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ORIGINAL PAPER

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Neogene–Quaternary structures in the border zone between Alps, Dinarides and Pannonian Basin (Hrvatsko zagorje and Karlovac Basins, Croatia)

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Abstract Analysis of Neogene–Quaternary structures from seismic lines, surface measurements and geological-mapping is presented from the border zone between the Alps, Dinarides and Pannonian Basin. First, Early Miocene extension was possibly characterised by ENE directed extension. It was partly synchronous with NW–SE shortening. Second, Middle Miocene extension was possibly characterised by NW–SE to WNW–ESE directed extension. Again, this event was followed by a new generation of thrusts related to end-Sarmatian shortening. The last, Late Miocene E–W to WNW–ESE directed extension was followed by a final shortening that created major, map-scale folds, basement pop-ups and inverted former basins. Geometry, onlap and thickness patterns of the youngest syn-tectonic basin fill indicate that this last, N–S to NW–SE directed shortening started in Late Pontian and continued up to the present time. When taking into account the wider surrounding area, it seems that the structures related to this latest shortening are arranged in often perpendicular directions, centred at the eastern end of the Periadriatic lineament. To explain this fan-like pattern of synchronous shortenings a kinematic model is proposed combining counter-clockwise rotation with north- or northwestward shift of the Dinaridic block with respect to the more stable Alpine buttress.

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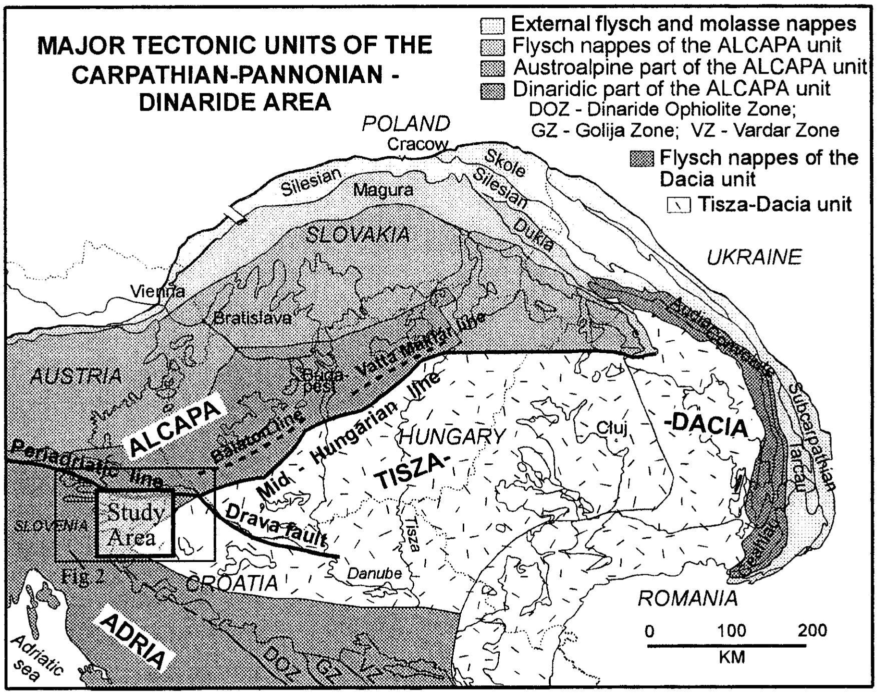
Introduction

The border zone between the Eastern and Southern Alps, Dinarides and Pannonian basin in north-western Croatia (Fig. 1) comprises highly deformed pre-Neogene units of both Alpine and Dinaridic origin (Pamić and Tomljenović 1998; Haas et al. 2000) with differing structural trends (Fig. 1). In this area tips of three major transcurrent faults of the Alpine–intra-Carpathian area intersect, or merge into each other (Figs. 1 and 2). The easternmost tip of the Periadriatic (Insubric) line (PAL), the major Alpine scar that separates Austro-Alpine and south-Alpine domains, is exposed here. These two domains experienced quite different kinematics and deformation style during the Cretaceous and Tertiary orogenic stages (e.g. Schmid et al. 1996). Further continuation of the PAL, however, is quite ambiguous because it is lost beneath the Neogene and Quaternary sedimentary fill of the Pannonian basin. It was proposed that dextral movement along the PAL led to the orogen-parallel, eastward directed extrusion and tectonic escape of the East Alpine units during the Early to Middle Miocene times (Ratschbacher et al. 1991). Balla (1985), Kázmér and Kovács (1985), Csontos et al. (1992) and Fodor et al. (1998) proposed that during this extrusion the PAL continued into the mid-Hungarian zone or line (MHZ, MHL) further to the east. This zone separates two terranes of the intra-Carpathian area, i.e. Alcapa to the north and Tisza-Dacia to the south (Fig. 1; Géczy 1973; Kázmér and Kovács 1985; Csontos et al. 1992; Csontos and Nagymarosy 1998). By analysing Latest Miocene to recent deformation in the area, Prelogović et al. (1998) proposed that the PAL bends more to the south-east and merges into the Drava fault (DF;

Fig. 1 Major tectonic units of the Carpathian–Pannonian–Dinaride area (modified after Csontos et al. 1992). *VZ* Vardar Zone, *GZ* Golija Zone, *DOZ* Dinaride Ophiolite Zone boundaries are from Aubouin et al. (1970)



Figs. 1 and 2) as indicated by the earthquake epicentre distribution pattern in the area.

In this paper we focused our attention on the Neogene to Quaternary deformation events in order to show their kinematics and timing. Information was obtained from seismic sections and to lesser extent from outcrop measurements. Finally, a tentative model integrating data obtained now and earlier from nearby regions is presented to discuss probable Neogene–Quaternary tectonic scenario(s) for this part of the Alpine belt.

Geological setting

The study area is located at the south-western corner of the Pannonian basin and the north-eastern edge of the Dinarides (Figs. 1 and 2). Morphologically it is characterised by a few isolated, up to 1,000-metre-high mountains composed of Mesozoic rocks that emerge out of the Neogene and Quaternary fill of the Pannonian basin. The largest are Ivanšćica, Medvednica and Žumberak Mts. exposing several pre-Neogene tectonostratigraphic units as: (1) a greenschist complex composed of metavolcanic and metasedimentary rocks with Eoalpine metamorphic age (122–110 Ma; Belak et al. 1995); (2) a Cretaceous ophiolite mélange with blocks of ophiolites, greywackes, radiolarites and limestones of different Mesozoic ages; (3) a Late Cretaceous–Palaeocene shallow to deep marine sequence with flysch character, and (4) a Late Permian–Cretaceous passive margin sequence with Middle Triassic mafic volcanic rocks and Late Jurassic–Early Cretaceous Maiolica-type micrites. Eocene limestones and breccias, accompanied by Oligocene marls are only locally preserved along the shear zone of the Donat fault, north of Ivanšćica Mt. (Fig. 2; Šimunić 1992). During Neogene extensional events, the earlier structural assemblage was broken apart and in great part subsided to form the basement of basins.

Most of Neogene rocks (1,600–2,500 m thick; Šimunić et al. 1983a), are preserved within several generally E–W striking synclines between Medvednica Mt. and the PAL. This region is known in the literature as Sava folds (Sikošek 1971, Placer 1998a), or Tertiary basin of Hrvatsko zagorje (Šikić et al. 1978, 1979) and extends towards the west in Slovenia (Fig. 2B). In the following we shall refer to this area as the Zagorje basin. Beside that region we investigated seismic sections from the Karlovac basin south of Žumberak Mt. (Fig. 2B). This is a small Neogene basin at the north-western corner of the much larger Sava basin, which extends to the south-east along the Sava River valley. The fill of these basins comprises four cycles (Eggenburgian–Ottnangian, Karpatian, Badenian–Sarmatian, Pannonian–Pontian; see Fig. 16) of Neogene sediments accompanied by volcanic rocks (Pamić and Pécskay 1996). All these cycles represent transgressive and regressive deposits. The last, Pliocene–Quaternary cycle is composed of mostly fluvial deposits (Šikić et al. 1979; Basch 1983b; Šimunić et al. 1983b; Šimunić 1992).

Methods

Seismic sections available in two key areas, i.e. the Zagorje and Karlovac basins were analysed (Fig. 2B).

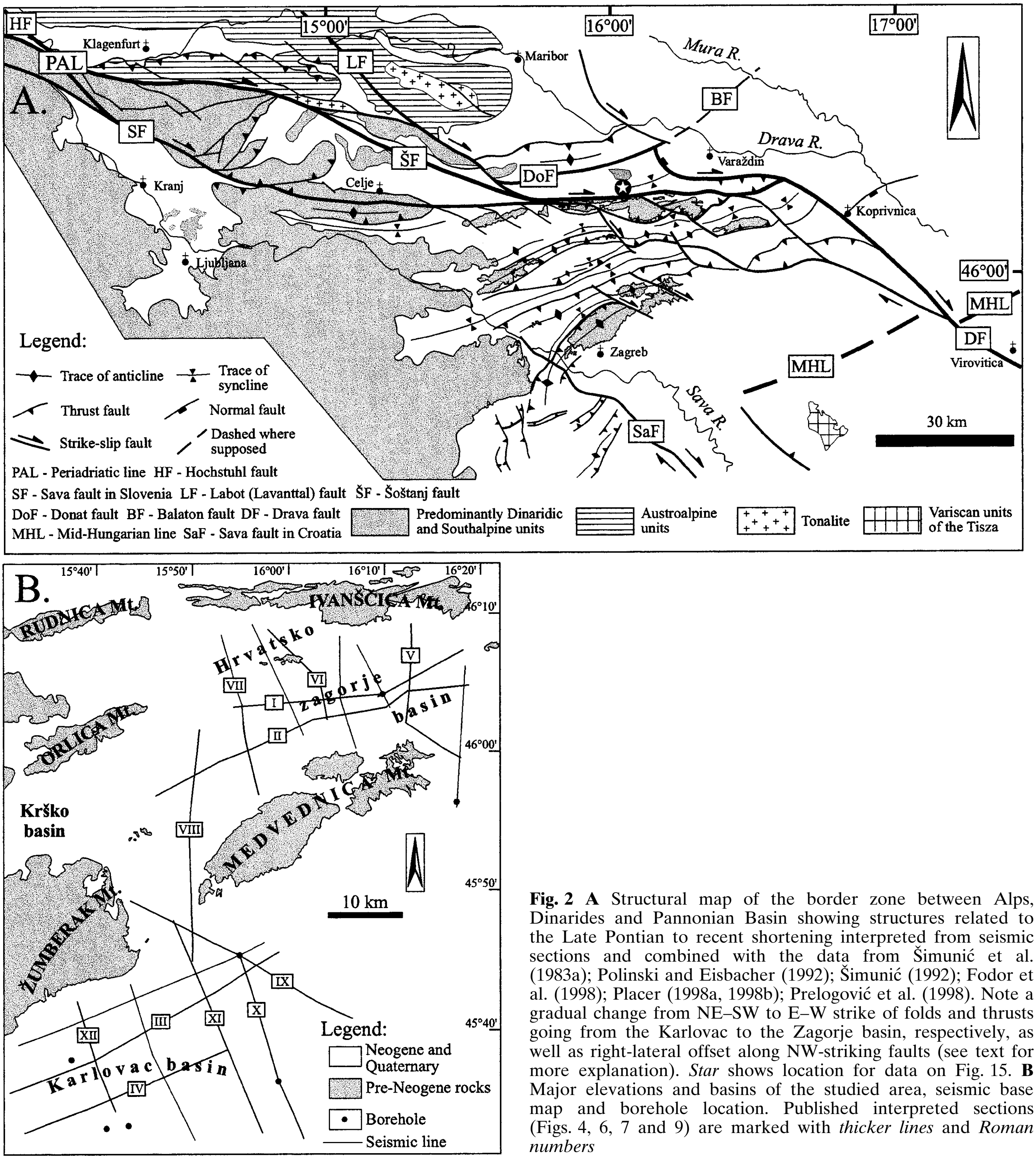


Fig. 2 **A** Structural map of the border zone between Alps, Dinarides and Pannonian Basin showing structures related to the Late Pontian to recent shortening interpreted from seismic sections and combined with the data from Šimunić et al. (1983a); Polinski and Eisbacher (1992); Šimunić (1992); Fodor et al. (1998); Placer (1998a, 1998b); Prelogović et al. (1998). Note a gradual change from NE–SW to E–W strike of folds and thrusts going from the Karlovac to the Zagorje basin, respectively, as well as right-lateral offset along NW-striking faults (see text for more explanation). *Star* shows location for data on Fig. 15. **B** Major elevations and basins of the studied area, seismic base map and borehole location. Published interpreted sections (Figs. 4, 6, 7 and 9) are marked with *thicker lines* and *Roman numbers*

In the Zagorje area the quality of the sections was affected by the hilly landscape. In the Karlovac basin area the younger vintage sections are better than the older ones. On all sections the base of Late Miocene (base Pannonian) formed a good regional reflector. On most sections the Middle Miocene sequence and a rather well-expressed basement reflector could be differentiated as well. In some parts of both areas a well-layered sequence dated in the available boreholes as Oligo-Miocene (possibly Early Miocene) was separated. Rarely, basement also contained well-layered strata, which proved to be either Triassic, or Late Cretaceous–Palaeocene strata. In these cases the limit of pre-Tertiary basement and Tertiary was hard to pick.

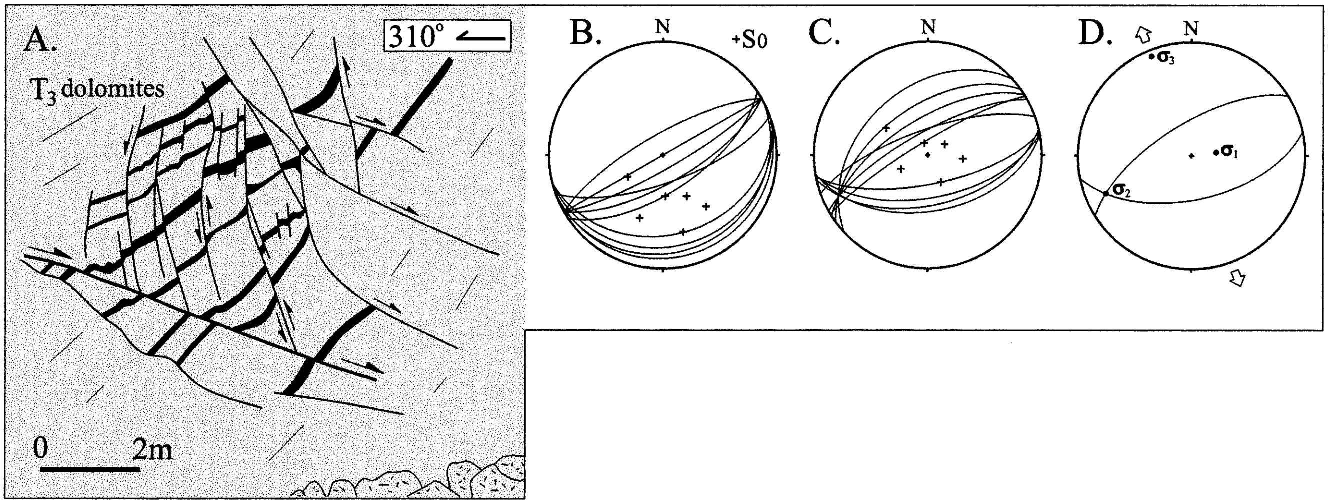


Fig. 3 Steps in graphical determination of principal palaeostress directions from conjugate normal faults. **A** Geometry and arrangement of conjugate normal faults offsetting dark stromatolite layers in Late Triassic dolomites (Žumberak Mt. eastern part). **B** Outcrop data. **C** After back-tilting to the presumed orientation during fault nucleation. **D** Pair of faults representing the mean orientation of two intersecting sets of faults used for determination of principle palaeostress directions (all diagrams are equal-area, lower-hemisphere stereoplots; fault and bedding planes are *large circles* and *crosses*, respectively)

The stratigraphy of the sections was calibrated by data from deep wells in the two basins. Unfortunately the available material did not allow to make a detailed sequence stratigraphy, so we relied on litho- and biostratigraphy in the wells and correlation of the characteristic seismic patterns and unconformities on the calibrated seismic sections. We also projected surface mapping data (Šikić et al. 1978; Basch 1983a; Šimunić et al. 1983a; Šimunić 1992) at depth along the sections. These data supported the stratigraphic correlation made by well control and seismic patterns.

Structural analysis and interpretation of structural events were made from younger to older. When considering the older events, the effects of younger ones were reconstructed. Hence normal faulting will be described at some places, where the present-day geometry of younger reflectors suggests thrusting, but thickness data and restoration prior to thrusting prove normal offsets.

In some cases correlation of outcrop structural-geological data with structures observed in seismic sections proved to be very useful. We visited 26 sites where Tertiary was exposed, but unfortunately the quality of these outcrops did not allow to obtain good and statistically validated observations. Therefore, we used 16 sites in pre-Tertiary rocks and one site in Neogene rocks, where fault structures remained preserved, and which lie adjacent to seismically defined structural zones. Fault data were treated by various methods to define the main shortening and stretching directions. Computations were done graphically using the method of Angelier and Mechler (1977) and by a reduced stress tensor calculation program of Sperner et al. (1993) and Sperner (1996) based on the method by Turner (1953), Angelier and Gougel (1979) and Spang (1972). In addition, we processed conjugate fault sets with clear offset but no striations by estimating palaeo-stress directions using the Coulomb failure law. Additionally, where hanging-wall block rotation along the low-angle normal faults was obvious, measured data were rotated back to the presumed orientation during fault nucleation. This was achieved by rotation of inclined strata back to horizontal (Fig. 3).

Results

Style and timing of relevant deformations

In the following, the main structures encountered in seismic analysis and in outcrops are described in greater detail. At a first glance the two areas around Medvednica Mt. have a different structural style: the Zagorje area is dominated by E–W striking folds, whereas these structures are absent in the Karlovac basin. At a closer look, however, one has to realise that the two adjacent areas have undergone a similar structural evolution, but the amplitude of some structures is different. Therefore, we describe the structures of the two areas together, in chronological order.

Early Miocene (Eggenburgian?–Ottnangian, ~20–18 Ma) normal faulting

On the NE–SW trending seismic sections of Zagorje normal fault-bounded blocks are displayed. These blocks often have a highly asymmetric, rotated wedge shape (Fig. 4, section II) and are bounded by shallow-dipping normal faults. The fill above the basement is composed of a syn-tectonic clastic sequence, which

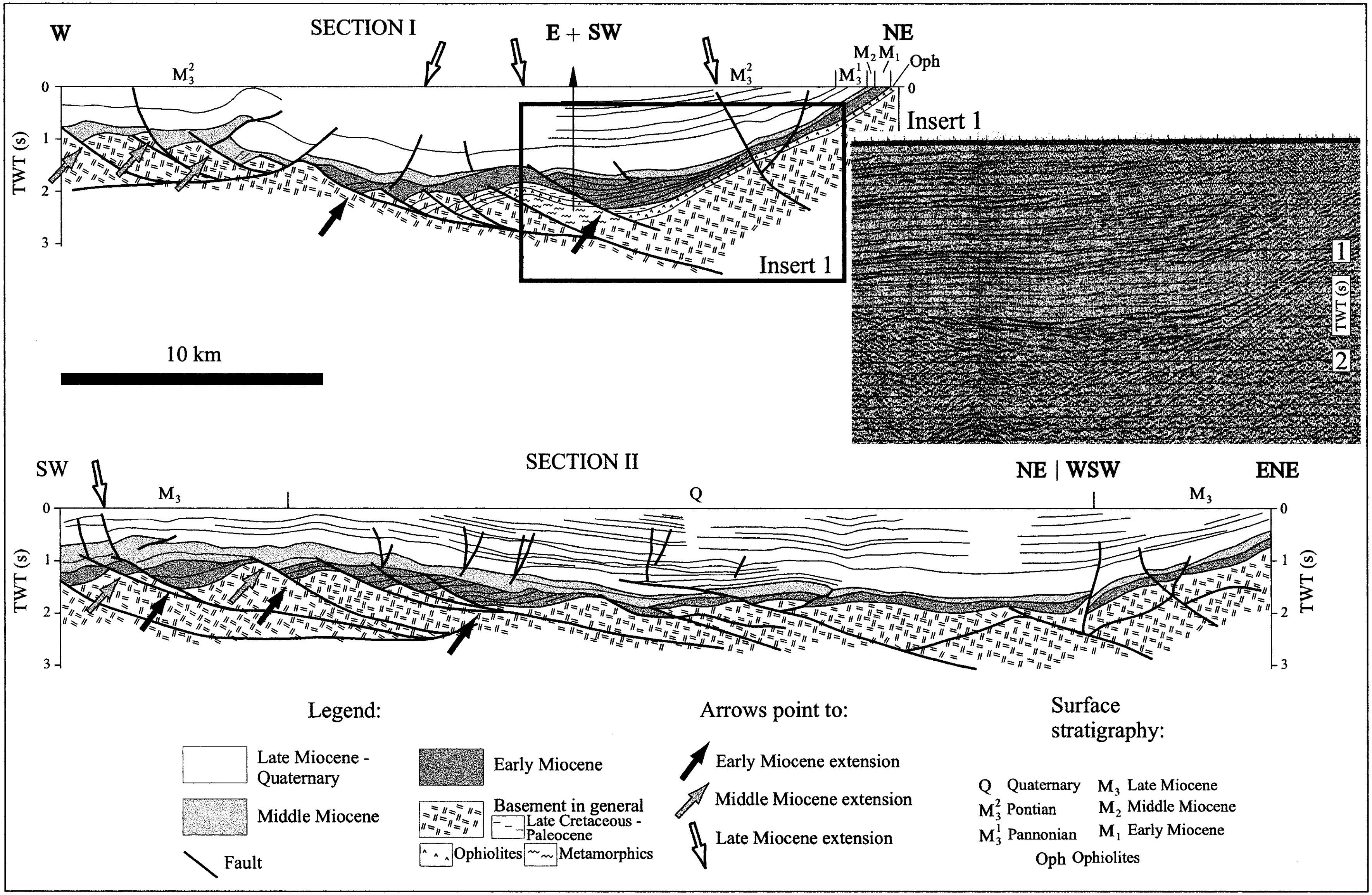


Fig. 4 Geoseismic sections from the Zagorje area. See text for explanation. For location of sections see Fig. 2B. Different *arrows* point to structures described in the text. *Box* indicates *insert*, part of original seismic section (scanned at 600 dpi)

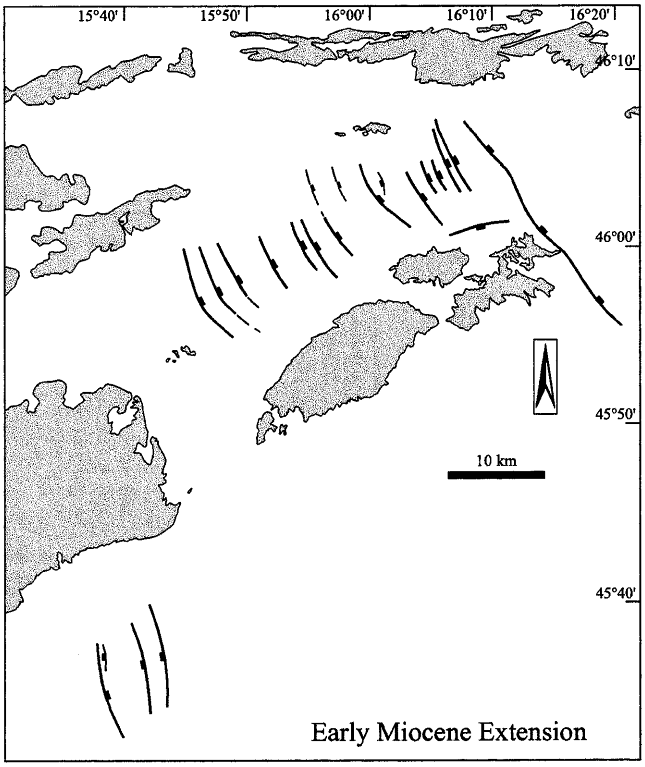


Fig. 5 Interpretative map of normal faults active during the Early Miocene. Correlation based on seismic sections is more reliable in the Karlovac basin, but very uncertain in the Zagorje basin

was penetrated and defined by the nearest borehole as an Early to Middle Miocene clastic sequence (Fig. 4, section I) known from the surface in the neighbourhood. These faults are hard to correlate because of the sparse seismic network and because of the complicated structure of the area. However, they are not, or badly seen on NW–SE trending seismic lines, therefore their orientation is probably parallel, or acute to NW–SE lines. We infer a NW–SE trend for these faults (Fig. 5).

In the Karlovac basin, a similar feature is seen on NE–SW oriented lines. Here, a more symmetrical basin is seen near two boreholes (Fig. 6, section IV). Projection of these wells into the section indicates that the first syntectonic fill of the depression is 'Oligo-Miocene' and Early Miocene clastics, followed by Badenian–Sarmatian clastics and marls. Although more symmetrical than in Zagorje, this basin is also bounded by major, relatively flat, ENE-dipping master normal faults and antithetic faults (Fig. 6, section III). Local structures correlate well on all seismic lines and are conformable with the basin margins, therefore a general NNW–SSE strike for the main normal faults was accepted (Fig. 5). If dip-slip movement is inferred (for a justification see below), this gives a main extension towards the ENE in present geographical co-ordinates.

NE–SW extension in Žumberak and Medvednica Mts. is not evident. Locally preserved Early Miocene in the central part of Medvednica Mt. does not show conspicuous normal faulting. On section XII (Fig. 6) the Early Miocene sequence ends in onlaps–downlaps and does not extend to the Žumberak Mt. either until the border fault. This suggests that Early Miocene elongation in the present-day mountains was not as important, as in the present-day basin areas. Adjacent, differently extended blocks call for NE–SW striking transfer faults. These faults do exist, but later movements hide their original role (see later). These possible transfer faults enable to postulate NE–SW dip-slip extension along the perpendicular master faults.

Late Early Miocene (Late Ottnangian? ~18 Ma) shortening

On the same strike-lines, especially on sections I and II (Fig. 4), some strata of the Early Miocene basin fill are truncated and onlapped by Middle Miocene (Badenian and Sarmatian) strata. This erosional event may indicate a sudden drop in the sea-level or a new tectonic event. On different sections trending NW–SE the latter can be demonstrated. Near Medvednica Mt. (Fig. 7, section V) the evident shortening-related structures are Plio-Quaternary. However, Early Miocene strata above the southern overthrust high are truncated, whereas they are preserved further south and north. Middle Miocene covers this erosional pattern in quasi-equal thickness. This pattern indicates a pre-Middle Miocene shortening. Such a pattern is also seen on sections VI and VII (Fig. 7), where the Early Miocene is eroded off the structural highs and preserved in their foreland.

There are some places, where the Early Miocene strata are not totally eroded, but their thickness changes are because of reverse faulting. On section VIII (Fig. 7) the Early Miocene is, as a rule, thinner above the protruding, slightly thrust basement highs, in the core of antiforms. Middle Miocene deposits cover both places uninterrupted (or even with thicker deposits above the thinned Early Miocene).

Again, the seismic network and occasional preservation of this event do not make a correct correlation possible, but such features are mostly seen on NW–SE oriented seismic lines. The places where this event can be demonstrated coincide with later thrusts or imbricate slices. Therefore we infer a NW–SE shortening (Fig. 8), which might have been (at least in part) synchronous with the aforementioned normal faulting. It seems that this shortening was more intensive in the Zagorje than in the Karlovac basin.

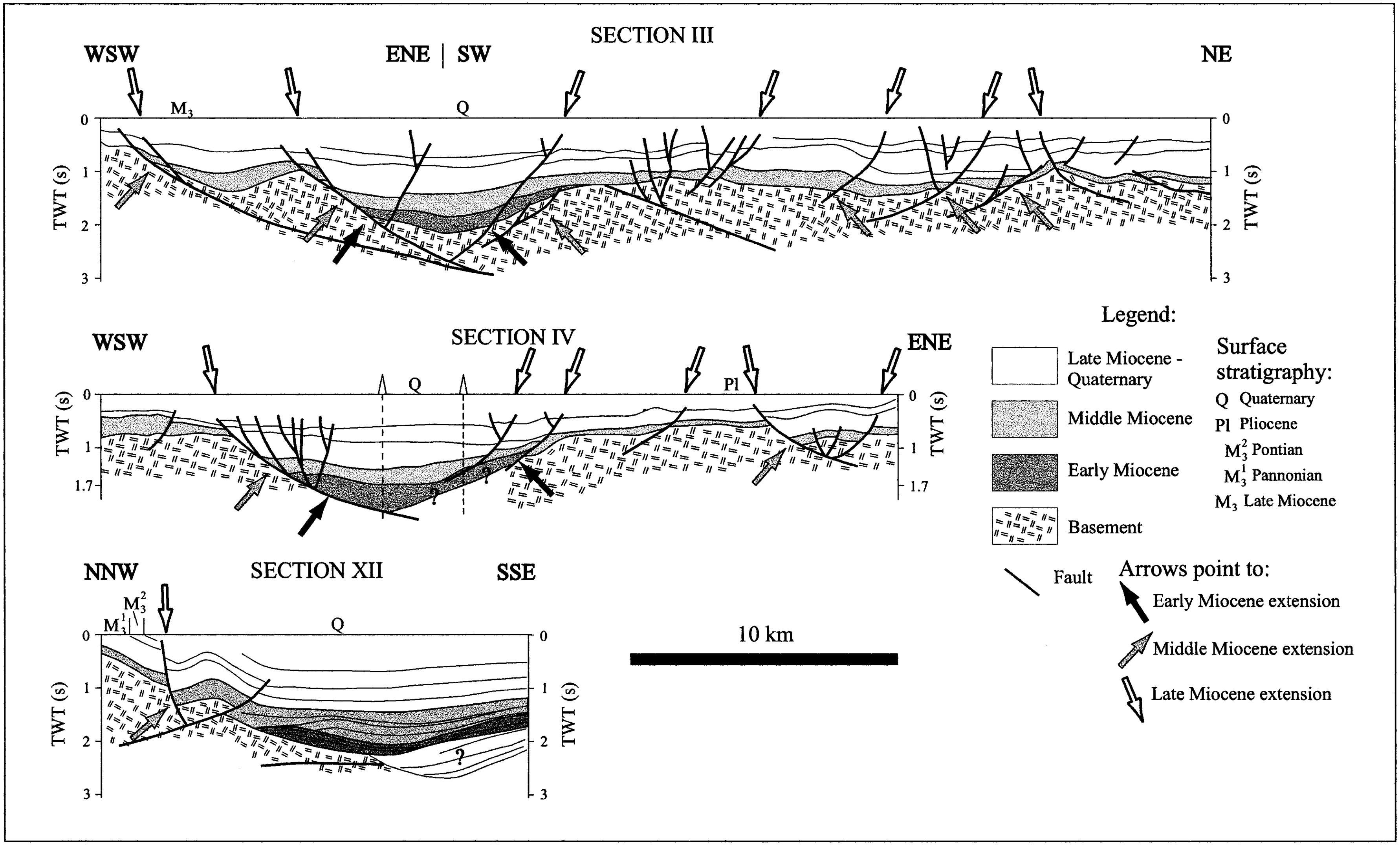


Fig. 6 Geoseismic sections from the Karlovac area. See text for explanation. For location of sections see Fig. 2B

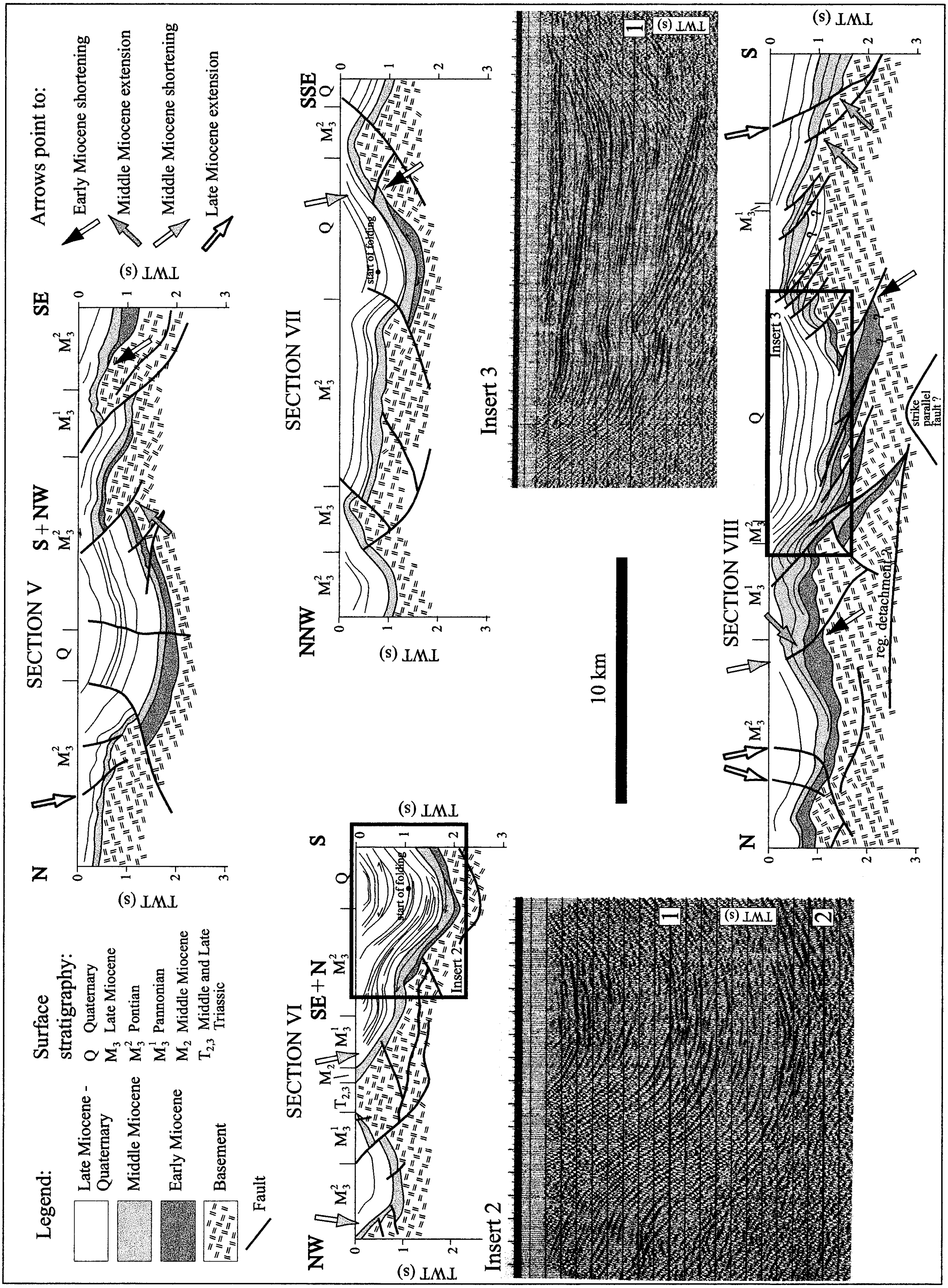


Fig. 7 Geoseismic sections from the Zagorje area. See text for explanation. For location of sections see Fig. 2B

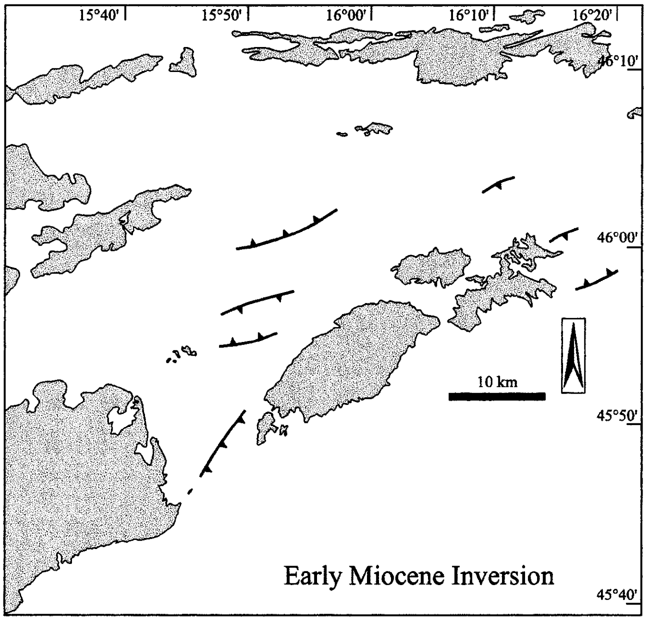


Fig. 8 Interpretative map of thrust faults active during the Early Miocene. Features interpreted from seismic sections. Correlation in case of the area near Zagreb is feasible

Middle Miocene (Karpatian?–Badenian–Sarmatian, ~17–12 Ma) strike-slip and normal faulting

Renewed faulting occurred along the master normal faults of the Karlovac basin (Fig. 6, sections III and IV). Traces of more important faulting occur along the sections near Žumberak and Medvednica Mts. (Fig. 6, section XII; Fig. 7, section VIII; and Fig. 9, sections IX, X, XI). These show smaller blocks bounded by Middle Miocene normal faults, which are later partly inverted. Although hampered by the reasons mentioned above, map-scale correlation of these faults is somewhat better than for the Early Miocene ones (Fig. 10). It indicates a co-existence of NNW–SSE and NE–SW oriented normal faults. The former ones seem to be located in more internal parts of both recent basins showing similar trend and geometry to those related to Early Miocene extension (compare Figs. 5 and 10). The latter ones seem to occur mostly in their border-zones. These fault patterns may be explained by WNW–ESE (E–W?) directed extension creating oblique slip on all faults. An alternative explanation is that the differently oriented faults played in successive E–W, then NW–SE directed extension episodes.

NE–SW oriented normal faults are particularly well preserved at the eastern margin of Žumberak Mt. (Tomljenović 1999, 2000) within blocks bounded by NE- and NW-striking strike-slip faults (Fig. 11). Overprinting relations between these two fault groups are weakly constrained because of alternating reactivation of strike-slip and normal motion.

A kinematically compatible set of strike-slip faults (in total 11 measurements from sites 5, 6, 8, 9, 14 and 15; Fig. 11) was recorded as a conjugate set of NW- and NE-striking dextral and sinistral faults, respectively (Fig. 12). Different methods used for palaeostress calculations all show that these faults accommodated NNE–SSW directed compression and contemporary WNW–ESE directed extension. The Mohr-circle diagram and the stress ratio (*R*) of 0.56 confirm the plane strain configuration, i.e. a pure strike-slip deformation.

Map-scale faults belonging to this group are shown on Fig. 11. Sinistral NE-striking faults predominate and are arranged into major fault zones that cut through pre-Neogene units and bound major Middle Miocene fault blocks. Dextral NW-striking faults are less frequent, striking along shorter distance, and are usually crosscut by sinistral faults. Thus, it seems that the two fault families were initiated as a conjugate set, but the NE-striking sinistral faults accommodated the bulk of motion and were more important than dextral ones.

Striated normal faults (in total 16 measurements from sites 1, 3, 6, 7, 8 and 10; Fig. 11) were recorded as a conjugate NE-striking set of oppositely dipping faults, which accommodated NW–SE directed extension (Fig. 12). Map-scale normal faults are frequent at the eastern and southern edge of Žumberak Mt. bounded by a few larger NE-striking sinistral strike-slip faults (Fig. 11). Similar faults form the north-western boundary of the Karlovac basin shown by subsurface analysis, too (Fig. 6, section XII).

Similar geometry and orientation was documented for a group of non-striated normal faults comprising 56 strongly weathered fault surfaces recorded mostly in Late Triassic dolomites (Fig. 11; sites 2, 3, 4, 9, 10, 13, 15 and 16). Normal character of these faults was documented by the offset of dark-grey to black stromatolite layers (Fig. 3). Orientation of principal palaeostress axes by the use of Coulomb law criteria corresponds well with the one calculated by P–B–T axes and numeric analysis for striated normal faults. This indicates that both groups belong to the same generation of normal faults accommodating NW–SE directed extension (Fig. 12).

Because microtectonic measurements were all carried out in pre-Neogene rocks, the age of faults cannot be constrained. We think, however, that the observed striated and non-striated normal faults are related to the Middle Miocene extensional event because their orientation, geometry and kinematic characteristics correspond fairly well with the NE-striking Middle Miocene normal faults documented from seismic sections (compare Figs. 10, 11 and 12). This is additionally supported by the fact that, on Žumberak Mt. in most of the sites where these normal faults were

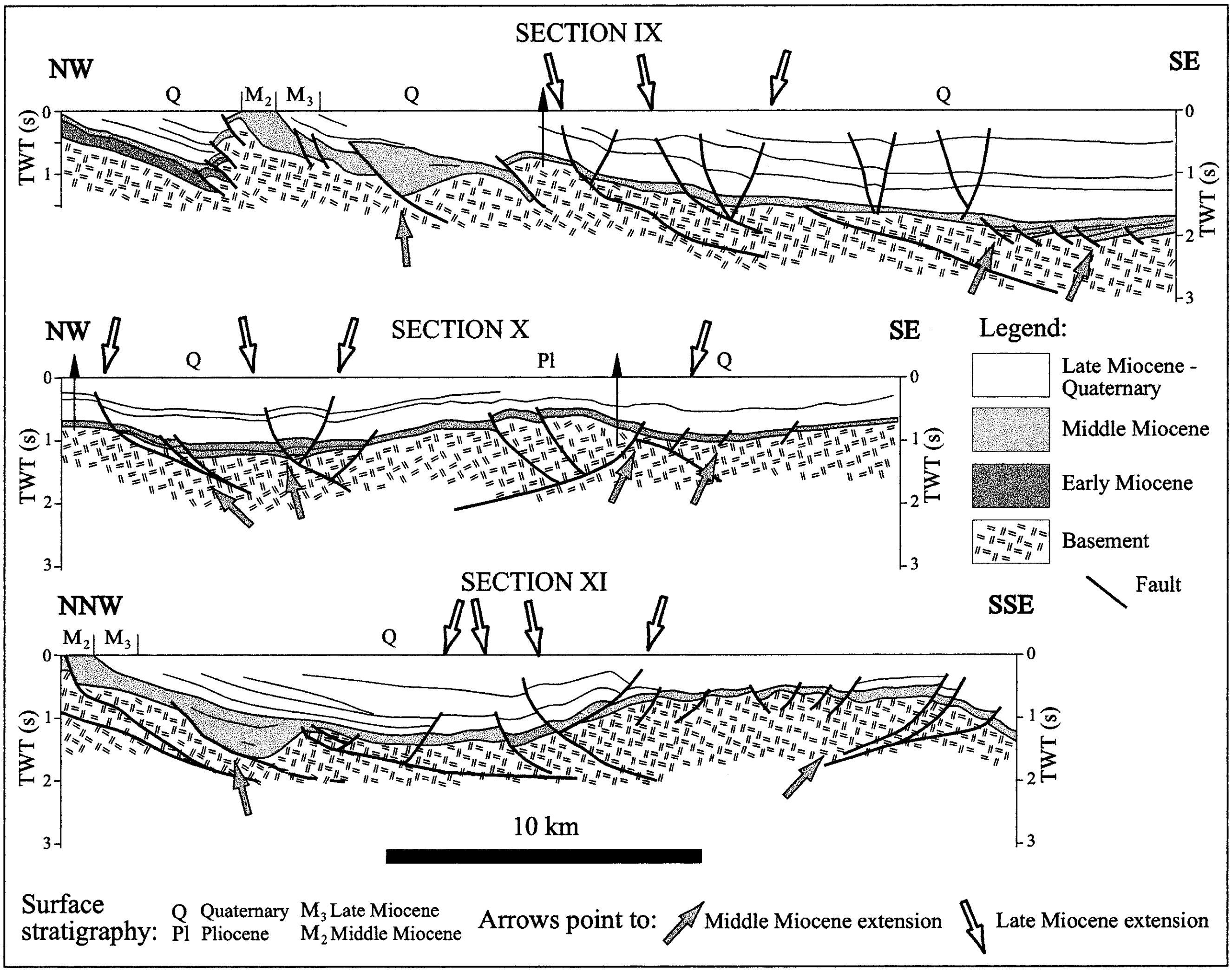


Fig. 9 Geoseismic sections from the Karlovac area. See text for explanation. For location of sections see Fig. 2B

observed, Middle Miocene strata unconformably and directly rest on pre-Neogene units.

End–Middle Miocene (Late Sarmatian, pre-Pannonian, ~12–11 Ma) shortening

The thickness variations of Middle Miocene may in part be caused by differential uplift and erosion as well. At some places, offset, overthrust basement and overlying Middle Miocene are eroded together to form an undisturbed base-Pannonian unconformity. Such a feature is seen on section VII, or on section VI (Fig. 7). This end-Sarmatian shortening might have been much more widespread, but because of later very intense overprint it is not easily proven. These fault zones, however, cannot be confidently correlated between seismic sections. End-Sarmatian uplift, is recently supposed by Vrsaljko (1999) to explain significant change in facies and fauna between exposed Sarmatian and Pannonian sequences on the southern slope of Medvednica Mt.

Late Miocene (Pannonian, ~11–10 Ma, and Early Pontian, 7 Ma) normal faulting

In several areas, especially in the Karlovac basin, older faults were reactivated during Late Miocene (Pannonian) time. This extensional reactivation is spectacular along the master growth fault of the Karlovac basin (Fig. 6, sections III and IV). The main trend of these faults is NNW–SSE (Fig. 13). Similar extension and offset is also seen on the NW–SE trending lines (e.g. section X, Fig. 9). Quite often smaller offset fault swarms are present, which form flower structures (e.g. sections IV, IX, Figs. 6 and 9, respectively). When reconstructed prior to subsequent shortening, these flowers have a negative offset. This indicates that the fault movement may have had a lateral shear component. A roughly E–W to WNW–ESE

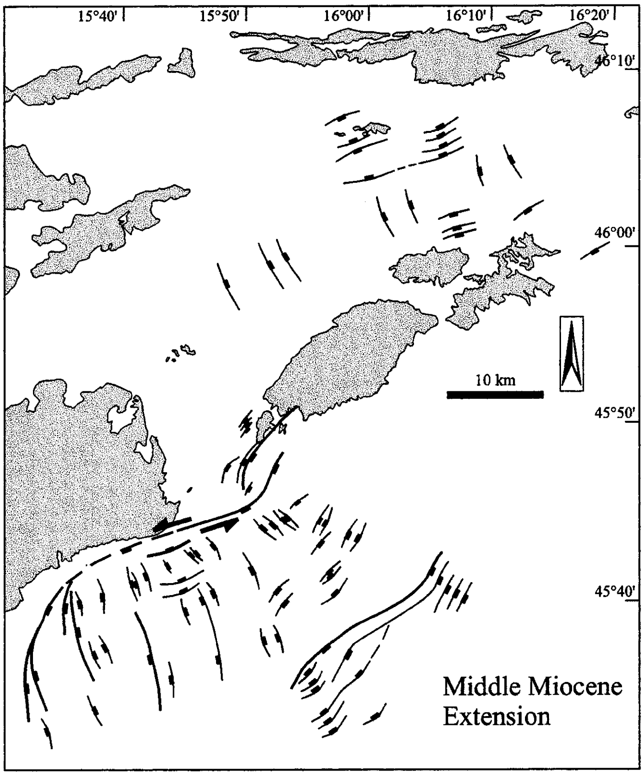


Fig. 10 Interpretative map of normal faults related to Middle Miocene extension. Features interpreted from seismic sections. Correlation is more certain in the Karlovac basin than in the Zagorje basin. Arrangement and orientation of faults suggest a bi-directional ENE–WSW and NW–SE -directed extension accommodated by reactivation of earlier NNW- and newly formed NE-striking faults, respectively. Note a NE-striking basin-margin fault in the Karlovac basin that accommodated extension and sinistral strike-slip displacement

extension direction is supposed to extend blocks along both NW- and NE-striking faults (Fig. 13).

In the Zagorje basin there is an observed thickness-change along some faults, which may be active earlier and later as thrust faults. Because of later inversion these faults are hard to correlate. Such faults can be seen on both the NE–SW striking (Fig. 4) and NW–SE striking sections (Fig. 7, sections V, VIII), therefore roughly E–W and NW–SE elongation may be inferred.

Similar synsedimentary extensional faults are observed in Pontian horizons as well. The subsidence continues along the main faults active in Pannonian times (e.g. section I, Fig. 4; sections III, IV, Fig. 6; section VIII, Fig. 7; section IX, Fig. 9). As in the Pannonian, the main subsidence is along NW–SE oriented faults, so similarly, a roughly E–W elongation direction is proposed.

Late Miocene–Recent (Early and Late Pontian–Pliocene–Quaternary, ~6–0 Ma) shortening

This event has the deepest impact on the structural setting of the study area. Numerous structures including major, map-scale folds, inverted basement pop-ups and inverted former sub-basins are found in both the Zagorje and the Karlovac basins. The Zagorje structures are much more prominent, however. These inverted structures appear mostly on the NW–SE oriented lines of the Zagorje basin (Fig. 7). Here, numerous thrusts put basement above rocks as young as Pannonian or even Pontian. The different episodes of major shortening can be dated with the help of the syn-tectonic basin fill. The geometry, onlap and thinning–thickening patterns indicate that the main folding started in late Early, or early Late Pontian (Fig. 7, sections VI, VII, Insert 2) and eventually stopped at the Pliocene–Quaternary boundary (onlaps in the middle part of section VIII, Insert 3, Fig. 7). However, some sections show that even these Quaternary strata are folded (Fig. 7, section VI, insert 2). Resolution loss of the seismic technique near surface does not enable to indicate a better timing for the reactivated shortening, but the major Zagreb earthquakes can be attributed to this activity (Prelogović et al. 1998). Going from the Karlovac into the Zagorje basin the strike of the folds, basement thrusts and pop-ups gradually changes from NE–SW to E–W (Fig. 2A). These structures are offset along dextral NW-striking strike-slip faults, which are arranged in an echelon array with respect to the PAL. The structures become tighter towards the north-east: basement pop-ups bounded by thrusts are more and more closely spaced and folds become tighter (Fig. 2A). On the sections oriented NE–SW only the overlapping thrusts sheets are seen in a strike-parallel view.

Microtectonic data related to Pliocene shortening in the Zagorje basin were recorded north of the PAL, between Ivanšćica and Ravnagora Mts., in the Lepoglava syncline (Fig. 2A). Even Plio-Quaternary rocks (Šimunić 1992), of this ENE-trending, gently ENE-dipping and partly overturned map-scale syncline are folded, thus indicating a Late Pliocene–Quaternary shortening. In its westernmost termination, where the syncline narrows and becomes tight, the folding was accompanied by cleavage in less competent marls and reverse faulting in competent calcarenite beds of Late Badenian age. Both the cleavage and the fault data indicate NW- to SE-directed shortening (Fig. 14).

Inversion in the Karlovac basin is less intensive. It is indicated by basement thrust over young Tertiary strata (Fig. 9, section IX), or by gentler N–S to NE–SW oriented domes corresponding to inverted former basins (Fig. 9, sections X and XI; Fig. 2A). On these sections positive flower structures are seen offsetting the highest resolved reflectors as well. Sections oriented NE–SW also show slight inversion of the

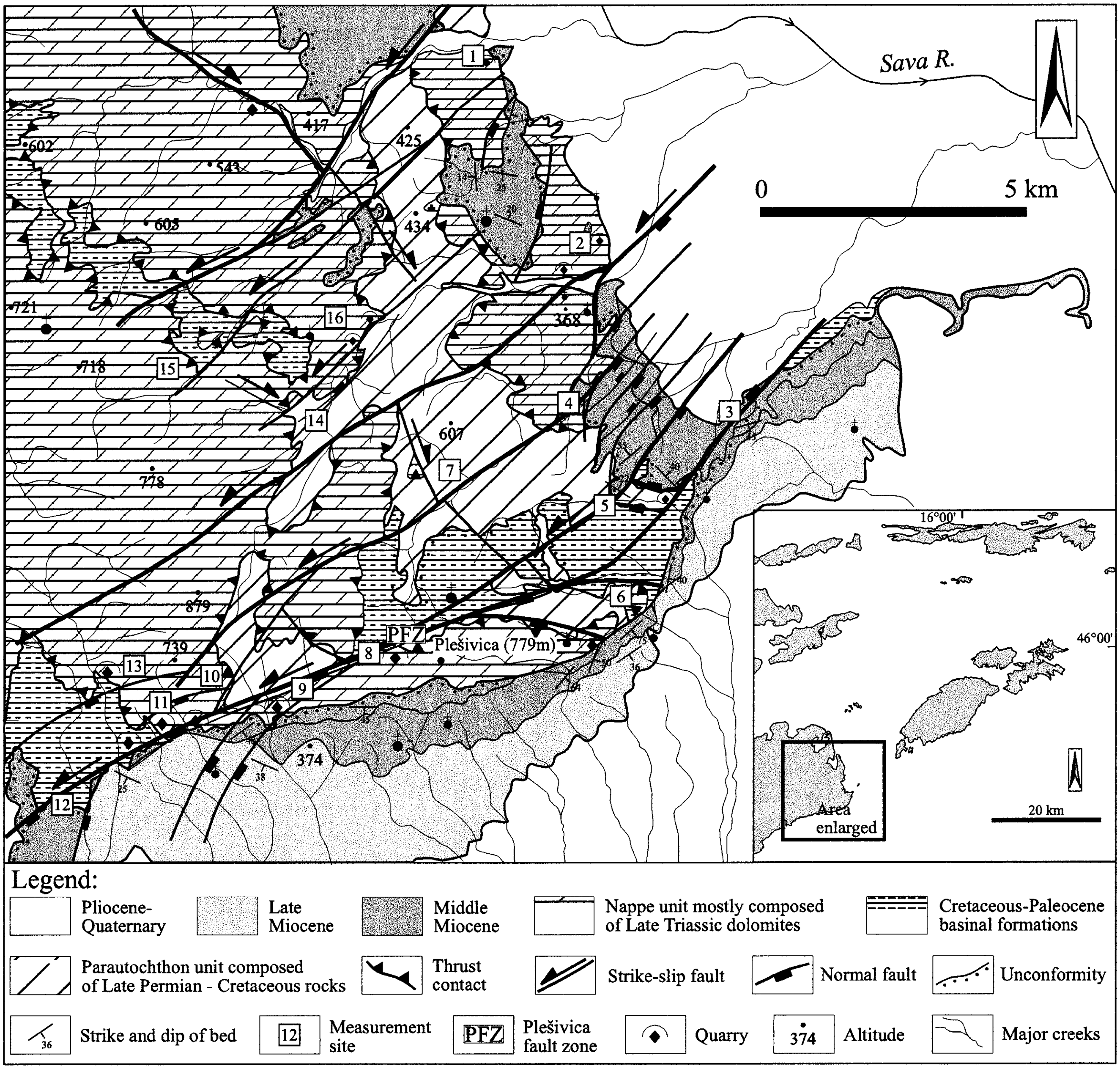


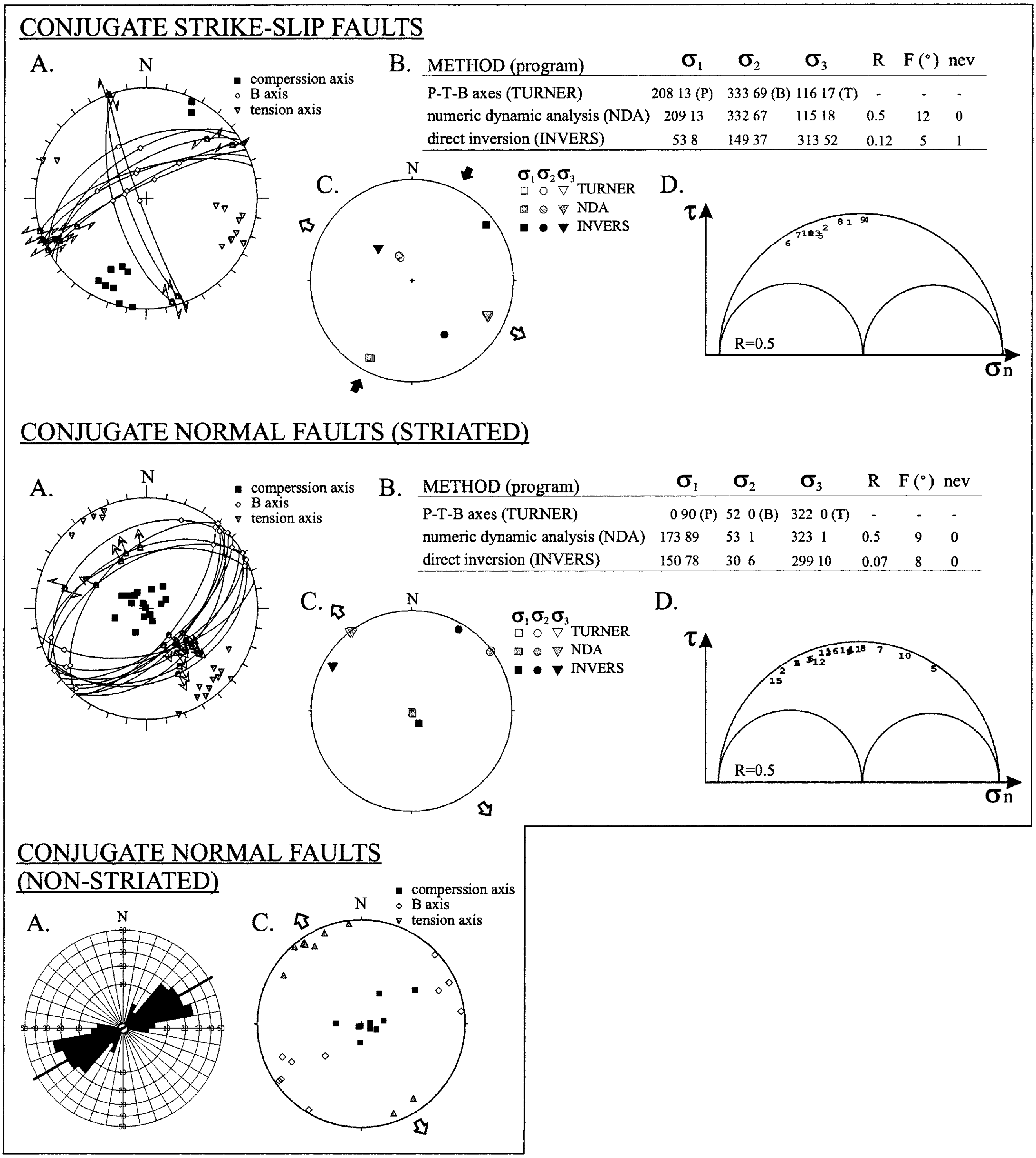
Fig. 11 Geological map of the eastern part of Žumberak Mt. (Tomljenović 2000, simplified after Šikić et al. 1978) showing faults presumed active during the Middle Miocene times. Note the predominance of NE-striking sinistral over NW-striking dextral faults connecting local zones of extension

former major basins and Pontian reflectors are slightly folded (Fig. 6, sections III, IV). Confidently correlated structures trend NE–SW or even NNE–SSW (Fig. 2A). Distribution of compressive elements suggests a roughly NW–SE directed shortening.

Geodynamic discussion

Main structural events

Summarising the main structural events of the study area (Fig. 15), in the Early Miocene (~20–18 Ma) the whole region underwent differential NE–SW to E–W stretching and (at least partly) perpendicular shortening. This is kinematically in a good correlation with data obtained from outcrops in Slovenia just north of the study area, where considerable dextral slip along the PAL took place under generally NNW–SSE compression and perpendicular stretching during the same period (Fodor et al. 1998). According to these authors, this resulted in separation of the Eisenkappel granite



CONJUGATE STRIKE-SLIP FAULTS

B.

METHOD (program)	σ_1	σ_2	σ_3	R	F (°)	nev
P-T-B axes (TURNER)	208 13 (P)	333 69 (B)	116 17 (T)	-	-	-
numeric dynamic analysis (NDA)	209 13	332 67	115 18	0.5	12	0
direct inversion (INVERS)	53 8	149 37	313 52	0.12	5	1

CONJUGATE NORMAL FAULTS (STRIATED)

B.

METHOD (program)	σ_1	σ_2	σ_3	R	F (°)	nev
P-T-B axes (TURNER)	0 90 (P)	52 0 (B)	322 0 (T)	-	-	-
numeric dynamic analysis (NDA)	173 89	53 1	323 1	0.5	9	0
direct inversion (INVERS)	150 78	30 6	299 10	0.07	8	0

CONJUGATE NORMAL FAULTS (NON-STRIATED)

Fig. 12 Fault population from the eastern margin of Žumberak Mt. separated into three groups according to the kinematic compatibility and quality of preservation. See text for explanation. **A** Equal-area, lower-hemisphere stereoplot showing orientation of faults, striae, displacement direction and principal palaeostress directions determined by the graphic method of Angelier and Mechler (1977) and rose diagram showing strike in case of conjugate normal faults (non-striated). **B** Orientation of principal palaeostress directions calculated by three different methods. **C** Equal-area, lower-hemisphere stereoplot showing results of palaeostress analysis. **D** Mohr circle calculated by the numerical dynamic analysis method by Sperner (1996)

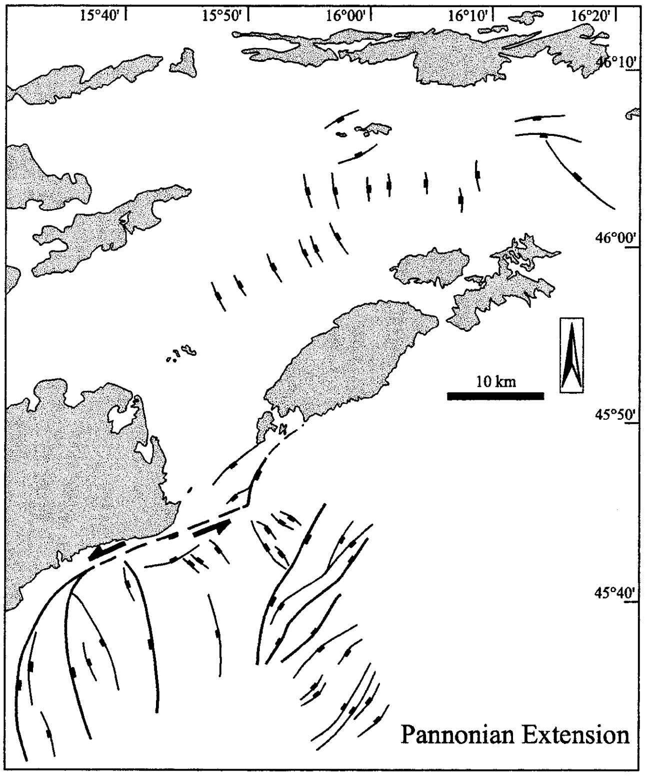
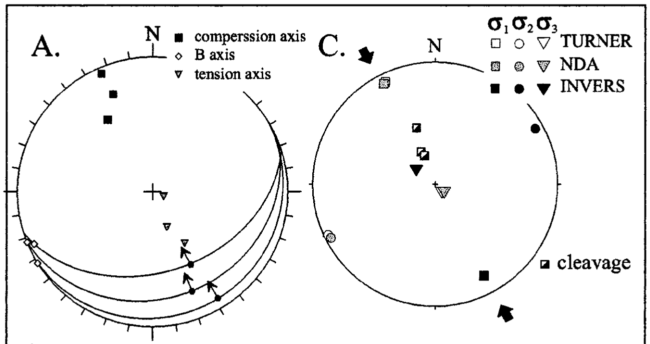


Fig. 13 Map of normal faults interpreted from seismic sections related to the Pannonian extension. Correlation is more certain in the Karlovac basin than in the Zagorje basin. Arrangement and orientation of faults suggest a bi-directional ENE–WSW and NW–SE directed extension accommodated by reactivation of both NNW- and NE-striking faults, respectively, inherited from Early to Middle Miocene times. Note a NE-striking basin-margin fault in the Karlovac basin that accommodated extension and sinistral strike-slip displacement



B.

METHOD (program)	σ_1	σ_2	σ_3	R	F (°)	nev
P-T-B axes (TURNER)	334 7 (P)	244 2 (B)	135 83 (T)	-	-	-
numeric dynamic analysis (NDA)	333 7	243 3	130 82	0.5	2	0
direct inversion (INVERS)	152 15	61 6	309 74	0.09	0	1

Fig. 14 Structural data measured in Late Badenian sequence at the southern limb of Lepoglava syncline north of Ivanščica Mt. (measurement site marked by star on Fig. 2A). **A** Equal-area, lower-hemisphere stereoplot showing orientation of faults, striae, displacement direction and principal palaeostress directions determined by the graphic method of Angelier and Mechler (1977). **B** Orientation of principal palaeostress directions calculated by three different methods. **C** Equal-area, lower-hemisphere stereoplot showing results of palaeostress analysis and orientation of contemporaneous cleavage

into numerous strike-slip duplexes stretched to the east along the combined PAL and MHZ and initial disruption of the previously uniform Palaeogene basin into north Hungarian and Slovenian sub-basins (i.e. extrusion of the coherent Alcapa block).

In the study area this deformational event was followed by a composite WNW–ESE or successive E–W to NW–SE elongation in the Middle Miocene (~18–12 Ma). As a result, earlier basins widened and new ones opened along NE-striking sinistral faults, showing geometry and kinematics similar to that of pull-apart basins generated along sinistral transtensional zones. Such zones were earlier proposed by Prelogović et al. (1995) and Tomljenović (2000) to explain the Middle Miocene extension in the Zagorje area. In a more regional view, this deformational event corresponds to the break up of the formerly coherent Alcapa block into an East-Alpine and a Pannonian–Carpathian part and to one of the principal extension phases of the Pannonian basin (Fodor et al. 1998, 1999). The dominance of elongation over shortening is explained by the possibility of eastward motion of rock masses.

We suppose that Middle Miocene kinematics in the study area continued into the Late Miocene as well, being shortly interrupted by Late Sarmatian shortening. The general elongation is replaced in the Late Pontian–Pliocene–Quaternary (~6–0 Ma) by N–S to NNW–SSE directed shortening and possibly partly coexisting E–W to ENE–WSW directed elongation. Latest Miocene to recent dextral transpression was demonstrated by Prelogović et al. (1998) in the area of northern Croatia. North of the study area this latest shortening was accommodated by a dextral transpression along the PAL and its accompanying NNW-striking faults (Polinski and Eisbacher 1992; Fodor et al. 1998; Placer 1998b). All these data account for N–S to NNW–SSE shortening. It seems that the same shortening determines the recent deformation pattern as well.

Very generally, the structural history of the study area can be characterised by a N–S to NNW–SSE compression and perpendicular extension directions throughout the Neogene–Quaternary period. The individual structures and their amplitude depend probably on the values of principal stresses and also on the distance of individual places to the main deformation zone: the PAL. When closer, the compressive structures are more prominent. The alternation of dominantly compressive vs dominantly extensive periods probably depends on the boundary conditions of the blocks in a complex interplay.

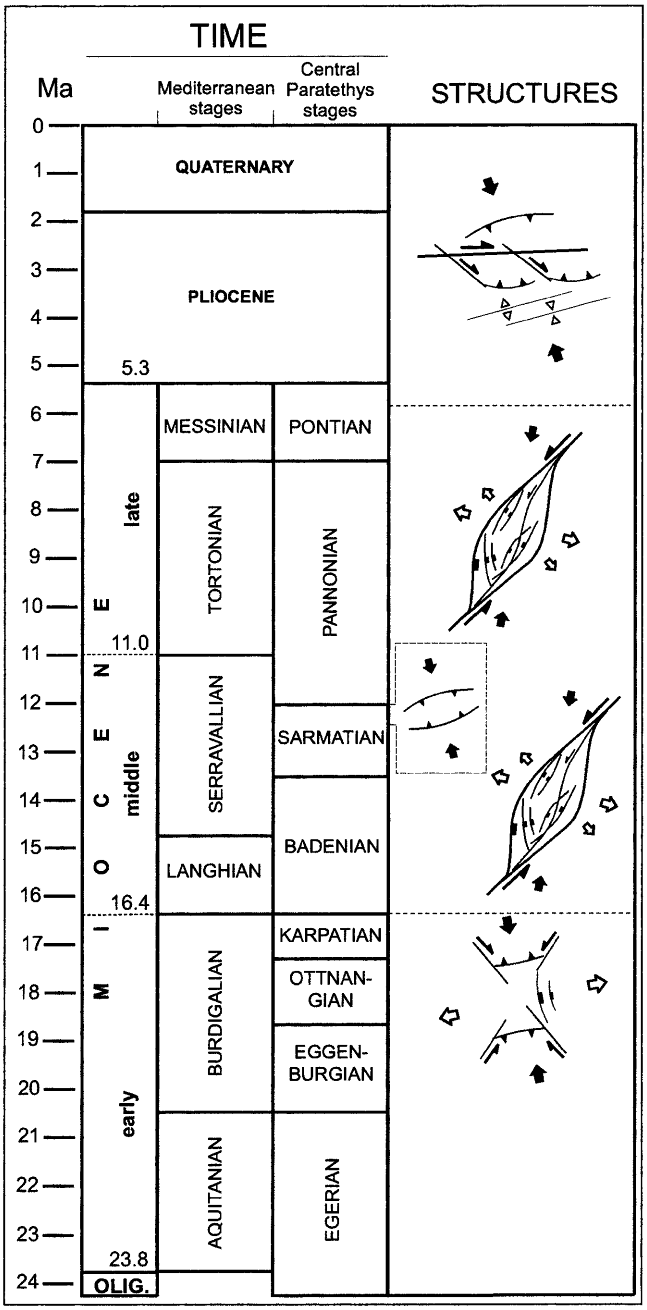


Fig. 15 Standard, i.e. Mediterranean and central Paratethys time scales for the Neogene (after Rögl 1998) and related schematic structural patterns for the study area

Dinaridic–Alpine–Pannonian junction

In the southern part of the study area, close the Dinarides, the general strike of the inverted structures is NE–SW, to become gradually E–W as we proceed towards the north (Fig. 2A). Similarly, in the southern parts, the inversion is less expressed, to become gradually more and more pronounced towards the north. The fan-shape distribution of young structural elements has to be explained.

The greater surrounding of the study area is dominated by two principal fault systems, i.e. the Periadriatic (PAL) and the Drava faults (DF; Figs. 2A and 16). Both are major right-lateral faults (e.g. Fodor et al. 1998; Prelogović et al. 1998), but their trend differs by ~30°. Both have a complex former history. The PAL bi- or trifurcates and is apparently crosscut by NW–SE directed right-lateral faults [e.g. Hochstuhl fault, Šoštanj fault, Labot (Lavanttal) fault; see Fig. 2A); Polinski and Eisbacher 1992; Fodor et al. 1998; Placer 1998b]. Numerous E–W striking folds and differently rotated strike-slip duplexes are found in the PAL zone more to the north as well (e.g. Fodor et al. 1998; Placer 1998b). This zone passes through the northern edge of the study area and is submerged beneath the sediments of the Pannonian basin. The DF zone, in turn, acts at present as a transpressive feature. Besides the right-lateral offsets, there are a number of NW–SE striking inverted structures, like the Bilogora Mt. at the western margin of the Drava River valley (e.g. Prelogović and Velić 1988; Prelogović et al. 1998; Fig. 16). Further south-east the Slavonian Mountains form a set of generally E–W to ESE–WNW ranging basement elevations, which are overthrust (frequently on northern margins) on Late Miocene or Pliocene rocks (Jamičić and Brkić 1987; Jamičić 1995). Very similar structures are found in the Hungarian part of the Pannonian Basin: the Mecsek and Villány Mts. are both E–W oriented structures caught in transpression in the Sarmatian, Pontian and possibly in the Quaternary (Csontos et al. 2000). Further north in the ENE–WSW directed Mid-Hungarian zone Late Miocene inverted rocks can be found (e.g. Tari 1994; Csontos 1995; Fodor et al. 1999). These are rimmed by elevated basement (e.g. the Transdanubian Central Range, Sacchi et al. 1999). Uplift has a complex young history, including Pannonian, Pontian and Quaternary.

It seems that repeatedly inverted or compressional features can be found in all, often perpendicular directions. More correctly, the compressive structures form a greater fan, centred at the eastern end of the PAL for the region outside the study area (Fig. 16), while in the study area they form the described curved trend (Fig. 2A). The episodes of intensive shortening in these belts correlate well with the scenario given for our study region. This complex pattern cannot be explained by a homogenous stress field. A quite simple explanation is to invoke inherited direction of the compressive structures, which will guide the trends of subsequent shortening. This is certainly a valid explanation in most cases, still, it is difficult to explain the reactivation of perpendicular structures during the same structural event.

We assume that the northern edge of the Dinaridic block is affected by earlier NNE–SSW striking structures (Fig. 17A), supported by structural studies of Mesozoic–Palaeocene formations in the Medvednica Mt. (Tomljenović, in preparation). These early struc-

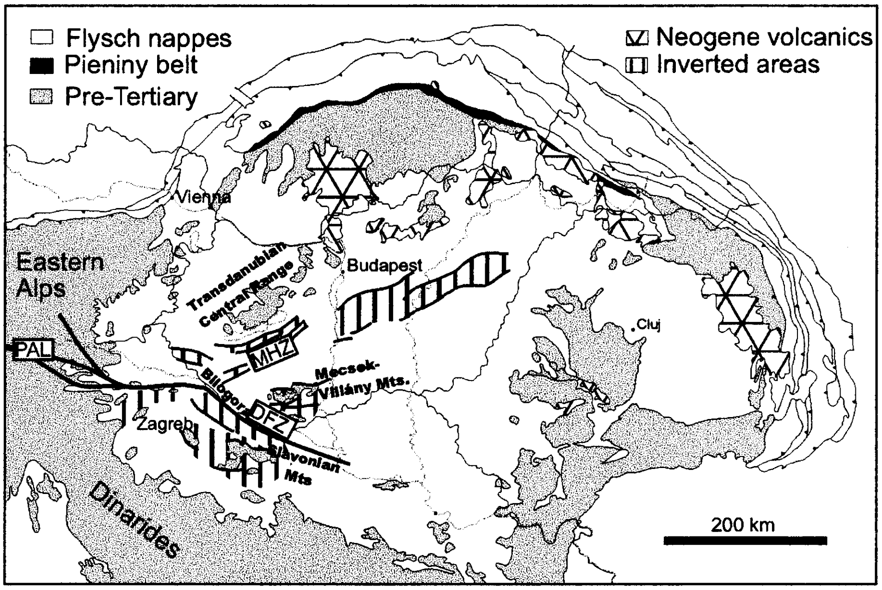


Fig. 16 Shortening-dominated areas (*vertical lines*) and structures in the western and central part of the Pannonian Basin (compiled after own work and data from Jamičić and Brkić 1987; Prelogović and Velić 1988; Csontos 1995; Jamičić 1995; Fodor et al. 1998, 1999; Prelogović et al. 1998; Sacchi et al. 1999). Note a fan-shape orientation of inverted structures centred at the easternmost end of the PAL

tures could also induce weakness zones that deform (and reactivate) easier during later events.

Models

In the models presented in the following the Dinaridic–Alpine–Pannonian area was simplistically represented by three blocks, which move differently during the Tertiary and are all limited by major fault zones (Fig. 17). The models are all based on the Dinaridic block moving towards the N–NW, as suggested by many authors and the general Europe–Africa convergence (e.g. Besse and Courtillot 1991; Márton 1993). Each model represents a thought-experiment that tests a different direction of convergence and tries to describe the consequences of these motions.

The northern edge of the Dinaridic block would enter into collision with the southern, E–W oriented border of the relatively stiff Alpine block. Their common interface is the wider PAL zone, including all the satellite faults and folded structures. It seems that in the study area the Dinaridic block (or at least its northern edge) is more deformed than the Alpine block.

The interface of the Dinaridic block towards the Pannonian one(s) runs along the DF zone. The limits of the Alpine and Pannonian blocks can be put at the Rába fault zone, which is also a complex, long-lived deformation zone (Kázmér 1986; Tari 1994).

The thought-experiments can be divided into translational and translational-rotational models. In models invoking only lateral shift we examined the possible effects of a north-westward shift parallel to the DF and a northward shift perpendicular to the PAL. Both shortening directions are plausible taking into account our seismic study and the number of measurements around the study area.

In the first model (Fig. 17B), north-westward motion causes pure right lateral shear along the DF, whereas the oblique collision of the north-eastern part of the Dinaridic block with the Alpine buttress causes intensive deformation at this corner. This oblique collision may generate inversion along the older structural trends in less deformed parts of the Dinaridic block. It also causes strong right lateral transpression along the E–W oriented PAL zone. Because of the oblique collision the inherited structures at the north-eastern corner of the Dinaridic block become gradually parallel to the more rigid Alpine buttress. WNW–ESE to NW–SE oriented tear faults accommodate differential shortening in this sector. The triangular block to the west of the Dinaridic block has to move to the west, though the amount of the movement is unclear. This movement could be consumed at the West Alpine front (e.g. Schmid and Kissling 2000). It is important to note that pure slip along the DF does not generate any other shortening or inversion structure either in the Dinaridic, or in the Pannonian block.

If we collide the Dinaridic block with the Alpine buttress in a northerly direction (Fig. 17C) the consequences will be somewhat different. The whole PAL will be under perpendicular shortening. This is especially valid in front of the NE corner of the Dinaridic block. In more westerly portions right lateral transpression could be achieved by the lateral extrusion of the triangular block in front of the Dinaridic one, to be consumed at the west Alpine convergent zone (Schmid and Kissling 2000). In this setting the northern part of the Dinaridic block would experience collisional deformation under generally N–S directed compression and simultaneous E–W directed extension.

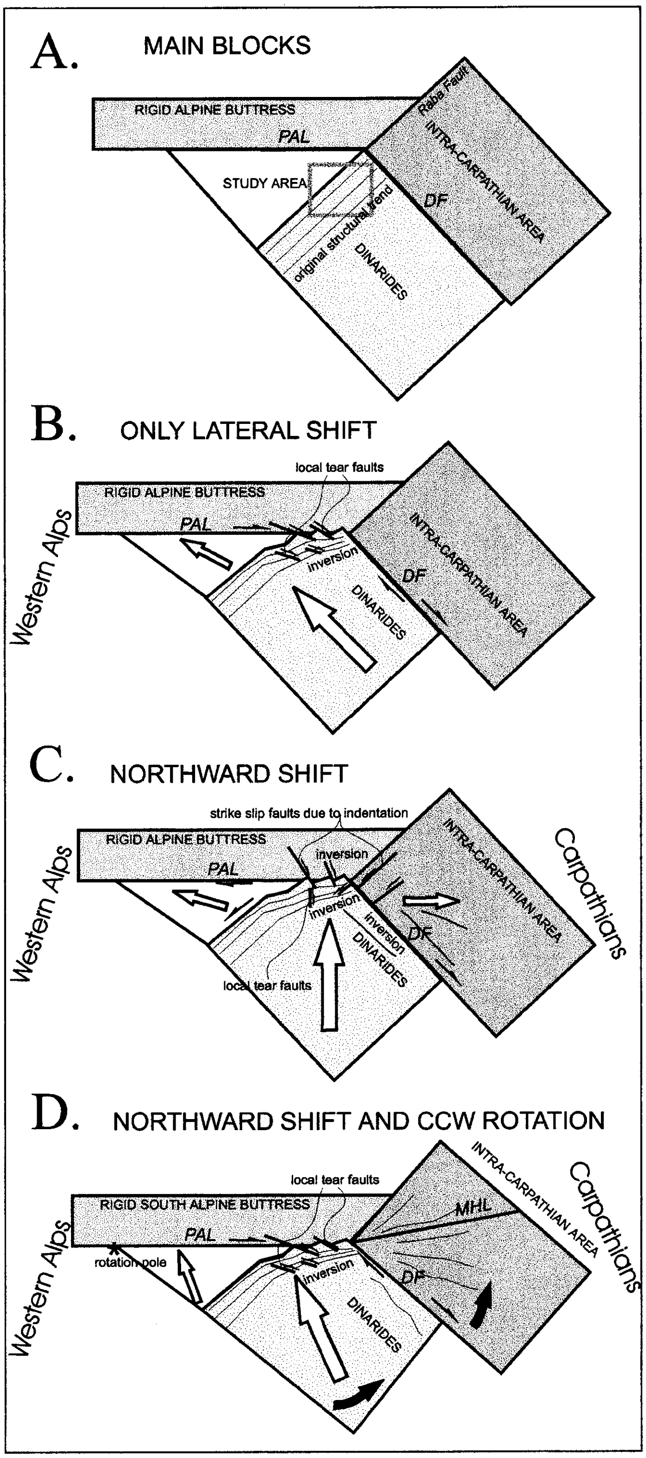


Fig. 17 Geodynamic models to explain the structural pattern of the study area and its surroundings. **A** Distribution of simplified blocks. **B** North-westward lateral shift of the Dinaridic block. **C** Northward shift of the Dinaridic block. **D** Northward shift of the Dinaridic block combined with counter-clockwise rotation. *Thin lines* indicate location and strike of inverted structures

This stress field would nucleate NW–SE and NE–SW striking dextral and sinistral-slip faults arranged in conjugate sets and a curved trend of shortening (E–W in the collision zone between the Alpine buttress and the Dinaridic block and more NE–SW oriented away from it, due to inheritance). In this scenario the DF would act as a right lateral transpressive boundary. Similarly, inversions and transpressional zones could be postulated in the neighbouring parts of the Pannonian block. Lateral escape of this block from the head-on collision zone can also be postulated. In progressive collisional deformation, in the zone adjacent to the collisional front, already nucleated NW–SE and NE–SW striking faults would offset earlier formed shortening structures. An important consequence of this model would be that lateral extrusion and resulting strike-slip type strain allow development of roughly N–S oriented normal faults, synchronously with perpendicular shortening and folding. Hence, we believe that this scenario could explain the deformation described for Early Miocene times.

In the rotational model (Fig. 17D) we supposed a bulk anticlockwise rotation of the Dinaridic block already documented by the first palaeomagnetic data obtained from the Croatian part of the Pannonian basin (Márton et al. 1999) around a pole somewhere in the western part of the Southern Alps and also evidenced in the western part of the Southern Alps (Schönborn 1992). This rotation is combined with the north-westward or northward lateral shift analysed above. Oblique collision caused by the lateral shift would develop its curved inversion features, right lateral slip along the DF and transpressive right lateral slip along the PAL zone. Rotation, on the other hand, would enhance convergence among the colliding corner and buttress, and at the same time would add shortening at the DF interface. Depending on the magnitude of this rotation this shortening could cause inversion features in a fan shape, in both the northern part of the Dinaridic and the southern part of the Pannonian block. Depending on inherited directions, this rotation could possibly explain the synchronous development of multidirectional thrusts. Hence, we believe that this scenario explains the above documented and presented deformational events during the Neogene times more accurately than the others. A slight change of shift direction would not seriously affect the tectonic regime. On the other hand, the boundary conditions especially in the eastern parts (free space or locked movements) would have an effect by stimulating or inhibiting normal fault activity.

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