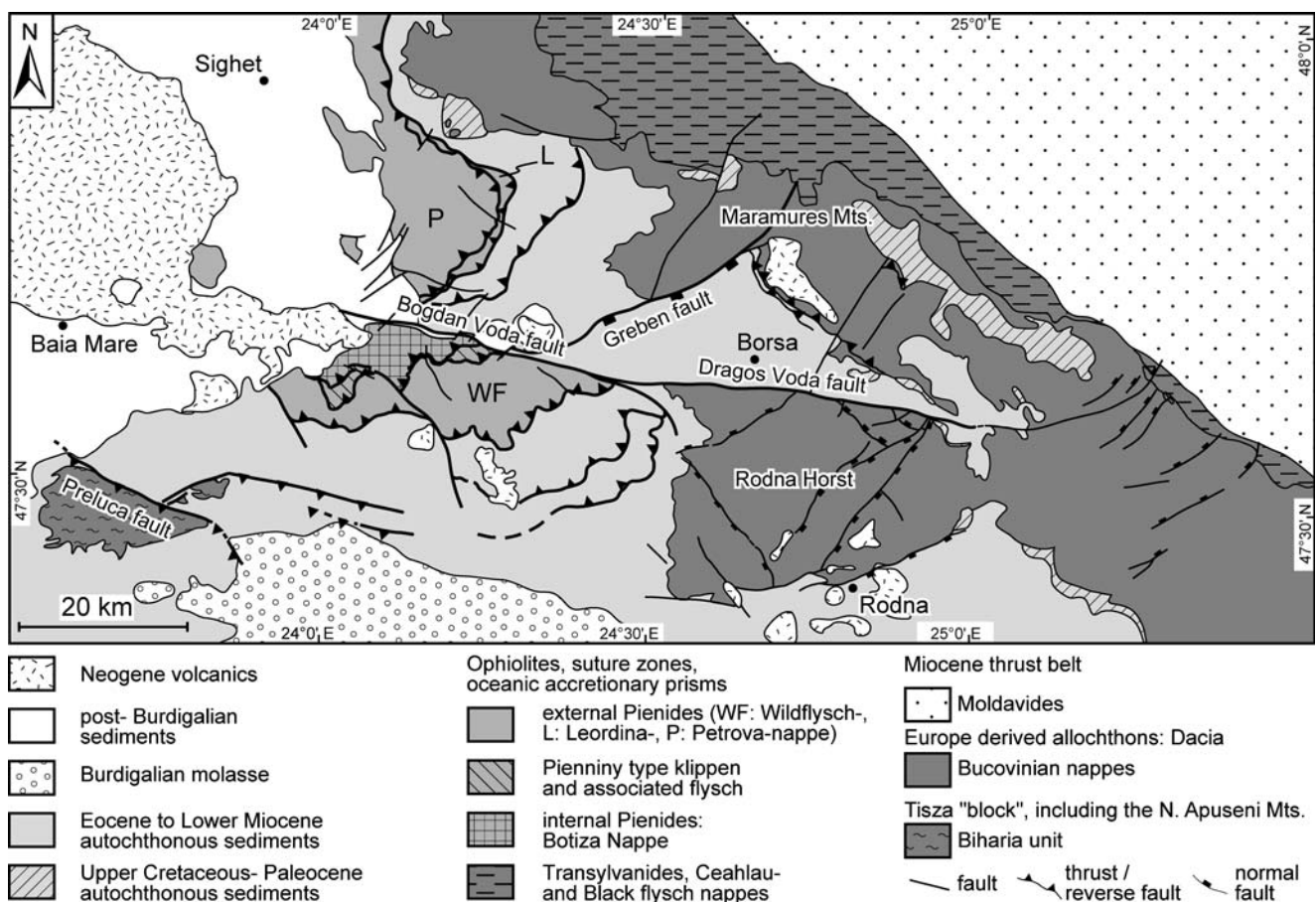


Fig. 2 Tectonic map of the study area based on published geological maps (1:50,000 and 1:200,000) of the Geological Survey of Romania, Dicea et al. (1980), Săndulescu (1980), Săndulescu et al. (1981) and Aroldi (2001)

and is sealed by Mid-Miocene volcanics. The Dragos-Voda fault to the east forms the northern limit of a horst-like crystalline body (“Rodna horst”, Fig. 2), built up by the Bucovinian nappe stack. Possible linkage of and mutual relationships between these two fault segments have been a point of discussion in the Romanian literature. While Săndulescu et al. (1981) interpreted the two faults as separate, Dicea et al. (1980) mapped a single continuous fault. Other authors (e.g. Huismanns et al. 1997, Györfi et al. 1999) mapped one single fault termed “Dragos-Voda fault”.

Methods

Derivation of kinematic axes

Kinematic axes (principal shortening and extension directions) were derived from meso-scale structures in order to analyse the regional tectonic history. For this purpose, fault-slip sets (orientation of fault plane, sense and direction of movement) were analysed. Fieldwork focussed on correlation of the kinematic data with large-scale structures.

The direction of movement being given by a lineation (mechanical striation or slicko-fibre orientation), the sense of movement was determined by criteria such as slicko-fibre growth direction, orientation of Riedel shears or offset of marker horizons. Inhomogeneous data sets were separated into homogenous subsets based on field observations, and their kinematic compatibility (Fig. 3).

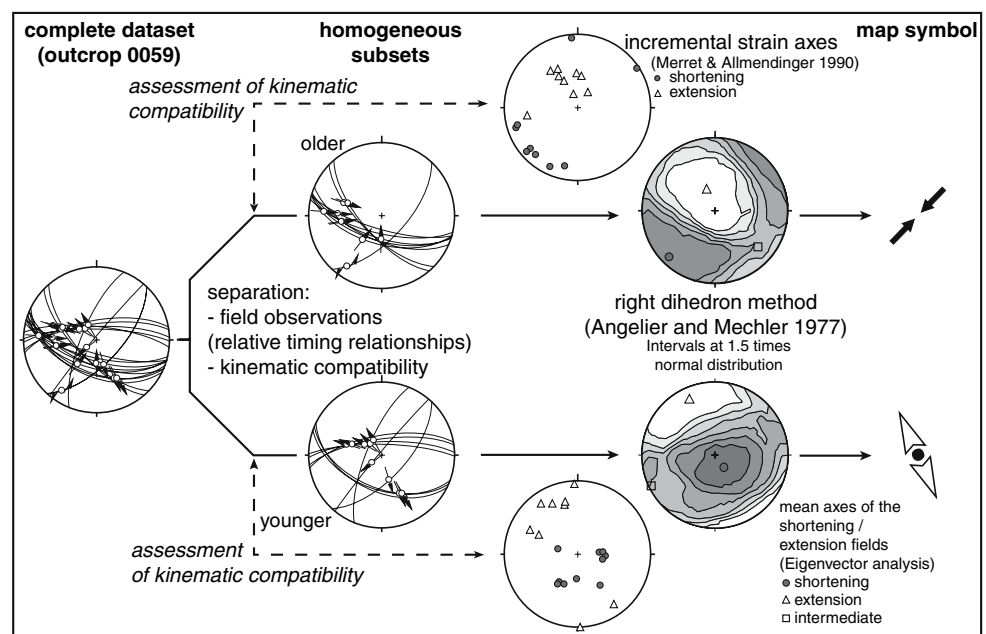
Kinematic axes were computed with the right dihedral method described by Angelier and Mechler (1977). Applicable to newly formed, as well as to reactivated pre-existing fractures, this simple graphical method reflects the bulk finite strain state (Pfiffner and Burkhard 1987). Eigenvectors and Eigenvalues (Bingham 1964) have been used to determine mean axes of shortening and extension (Fig. 3). A tabular overview on the analysed stations is found in Appendix 1. For calculation of kinematic axes and visualisation of fault sets we used the software TectonicsFP (Franz Reiter and Peter Acs©1996–2000: <http://www.go.to/TectonicsFP>; based on TectonicVB by Hugo Ortner).

Fission track analysis

Apatite mineral concentrates were prepared by conventional crushing, sieving, magnetic and heavy liquid separation. The grains were mounted in epoxy resin, polished and etched for 40 s at room temperature in 6.5% HNO₃. Samples were analysed using the external detector method (Gleadow 1981), with muscovite as an external detector. Irradiation was carried out at the High Flux Australian Reactor with neutron fluxes monitored in CN5. Muscovite was etched 40 min at room temperature in 40% HF.

Fission tracks were counted on a computer-controlled Zeiss microscope at magnifications of X1250 (dry). Ages were calculated using the zeta-calibration method (Hurford and Green 1983) with a zeta-value of 355.96 ± 9.39 (CN5, Durango). For data processing the

Fig. 3 Flow chart for the analysis of fault-slip data. For the separation of homogenous subsets field observations as well as kinematic compatibility have been used. Kinematic compatibility has been assessed using plots of the fault sets and correspondent incremental strain axes (Marret and Allmendinger 1990). For map display mean axes of shortening and extension are used. Intersection relationships in the analysed outcrop show exemplary, that transpression was followed by transtension during the post Burdigalian stages



windows software TRACKKEY (Dunkl 2002) was used. All ages are central ages (Galbraith and Laslett 1993), with errors quoted as 1σ . Closure temperatures for apatite are $90 \pm 30^\circ\text{C}$, the uncertainty being given by the lower and upper limits of the apatite fission track partial annealing zone (Gleadow and Duddy 1981; Gallagher et al. 1998).

Structural analysis

Early Burdigalian top-SE thrusting of the Pienides

The emplacement of the Pienides during Burdigalian times (Fig. 2) also led to the imbrication of the autochthonous cover of Tisza-Dacia. Deformation

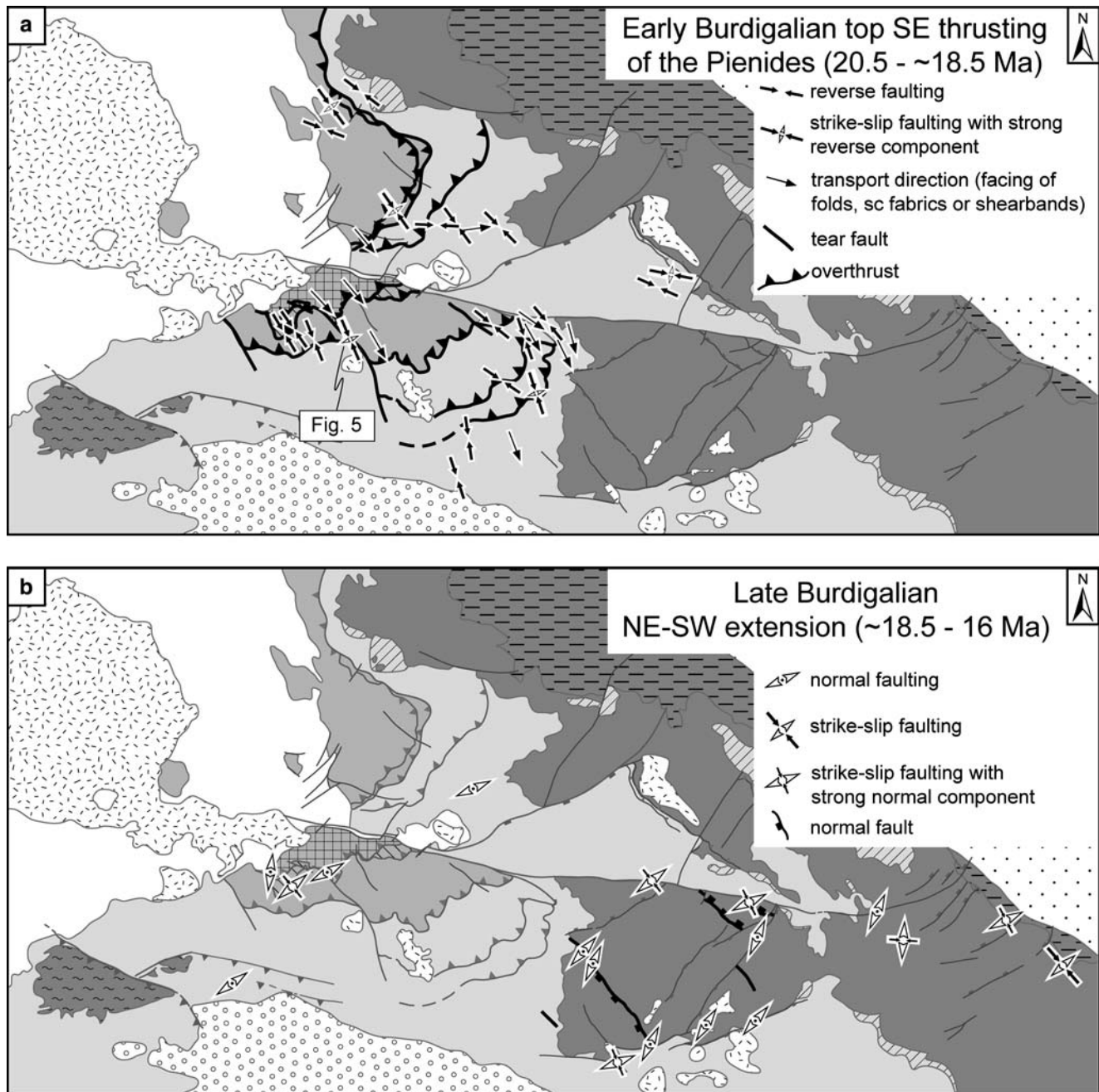


Fig. 4 Kinematics and structures related to the Burdigalian deformation phases. **a** Early Burdigalian emplacement of the Pienides shows consistent top-SE thrusting. The pronounced bends in the nappe front are interpreted as a result of a change in

thrust geometry featuring frontal and lateral ramps as well as tear faults (see text). **b** Subordinate NE-SW extension, related to SE-striking normal faults of Late Burdigalian age

related to the emplacement of the Pienides is primarily controlled by the more incompetent silty-marly flysch units, which are serving as detachment horizons. The more massive sandy layers only display moderate brittle deformation, even close to nappe contacts. Cataclastic shear zones related to nappe emplacement are the predominant deformation features, while folding is only locally developed. Within marly layers shear-bands and/or SC-type fabrics can locally be observed. The shortening direction related to the emplacement of the Pienides was evaluated by kinematic analysis of mesoscale faulting found near major cataclastic shear zones. Transport direction was inferred from the facing direction of outcrop-scale folds and/or SC-type fabrics and shear-bands.

The deduced kinematic directions (Fig. 4a) reveal a consistent displacement direction towards the SE (Appendix 2), both for the Pienides as well as for the imbricates of the autochthonous cover of Tisza-Dacia. The relative timing of fault sets found in two outcrops (Appendix 2, stations 0639, 0584) suggests a possible minor change in transport direction from top-SE towards top-ESE.

The frontal thrust of the Pienides has an extremely variable trace in map view (Fig. 4a), showing alternating SW- and SE-striking segments. Outcrops along the northernmost SE-striking thrust segment (Fig. 4a) expose SSE-striking strike-slip fault zones with a significant reverse component. The predominantly transpressional deformation encountered along this segment (Appendix 2, Station 0639), suggests a lateral ramp geometry. The thrust front of the Pienides south of the Bogdan-Voda fault shows three major sharp bends in map view (Fig. 4a). At one of the bends a steeply dipping dextral strike-slip fault zone, sub-parallel to the transport direction (Fig. 5), is interpreted as a tear fault. The increase of shortening within the autochthonous cover of Tisza-Dacia, observed in front of the Pienides towards the northeast, is a map-scale argument in favour of this interpretation.

The timing of Pienide nappe emplacement and related structures is constrained by stratigraphic arguments. The youngest thrust strata are Aquitanian in age (Dicea et al. 1980), and thrust contacts are sealed by Badenian-age (16 to ~13 Ma) sediments. Hence, an intra-Burdigalian activity can be inferred. The fact, that structures related to Late Burdigalian extensional deformation (see below) overprint nappe emplacement features, allows us to suggest an Early Burdigalian (20.5–18.5 Ma) age for the emplacement of the Pienides.

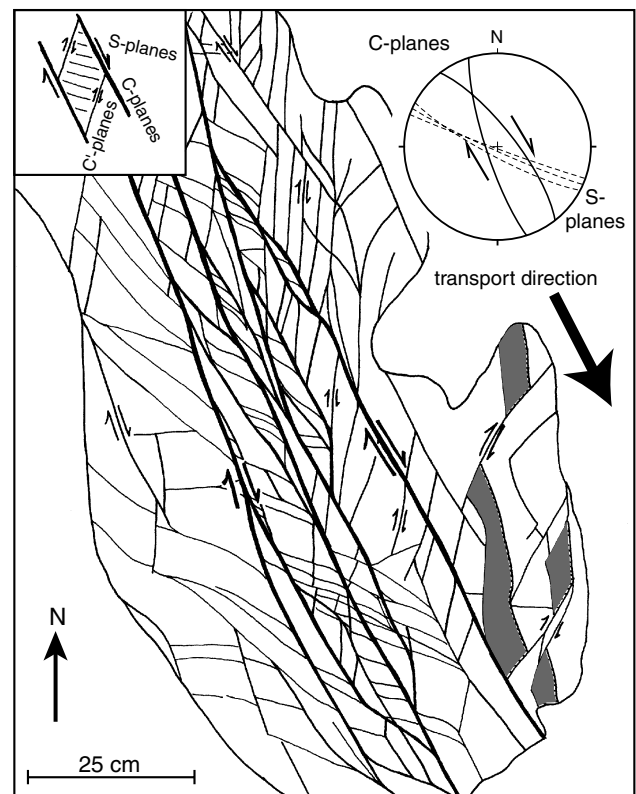


Fig. 5 Outcrop sketch (map view) of a cataclastically deformed fault zone at the NW–SE striking nappe contact of the Pienides against the autochthonous cover of Tisza-Dacia (see Fig. 4a). The fine-grained siliciclastics (homogenous clay rich silts) are dissected by anastomosing shear zones featuring shear band geometries. Shaded areas indicate offset of silty marker horizons. The strike-slip dominated kinematics confirm the interpretation of the NW–SE striking contacts as tear faults

Late Burdigalian NE–SW extension

While SE-trending normal faults are rarely observed in the sedimentary cover, they are more abundant within the basement units of the study area. The most prominent of these SE-striking faults are found within the SW part of the Rodna massif (Fig. 4b), where they offset Bucovinian-type basement as well as Oligocene strata. Kinematic analysis of these faults yielded NE–SW to NNE–SSW extension, i.e. normal faulting with a minor strike-slip component (Fig. 4b; Appendix 3).

Field evidence clearly suggests that these normal faults overprint structures related to the emplacement of the Pienides (e.g. Station 0236, Appendix 2, 3). Since structures of this phase are cut by the Dragos-Voda fault while Badenian (16 to ~13 Ma) strata are unaffected, we assume a pre-Badenian (18.5 to 16 Ma) age for this extensional deformation.

Post-Burdigalian structures

Emplacement of the Pienides was post-dated by extensive faulting. Strike-slip activity along the Bogdan-Drăgos-Voda fault system can be subdivided into an earlier transpressional stage followed by transtension.

Transpressional stage

Open folds with SE- to ESE-striking fold axes (Fig. 6a) evidence post-Burdigalian shortening in the sedimentary units of the study area. Wavelengths of these folds range between outcrop-scale up to several hundreds of meters. While fold limbs are only weakly inclined

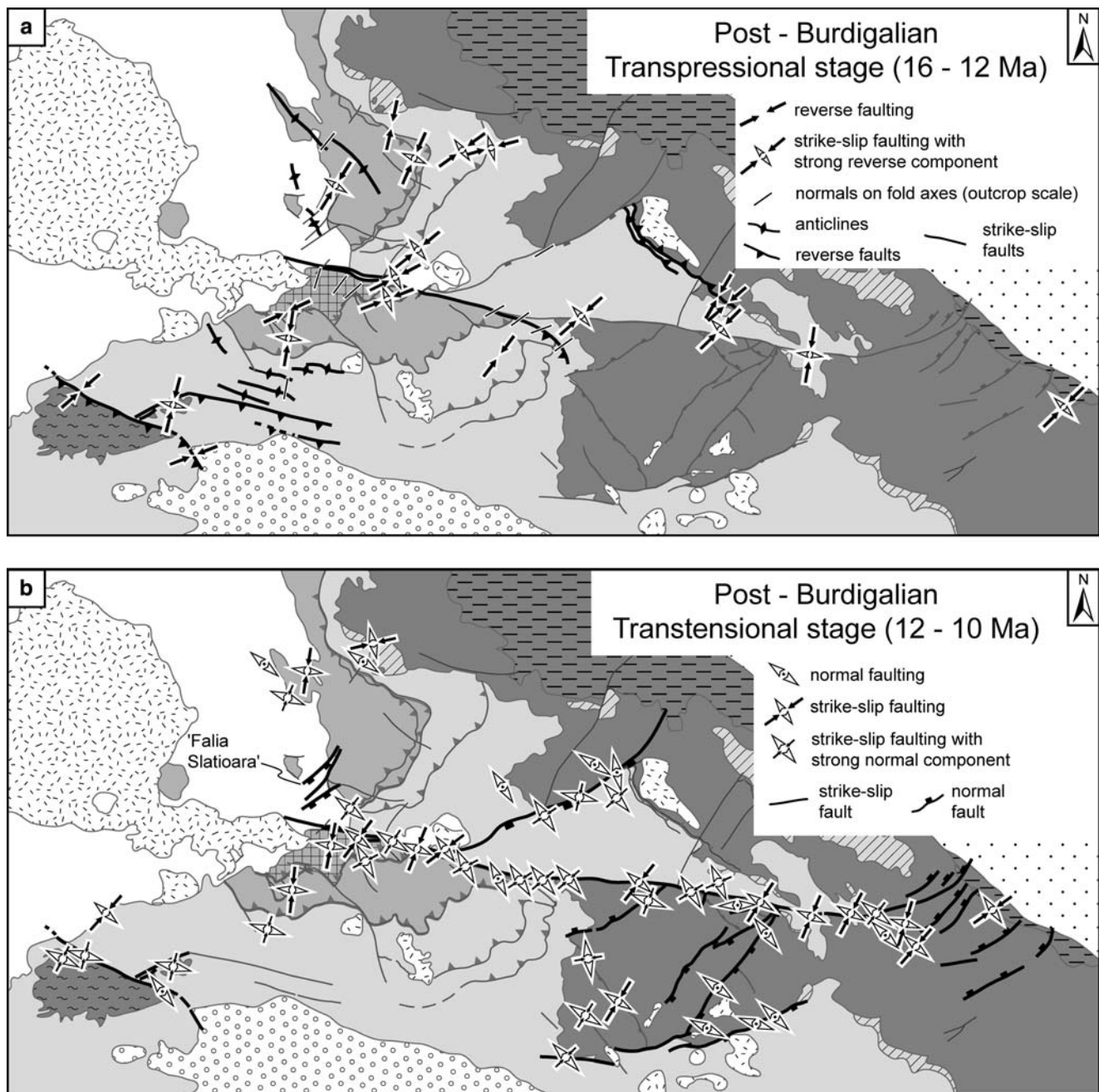
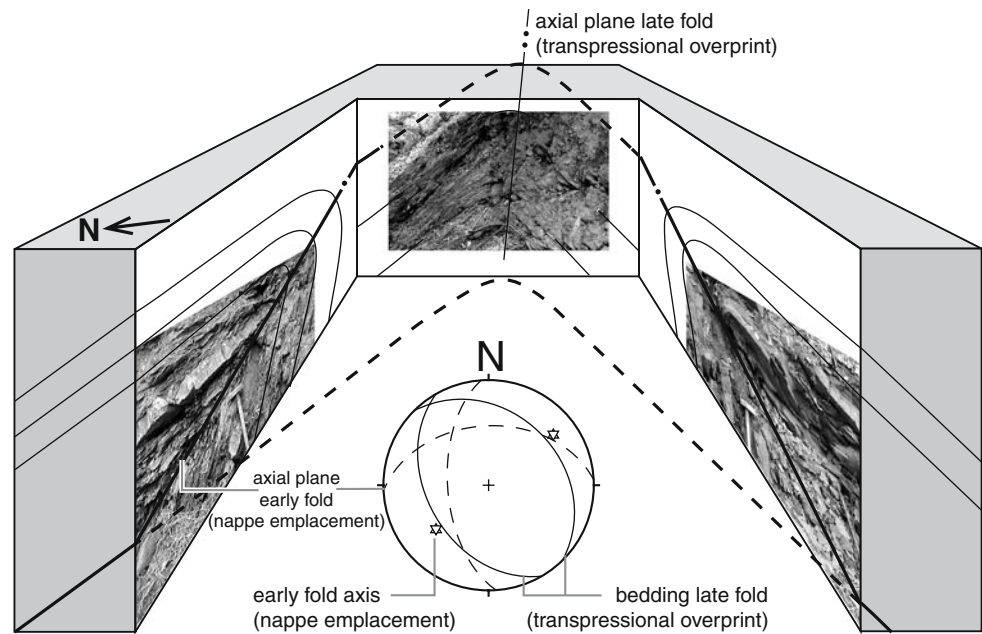


Fig. 6 Kinematics and structures related to the post-Burdigalian (16 to 10 Ma) activity of the Bogdan- and Drăgos-Voda faults. Transpression (a) precedes transtension (b). Shortening is

SW–NE during both phases. Note the linked Bogdan-Voda and Drăgos-Voda fault activity during the transtensional stage

Fig. 7 Schematic block diagram of an outcrop showing the overprinting of nappe emplacement structures. The tight asymmetric folds developed during nappe emplacement (*left and right*) are refolded by an upright open fold with SE-trending fold axis. Such folds are related to the post Burdigalian transpressional stage and can be found throughout the study area



south of the Bogdan-Voda fault, they reach dip angles of up to 50° in the north. These SE- to ESE-striking folds overprint earlier nappe emplacement structures (Fig. 7). Approaching the fault trace of the Bogdan-Voda fault, this late-stage folding locally intensifies, which leads to isoclinal folding around steeply inclined fold axes.

Faulting with a strong reverse component is found throughout the study area and is documented in map scale (Fig. 6a), as well as in outcrop scale (Appendix 4). The most dominant types of structures are SE-striking reverse faults (e.g. back-thrust E of Borsa, Appendix 4, Station 0809; Preluca fault, Appendix 4, Station 0259), as well as E-striking transpressional faults (e.g. the Bogdan-Voda fault; Appendix 4, Stations 0682, 0675). During this transpressional phase the Bogdan-Voda fault terminates at the Rodna horst in a thrust splay geometry.

In summary, the kinematic analysis yields transpression with NE–SW shortening and minor NW–SE extension.

Transtensional stage

E-trending strike slip faults (e.g. Bogdan-Drăgos-Voda fault system) as well as SW-striking normal faults (e.g. Greben fault) can be attributed to the transtensional stage (Fig. 2). Deformation found along and associated with the Bogdan-Voda and Drăgos-Voda faults is dominated by sinistral strike-slip faulting often featuring a normal component.

Striations plunge about 5–15° to the west along the Bogdan-Voda fault and up to 20° along the Drăgos-Voda fault (Appendices 5, 6). These strike-slip faults are commonly accompanied by sets of SW-striking normal faults (Appendices 5, 6).

The E-trending strike slip faults as well as SW-striking normal faults yield regionally consistent kinematic axes. The extensional axes are oriented sub-horizontally NW–SE. Shortening axes strike SW, with dip angles depending on the relative amount of the normal and strike-slip components respectively.

Near its eastern termination, the Bogdan-Drăgos-Voda fault system splays into an array of SW-trending normal faults with a left-lateral component. These “horsetails”, which accommodated only minor displacements, allowed for “distributed” sinistral offset. This is reflected by the lack of a map-scale discrete offset of major pre-existing tectonic boundaries, such as the front of the Bucovinian nappes (Fig. 2). Kinematic axes derived for these SW–NE trending normal faults are compatible with those derived for the Bogdan-Drăgos-Voda fault system (Fig. 6b, Appendix 5). Sinistral transtension is further documented along the Preluca fault, where it overprints a preceeding phase of top NE thrusting (Fig. 6b, Appendix 6).

Stratigraphical timing constraints regarding post-Burdigalian deformation

The formation containing the Lower Badenian Dej tuff represents an ideal marker horizon in the

northern part of the study area. Post-dating Burdigalian age deformation, it is affected by both the transpressive and transtensive stages along the Bogdan-Voda and the Dragos-Voda fault and hence provides a lower time bracket of 16 Ma (i.e. onset of the Badenian). The Preluca fault also shows post 16 Ma activity, indicated by Burdigalian strata affected by NE–SW shortening (Appendix 4, Station 0260).

The upper time bracket of post-Burdigalian deformation is well defined by the Neogene volcanic body near Baia Mare (Fig. 2). The 10 Ma old volcanics

constituting the main body (Pécskay et al. 1995) seal the Bogdan-Voda fault (Fig. 2).

Overprinting criteria observed at outcrop and map scales indicate that transpression was followed by transtension. For example the SE-striking back-thrust east of Borsa is cut by the younger Greben normal fault (Fig. 6). The timing of the change from transpression to transtension is derived from Antonescu et al. (1981). These authors map SW-trending faults (e.g. “Falia Slatioara”, Fig. 6b) which are cutting strata younger than ~12.2 Ma (Lower Bessarabian in Antonescu et al. 1981). Since the strike of the faults

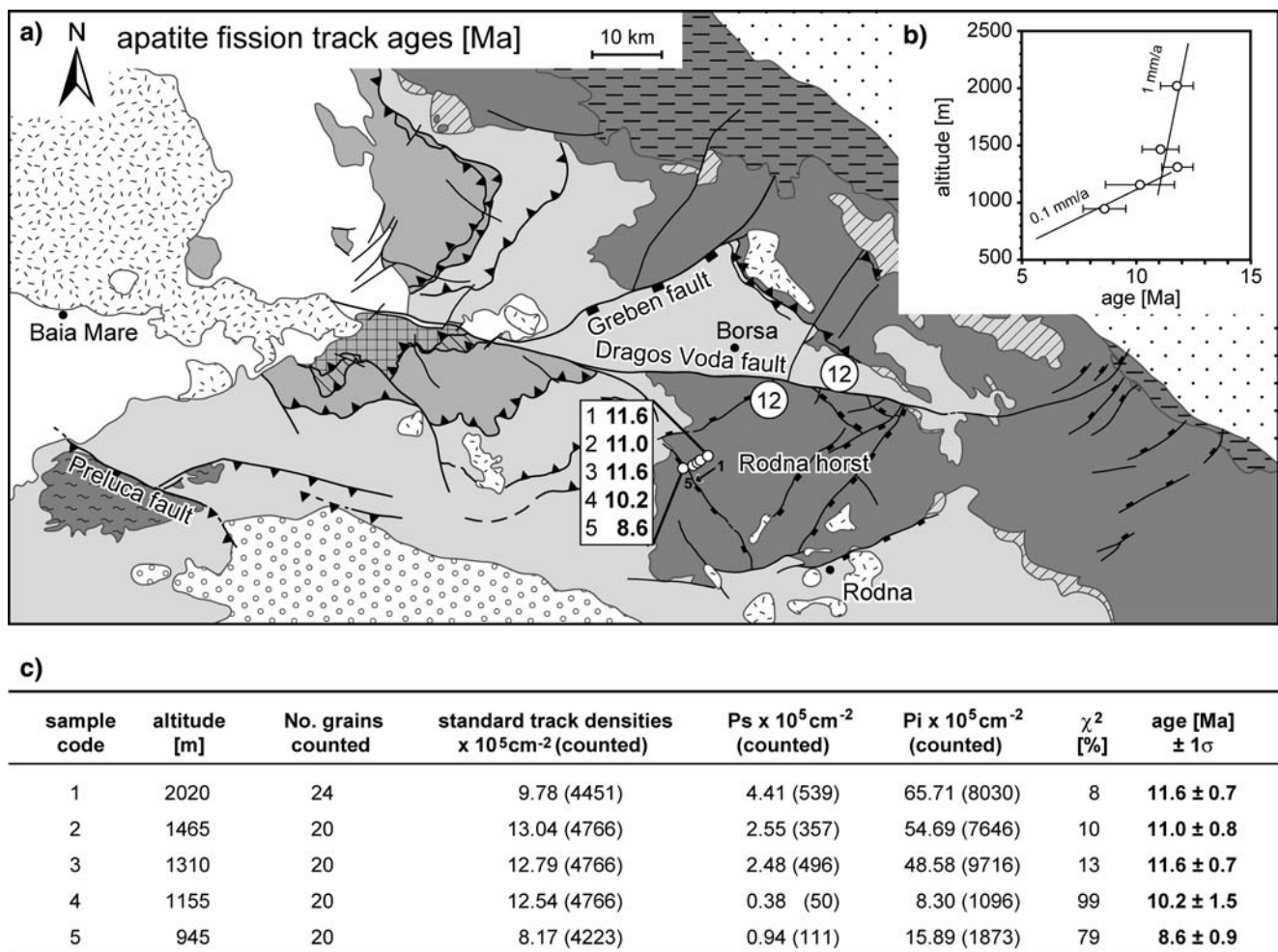


Fig. 8 Results of apatite fission track analyses. All samples were analysed using the external detector method (Gleadow 1981) and ages were calculated using the zeta-calibration method (Hurford and Green 1983) on the base of the Durango standard with a zeta value of 355.96 ± 9.39 **a** Tectonic map showing apatite fission track data. Samples labelled with circles are from Sanders (1998). **b** Altitude versus age diagram of the apatite fission track ages. The ages show relatively fast exhumation (at least 1 mm/a) between 12 and 11 Ma followed by slow exhumation (around

0.1 mm/a) after 10 Ma. **c** Table regarding the apatite fission track data. *Column 1* gives the sample code, *column 2* the altitude above sea level, *column 3* the number of dated grains. *Columns 4, 5 and 6* show standard, spontaneous and induced track densities, respectively, and the number of counted tracks in brackets. *Column 7* gives Chi-square probability (Galbraith 1981) and *column 8* apatite fission track central ages (Galbraith and Laslett 1993), which are the weighted mean of the single grain ages

mapped by Antonescu et al. (1981) is compatible with normal faults related to the transtensional stage, we infer the onset of transtension to have commenced at around 12 Ma ago.

Constraints from fission track data

Due to the lack of stratigraphical timing constraints along the Dragos-Voda fault, its activity was indirectly dated by inferences from the cooling history of the syn-kinematically exhumed Rodna horst (Fig. 8). A vertical profile covering about 1,000 m of altitude difference has been sampled for apatite fission track analysis (5 samples). The uppermost sample is taken close to the projected basal unconformity of the overlying Tertiary sediments. The presented samples have been selected from a larger set of data that is discussed in more detail in Gröber (2006).

Burial by Eocene to Lower Miocene sediments led to total annealing of fission tracks in all samples, as evidenced by the fact that all samples passed the Chi-square test (Fig. 8c; $X^2 > 5\%$). Subsequent cooling through the apatite fission track annealing zone yielded Middle to Late Miocene cooling ages (11.6 to 8.6 Ma; Fig. 8), where the youngest ages are found at the lowest altitudes of the profile. The three uppermost samples span 710 m, but yield similar ages (11.6, 11.0 and 11.6 Ma). A significant decrease in age can only be observed in the two lowermost samples (10.2 and 8.6 Ma). The altitude versus age relationship thus suggests enhanced exhumation between 12 and 11 Ma with exhumation rates of at least 1 mm/a. After 10 Ma the rate of exhumation decelerates to around 0.1 mm/a (Fig. 8b). Our data are in agreement with data by Sanders (1998), also depicted in Fig. 8a.

The enhanced cooling of the Rodna horst through the apatite partial annealing zone between 12 and 11 Ma is interpreted to be caused by fault-bounded exhumation in the footwall of the sinistral transtensive Dragos-Voda fault. This indirect dating of the transtensional stage based on apatite fission track analysis is consistent with stratigraphical timing constraints (12–10 Ma, see above) for transtension along the Bogdan-Voda fault. The concurrent time constraints, independently derived, support the conclusion that the Bogdan-Voda and Dragos-Voda faults acted as a single continuous fault during this second transtensional stage. Additionally, the apatite fission track data corroborate that the transtensional stage between 12 and 10 Ma represents the main phase of activity along the Dragos-Voda fault.

Synthesis of data

Burdigalian thrusting of the Pienides followed by NE–SW extension

Analysis of the structures related to the Burdigalian-age emplacement of the Pienides consistently yielded top-SE transport (Fig. 4a). Thrusting of the Pienides and within the autochthonous cover of Tisza-Dacia was coeval, as indicated by stratigraphic timing criteria corroborated by our kinematic analyses. A change from top-SE to top-ESE transport, as suggested by two of the studied outcrops, could not be consistently documented for the study area.

At first sight, the constant displacement directions inferred for the thrusting of the Pienides is in contradiction to the extremely variable trace of the frontal thrust in map view. The most likely explanation for the arcuate shape of the Pienide nappe contact is a laterally changing thrust plane geometry, with SW striking frontal ramps alternating with SE-striking tear faults and/or lateral ramps.

Although SE-striking normal faults, generated by a phase of SW–NE extension, are found throughout the study area, they are more abundant in the basement rocks of the Rodna horst (Fig. 4b) than in the Oligocene sediments. The age of this normal faulting is inferred as Late Burdigalian.

Post-Burdigalian faulting along the Bogdan- and Dragos-Voda faults

Our observations indicate a significant component of shortening during the earlier stage of left-lateral strike-slip movements along the Bogdan-Voda fault, which terminated towards the east along a SE striking thrust-splay, as mapped by Săndulescu (1994) and Dicea et al. (1980). Due to the scarcity of evidence for coeval transpressive deformation along the Dragos-Voda fault, we regard its role during this earlier stage of the post-Burdigalian deformation as subordinate. Hence, the two fault segments were not yet linked, and much of the offset along the Bogdan-Voda fault was taken up by thrusting along its eastern termination. In the eastern part of the study area (near Borsa), a SE-trending back-thrust represents the major feature formed during this transpressive post-Burdigalian stage (Fig. 6a). The differences in deformational style between west and east may be due to earlier structures, particularly to the presence of a basement high in the area of the Rodna horst. This horst already existed during the Eocene. While the shallow marine Iza limestone formed on the

Rodna horst, the pelagic sediments of the Vaser Formation were deposited north of it (Săndulescu et al. 1991; Kräutner et al. 1982). During the subsequent sinistral-transtensive stage the Bogdan-Voda and Dragos-Voda faults were kinematically linked; they acted as a single Bogdan-Dragos-Voda fault system, as mapped by Dicea et al. (1980). This is confirmed by structural and kinematic data and is also very evident from map-view. Additionally, intensely faulted outcrops situated at the junction between the two segments yield similar kinematics (Appendices 5, 6, Stations 0462, 0481, 0079) further corroborate this interpretation.

Since the major SW-trending normal faults within the Rodna horst and in the Maramures Mountains (i.e. the Greben fault) are kinematically compatible with this sinistral-transtensive activity along the Bogdan-Dragos-Voda fault system, we regard their activity as contemporaneous. The transtension along the Bogdan-Dragos-Voda fault system led to final cooling and exhumation of the Rodna horst from 12 Ma onwards, as indicated by apatite fission track data. Towards the east, the net left-lateral offset along the Bogdan-Dragos-Voda fault system decreases due to the distribution of deformation into a horse-tail like array of SW-trending normal faults. At the contact of the inner East Carpathians with the Miocene thrust belt of the Moldavides the localised offset diminishes to almost zero. Transtension also affected the southeastern part of the study area, where the entire Rodna horst is affected and partly bounded by SW-striking normal faults (Fig. 6b; Appendix 6). Subordinate reactivation by transtension is also observed along the Preluca fault.

Estimates of horizontal and vertical components of displacement across the Bogdan-Voda and Dragos-Voda faults

Since movement along the Bogdan-Voda fault segment accumulated during two stages, we first evaluate the offsets along the Dragos-Voda fault, which was essentially active only during the later transtensive stage.

Based on published maps (Geological Survey of Romania) and stratigraphic logs of the sediments juxtaposed against the crystalline basement units (Dicea et al. 1980) the south-side-up vertical offset across the Dragos-Voda fault south of Borsa (Fig. 2) can be estimated to reach 2 km. Assuming that the average measured pitch of striations at the Dragos-Voda fault of 15° (Appendices 5, 6) indicates the

movement vector during transtension, the horizontal displacement had to be in the order of 7 km.

Since offset along the Dragos-Voda fault continuously decreases from west to east due to coevally active SW-trending normal faults, the offset for a specific point can be estimated by a simple linear interpolation using the previously mentioned displacement estimates together with the horizontal distance between Borsa and the point of negligible offset at the horsetail splay.

Thus the maximum offset of the Dragos-Voda fault segment, accumulated in its westernmost part, can be estimated to reach values in the order of 11 km (horizontal) and 3 km (vertical), respectively. For the eastern part of the Rodna horst our linear approach predicts a vertical offset in the order of 1 km. Apatite fission track ages from this region (Sanders 1998) are identical on either side of the Dragos-Voda fault (Fig. 8), thus also indicating minor (i.e. < 1 km) vertical displacement below data resolution.

A total lateral offset of about 25 km for the Bogdan-Voda fault can be deduced from the left-lateral offset of the Pienide thrust front (Fig. 2). The north side down component is evidenced by the relative offset of the post-Burdigalian strata (Fig. 2). From the shallow plunge of lineations observed at the Bogdan-Voda fault (5° west), a total vertical offset of about 2.5 km is obtained. Using the estimate of total lateral offset along the Dragos-Voda fault (see above), we infer that at least 11 km lateral and 1 km vertical offset were produced during the transtensional stage.

It should be noted, that the marked difference in vertical offsets between the Bogdan-Voda fault segment (1 km) and Dragos-Voda fault segment (3 km) during the transtensional stage is accommodated by the SW-trending Greben fault. Based on published geological maps (Geological Survey of Romania), the vertical offset at the Greben fault is estimated to reach about 2 km.

Discussion of earlier work and large-scale correlations

Comparison with previous data from the working area

Our observations and conclusions are largely comparable to a previous study in this area carried out by Györfi et al. (1999). However, we consider SW–NE shortening to be post-Burdigalian rather than Oligocene in age. Györfi et al. (1999) correlated the Late Miocene activity of the Bogdan-Dragos-Voda fault system with extensional features of Early Pannonian

(~9 to 11.8 Ma) age described in seismic studies from the Pannonian basin. This time frame is compatible with our timing estimates for the transtensional stage (12 to 10 Ma).

The conclusions of Huismans et al. (1997) strongly differ from our interpretation. The major difference to our study is that we regard the Early Burdigalian emplacement of the Pienides as top-SE directed rather than due to NNE–SSW compression. We partly disagree with Ciulavu (1999), who argued that extensional veins filled by hydrothermal ore deposits, dated to 8.7 ± 0.4 Ma (Pécskay et al. 1994) and found within the volcanic body of Baia Mare, point towards a post-10 Ma activity of the Bogdan-Voda fault. On the available maps the pyroxene andesites (10.1–10.9 Ma, Pécskay et al. 1994), constituting most of the volcanic body of Baia Mare, are not crosscut by the Bogdan-Voda fault. Hence we conclude, that major activity along the Bogdan-Dragos-Voda fault system ceased at some 10 Ma ago, while the mineralized veins indicate partial reactivation of minor importance only.

Burdigalian top-SE thrusting of the Pienides followed by NE–SW extension in the larger scale context

Based on seismic studies located in central Hungary Csontos and Nagymarosy (1998) report Oligocene to Lower Miocene-age thrusting of ALCAPA onto Tisza-Dacia along the Mid-Hungarian line. In agreement with Csontos and Nagymarosy (1998) and Csontos and Vörös (2004) we consider the Pienide nappe contact as representing the eastward continuation of the Mid-Hungarian fault zone during Burdigalian times. Since the Pienides are correlated with parts of the Western Carpathians (Săndulescu et al. 1981; Săndulescu 1994), i.e. with units that are clearly part of what is commonly referred to as “ALCAPA”, they are considered to represent the easternmost tip of ALCAPA.

Many authors postulate a significant (in the order of 90°) clockwise rotation of Tisza-Dacia during its Mid-Miocene emplacement (e.g. Fodor et al. 1999, Márton and Fodor 2003). Such rotations should cause progressive reorientation of earlier formed structures (i.e. our nappe emplacement structures) as they are passively rotated together with the Tisza-Dacia block. However, we observed no regionally consistent evidence for such a change in transport directions. Thus we conclude that a major part of the rotation commenced earlier, possibly in the Early Oligocene, as is discussed in Györfi et al. (1999). This would

imply that shortening across the Mid-Hungarian fault zone (Csontos and Nagymarosy 1998) and the emplacement of the Pienides in northern Romania only reflect the last stage of the juxtaposition of the ALCAPA and Tisza-Dacia blocks, a process that initiated much earlier (Csontos and Nagymarosy 1998). Comparable to the Late Burdigalian (~18.5 to 16 Ma) NE–SW extension documented in this study, Csontos and Nagymarosy (1998) report Early to Mid-Miocene extension within the Pannonian basin i.e. also along the Mid-Hungarian fault. Fodor et al. (1999) interpret NE–SW extension (17 to 15 Ma) within the Pannonian basin system as being related to back arc extension in the context of subduction roll-back in the Carpathians.

In conclusion, we regard Early Burdigalian top-SE thrusting of the Pienides, i.e. the easternmost tip of ALCAPA, to be related to transpression along the Mid-Hungarian fault zone in the context of lateral extrusion of ALCAPA. Subsequent Late Burdigalian NE–SW-directed extension marks the extensional overprint of the Tisza-Dacia block due to ongoing roll-back in the northernmost East Carpathians.

Post-Burdigalian activity along the Bogdan-Dragos-Voda fault system in the larger scale context

While subduction rollback migrates eastwards due to propagating slab detachment (Wortel and Spakman 2000) convergence in the western Carpathians comes to a halt and most likely leads to a pronounced change in deformational style along the Mid-Hungarian fault zone (Fodor et al. 1999). Late Badenian to Sarmatian (14 to 11 Ma) NW–SE extension in the Pannonian basin (Fodor et al. 1999) is interpreted as a period of left lateral transtension along the Mid-Hungarian fault zone (Csontos and Nagymarosy 1998).

The left-lateral activity of the Bogdan-Voda and Dragos-Voda faults (16 to 10 Ma) coincides with this phase of sinistral transtension along the Mid-Hungarian fault zone and suggests a direct kinematic link between all these faults during this time interval. We suggest that the differing kinematics in our working area—transpression followed by transtension—may be explained by the “docking” of Tisza-Dacia with the European foreland. Starting in Late Burdigalian times, NE-directed thrusting of the Miocene thrust belt (Matenco and Bertotti 2000) led to “soft collision” of Tisza-Dacia with the European foreland in the East Carpathians between some 16 and 10 Ma ago. This scenario is comparable to the Western Carpathians, where Sperner et al. (2002) correlate NNE–SSW compression

(dated by these authors as Oligocene (?) to Mid-Miocene) with “soft collision” between ALCAPA and the European continent. Final emplacement of the northern part of Tisza-Dacia induces the change towards the transtensional activity along the Bogdan-Dragos-Voda fault system. This transtensional stage is coeval to Late Sarmatian strike-slip activity in the external Miocene thrust belt of the East Carpathians (Matenco and Bertotti 2000).

Our data indicate a direct kinematic link between the Mid-Hungarian fault zone, the Bogdan-Voda fault and the Bogdan-Dragos-Voda fault system since post-Burdigalian times. However, since the Bogdan-Voda and Dragos-Voda faults are located within the Bucovinian basement (i.e. within the Dacia Block) they should not be considered as representing the continuation of the Mid-Hungarian line as defined by Csontos and Nagymarosy (1998). Moreover, the amount of displacement documented for the Bogdan-Dragos-Voda fault system (~26 km) rapidly diminishes towards the east. Its termination before reaching the foreland fold-and-thrust-belt, as well as the coeval activity at the Preluca fault and faulting south of the Rodna horst, suggests a rather distributed linkage of the foreland fold-and-thrust-belt with the extensional back-arc domain in post-Burdigalian times. This is in agreement with the interpretation of Matenco and Bertotti (2000), who demonstrated that deformation caused by the final ESE-ward emplacement (Latest Sarmatian-Early Meotian, ~10 to 8 Ma) was distributed over large parts of the East Carpathians. According to these authors the ESE movement of the central sectors of the Eastern Carpathians was accommodated by numerous E-W trending sinistral faults located east of our study area, rather than by one major strike-slip fault such as the Bogdan-Dragos-Voda fault system.

Conclusions

1. Early Burdigalian (20.5 to ~18.5 Ma) SE-directed emplacement of the Pienides, i.e. the eastern tip of ALCAPA, onto Tisza-Dacia is correlated with the thrusting of ALCAPA over Tisza-Dacia along the Mid-Hungarian line observed in the subsurface of the Pannonian basin (Csontos and Nagymarosy 1998). The Pienide nappe front in Maramures is kinematically linked to dextrally transpressive

movements along the Mid-Hungarian fault zone that, together with the Periadriatic line, accommodates the lateral extrusion of ALCAPA.

2. Minor Late Burdigalian (18.5 to 16 Ma) NE–SW extension is interpreted as due to back-arc extension related to subduction roll back in the northernmost East Carpathians.
3. In post-Burdigalian (post-16 Ma) times a pronounced change in the tectonic regime led to NE–SW shortening and NW–SE extension. This change correlates with “soft collision” of Tisza-Dacia with the European foreland and the migration of active subduction from N to S along the Miocene foredeep of the Eastern Carpathians. Post-Burdigalian deformation was concentrated along the Bogdan-Voda and Dragos-Voda faults. Sinistral transpression (16 to 12 Ma) was mainly restricted to the Bogdan-Voda fault, which terminated eastwards in a thrust splay geometry. Sinistral transtension (12 to 10 Ma) was kinematically linked along the Bogdan- and Dragos-Voda fault segments (Bogdan-Dragos-Voda fault system). During this transtensional stage, coevally active SW–NE trending normal faults reduced the left-lateral offset towards the east, where the fault system terminates in an extensional horse-tail splay. The Bogdan-Dragos-Voda fault system is kinematically linked to the Mid-Hungarian fault zone during the post-Burdigalian stages, albeit deformation is distributed over large parts of the East Carpathians.

Acknowledgments We are very grateful for an excellent introduction into the geology of the area by M. Săndulescu and L. Matenco and for all the discussions we had with them and with all the other Romanian colleagues. We would also like to particularly mention the fruitful interactions with L. Csontos, L. Fodor, S. Kovács, M. Marin, E. Márton, C. Pero, D. Radu, D. Badescu and C. Krezsek during our study. M. Marin is gratefully acknowledged for providing additional data from the eastern part of the study area. The careful and constructive review by L. Ratschbacher significantly improved a first version of the text. This work was financed by NF-projects Nr. 21-64979.01, Nr. 200020-105136/1 and Nr. 200021-101882/1, granted to B.F. and S.Sch., respectively.

Appendix 1

Table 1.

Table 1 Tabular overview on fault-slip data

No.	X	Y	Lithology	Rock age	Shortening		Inter-medi- ate		Extension		r	Regime	n data
Data correlated to Early Burdigalian nappe emplacement													
0006	24.7279	47.6816	Fine flysch	Eocene	101	01	206	57	005	31	1	Compressional strike slip	36
0215	24.3295	47.7339	Flysch	Oligocene	324	03	233	22	062	68	3	Reverse faulting	3
0236	24.0302	47.5991	Flysch	Eocene	149	21	054	07	308	66	1	Reverse faulting	10
0248	24.0344	47.5970	Red marl	Late Cretaceous	145	12	053	08	290	75	2	Reverse faulting	6
0272	24.1638	47.9015	Conglomerate	L. Alb–Cenomanian	307	14	040	10	164	73	2	Reverse faulting	5
0288	24.4847	47.6128	Flysh	Rupelian	140	03	050	01	306	87	2	Reverse faulting	8
0291	24.4334	47.5459	Red marl	Late Cretaceous	124	02	034	21	219	69	2	Reverse faulting	5
0314	24.2191	47.7545	Flysch	Lutetian–Priabonian	145	00	236	81	055	09	3	Compressional strike slip	7
0322	24.4250	47.5912	Flysch	Rupelian	129	02	219	15	031	75	1	Reverse faulting	6
0326	24.3450	47.4183	Sandstone	Oligocene	342	16	072	01	167	74	2	Reverse faulting	7
0414	24.3011	47.7350	Flysch	Rupelian	093	04	185	32	357	58	1	Reverse faulting	6
0453	24.4006	47.7251	Flysch	Rupelian	315	02	224	28	049	62	1	Reverse faulting	7
0584	24.0641	47.5791	Flysch	Priabonian? Oligocene	158	01	068	07	257	83	1	Reverse faulting	18
0639	24.0950	47.8813	Red marl	Late Cretaceous	137	09	233	36	035	52	1	Compressional strike slip	30
0692	24.0752	47.8488	Flysch	Lutetian–Priabonian	111	18	014	22	237	61	3	Reverse faulting	6
0743	24.7105	47.6698	Marl	Eocene	102	12	354	54	200	33	3	Reverse faulting	5
0822	24.3608	47.4721	Flysch	Rupelian –Aquitanian	352	05	261	14	100	76	2	Reverse faulting	19
0892	24.4782	47.5418	Marl	Turonian–Priabonian	162	23	331	67	070	04	1	Compressional strike slip	11
1025	24.4616	47.5955	Marl	Turonian–Priabonian	341	05	248	28	079	61	1	Reverse faulting	14
1056	24.1420	47.5801	Flysch	Priabonian-? Oligocene	157	30	037	40	271	35	2	Compressional strike slip	5
Data correlated to Late Burdigalian SW–NE extension													
0236	24.0302	47.5991	Flysch	Eocene	148	36	306	51	050	11	1	Extensional strike slip	29
0267	23.9266	47.4746	Flysch	Chattian–Aquitanian	251	72	145	05	054	17	3	Normal faulting	3
0368	24.9089	47.5638	Crystalline	Basement	285	73	114	17	023	03	1	Normal faulting	14
0374	24.6976	47.6213	Crystalline	Basement	141	12	329	77	232	02	2	Extensional strike slip	5
0376	24.8780	47.5983	Crystalline	Basement	184	58	326	26	064	17	1	Extensional strike slip	11
0633	24.3596	47.7297	Flysch	Rupelian	114	61	343	20	246	20	2	Normal faulting	8
0765	25.1171	47.5908	Crystalline	Basement	144	78	293	10	024	06	3	Normal faulting	5
0792	24.7005	47.4143	Crystalline	Basement	325	62	109	24	206	15	3	Normal faulting	3
0799	24.8962	47.4492	Crystalline	Basement	037	68	130	01	221	21	1	Normal faulting	25
0801	24.8055	47.4421	Crystalline	Basement	357	56	113	17	212	29	2	Normal faulting	9
0802	24.5876	47.5191	Crystalline	Basement	087	71	297	17	204	09	1	Normal faulting	43
0804	24.5811	47.5256	Crystalline	Basement	100	69	315	17	222	11	1	Normal faulting	7
0816	24.6441	47.3919	Conglomerate	Eocene	139	36	003	45	248	24	2	Extensional strike slip	6
0915	24.0888	47.6218	Flysch	Ypresian–Lutetian	128	81	331	08	241	03	3	Normal faulting	3
0925	23.9891	47.6164	Flysch	Ypresian–Lutetian	161	70	275	08	007	18	2	Normal faulting	6
M 30	25.1658	47.5551	Crystalline	Basement	263	34	116	51	004	16	2	Extensional strike slip	11
M 41	25.4644	47.5276	Crystalline	Basement	139	12	270	72	046	13	2	Strike slip	8
M 66	25.3566	47.5826	Crystalline	Basement	146	19	016	63	243	19	2	Extensional strike slip	7
Data correlated to post-Burdigalian transpressional stage													
0008	24.2418	47.6984	Tuff	Badenianmj	050	10	298	65	145	22	1	Compressional strike slip	13
0059	24.8196	47.6257	Conglomerate	Lutetian	225	12	130	23	339	63	2	Compressional strike slip	9
0147	24.2452	47.8174	Flysch	Lutetian–Priabonian	024	05	284	66	116	23	2	Compressional strike slip	16
0237	24.0220	47.5875	Flysch	Oligocene–E. Miocene	001	06	298	73	098	16	2	Compressional strike slip	11

Table 1 continued

No.	X	Y	Lithology	Rock age	Shortening		Inter-mediate		Extension		r	Regime	n data
0259	23.6433	47.5093	Crystalline	Basement	089	01	139	24	317	66	1	Reverse faulting	7
0260	23.8639	47.4366	Flysch	Burdigalian	249	06	157	13	006	76	3	Reverse faulting	3
0276	24.2015	47.8582	Flysch	Oligocene	192	16	101	02	004	74	2	Reverse faulting	6
0310	24.1013	47.7794	Flysch	Priabon	212	13	321	55	114	32	1	Compressional strike slip	12
0322	24.4274	47.5643	Flysch	Rupelian	037	10	305	11	167	76	3	Reverse faulting	2
0357	24.8414	47.6499	Crystalline	Basement	049	03	318	18	147	72	1	Reverse faulting	6
0360	24.9921	47.5859	Flysch	Lutetian	189	04	094	52	282	38	1	Compressional strike slip	13
0462	24.4936	47.6215	Limestone	Lutetian–Priabonian	048	05	313	45	143	45	1	Compressional strike slip	6
0556	23.8153	47.4966	Crystalline	Basement	014	08	112	45	276	44	2	Compressional strike slip	9
0631	24.3719	47.8333	Flysch	Oligocene	255	00	345	61	165	29	1	Compressional strike slip	5
0632	24.3395	47.8286	Flysch	Oligocene	054	02	323	25	149	65	2	Compressional strike slip	7
0675	24.2141	47.6546	Flysch	Oligocene	249	03	351	76	159	13	1	Compressional strike slip	8
0682	24.2234	47.6636	Flysch	Oligocene	063	11	159	29	314	59	3	Compressional strike slip	5
0809	24.8339	47.6486	Marl/limestone	Lutetian–Priabonian	210	04	119	02	001	86	1	Reverse faulting	12
0917	24.0219	47.6177	Flysch	Ypresian–Lutetian	245	03	154	17	344	73	2	Reverse faulting	13
Data correlated to post-Burdigalian transtensional stage													
0059	24.8196	47.6257	Conglomerate	Lutetian	144	72	245	03	336	17	1	Extensional strike slip	9
0060	24.7894	47.6107	Crystalline	Basement	235	38	063	52	328	04	1	Extensional strike slip	11
0079	24.4717	47.6215	Limestone	Lutetian–Priabonian	223	46	069	41	327	13	1	Extensional strike slip	9
0095	24.4103	47.6212	Flysch	Lutetian–Priabonian	208	76	066	11	334	08	3	Normal faulting	5
0152	24.1337	47.6965	Tuff	Badenian	219	27	036	63	128	01	2	Extensional strike slip	5
0170	24.1472	47.6656	Flysch	Ypresian–Lutetian	037	16	189	72	304	08	2	Strike slip	5
0180	24.3487	47.6356	Flysch	Lutetian–Priabonian	245	35	058	55	152	03	2	Extensional strike slip	11
0236	24.0302	47.5991	Flysch/marl	Late Jur–Eocene	186	11	072	65	281	22	1	Strike slip	19
0259	23.6433	47.5093	Crystalline	Basement	016	44	193	46	285	02	1	Extensional strike slip	7
0272	24.1638	47.9015	Conglomerate	L. Albion–Cenomanian	077	09	324	67	171	21	2	Strike slip	5
0275	24.1536	47.8973	Limestone	Lutetian–Priabonian	156	71	038	09	305	16	2	Normal faulting	7
0292	24.4926	47.7065	Flysch	Rupelian	069	53	229	35	326	10	2	Extensional strike slip	7
0297	24.5695	47.7276	Flysch	Oligocene	196	24	359	65	103	06	2	Extensional strike slip	7
0346	25.1493	47.5659	Crystalline	Basement	316	61	225	00	135	29	2	Normal faulting	6
0360	24.9921	47.5859	Sandstone	Lutetian	203	10	060	77	295	08	1	Strike slip	18
0363	24.8924	47.6024	Crystalline	Basement	213	20	021	70	122	04	1	Strike slip	14
0368	24.9089	47.5638	Crystalline	Basement	273	60	043	21	142	21	2	Normal faulting	10
0369	24.6908	47.5981	Crystalline	Basement	131	68	023	07	291	21	2	Extensional strike slip	11
0374	24.6976	47.6213	Crystalline	Basement	219	14	049	75	310	02	2	Strike slip	20
0385	24.6186	47.7480	Flysch	Oligocene	227	21	055	68	318	03	2	Extensional strike slip	4
0386	24.6177	47.7499	Crystalline	Basement	248	63	080	27	348	05	1	Normal faulting	12
0387	24.6069	47.7611	Crystalline	Basement	161	70	037	12	303	16	1	Normal faulting	9
0390	24.0066	47.8386	Tuff	Badenian	016	36	213	53	112	08	2	Extensional strike slip	7
0413	24.8755	47.5983	Crystalline	Basement	298	76	178	88	088	12	2	Normal faulting	8
0452	24.4124	47.7375	Flysch	L. Lutetian/Bartonian	050	73	238	16	147	02	2	Normal faulting	8

Table 1 continued

No.	X	Y	Lithology	Rock age	Shortening		Intermediate		Extension		r	Regime	n data
0462	24.4936	47.6215	Limestone	Lutetian–Priabonian	224	66	051	24	320	03	1	Extensional strike slip	12
0481	24.5200	47.6219	Crystalline	Basement	225	51	052	39	319	03	1	Extensional strike slip	14
0534	23.6282	47.5041	Crystalline	Basement	022	45	213	44	117	06	3	Extensional strike slip	4
0550	23.8101	47.4680	Crystalline	Basement	320	81	053	00	143	09	3	Normal faulting	6
0556	23.8153	47.4966	Crystalline	Basement	191	14	055	70	284	13	2	Extensional strike slip	9
0588	23.9867	47.5482	Flysch	Early Miocene	163	50	032	29	287	25	2	Extensional strike slip	11
0625	24.1412	47.6479	Tuff	Ypresian–Lutetian	244	52	061	38	152	01	1	Extensional strike slip	26
0681	24.2230	47.6629	Sandstone	Badenian	213	37	051	51	310	09	1	Strike slip	18
0712	23.9619	47.8797	Sandstone	Badenian	051	64	218	26	311	05	1	Normal faulting	9
0720	24.1340	47.6577	Flysch	Ypresian–Lutetian	011	04	116	76	280	14	3	Strike slip	8
0733	24.0414	47.8737	Tuff	Badenian	009	29	202	61	102	05	1	Strike slip	17
0758	25.1234	47.5824	Dolomite	Basement	038	01	132	82	308	08	1	Extensional strike slip	23
0774	24.5453	47.4003	Crystalline	Basement	030	39	246	45	136	19	2	Extensional strike slip	8
0797	24.9295	47.4590	Conglomerate	Cretaceous	345	46	228	13	133	23	1	Normal Faulting	13
0799	24.8962	47.4492	Crystalline	Basement	021	70	198	20	289	01	2	Normal faulting	9
0801	24.8055	47.4421	Crystalline	Basement	036	61	204	28	296	05	2	Normal faulting	11
0804	24.5811	47.5256	Crystalline	Basement	035	54	272	21	171	27	2	Extensional strike slip	8
0807	24.5791	47.4538	Crystalline	Basement	028	36	219	53	122	05	3	Extensional strike slip	4
0814	24.6391	47.4729	Crystalline	Basement	032	04	203	86	302	01	3	Strike slip	10
0818	24.8228	47.4932	Crystalline	Basement	134	82	037	01	307	08	1	Normal Faulting	22
0832	24.2835	47.6576	Flysch	Rupelian	053	08	180	78	321	10	1	Strike slip	21
0838	24.2668	47.6507	Sandstone	Badenian	022	05	267	78	113	11	1	Strike slip	37
0897	23.6856	47.5602	Sandstone	Badenian	042	02	148	82	312	08	2	Strike slip	5
M 19	25.0739	47.5916	Crystalline	Basement	208	03	101	79	299	10	1	Strike slip	12
M 27	25.1569	47.5714	Crystalline	Basement	017	02	162	84	107	05	1	Strike slip	9
M 32	25.1724	47.5521	Crystalline	Basement	041	03	139	73	310	17	1	Strike slip	15
M 41	25.4644	47.5276	Crystalline	Basement	055	01	150	82	324	08	2	Strike slip	7

no. reference number of outcrop, prefix M: data provided by Mihai Marin

X/Y coordinates of the outcrops in decimal degrees Lat/Long, WGS 84

shortening/intermediate/extension: orientation of respective mean kinematic axes, derived by eigenvector analysis of the shortening/extensional fields obtained by the right dihedral method (Angelier and Mechler 1977)

r data quality rating: 1, good; 2, moderate; 3, poor

regime tectonic regime of deformation assessed by the distribution of incremental strain axes (Marret and Almendinger 1990). Reverse faulting, normal faulting, strike-slip faulting: well-clustered shortening and extension axes; compressional strike-slip: well clustered shortening axes with great circle distribution of extensional axes; extensional strike-slip: well clustered extension axes with great circle distribution of shortening axes

n data number of fault-slip sets attributed to respective regime, only fault-slip sets with certain slip sense have been included

Appendix 2

Figure 9.

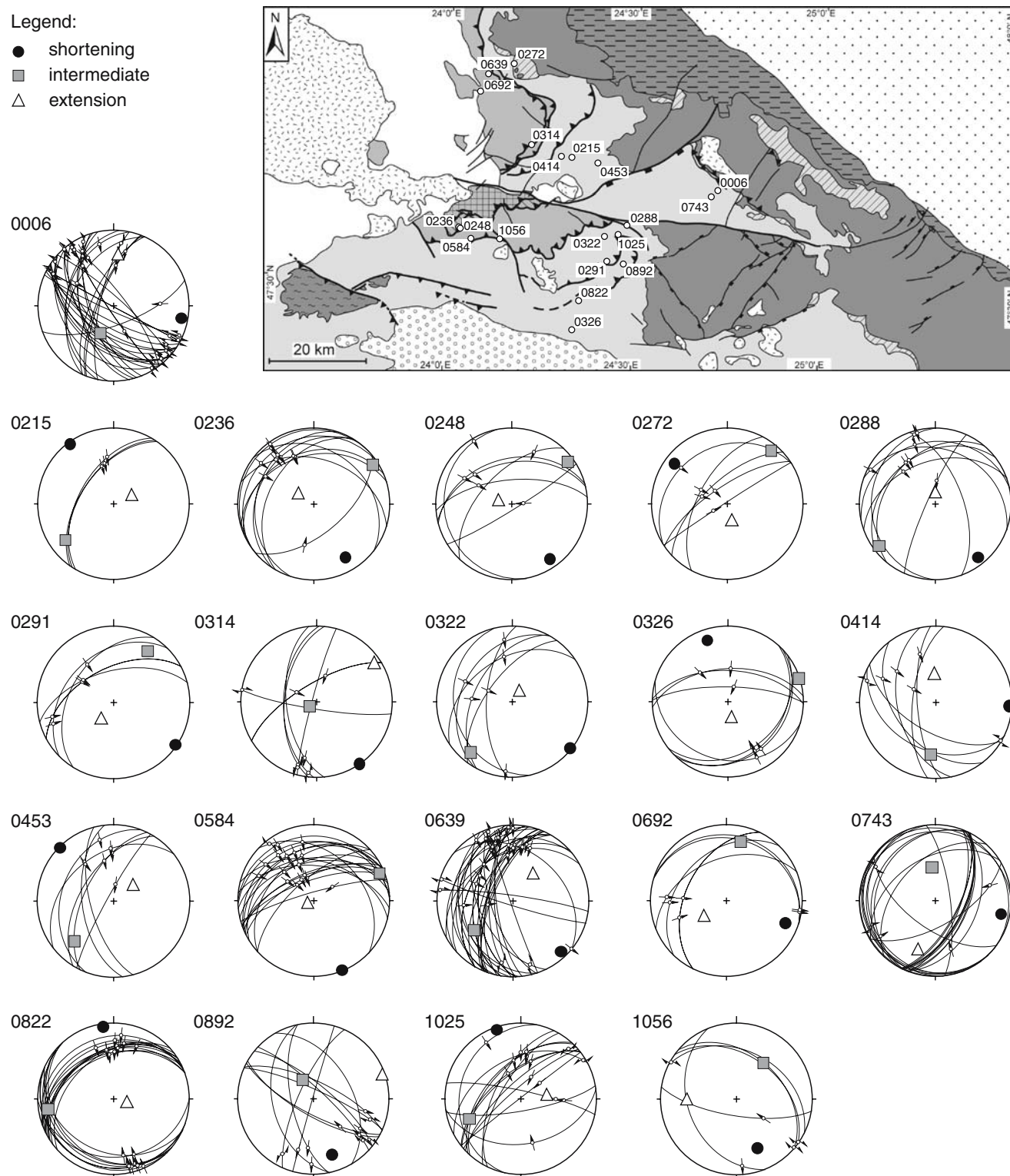


Fig. 9 Fault-slip data (Early Burdigalian top SE-thrusting of the Pienides)

Appendix 3

Figure 10.

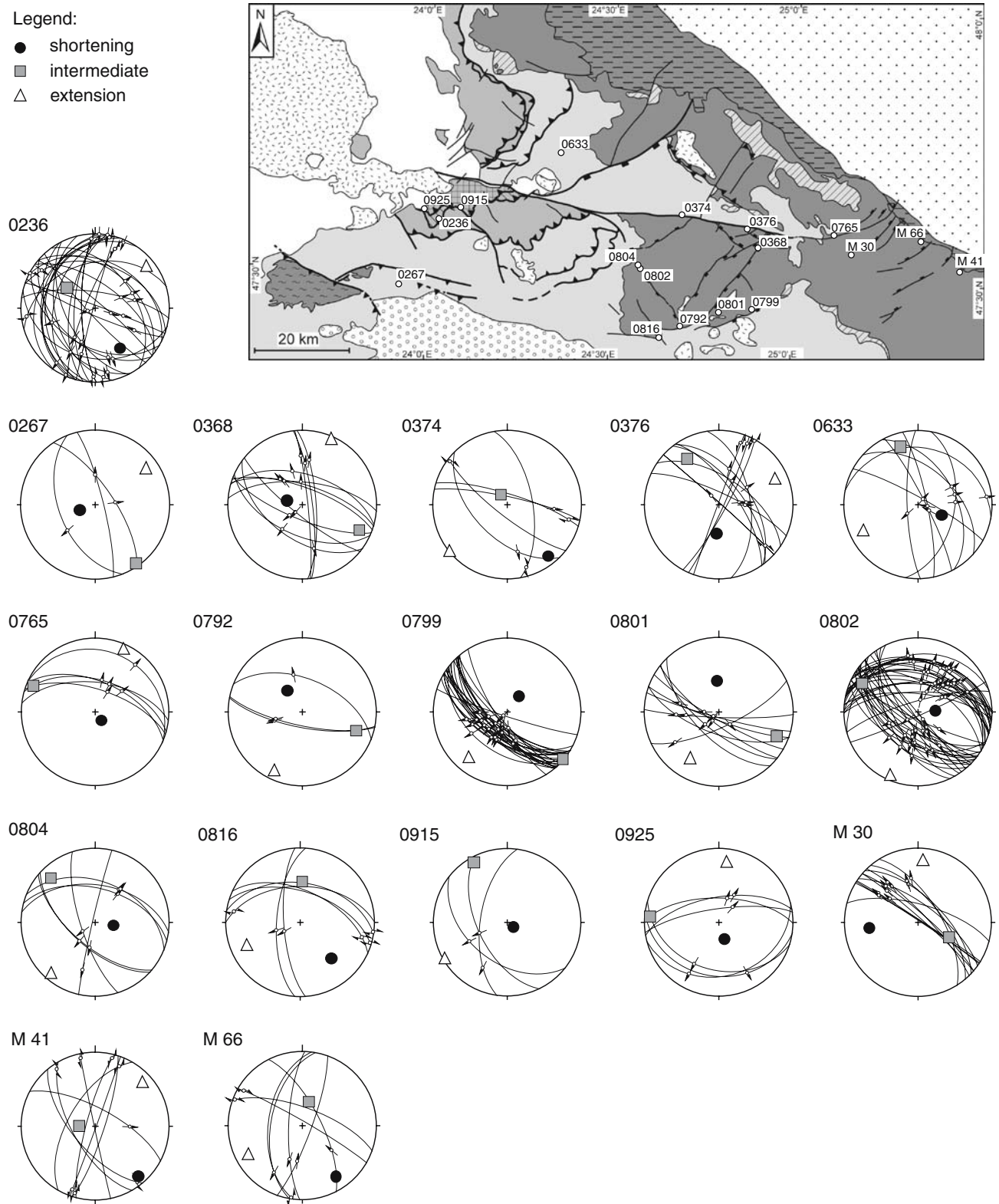


Fig. 10 Fault-slip data (Late Burdigalian NE–SW extension)

Appendix 4

Figure 11.

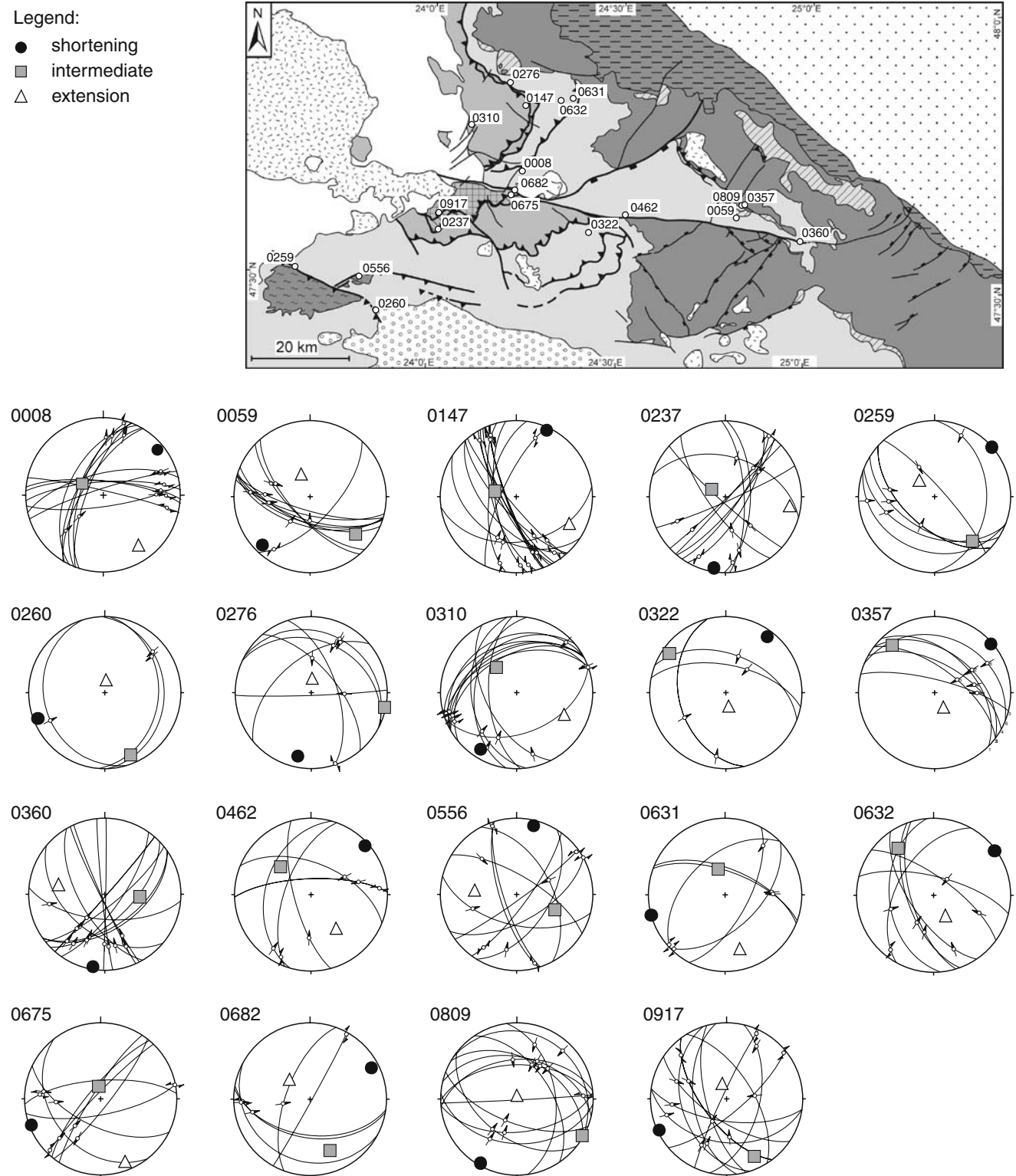
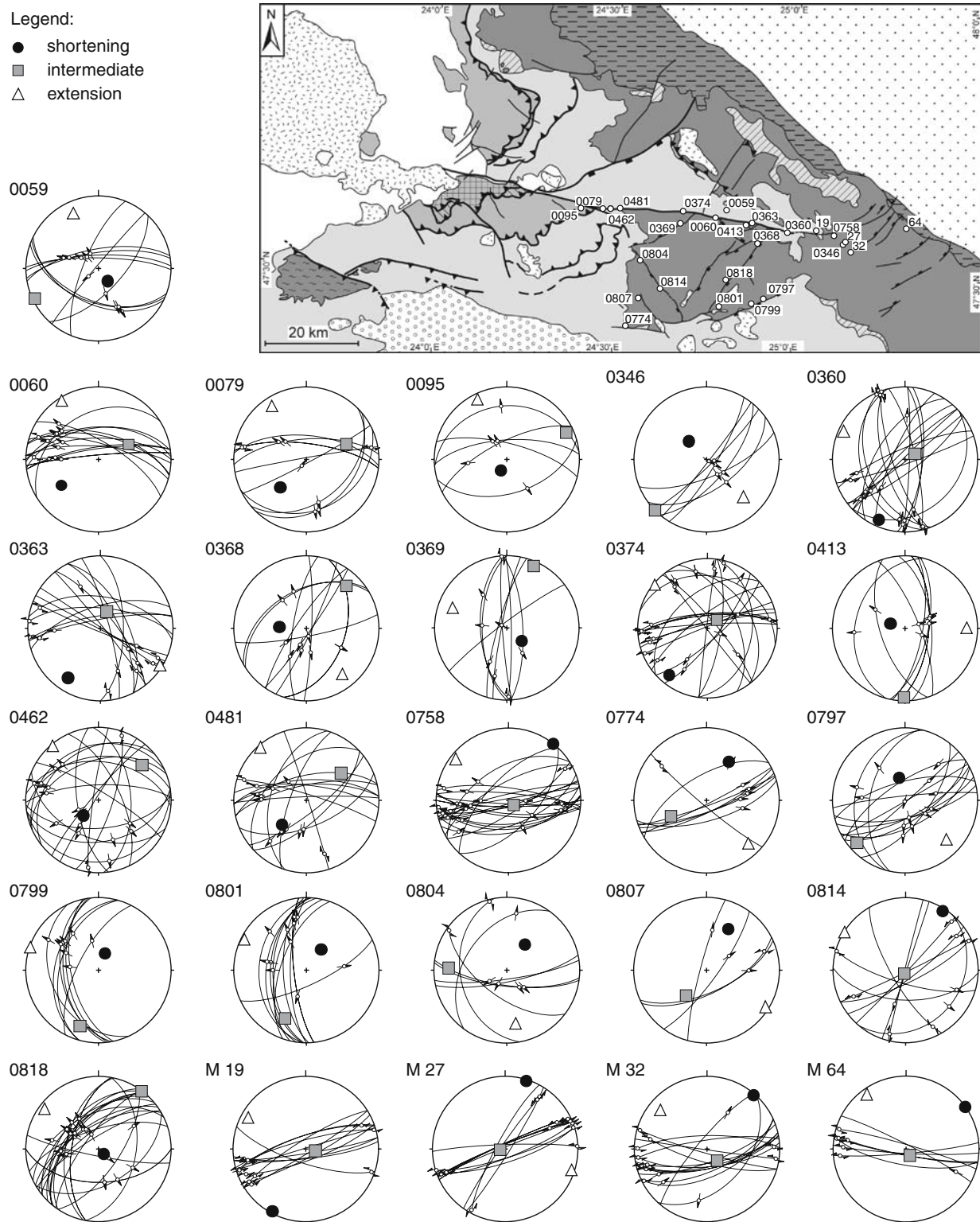


Fig. 11 Fault-slip data (post-Burdigalian transpressional stage)

Appendix 5

Figure 12.

**Fig. 12** Fault-slip data (post-Burdigalian transtensional stage, eastern stations)

Appendix 6

Figure 13.

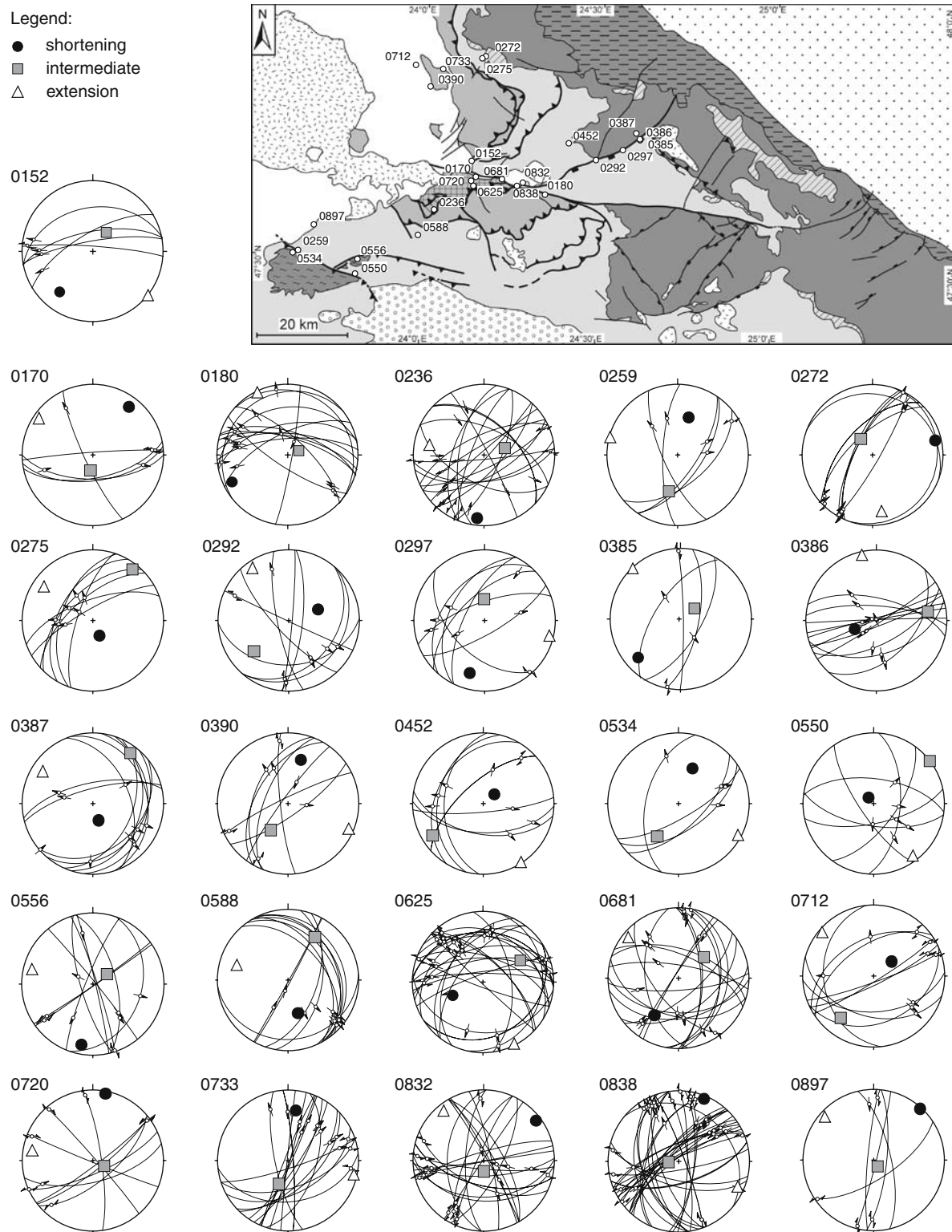


Fig. 13 Fault-slip data (post-Burdigalian transtensional stage, western stations)

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