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Plio–Quaternary Geometry and Kinematics of Ptolemais Basin (Northern Greece): Implications for the Intra-Plate Tectonics in Western Macedonia

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Key words: Progressive shear strain, Intra-plate tectonics, Ptolemais Basin, Western Macedonia, Northern Greece.

Abstract

An integrated structural study of the Ptolemais basin of Northern Greece allows assessment of deformation processes and their implication in the Pliocene–Quaternary structural evolution of this part of Western Macedonia. Normal and reverse faults within Plio–Quaternary sediments, NE–SW striking anticlines in both Plio–Quaternary sediments and pre-Tertiary basement-units, torsions and deformation partitioning, highlight the particular characteristics of intra-plate deformation. Field investigations and drilling data infer the conclusion that intra-plate processes were governed by progressive shear strain during the Plio–Quaternary. A new kinematic model for the development of the Ptolemais basin is proposed, showing the importance of progressive shear strain.

1. INTRODUCTION

Geological evidence in the Hellenic orogenic belt of eastern Mediterranean confirms complex Neogene–Quaternary tectonic processes, both in the orogenic front of the Central and South Aegean, and in the back-arc domain of the North Aegean and Western Macedonia (STEWART & HANCOCK, 1991; PIPER & PERISSORATIS, 2003; KREEMER et al., 2004; DIAMANTOPOULOS, 2004; OCAKOGLOU et al., 2005). These observations make evident the importance of heterogenous strain, including co-existence of strike-slip, rotational and ductile structures. Since deformation and strain outline three-dimensional quantities, structural heterogeneity from the lithospheric-scale to the grain-scale of observation mark an essential constituent of strain (JONES et al., 2005; DE PAOLA et al., 2005).

This work analyzes the Plio–Quaternary structures and the deformation style in the Ptolemais basin of Western Macedonia in Northern Greece. New structural data, observed in the Ptolemais basin are presented in order to elucidate the principal deformation styles and mechanisms in this area (Fig. 1). Distribution of deformational structures, the geometry and kinematics of deformation, and a new kinematic model for the Ptolemais basin are also addressed. Finally, an integrated evaluation of new data and their implications allows a new improved comprehension of intra-plate tectonics of Western Macedonia.

1.1. Previous studies and target of this work

Previous studies of the Ptolemais basin by PAVLIDES (1985), DOUTSOS & KOUKOUVELAS (1998), MOUNTRAKIS et al. (1999), and GOLDSWORTHY & JACKSON (2000) provided an insight into the importance of active faults and their role in the geomorphology and seismology of this basin. Structural data presented in these papers were mainly concerned with the geometry and kinematic characteristics of the observed fault sets. According to PAVLIDES (1985) and MOUNTRAKIS et al. (1999), multiple tectonic phases during Miocene–Quaternary times were recognized, each characterized by compressional or extensional structures.

New structural analysis of the Ptolemais basin in Western Macedonia presented in this paper, allows revision of previous assumptions on the geometry, kinematics and the tectonic evolution of this part of Northern Greece (Fig. 1). This structural synthesis is based on data obtained by field analysis, drilling and geophysical investigations, which document the main structural pattern within Plio–Quaternary sediments, the sub-surface geometry of the Ptolemais basin fill and also the re-activation of the pre-Miocene structures by Plio–Quaternary tectonics. The study area is an open-pit lignite mine exploited by the Public Power Corporation of Greece (PPC).

2. GEOLOGY OF WESTERN MACEDONIA

Geological data, geophysical studies and GPS measurements in Western Macedonia denote on-going tectonic

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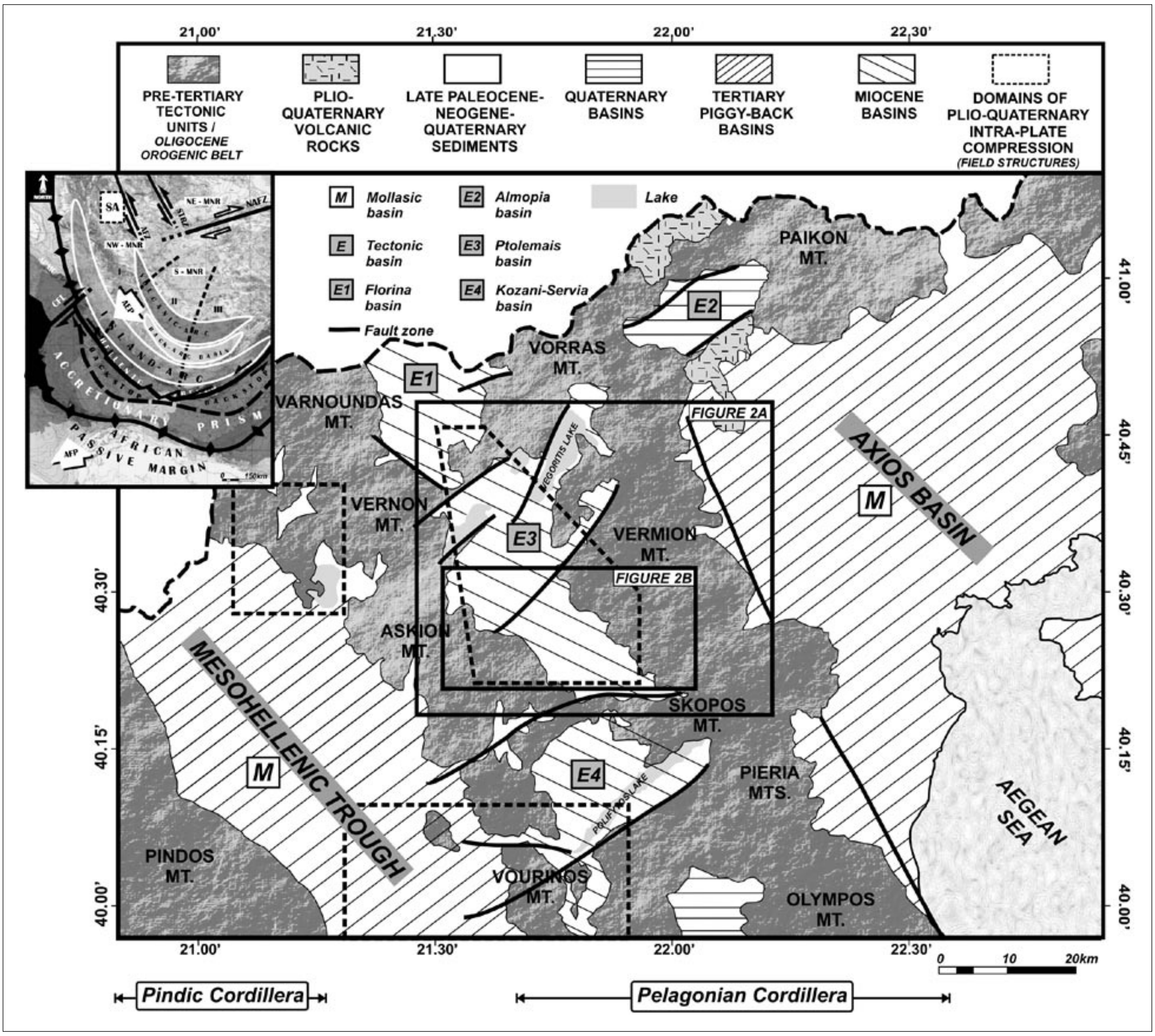

Fig. 1 Tectonic map of Western Macedonia. Three distinctive domains (dotted black boxes) with compressional field structures are illustrated, see MOUNTRAKIS (1983), FOTIS (2004) and DIAMANTOPOULOS (2004). Inset map: The Hellenic orogenic arc in the Eastern Mediterranean, based on MARIOLAKOS et al. (2004) and DIAMANTOPOULOS (2004). Legend for inset map: AEP – Aegean plate; AFP – African plate; APMC – Apulia micro-continent; CFZ – Cephalonia Fault Zone; NAF – North Anatolia Fault; AFZ – Axios Fault Zone; STRMZ – Strymon Fault Zone; MNR – Morpho–Neotectonic Region; SA – Study area.

activity (MOUNTRAKIS et al., 1999; FOUNTOULIS et al., 2002; DRAKATOS et al., 2005; BURCHFIEL et al., 2005). Here, several tectonic basins of continental origin developed during Miocene–Quaternary times (the Florina, Ptolemais, Kozani–Servia, Almopia basins – Fig. 1). The presence of Plio–Quaternary volcanism in the Almopia basin (VOUGIOUKALAKIS et al., 2004 and reference there in), also indicates re-arrangement of the lithospheric material. The physiography of Northwestern Greece is characterized by the two elevated domains of Pelagonian and Pindic Cordillera as well as by the two subsided domains of the Mesohellenic and Axios basins (Fig. 1). The latter are interpreted as Tertiary (AUBOUIN, 1965) piggy-back basins with thick sedimentary accumulations.

3. GEOLOGY OF THE PTOLEMAIS BASIN

Sedimentary fill of the Ptolemais basin includes terrestrial and lacustrine sediments of Miocene up to Pleistocene age, abundant in lignite reserves (KOUKOUZAS et al., 2000; KVACEK et al., 2002). STEENBRINK (1998) studied distinctive sedimentary facies and concluded that the basin formation started during the Tortonian. DIAMANTOPOULOS & DIMITRAKOPOULOS (2004a) by synthesis of tectono–sedimentary data, recognized three distinctive lignite members of Miocene, Pliocene and Pleistocene age, intercalated with clastic sediments. The same authors also recognized two major unconformities within the sedimentary basin succession, i.e. the first one at the base of the Miocene, (between the first terrestrial sediments and the pre-Ter-

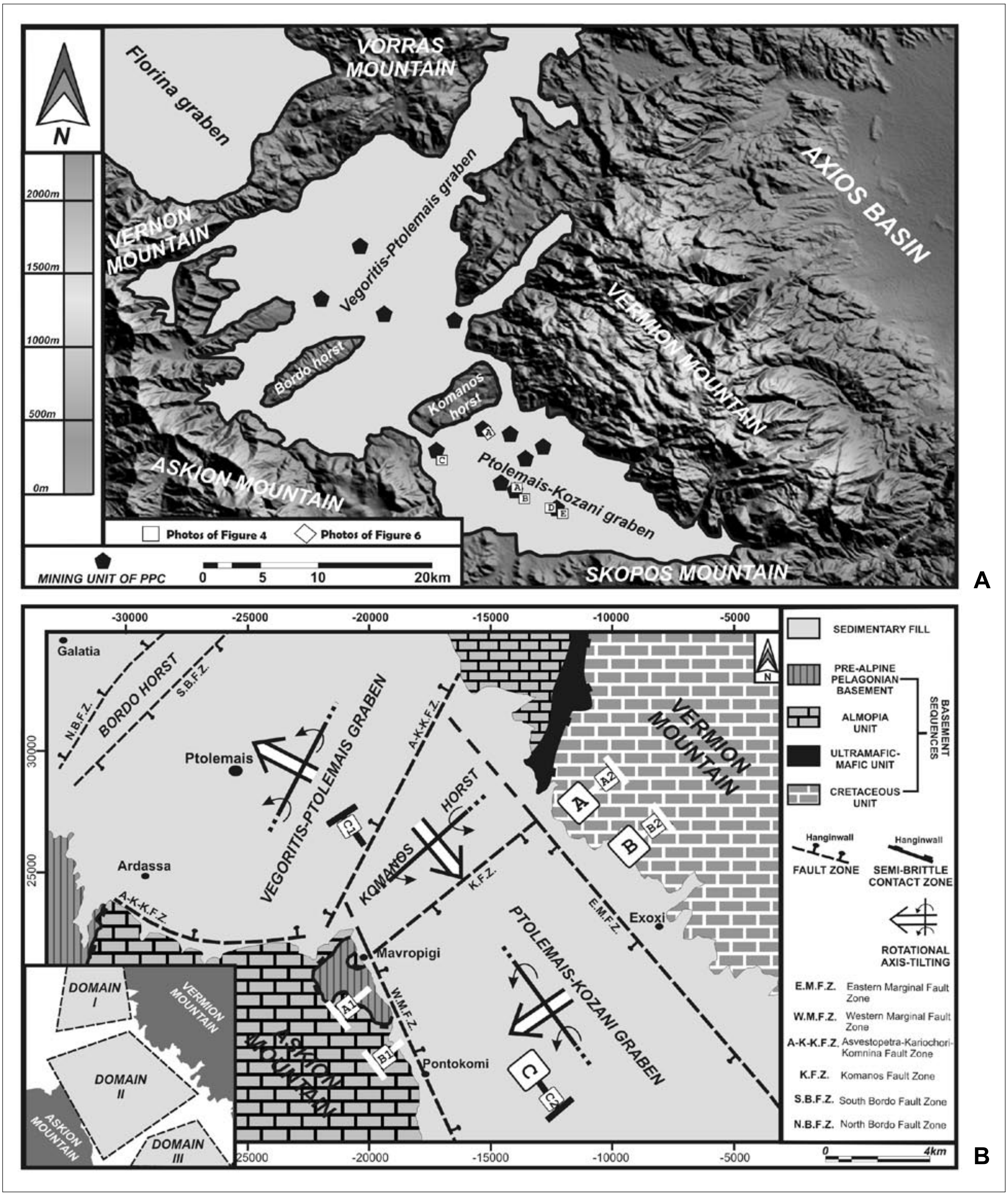

Fig. 2 (A) Digital elevation model of Western Macedonia. Photos of Figs. 4 and 5 are depicted. (B) Simplified tectonic map of the southern part of the Ptolemais basin. Inset map shows the spatial distribution of the analyzed drillings in three domains I, II and III of Fig. 3. The location of the geological sections A–B–C of Fig. 7 is also illustrated.

tiary basement units), and the second one between the Pleistocene strata and the Pliocene sediments. Arrangement and geometry of lignite layers of the Ptolemais basin indicate a westward migration from the eastern marginal domain (Vermion mountain) toward the western marginal domain (Askion and Vernon mountains), (DIAMANTOPOULOS & DIMITRAKOPOULOS, 2004a).

Pre-Tertiary basement rocks of the Ptolemais basin can be subdivided into four distinctive tectonic units, (Fig. 2b). From the lowermost to the highest unit, they are: (I) pre-Alpine Pelagonian Basement, separated into Schist sub-unit, the Gneiss sub-unit, the granitoid mylonites and the granites (BRUNN, 1956; MOUNTRAKIS 1983; DIAMANTOPOULOS, 2005), (II) Almopia Unit, with Triassic–Lower Jurassic marbles and meta-

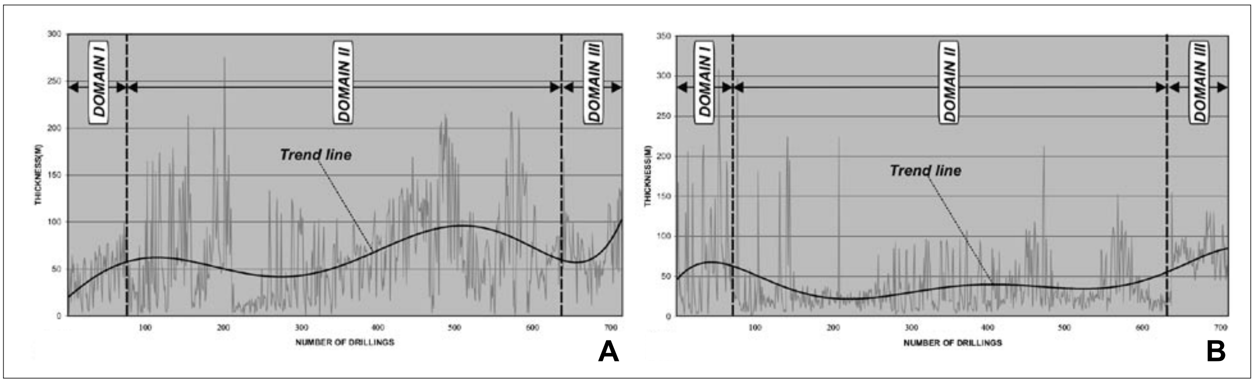

Fig. 3 (A) Quantitative thickness variation of the Pliocene lignite sequences; (B) Quantitative thickness variation of the Plio–Quaternary sediments (overburden cover of Pliocene lignites). The spatial distribution of the domains I, II and III is depicted in the inset map of Fig. 2.

sediments of Late Jurassic age (DIAMANTOPOULOS, 2005), (III) Ultramafic–Mafic Unit of Mesozoic age, and (IV) Cretaceous Unit, with platform limestones and Maastrichtian flysch (MERCIER, 1968). Steep and low-angle shear zones, formed in brittle–ductile conditions, separate distinctive tectonic units. Recent structural studies show that during the Oligo–Miocene, a strong orogen-perpendicular stretching re-arranged the geometry of the pre-Tertiary sequences (MOUNTRAKIS, 2004; DIAMANTOPOULOS, 2005). The NW–SE strike of the Ptolemais basin is controlled by pre-existing shear zones in pre-Tertiary basement units, which accommodated Oligocene stretching of the Internal Hellenides (DIAMANTOPOULOS, 2005). These inherited structures correspond to several shear zones between pre-Tertiary basement sequences.

3.1. Morphotectonic units of the Ptolemais Basin

The morphotectonic structure of the Ptolemais basin comprises several fault-bounded blocks of different order. Based on drilling and geophysical data, combined with a study of sub-surface and surface morphology, the following morphotectonic sub-units can be distinguished (DIAMANTOPOULOS & DIMITRAKOPOULOS, 2004a, b; Fig. 2):

a) NE–SW trending Vegoritis–Ptolemais sub-basin, characterized by NE–SW orientated normal faults;
b) NE–SW trending Bordo horst;
c) NE–SW trending Komanos horst, which divides the Vegoritis–Ptolemais and Ptolemais–Kozani sub-basins;
d) NW–SE Ptolemais–Kozani sub-basin, with a rhomb-like geometry.

The Bordo and Komanos horsts represent pre-existing structures, which were re-activated during Plio–Quaternary times. A significant difference in deformation style between the Vegoritis–Ptolemais and Ptolemais–Kozani sub-basins is indicated by their different strike and internal morphology, and by the greater depth and width of the Vegoritis–Ptolemais sub-basin. They also show a great difference in lithostratigraphic development and sedimentary evolution, which makes stratigraphic correlation of Plio–Quaternary strata between these sub-basins difficult (DIAMANTOPOLOUS & DIMITRAKOLOPOUS, 2004a).

3.2. Quantitative and qualitative analysis of borehole data

Borehole data, which include 720 boreholes that penetrated the Plio–Quaternary basin fill and 50 boreholes that reached the pre-Tertiary basement have been taken into account, and are distributed in 3 domains (Fig. 2b). The thickness of the Pliocene lignite sequence and also the thickness of the Plio–Quaternary sediments (the overburden of the Pliocene lignite sequence) have been quantitatively analyzed. Diagrams A and B of Fig. 3 shows the following thickness-variation pattern:

a) Thicknesses of the lignite sequences show a marked variation throughout the Ptolemais basin. A local increase in thickness of more than 100 m indicates that sub-surface reverse faulting is very probable. Field data, which are described below, support this presumption.
b) The thickness of the Plio–Quaternary sediments also shows variation with respect to location within the basin. Again, local thickness increase could possibly indicate subsurface reverse faulting.

The above described data indicate that strong syn-sedimentary tectonics took place during sedimentation of the lignite and during deposition of the overlying Quaternary sediments. Field studies in all mines of the PPC confirm this aspect. However, the main thickness variations of the analyzed strata were determined within the central part of the Ptolemais basin, i.e. in domain II in Fig. 3, where the Komanos tectonic horst is located.

3.3. Tectonic structures within the sedimentary basin fill

Tectonic structures in Plio–Quaternary sediments of the Ptolemais basin include brittle and brittle–ductile

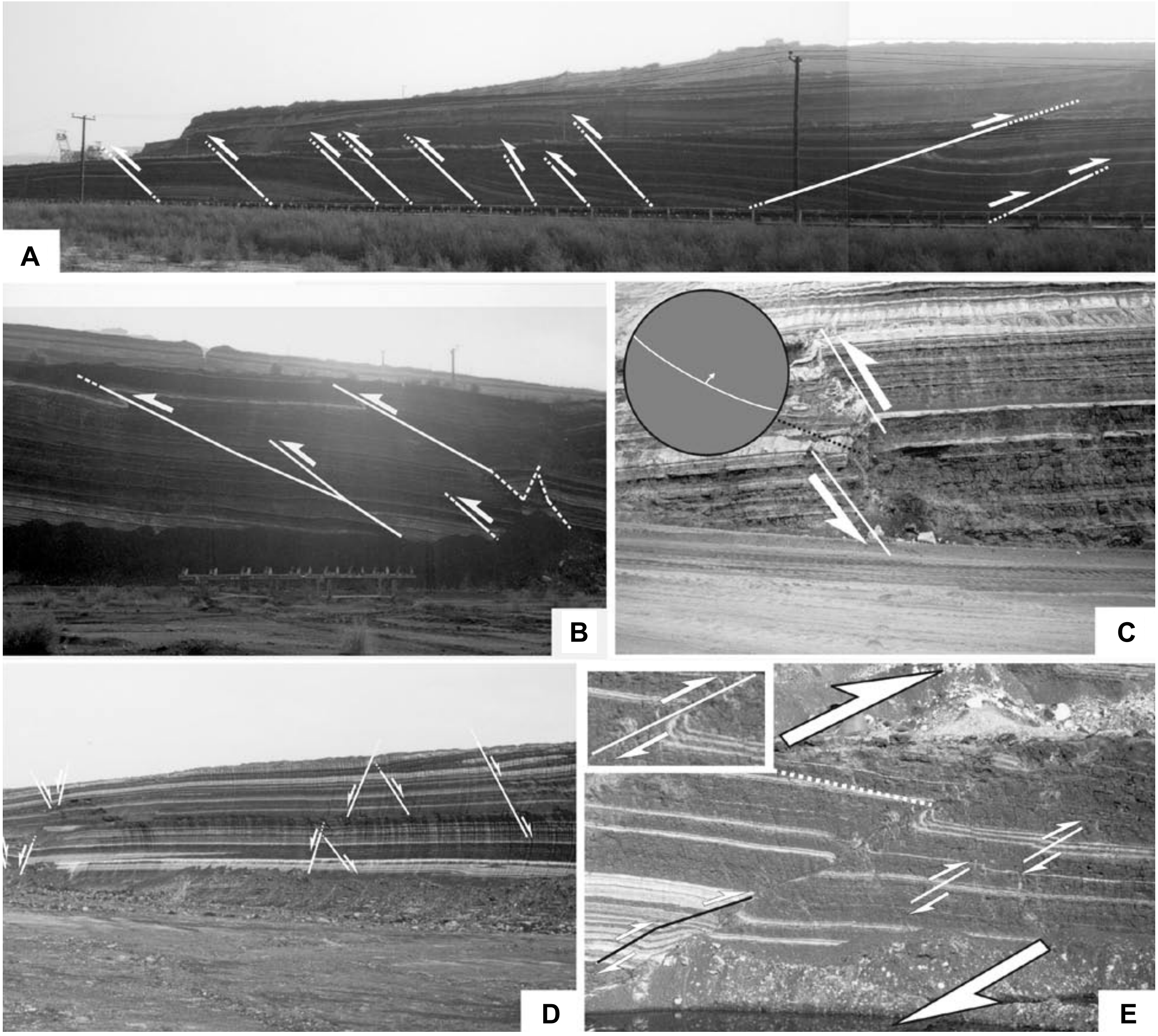

Fig. 4 (A) Reverse faults in the Kardia mine forming a pop-up structure; (B) Successive reverse faults in the Kardia Mine; (C) Reverse fault in the Mavropigi lignite field, stereographic projection includes its geometric characteristics; (D) Normal faults in South field; (E) Reverse fault and secondary reverse displacements in South field.

structures of both extensional and compressional origin. In all mines of the PPC (Amyntaion mine, South field, Kardia mine, Major Field, Komanos mine, North field and Mavropigi field) steep to low-angle reverse faults of both N–S and E–W strike have been observed (Figs. 4a–c, e, 5c, 6a (III)). These reverse faults form pop-up stacks and co-exist with normal faults of planar and listric geometry (Figs. 4d, 5c–f). The confirmed presence of these faults throughout the Ptolemais basin shows how common this structural pattern is. Co-existing pop-up structures and normal faults directly indicate the problem of interpreting kinematics and the style of deformation.

DIAMANTOPOULOS (2004), showed that large sub-surface basement-faults in the western margin of the Ptolemais–Kozani sub-basin have influenced the thickness and lithofacies characteristics of the sedimentary fill by creating SW-ward tilted fault blocks around NW–SE trending rotational axes (Figs. 2b, 7). Surface morphology in the western margin of the Ptolemas–Kozani sub-basin is controlled by the sub-surface morphology, which in turn is defined by an anticline structure in basement-units, as illustrated in the tectonic sketch of Fig. 6b. Thus, a coincidence between the sub-surface fold geometry and the surface morphology is confirmed.

Furthermore, at the boundary between the Ptolemais–Kozani and Vegoritis–Ptolemais sub-basins, a NE–SW striking anticline is determined, as well as in the western marginal part, where both the Plio–Quaternary sediments and the basement-units are folded in a km-size anticline (Fig. 6b). This anticline structure also continues basinwards (at the northern boundary of Ptolemais–Kozani sub-basin), where the top of the Pliocene lignites appears at the surface.

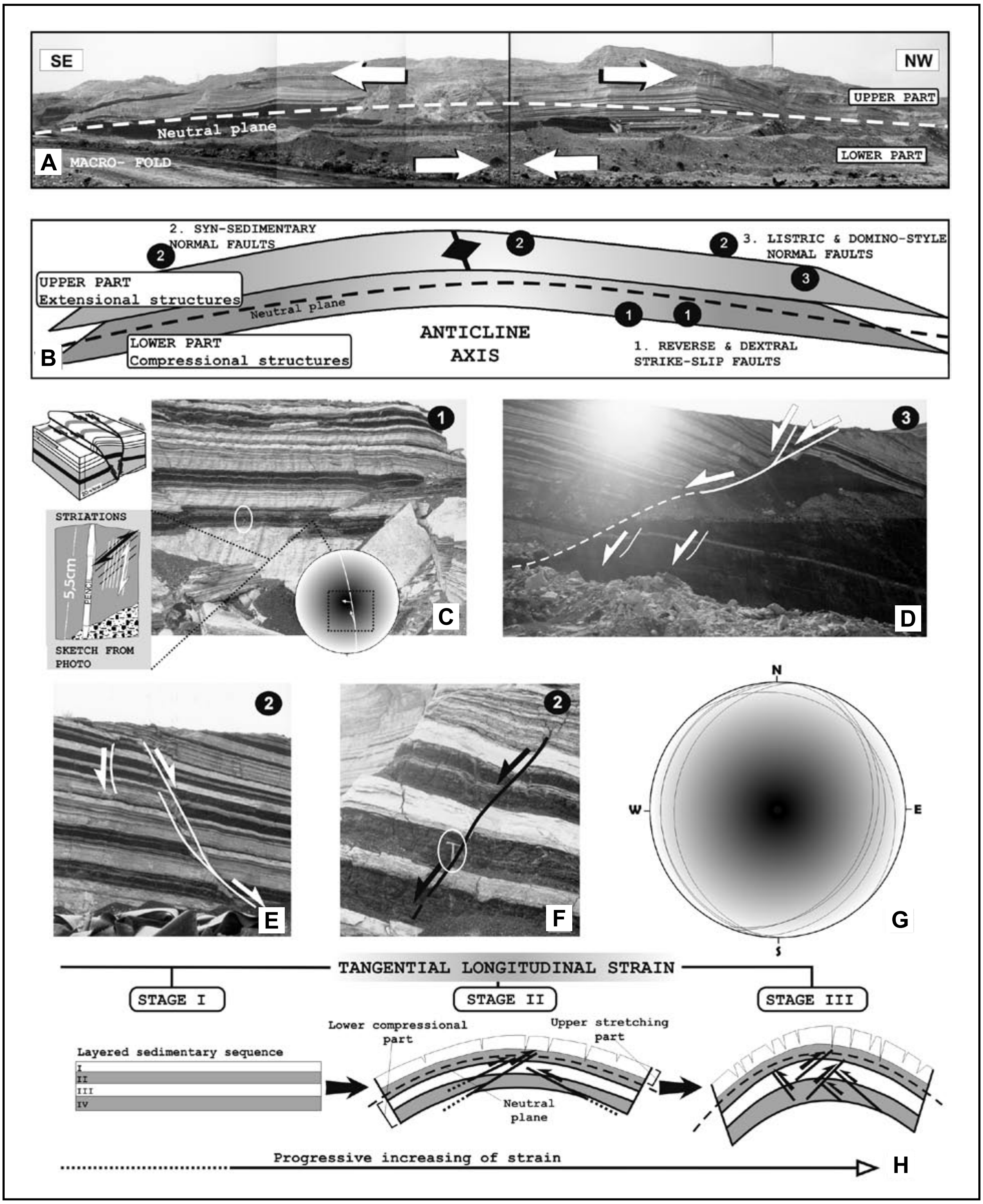

Fig. 5 (A) Anticline structure in the Pliocene lignite sequence; (B) Schematic profile – the black numbered circles correspond to structures observed in the upper (extensional) and lower (compressional) parts of the NE–SW anticline; (C) Pop-up structure with reverse and dextral strike-slip faults, two separated sets of striation systems are depicted in the sketch and in the stereographic projection; inset sketch show the three-dimensional view of this structure; (D) Listric and domino-style normal faults; (E and F) Normal faults of listric geometry; (G) Stereographic projection (of lower hemisphere) of the bedding within the anticline; H) Three evolutionary stages show the genesis of a tangential longitudinal fold.

These anticlines were also directly observed in the field (Fig. 5a, b). Within the upper parts of the anticlines, several normal faults indicate extension, while the lower part is dominated by reverse faults and experienced compression (Fig. 5). These structural data, in combination with anticline geometry sediments (see stereographic projection of Fig. 5g) suggest the predominant operation of a tangential longitudinal strain mecha-

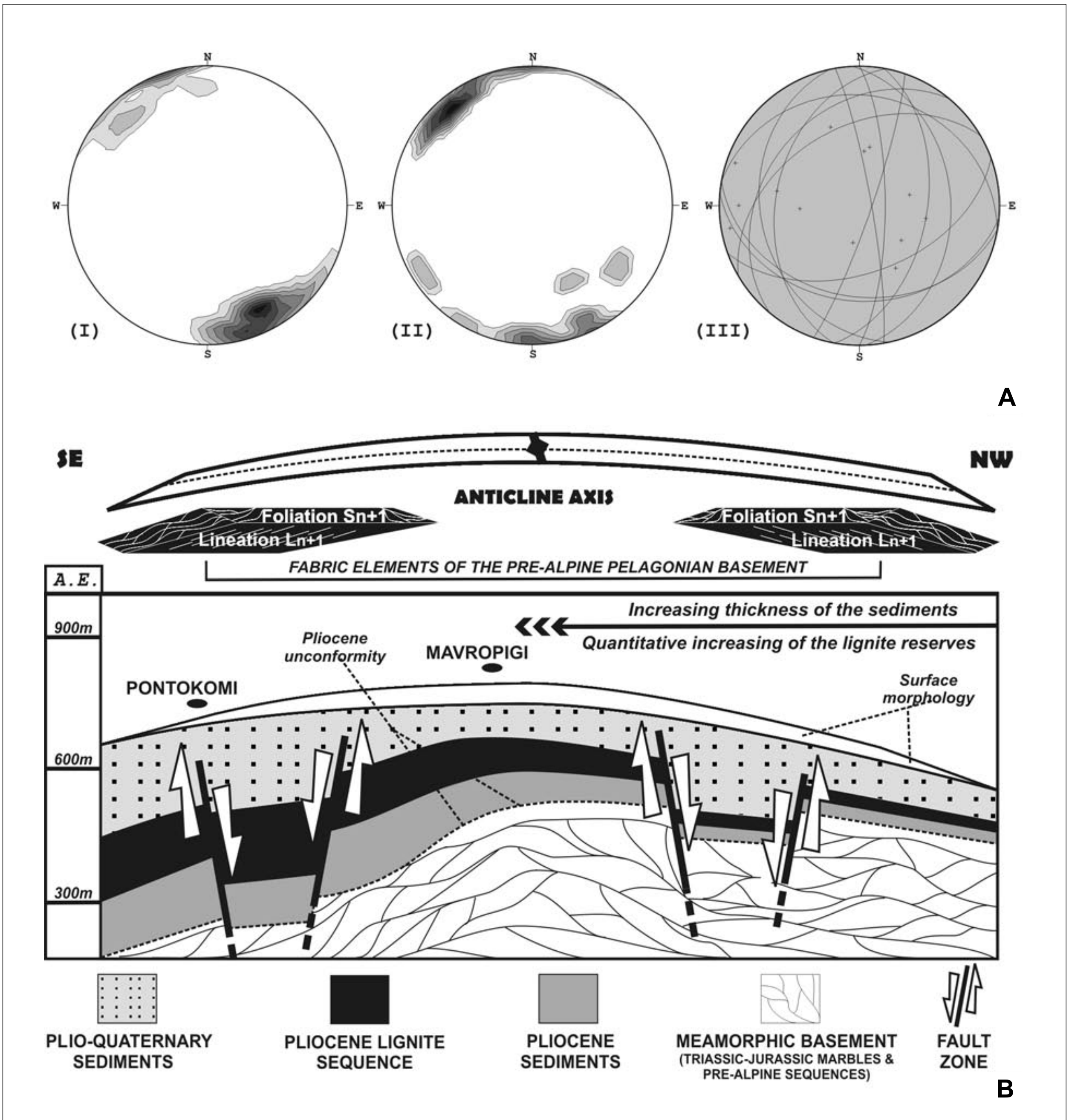

Fig. 6 (A) Orientation data. Legend: (I) Contoured plot of fold axes of the pre-Alpine Pelagonian basement in the western margin of the Ptolemais–Kozani sub-basin. (II) Contoured plot of L-fabric elements of the pre-Alpine Pelagonian basement in the western margin of the Ptolemais–Kozani sub-basin. (III) Planes of reverse faults of Plio–Quaternary sediments in the mining units of the PPC. (B) 2D-representation of the tectonic structure of the western margin of the Ptolemais–Kozani sub-basin, based on more than 550 drillings data of the PPC (from DIAMANTOPOULOS, 2004).

nism during anticline formation (BOBILLO-ARES et al., 2000 and references therein). Different stages in the formation of these fold-types are shown in Fig. 5h.

The Quaternary ductile–brittle structures described are also documented in the metamorphic basement-units in the western margin of the Ptolemais–Kozani sub-basin. Structural analysis of the pre-Alpine Pelagonian basement revealed that folds of both syn- and post-metamorphic origin gently plunge to the NW and SE, probably due to a later superimposed folding around a NE–SW trending fold axis (Fig. 6a, projection I). A similar pattern is also seen in the orientation of the main L_{n+1} stretching lineation of the pre-Alpine Pelagonian basement units (Fig. 6a projection II). In addition, the NE–SW striking anticlines in klippen of the Triassic–Jurassic marbles of eastern Askion and the eastern Vernon mountains, have also been determined by DIAMANTOPOULOS (2005). Thus, the spatial arrangement of Alpine (pre-Miocene) folds coincides with the Plio–Quaternary anticlines, revealing the re-working of the basement-sequences.

3.4. Kinematics of deformation

Plio–Quaternary sedimentary fill of the Ptolemais–Kozani sub-basin represents a westward tilting sequence, where the eastern margin is uplifted relative to the western margin. This is clearly observed in geological sections A and B of Fig. 7. A similar geometry is also seen further north in the Vegoritis–Ptolemais sub-basin, where the sedimentary fill is tilted towards the west–northwest (Fig. 2b). This tilting is interpreted as a result of an approximately NW–SE trending axis throughout the basin. Analysis of the geometry of Pliocene lignites shows internal rotations of lignite fault-bounded blocks (geological section C of Fig. 7). Throw variation patterns in recognised sub-surface faults within Plio–Quaternary sedimentary fill also indicate their role and control on the basin history (Fig. 7d). Involvement of Quaternary sediments in this tilting and rotation reveals the very recent re-arrangement of the basin marginal domains.

4. DEFORMATIONAL PATTERN

The above patterns, including structures in both the sedimentary fill and its pre-Tertiary basement-units, indicate the complexity of deformation. Given this evidence, the following must be considered in a new interpretation of the structural evolution of the Ptolemais basin:

a) a westward tilting of the sedimentary fill in the Ptolemais–Kozani sub-basin and a west–northwestward tilting of the sedimentary fill in the Vegoritis–Ptolemais sub-basin;

b) a rhomb-like morphology of the Ptolemais–Kozani sub-basin (DIAMANTOPOULOS & DIMITRAKOPOULOS, 2004a);

c) the left-lateral strike-slip fault in the western marginal domain (DIAMANTOPOULOS, 2004);

d) the co-existence of reverse and normal faults in all mines of the PPC;

e) anticline structures with a NE–SW axis trend in the internal parts of the basin;

f) the kinematics of the deformation of Pliocene lignites in the boundary between the Ptolemais–Kozani and Vegoritis–Ptolemais sub-basins (DIAMANTOPOULOS & DIMITRAKOPOULOS, 2004b);

g) the deformation partitioning between the marginal zones of the basin (DIAMANTOPOULOS, 2004);

h) the thickness variation of the Pliocene lignites and of the Plio–Quaternary sediments;

i) the different stratigraphy and sub-surface morphology between the Ptolemais–Kozani and Vegoritis–Ptolemais sub-basins, making the stratigraphic correlations difficult (DIAMANTOPOULOS & DIMITRAKOPOULOS, 2004a), and

j) the Quaternary ductile–brittle deformation of the basement-units in eastern Askion and the eastern Vernon mountains (DIAMANTOPOULOS, 2005).

The main characteristic of the post-orogenic evolution of Western Macedonia are:

(i) the convergent velocity field of the upper crustal levels in an E–W direction, as deduced from GPS data, (FOUNTOULIS et al., 2002),

(ii) the heterogeneous structure of the upper crust levels due to intricate pre-Miocene nappe-emplacements, as documented by geophysical and structural studies (DRAKATOS et al., 2005; DIAMANTOPOULOS 2005),

(iii) the Plio–Quaternary thermo–mechanical disequilibrium of the crust, resulting in the formation of volcanic centres (VOUGIOUKALAKIS et al., 2004, and references therein).

These allow the conclusion that intra-plate deformation of Western Macedonia is dominated by progressive shear strain, which is proposed in the deformation model of Fig. 8, where the principal axes of extension and compression, transtension and transpression are controlled by progressive sinistral simple shear. The co-existence of all the above tectonic structures also reflects the inhomogeneous spatial distribution of stresses.

5. TECTONIC ORIGIN OF PTOLEMAIS BASIN AND INTRA-PLATE TECTONICS OF WESTERN MACEDONIA

The proposed model of progressive shear strain, the sub-surface morphology of the Ptolemais basin, as well as the heterogeneous sedimentary evolution between the sub-basins of the Ptolemais basin, constitutes criteria for identifying the domination of strike-slip kinematics. Alternatively, stretching of the upper crust that resulted in basin formation is thought to have taken place with contemporaneous strike-slip displacements and torsion. A remarkable point of this connotation is that the above data agree well with data obtained by analogue modeling of pull-apart basins (AYDIN & NUR, 1982; RAHE et al., 1998; SIMS et al., 1999; KIM et al., 2004; WALDRON, 2005).

It is also noteworthy that during and after the Miocene, the investigated area represents a stable back-arc domain, without plate re-organizations in the geodynamic regime of Northern Greece. Apart from a south–westwards migration of the orogenic front of the Hellenides (LE PICHON et al., 2002; MOUNTRAKIS, 2004), new plate re-organizations are not recognised. Therefore, differentiation in the stress regime is not justified. This is reinforced by the fact that since the Tortonian the stable north–western convergent motion between the African and European plates in the Hellenic realm has been determined (MAZZOLI & HELMAN,

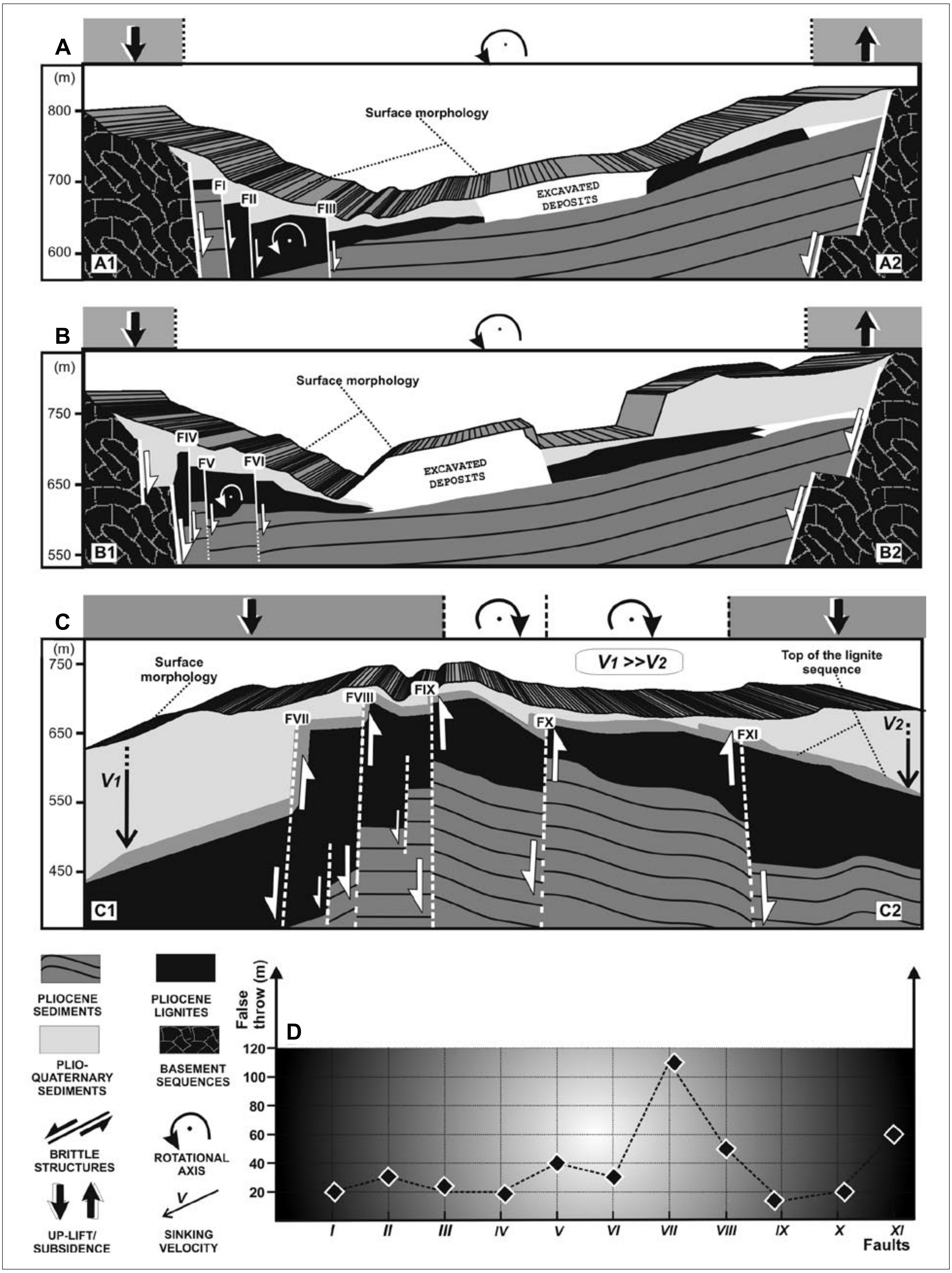

Fig. 7 Geological cross-sections, for location see Fig. 2. More than 100 drillings have been analyzed in order to determine the geometry of the sedimentary fill. In the upper part of each section the kinematic pattern of the separated morphotectonic sub-units is shown. (A) Geological section from east (right side) to west (left side) direction. A westward tilting of the sedimentary fill is apparent together with complex structural patterns in the western marginal domain. (B) Geological section in an east (right side) to west (left side) direction. A westward tilting of the sedimentary fill is apparent together with complex structural patterns and torsions in the western marginal domain. (C) Geological section in southeast (right side) to northwest (left side) direction. The arrangement of a mega-anticline structure, including rotated lignite fault-bounded blocks, is visible. V_1 and V_2 represent the sinking velocities of the lignite sequence toward the northwest and southeast, respectively. (D) False throws of the recognized faults. Numbering in the horizontal axis of the diagram corresponds to the faults in the previous cross-sections.

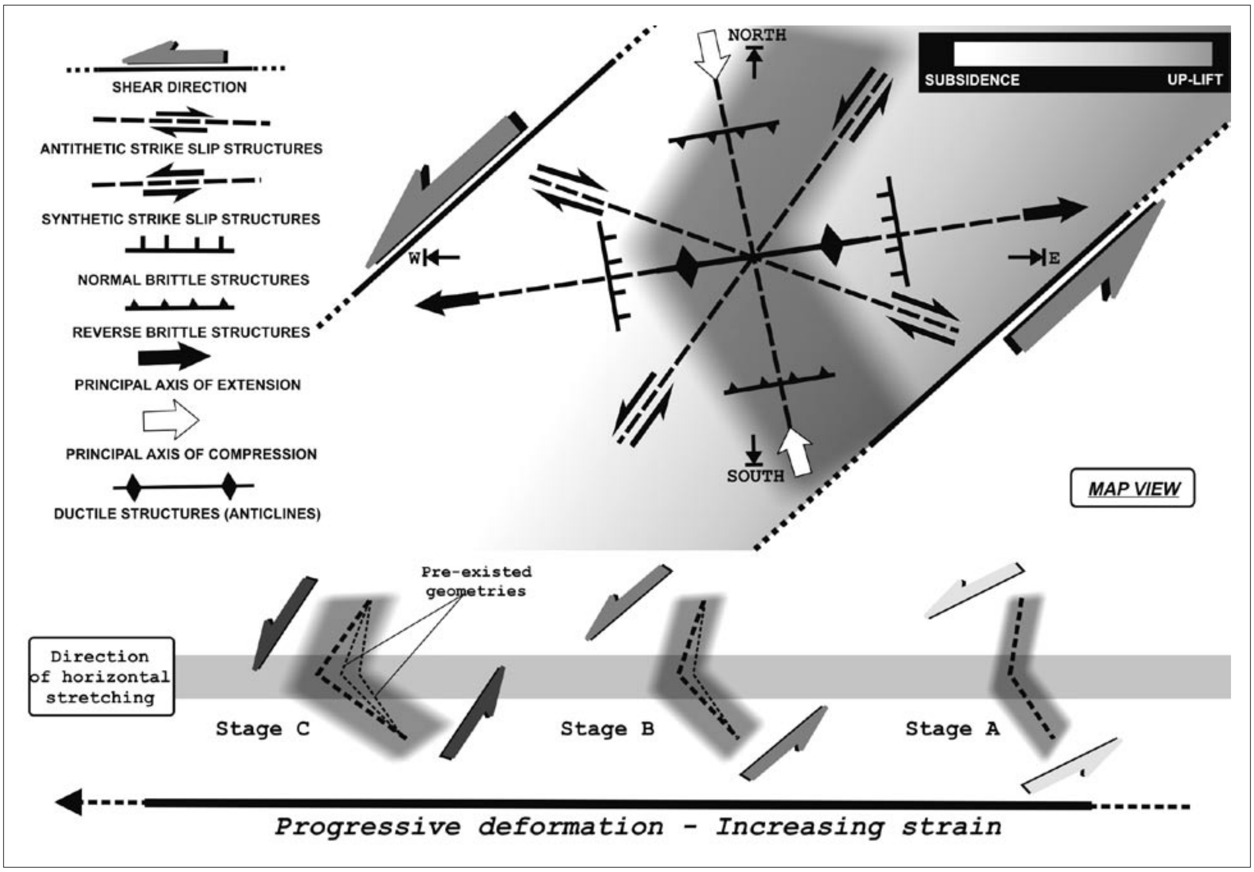

Fig. 8 Proposed kinematic model for the Ptolemais basin. It is suggested that progressive shear stain dominates during the evolution of the basin, producing variable fault patterns and torsions. The shadow-like feature within the sketch shows the geometry of the basin, presumably fitting to a kink-like structure. At the base of the sketch the geometrical evolution of the Ptolemais basin is represented.

1994). However, the Late Miocene–Early Pliocene onset of activity of the North Anatolian Fault (BOZKURT, 2001) notes the role of a deep structure, which resulted in marked differentiation of stress gradients in the upper crust.

In this framework, isostatic compensation of the previously collapsed crust in the Oligocene, and deformation induced by thermo–mechanic disequilibrium of the upper crust, would provide the major generators in the formation of the intra-plate basins in Western Macedonia. These suggest that the major palaeogeographic modifications have taken place during the Plio–Quaternary. In addition, although Western Macedonia is described as a seismically inactive area (PAPAZACHOS, 2002), the above evidence is a record of on-going tectonic activity in the upper crust. Thus, as FOUNTOULIS et al. (2002) concluded, creep deformation is assumed to be dominant. Three major pieces of evidence also indicate the lateral transmission of intraplate stresses throughout Western Macedonia. The Plio–Quaternary re-arrangement of the marginal domains of the Ptolemais basin, the observed heterogeneity in the sedimentary evolution of the basin and the Quaternary volcanism over Western Macedonia corroborate the former consideration.

6. CONCLUSIONS

The above analysis suggests the following new conclusions:

– Quantitative drilling analysis and field studies suggest that strong syn-sedimentary deformation took place during the Plio–Quaternary in the sedimentary fill of the Ptolemais basin.

– Several lines of evidence indicate structural heterogeneity within the Ptolemais basin. Normal and reverse faults, strike-slip faults, anticlines with a NE–SW axis direction and torsions co-exist within the sedimentary fill.

– The previously formed pre-Miocene structures have been affected by Plio–Quaternary deformation, and can be particularly observed in the western margin of the Ptolemais–Kozani sub-basin, where concordant geometry between the basement-units and the Plio–Quaternary sediments are well-documented.

– Progressive shear strain, affecting both the Plio-Quaternary sedimentary fill and the basement-units, is considered as dominant. This is compatible with the spatio–temporal evolution of Western Macedonia since Miocene times. These suggest that the major palaeogeographic modifications have taken place within the Plio–Quaternary.

– Isostatic compensation of previously collapsed crust in the Oligocene, and deformation induced by thermo–mechanic disequilibrium of the upper crust, would provide the principal reason for development of intra-plate basins in Western Macedonia.

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