Neotectonic and seismological data concerning major active faults, and the stress regimes of Northern Greece

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Abstract: Northern Greece is an intracontinental region behind the Hellenic subduction zone, with widespread seismic activity (ranging from low to high), with strong destructive earthquakes of $M \geq 6.0$ in historical to recent times. Geological and seismological data indicate that recent seismic activity is mainly localized along large, inherited, fault zones, which have transected Northern Greece since Oligocene–Miocene times. The main active fault zones in Thrace, and Eastern and Central Macedonia strike approximately east–west, with lengths of 40–120 km. Fault segments strike WNW–ESE to ENE–WSW and range from 10 to 30 km in length. In Western Macedonia the main active fault zones strike NE–SW to ENE–WSW with lengths of 40–60 km and consist of 10–30 km segments. The region's strong earthquakes are usually associated with reactivation of these fault segments and are estimated at $M = 5.6$–6.5. Focal mechanisms and fault-slip data from the fault zones indicate a change in the trend of extension axes from NNE–SSW in Eastern Macedonia–Thrace to NNW–SSE in Western Macedonia. Thus, neotectonic and seismological data suggest that variations in fault patterns, as determined from the large inherited fault zones transecting Northern Greece, are the major factor governing this change in the trend of maximum extension. This interpretation is consistent with the long-lived arcuate shape of the Hellenic subduction zone.

Brittle deformation within intracontinental regions is usually associated with distributed faulting and seismic activity. However, within such broad deforming regions some parts, although transected by large faults, are characterized by relatively less intense seismic activity and slip rates. Northern Greece lies in the inner part of the continental collision region of NW Greece and Albania, close to the intensely north–south Aegean extended Sea. This deformation is driven by the Hellenic subduction zone and the westward extrusion of Anatolia (Fig. 1a). In the older Greek seismic code, some large areas of Macedonia (e.g. Western Macedonia) are classified as almost 'aseismic' and other adjacent ones (e.g. Central Macedonia) as highly seismic.

Recent instrumental data obtained from the regional seismological network of the Aristotle University of Thessaloniki, after its installation in 1980, have confirmed the existence of significant seismicity in Northern Greece (Fig. 1b), particularly along narrow rupture zones (Papazachos *et al.* 2001). Furthermore, large earthquakes have been reported in historical times (Papazachos & Papazachou 2003) and several strong and destructive ones have been recorded instrumentally during the last century. Of these, the best known are the 1978 Thessaloniki earthquake of $M = 6.5$ (Papazachos *et al.* 1979) and the 1995 Kozani–Grevena earthquake (Pavlides *et al.* 1995; Mountrakis *et al.* 1996*c*, 1998; Papazachos *et al.* 1998*a*), with the latter occurring in the 'low seismicity' Western Macedonia region.

The rupture zones in Northern Greece need a thorough re-examination in the light of recent advances in our understanding of active faulting and the new data provided by the Aristotle University seismological network. Our aim is to identify the large active fault zones in Northern Greece from their geometric, kinematic and seismotectonic features, to define controlling stresses, and to elucidate the continuity or extent of these zones. The main aim is to better understand the active deformation of these areas and to determine whether fault deformation in Northern Greece is concentrated into relatively narrow bands or zones. As one of the major issues in continental mechanics is how fault slips in the upper crust reflect more distributed flow in the lower lithosphere (e.g. McKenzie & Jackson 1983; Molnar & Gipson 1994; Bourne *et al.* 1998), information about active faulting and driving stresses in such areas is very useful.

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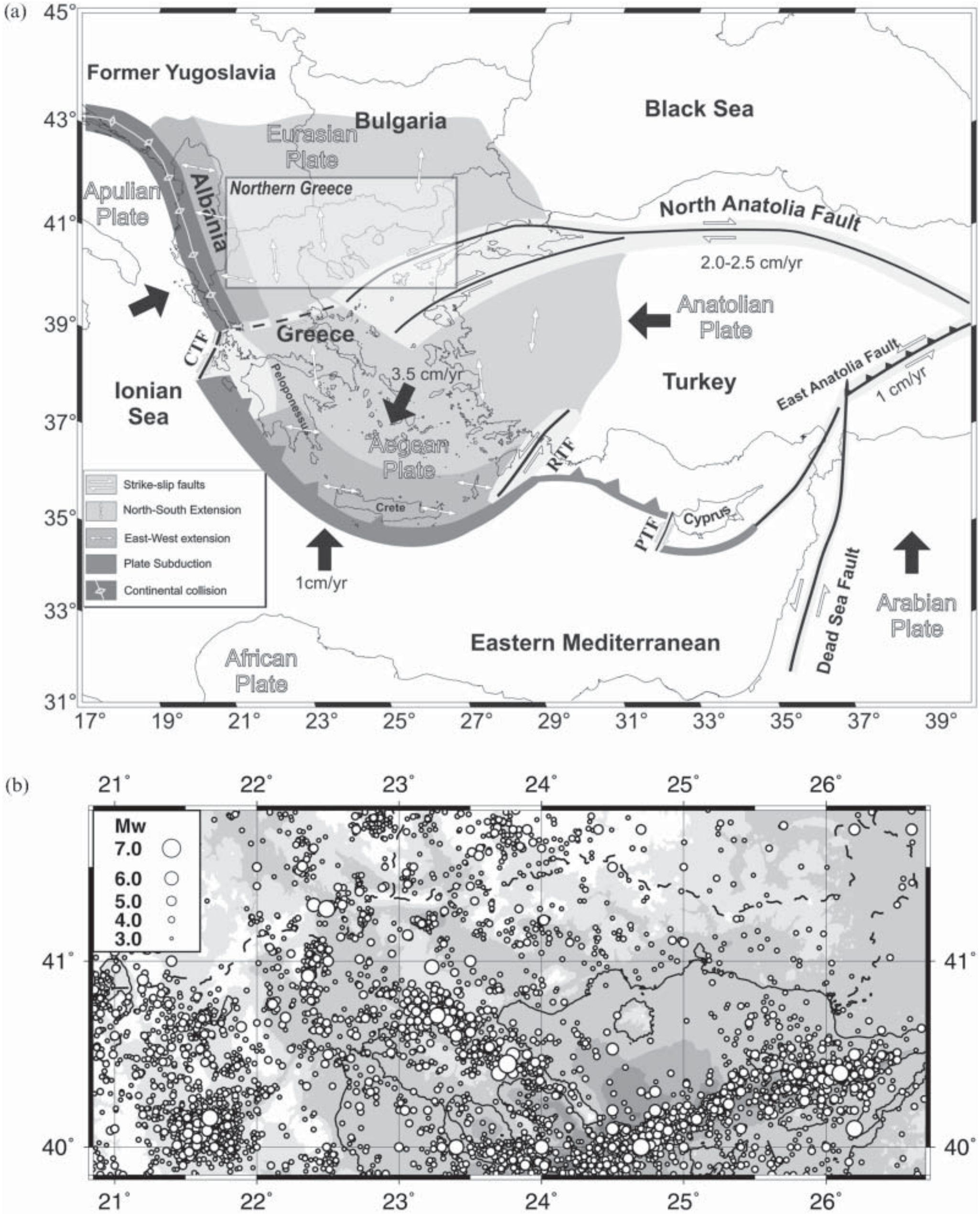

Fig. 1. (**a**) Schematic map showing the position of Northern Greece in the broader Eastern Mediterranean geotectonic regime (modified from Papazachos & Papazachou 2003). (**b**) Spatial distribution of instrumentally recorded earthquakes (1911–2004) with magnitudes $M \geq 3.0$ for the broader study area. CTF, Cephalonia Transform Fault; RTF, Rhodes Transform Fault; PTF, Paphos Transform Fault.

Geology and seismotectonics of Northern Greece

Northern Greece lies in the inner part of the Hellenic orogen and comprises rocks belonging to the Internal Hellenide zones and the Hellenic hinterland. The Mesozoic to Tertiary Alpine orogeny began, on a more regional scale, with the convergence of the Eurasian plate and the Cimmerian and Apulian continental fragments (Mountrakis *et al.* 1983; Mountrakis 1986; Robertson *et al.* 1996). The rocks of these zones form the pre-Alpine and Alpine basement of Northern Greece, on which large Neogene and Quaternary basins developed. The late collisional processes dating from Late Oligocene–Early Miocene times were associated with large strike-slip faults that are recognized in Thrace (Karfakis & Doutsos 1995), Central Macedonia (Tranos 1998; Tranos *et al.* 1999) and Western Macedonia (Mountrakis 1983; Zelilidis *et al.* 2002; Vamvaka *et al.* 2004).

From the Late Miocene onwards, the subduction of the African plate beneath Eurasia along the section of the Hellenic arc from the Ionian Islands southwards to Crete and further east to Rhodes has dominated Greece and created the Hellenic volcanic arc. Northern Greece is characterized by intracontinental brittle deformation; it lies within the internal part of the Hellenic subduction zone and reveals considerable extensional deformation, orthogonal to the subduction zone. Other geotectonic processes include the continuing collision of Eurasia and the Adriatic microplate and the lateral extrusion of the Anatolia microplate towards the Aegean Sea (McKenzie 1978; Taymaz *et al.* 1991; Papazachos 1999). The influence of the latter processes on Northern Greece is being considered although recent papers suggest that the right-lateral strike-slip deformation of the North Aegean Trough, activated by the lateral extrusion of Anatolia westwards, also encompasses faults in Central Macedonia and Eastern Thrace (Pavlides *et al.* 1990; Koukouvelas & Aydin 2002). In addition, Koukouvelas & Aydin (2002) have attributed the exposure of large basins in Central Macedonia and Thrace to the contemporaneous activation of faults that strike ENE–WSW and function as right-lateral strike-slip faults, and NW–SE-striking normal faults.

Since the Late Miocene, the neotectonic deformation of Northern Greece has been dominated by an extensional stress regime, with the least principal stress axis (σ_3) oriented NE–SW during the Late Miocene–Pliocene and north–south during the Early Pleistocene–present (Mercier *et al.* 1989). The NE–SW extensional stress field mainly activated NNW–SSE- to NW–SE-striking normal faults and led to the formation of many fault-bounded basins (e.g. Drama, Strymonas, Axios–Thessaloniki and Ptolemais), whereas the north–south extensional stress field has mostly activated east–west trending normal faults, thus reshaping the already developed fault-bounded basins.

However, the least principal stress axis (σ_3) of the contemporary stress field, as determined from neotectonic observations, reveals a distinct change from NNE–SSW in Eastern Macedonia and Thrace to NNW–SSE in Western Macedonia (Mercier 1981; Le Pichon *et al.* 1982; Mercier *et al.* 1987; Tranos & Mountrakis 1998). A similar spatial variation is also observed in the T-axis of the available earthquake fault-plane solutions and the corresponding strain-rate tensor extensional eigenvalues (Papazachos *et al.* 1992; Papazachos & Kiratzi 1996). This has been attributed either to a spatial change of the lithospheric loading as a result of contemporary lithospheric processes (Mercier *et al.* 1987) or to the pre-existing fault pattern (Tranos & Mountrakis 1998), and the fact that the faults behave not only in an Andersonian mode, but also obey the 3D deformational strain (Tranos 1998; Tranos & Mountrakis 1998).

Seismic activity and fault-plane solutions in Northern Greece

The most recent seismic activity in Northern Greece, as shown by the $M \geq 3.0$ earthquakes of 1982–2001 (Fig. 2), strongly reflects the aftershock sequences related to the latest strong events, such as the 1978 Thessaloniki, 1990 Griva and 1995 Kozani–Grevena earthquakes. The seismic information clearly defines the rupture zones associated with these strong earthquakes and indicates areas of high seismicity; it also indicates the strike of some fault zones. For this reason, a recently developed database of fault-plane solutions derived from the seismological network of the Aristotle University of Thessaloniki was used to define the seismotectonic characteristics of the active faults and to complement available geological information (i.e. neotectonic criteria; also geometric and kinematic characteristics) used to recognize such faults.

The seismological and neotectonic criteria that have been used for the characterization of faults as being active are those already adopted during the neotectonic mapping of Greece by the Greek Earthquake Planning and Protection Organization. Seismically active faults are defined as being directly associated with well-defined historical earthquakes. Using only stratigraphic criteria, active faults are defined as those activated since the late Pleistocene. Additionally, several other features of faults are used, such as: (1) Geomorphological features, i.e. the linear trend of a mountain front along which successive Quaternary fan or colluvial deposits, triangular facets, fault scarps etc. are distributed; (2) Tectonic features, i.e. correlation of fault-slip data

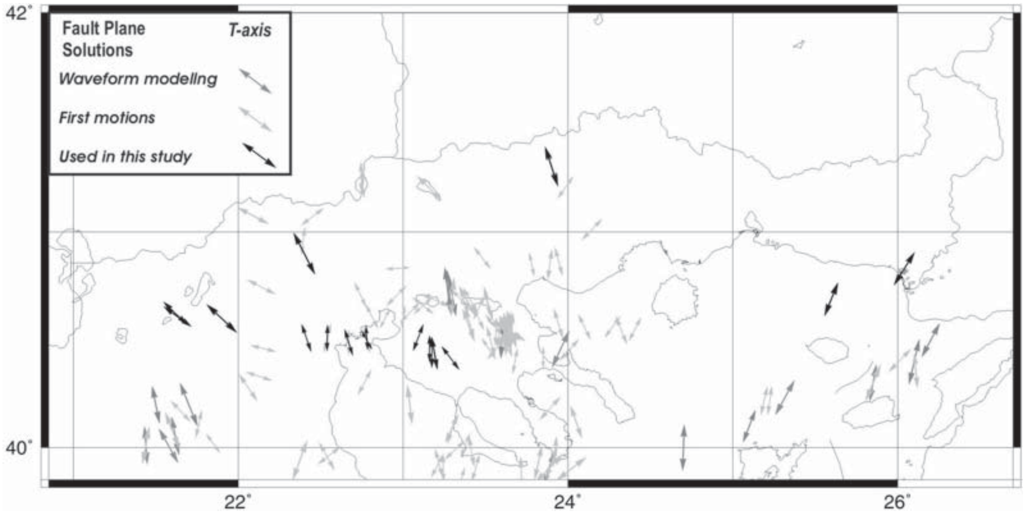

Fig. 2. Distribution of available extension (T) axes, corresponding to the most recent database of earthquake fault-plane solutions for the study area (Papazachos *et al.* 2004). Information corresponding to fault-plane solutions was determined using different methods, as well as those used in the present study for specific fault zones, as are denoted by different arrows (see key).

with those of verified, well-known seismic faults with similar orientations; (3) linear alignment of springs or spring deposits.

In addition to data from the Thessaloniki network, the database includes fault-plane solutions of large and intermediate magnitude events, as determined by waveform modelling, from international centres (Harvard, ETH, INGV, etc.) or elsewhere, together with several intermediate and smaller-magnitude events as determined from first motions. The procedure for finding first-motion fault-plane solutions was calibrated using the available common solutions from waveform modelling (Papazachos *et al.* 2004). The spatial distribution of extension axes, as determined from earthquake fault-plane solutions, is presented in Figure 2, where black vectors denote the σ_3-axes used in the detailed analysis of the selected active faults presented below. The fault-plane solutions were correlated with field observations along the faults to help define their activity.

Faulting of the area

To identify the active rupture zones exposed in Northern Greece, we tried to combine information from the latest seismic activity with that from geological observations along the large fault zones, or as reported in previous work. The most important issues are the spatial distribution and focal mechanisms of both small and large magnitude earthquakes. This information has been used to locate the strain mainly along large fault zones, which are the most likely to produce strong earthquakes.

To compare easily the principal strain axes derived from focal mechanisms with fault-slip data recorded along the faults studied, these faults were analysed with a simple graphical method that constructs the kinematic axes of the faults, i.e. the principal incremental shortening (P) and extension (T) axes using the program 'FaultKin' (Allmendinger 2001). Each pair of axes lies in the movement plane of the fault (i.e. a plane perpendicular to the fault plane that contains the unit vector parallel to the direction of accumulated slip, and the normal vector to the fault plane). Each pair of axes makes an angle of 45° with both vectors. To distinguish the shortening and extension axes, information on the relative sense of slip is needed. Also, the principal stress axes (σ_1, σ_2, σ_3) of the rupture zones were defined using a program Duyster (1999). This calculates the stress directions from the recorded fault-slip data with the PT method after Turner (1953). The method is a very simple way to determine palaeostress directions assuming that fractures generate parallel to σ_2 with the angle Θ between the σ_1 and the fault plane being 30°. Although this is valid according to the Mohr–Coulomb criterion applied to a homogeneous rock mass, experimentally obtained values of

Θ range between 17° and 40° (e.g. Hubbert 1951; Byerlee 1968; Jaeger & Cook 1979) and imply that an angle of $\Theta = 30°$ is a reasonable approximation.

Using this approach we subdivide the large area 1 Northern Greece into three areas, which, from east to west, are Eastern Macedonia and Thrace, Central Macedonia and Western Macedonia.

The fault pattern, as defined by the larger fault zones, can be briefly described as follows. (1) Eastern Macedonia and Thrace are dominated by NE–SW- and east–west-striking faults. (2) In Central Macedonia large basins strike NNW–SSE to NW–SE; however, east–west-striking faults dominate the recent fault pattern. (3) In Western Macedonia, NE–SW- to ENE–WSW-striking faults predominate, with subordinate NW–SE- and east–west-striking faults. On this basis the following large rupture zones have been established (Fig. 3).

Eastern Macedonia and Thrace

The mountainous Eastern Macedonian–Thrace region includes several large east–west-striking fault-bounded basins, namely the Alexandroupolis, Drama and Kavala–Xanthi–Komotini basins. This area has low seismicity, with very few historically reported earthquakes; of these, Drama in 1829 ($M = 7.3$) and 1867 ($M \approx 6.0$), Komotini ($M = 6.7$) in 1784 and Didimoticho ($M = 7.5$) in 1752 were the strongest (Papazachos & Papazachou 2003). This low activity is puzzling, as Eastern Macedonia and Thrace are close to the seismically active North Aegean Trough and contain kilometres-long fault zones of similar strike (i.e. large east–west- to ENE–WSW-striking fault zones), which dominate the fault pattern of the area.

The east–west-striking fault zones include two different geometric types: (1) large rectilinear fault zones with constant east–west strike; (2) fault zones related to faults whose strike varies from NE–SW to WNW–ESE and that coalesced during the neotectonic period, e.g. the Kavala–Xanthi–Komotini fault.

In the second case, the NE–SW- and WNW–ESE-striking faults bounded the Eocene–Oligocene molasse-type sediments and controlled exposures of Oligocene volcanic rocks (see also Karfakis & Doutsos 1995).

The main fault zones exposed in Eastern Macedonia and Thrace are Kavala–Xanthi–Komotini, Maronia–Alexandroupolis, Drama–Prosotsani, Serres–Nea Zichni and Ofrinio–Galipsos, which all strike more or less east–west.

Kavala–Xanthi–Komotini fault zone

The Kavala–Xanthi–Komotini fault zone, the most important in Eastern Macedonia–Thrace, is an east–west master fault zone >120 km long (Lyberis 1984) that runs very close to the cities of Kavala, Xanthi and Komotini (Figs 3 and 4a). This clearly demonstrates the importance of assessing the related seismic hazard. Although the fault zone generally strikes east–west, it comprises four fault segments that vary in strike from NE–SW to WNW–ESE and reveal different geological features (Mountrakis & Tranos 2004). The four segments are as follows:

Chrisoupolis–Xanthi fault segment. This 35 km long NE–SW-striking (*c.* 55°) segment runs along the SE slopes of Mt Lekani, between the coast east of the city of Kavala and the city of Xanthi. The fault separates the marbles of the Pangeon Unit in the footwall from the tectonically overlying migmatites and gneisses of the Sidironero Unit that constitute the hanging wall, along with overlying post-Alpine Tertiary molasse-type sediments (Kilias & Mountrakis 1998). The segment is characterized by remarkable triangular facets and fault scarps. The fault surface strikes NE–SW and dips at moderate angles towards the SE, and is well exposed at Paradisos village. A thin, dark brown oxidized carapace covers this fault surface, and records three generations of slickenlines (Fig. 4a). The older slickenlines indicate strike-slip movement, whereas the younger indicate a NNW–SSE extension axis (T).

Xanthi–Iasmos fault segment. This 27 km long segment strikes WNW–ESE to east–west. It runs from the city of Xanthi to the east of Iasmos village, until it ends against a NNW–SSE rectilinear fault trace along Xiropotamos stream. This segment contains several subparallel fault branches that form successive fault scarps, with the most basinward ones being the most impressive. The fault affects the metamorphic rocks of the Sidironero Unit and the Tertiary molasse-type sediments; it also affects the Late Oligocene Xanthi granitoid (*c.* 28 Ma, Kyriakopoulos 1987), forming well-exposed fault surfaces dipping steeply southward. The slickenlines along this segment indicate successive strike-slip movements, with an oblique left-lateral normal movement and finally a right-lateral oblique movement (Fig. 4a).

Iasmos–Komotini fault segment. This 16 km long segment strikes ENE–WSW and comprises two parallel left-stepping and overlapping fault strands: the Polyanthos–Mega Piston and Mega Piston–Agiasma fault strands, which are about 6 km and 13 km long, respectively (Fig. 4a).

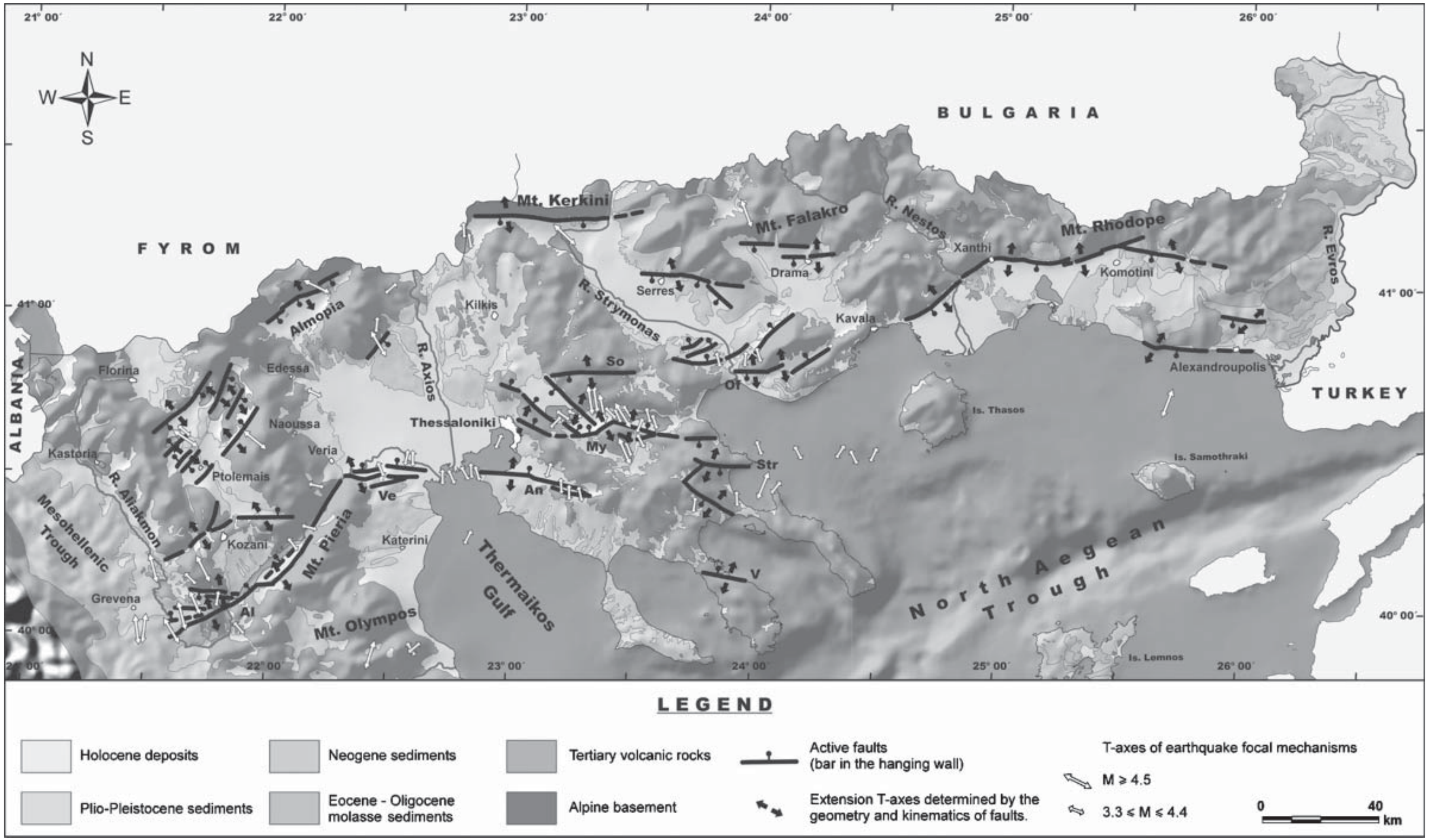

Fig. 3. Generalized geological–tectonic map showing the main active fault zones of Northern Greece, the extension axes (T) as determined by the focal mechanisms of the $M \geq 3.3$ earthquakes instrumentally recorded in the region, and the fault-slip data collected along the fault zones. Al, Aliakmonas; An, Anthemountas; My, Mygdonia; Of, Ofrinio; So, Sochos; Str, Stratoni; V; Vourvourou; Ve; Vergina.

These fault segments juxtapose basement with Plio-Quaternary fanglomerates and Holocene deposits that entirely cover the underlying Neogene sediments of the Komotini basin (Diamantis 1985). However, the Mega Piston–Agiasma strand can be traced further northeastwards. Along this fault Tertiary molasse-type sediments were juxtaposed with the metamorphic rocks of the Rhodope massif, suggesting that the NE–SW-striking faults are older, perhaps reactivated pre-Neogene structures. The Iasmos–Komotini fault segment is characterized by multiple reactivations revealing slickenlines of right-lateral strike-slip movement overprinted by younger ones that indicate normal-sense reactivations.

Komotini–Sapes fault segment. This segment, over 30 km long, reveals a complicated geometry, as it resembles several WNW–ESE and east–west synthetic fault strands <8 km long that dip SSW to south at medium to high angles (Fig. 4a). Predominant are the Tichiro, Gratini, Dokos and Fillira–Skaloma faults, which gradually lower the hilly landscape towards the south. This is a boundary fault, striking WNW–ESE, which controlled the deposition of molasse-type and especially Neogene sediments (Karfakis & Doutsos 1995). Our mapping indicates that WNW–ESE-striking faults are truncated by east–west trending faults, e.g. the east–west Gratini fault truncates the WNW–ESE Tichiro fault, whereas other smaller and non-continuous east–west-striking faults have been observed to continue westwards to the city of Komotini. Right- and left-lateral oblique normal movements here give rise to NNE–SSW and north–south extension, respectively, along this fault segment. The youngest activity can be traced east of Polyanthos village, where a rectilinear fault line, a few tens of metres long, with a vertical offset of less than a metre, has been found within the Plio-Pleistocene fanglomerate sediments of the hanging wall.

Concerning the latest kinematics of the Kavala–Xanthi–Komotini fault zone, the latest slickenlines recorded along the variously oriented fault segments are related to normal reactivations and define a stress ellipsoid whose least principal stress axis (σ_3) is oriented almost north–south (Fig. 4b).

The most recent seismic activity along the fault zone is around Komotini city, where a destructive $M=6.7$ earthquake was reported in 1784 (Papazachos & Papazachou 2003). It seems reasonable to associate this earthquake with the Komotini–Sapes fault segment, as the latter faces the epicentre (Fig. 4a) and a young fault scarp has been found cutting the Plio-Pleistocene fanglomerate sediments of its hanging wall.

Maronia–Alexandroupolis fault zone

This 35 km long east–west-striking fault zone localizes the coast from Maronia village to the city of Alexandroupolis (Figs 3 and 4a) and is very important for a seismic hazard assessment of the city, which is built on its extension. However, this zone does not exhibit a single traceable fault surface, but rather seems to comprise fault segments of WNW–ESE and ENE–WSW strike. Hence, another fault strand could be present in this fault zone; i.e. the 7 km long, WNW–ESE-striking Avantas fault, which bounds the Alexandroupolis basin to the north (Fig. 4a). Close to Avantas village this is clearly observed to modify the contact between overlying Eocene–Oligocene clastic marls and clays and underlying Upper Lutetian nummulitic limestones, which dip southwards at moderate angles, forming a rectilinear, steep fault scarp along which fault slickensides exhibit right-lateral oblique slickenlines and indicate a NE–SW extension axis (T) (Fig. 4c).

The WNW–ESE-striking fault segment controls the coastline east of Maronia village, forming steep corrugated slickensides, which dip SSW at about 60°. It also affects the Mesozoic and Tertiary rocks and forms a composite cataclastic zone with corrugated slickenside surfaces and a 1 m thick cohesive cataclasite. The slickensides exhibit dip-slip slickenlines and shearing microstructures that indicate normal reactivation and a NNE–SSW extension axis (T) (Fig. 4c). Horizontal continental-type Pleistocene deposits abut these fault slickensides. The small antithetic faults in those sediments suggest Quaternary reactivation of the fault.

The closest earthquake ($M=4.6$, 25.60°N, 40.69°E), which occurred in the hanging wall of this fault on 5 March 2002, was located in the Thracian Sea, between the coast and the island of Samothraki. Its focal mechanism exhibits similar geometry and kinematics to the western segment of the fault zone (Fig. 4c and d) suggesting that it is active. A similar conclusion can be drawn from a fault-plane solution of the $M=5.1$ earthquake that occurred close to this fault zone on 27 June 2004 (26.04°N, 40.78°E). This exhibits a similar strike and extension axis (T) to the Avantas fault, although it seems to have a more significant right-lateral strike-slip component.

Drama–Prosotsani fault zone

The 30 km long east–west-striking Drama–Prosotsani fault zone is located on the southern slopes of Mt Falakron and places the Neogene–Quaternary sediments of the Drama basin against the marbles of the pre-Miocene basement (Figs 3 and 5a). The zone has a rather

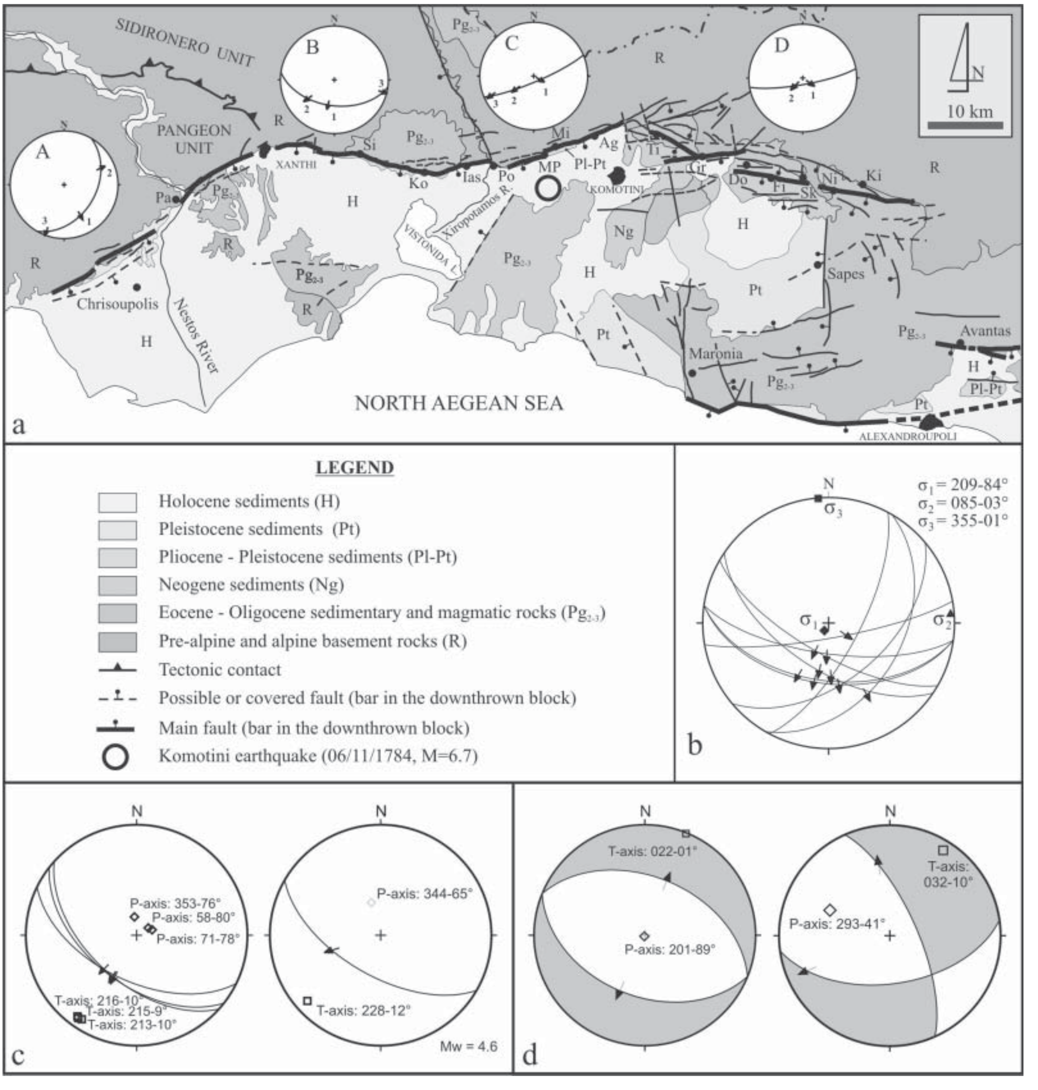

Fig. 4. (**a**) Generalized geological–tectonic map of the Kavala–Xanthi–Komotini and Maronia–Alexandroupolis fault zones (modified from Mountrakis & Tranos 2004). Stereographic projections on the map show the main movements of the fault zone segments, with 1, 2, 3, being the order from the oldest to the youngest movements. Pa, Paradisos; Si, Simantra; Ko, Koptero; Ias, Iasmos; Po, Polyanthos; MP, Mega Piston; Mi, Mischos; Ag, Agiasma; Ti, Tichiro; Gr, Gratini; Do, Dokos; Fi, Fillira; Sk, Skaloma; Ni, Nikites; Ki, Kinira. (**b**) The contemporary stress regime, as defined by the latest normal movement along the Kavala–Xanthi–Komotini fault zone, using the program by Duyster (1999). (**c**) Stereographic projection of the latest movement of the Maronia–Alexandroupolis fault zone and Avantas fault. (**d**) Focal mechanisms of the earthquakes closest to the fault zone. The latest movement of the fault zone corresponds well to that defined by the focal mechanisms and indicates a NNE–SSW to NE–SW extension axis (T).

complicated geometry, with a main east–west-striking boundary fault, the Prosotsani fault and, basinwards, several smaller, subparallel and interrupted fault strands that dip steeply southward. The latter faults delineate another east–west-striking fault branch, the Drama fault; along with the Prosotsani fault this forms a right-stepping fault geometry covered by an extensive alluvial plain, which is also affected by steep to vertical east–west- to ENE–WSW-striking mesoscale joints and faults. This alluvial plain obscures the trace of the main fault, suggesting that the slip rate of the fault zone, particularly the boundary fault, is rather small.

The latest observed movement along the Drama fault has a normal offset. Near Kaliphytos village (Fig. 5a), we observed that the fault rock, Quaternary reddish cemented brecciated fault gouge, is transected by younger faults, indicating normal reactivation, and that Quaternary screes and fanglomerates rest with a buttress unconformity on Neogene sediments. In addition, the presence of travertine deposits associated with perennial springs (e.g. in the centre of the city of Drama and in Mylopotamos village) along the Drama fault branch also suggests recent reactivation.

The kinematics of the Drama–Prosotsani fault zone, as defined by the latest slickenlines (Fig. 5b), corresponds to a north–south extensional strain field. A similarly oriented extension axis (T = 162–12°) is defined by the focal mechanism of the nearby M = 5.5 Volakas earthquake that occurred on 9 November 1985 (23.9°N, 41.3°E).

Serres–Nea Zichni fault zone

The east–west-striking Serres–Nea Zichni fault zone lies east of the NW–SE-striking Neogene Strymon basin and defines the basin boundary east of the city of Serres (Figs. 3 and 6). This fault is about 30 km long and controls the deposition of the Quaternary sediments along the southern slopes of Mt Menikion, from the city of Serres to Nea Zichni village. It exhibits a complicated geometry, as it includes several fault segments of ENE–WSW, east–west and NW–SE strike. These are: (1) the Serres segment; (2) the Eptamili–Ag. Pnevma segment; (3) the Ag. Pnevma–Metalla segment; (4) the Dafnoudi–Nea Zichni segment.

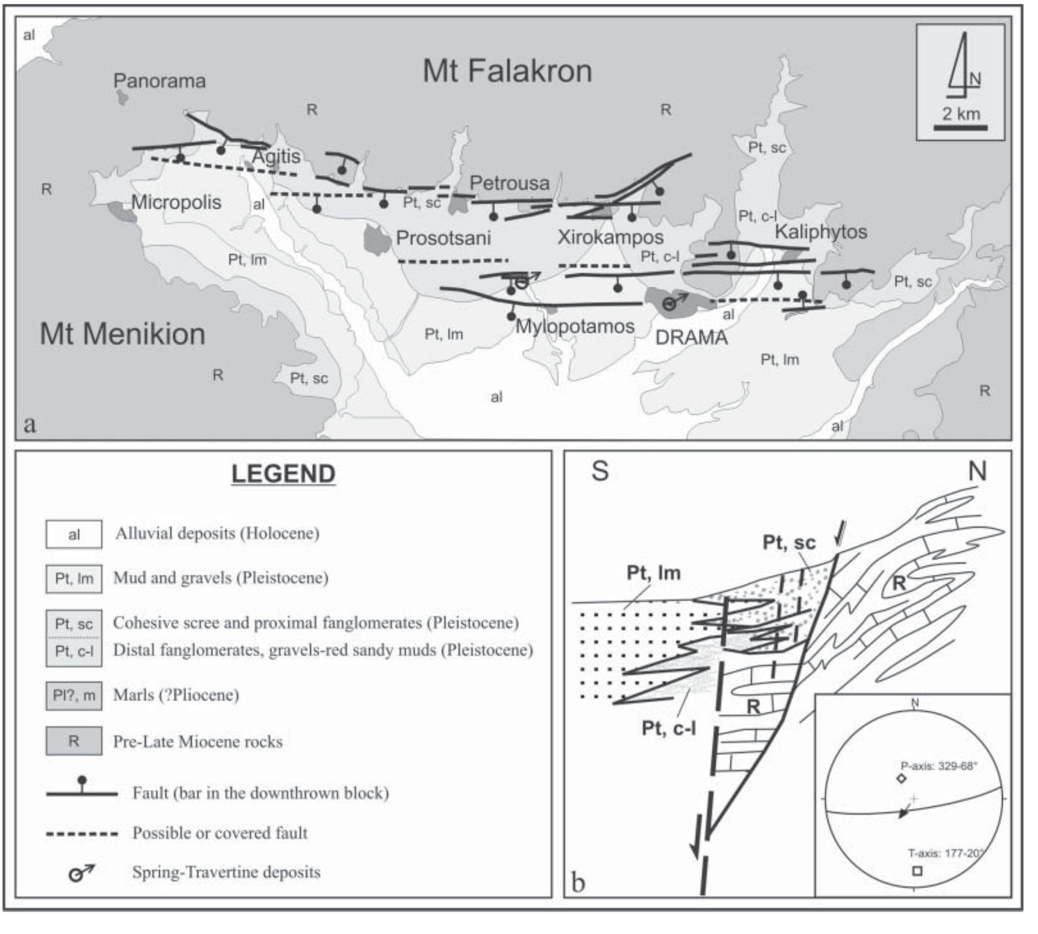

Fig. 5. (**a**) Generalized geological–tectonic map and (**b**) schematic cross-section and stereographic projection of the latest movement and the defined P, T kinematic axes of the Drama–Prosotsani fault zone.

The Serres fault segment, exposed between Lefkonas and Eptamili villages, runs through the city of Serres. It includes ENE–WSW- and east–west-trending faults that differentiate a hilly area to the north, made up of Neogene sediments, from the Quaternary floodplain to the south for a length of about 6.5 km.

The east–west-striking Eptamili–Ag. Pnevma and WNW–ESE-striking Ag. Pnevma–Metalla fault segments are the main boundary faults that separate the crystalline basement from the Neogene sediments of the Strymon basin. These are both *c*. 10 km long and consist of subparallel faults towards the basin that dip southwards at high to very high angles. The fault surfaces are dominated by normal slickenlines that overprint older strike-slip slickenlines (Tranos & Mountrakis 2004). The strike-slip slickenlines exhibit similar kinematics to that of the similarly oriented faults that were observed within Neogene sediments, north of the city of Serres (Karistineos 1984), but not within the Quaternary sediments of this area.

The strong modification of this boundary related to Quaternary normal reactivation of fault segments has resulted in the juxtaposition of upper Pleistocene fan deposits with the basement.

Although no data are available for any historical earthquakes in the Serres–Nea Zichni fault zone, considering its possible future reactivation, it seems that the potentially most active sections are the Eptamili–Ag. Pnevma and Ag. Pnevma–Metalla segments, which both define a NNW–SSE extension and which both affect the later Quaternary sediments.

Ofrinio–Galipsos fault zone

Along the southern slopes of Mt Pangeon, east of the River Strymon (Fig. 3), that is a 10 km long fault array composes of three synthetic subparallel east–west-striking faults that dip steeply southwards, as mapped between the villages of Ofrinio and Galipsos. The northernmost of these faults bounds Neogene sediments and delineates the east–west front of the mountain. In places, it forms triangular facets and fault scarps that dip steeply southward. The southern faults affect the Neogene sediments, causing tilting of up to 40°,

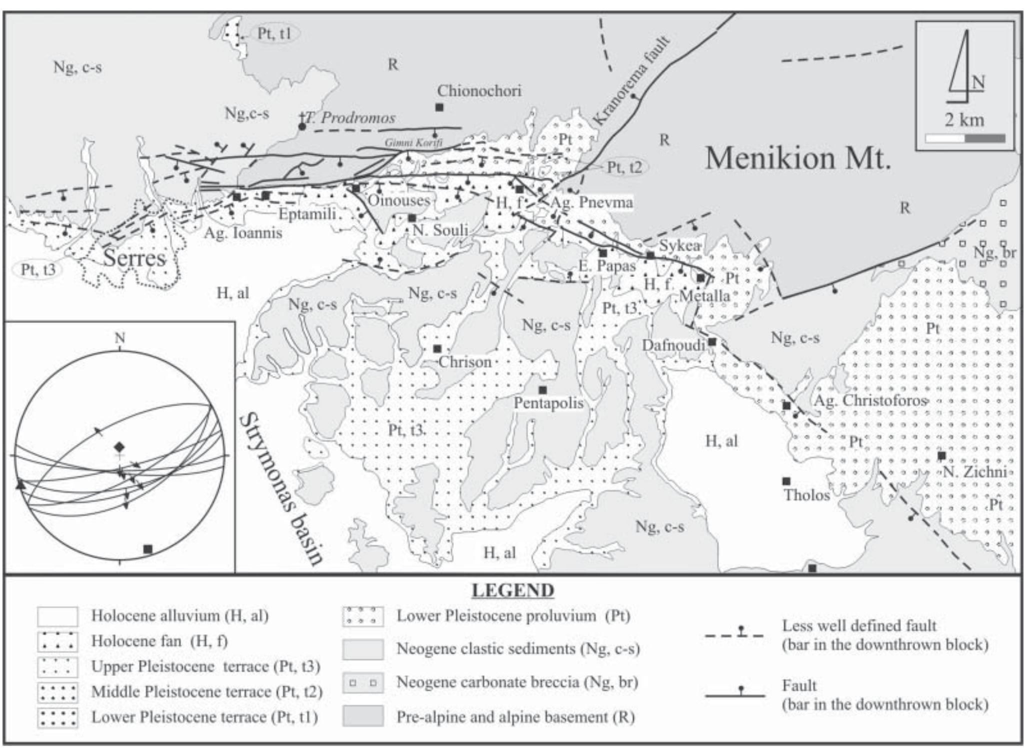

Fig. 6. Geological–tectonic map of the Serres fault zone (modified from Tranos & Mountrakis 2004). Inset: stereographic projection (equal area, lower hemisphere) of the fault-slip data along the fault zone. ◆, σ_1; ▲, σ_2; ■, σ_3.

to either the south or the north. In addition, near Galipsos village small steeply- dipping normal fault surfaces located along the trace of the boundary fault have affected Quaternary alluvial fan deposits (Tranos 1998), suggesting Quaternary reactivation. The Ofrinio–Galipsos fault zone extends ENE as far as the south-dipping normal faults of the Kavala–Eleftheroupoli fault zone, although it seems to truncate the latter.

The fault-slip data along the fault zone indicate a NNW–SSE extension axis (T) and a subvertical shortening axis (P) (Fig. 7).

Central Macedonia

Central Macedonia possesses several Neogene–Quaternary basins, namely the Thessaloniki, Yanitsa, Kilkis, Mygdonia and Strymon basins, which strike NW–SE and east–west, forming large plains between the mountainous terrain of the pre-Alpine and Alpine basement (Fig. 1).

The fault pattern of Central Macedonia is similar to that of Eastern Macedonia and Thrace, i.e. east–west, varying from WNW–ESE to ENE–WSW, and includes faults that strike NW–SE and NE–SW. More precisely, the prevalent east–west-striking faults form large fault systems that bound Neogene and Quaternary basins. The NW–SE-striking faults follow the orogenic fabric and form large NW–SE Neogene basins. These faults are nowadays less well defined, as they have been cut or truncated by east–west-striking faults (Tranos *et al.* 2003).

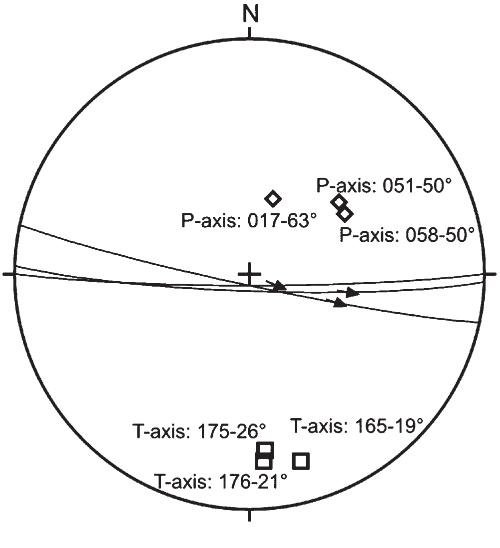

Fig. 7. Stereographic projection (lower hemisphere, equal area) of the latest movement along the boundary fault of the Ofrinio–Galipsos fault zone and the P, T. kinematic axes.

The most significant east–west-striking faults exposed in Central Macedonia (Fig. 1) are the South Mygdonia fault system, the Stratoni fault, the Sochos–Mavrouda fault zone, the Vourvourou fault, the Northern Almopias fault zone, the Kerkini fault zone, the Anthemountas fault zone and the Northern Pieria fault zone. After the 1978 Thessaloniki earthquake, several of these were described in detail. Here, we will summarize those faults for which published information exists; i.e. the Southern Mygdonia fault system, the Stratoni fault, the Sochos–Mavrouda fault zone, the Vourvourou fault and the Northern Almopia fault zone.

Southern Mygdonia fault system

The Southern Mygdonia fault system (Fig. 3), the most intensely studied in Northern Greece (Papazachos *et al.* 1979; Mercier *et al.* 1983; Mountrakis *et al.* 1983, 1996*a*,*b*; Pavlides & Kilias 1987; Tranos 1998; Tranos *et al.* 2003), delineates the stretched Mygdonia graben to the south for 60 km. Its complex geometry has resulted from the coalescence of pre-existing 25 km long WNW–ESE-striking faults and 10 km long NE–SW- to ENE–WSW-striking faults that dip steeply to the north and which were reactivated in Quaternary to Recent times as active normal fault segments defining north–south extension. Fault segments of this fault zone were reactivated, causing the 1978 Thessaloniki earthquake; because of this reactivation, impressive seismic fissures have been observed for 20 km along the fault zone (Papazachos *et al.* 1979).

Stratoni fault

The Stratoni fault is also an east–west-striking active normal fault with an observed length of 15–20 km (the sea obscures its eastward extension) and defines north–south extension (Pavlides & Tranos 1991). According to Pavlides & Tranos, the 1932 Ierissos earthquake of M = 7.1 was possibly due to reactivation of the Stratoni fault.

Sochos–Mavrouda fault zone

The *c.* 30 km long Sochos–Mavrouda fault zone strikes east–west and dips southwards (Mountrakis *et al.* 1996*a*). The most active segments of this zone are the Sochos and Mavrouda faults, which have similar strikes and lengths of about 8–10 km, forming a right-stepping geometry. The faults define rectilinear mountain slopes, along which Quaternary scree and fan sediments were deposited in the hanging wall, whereas triangular facets characterize the mountain escarpments in the footwall. These faults typically undergo normal reactivation that defines north–south extension (Mountrakis *et al.* 1996*a*). The 1932 Sochos earthquake of M = 6.2 in this area (Papazachos & Papazachou 2003) was possibly due to reactivation of the Sochos fault zone.

Vourvourou fault

The Vourvourou fault was described by Tranos (1998) as a *c.* 15 km long WNW–ESE-striking normal fault that dips steeply NNE and downthrows the mountainous terrain of the Sithonia Peninsula of Chalkidiki at its northern end. The fault exhibits more than one reactivation; the latest one defines a subhorizontal extension axis oriented NNE–SSW.

Northern Almopia or Aridea fault zone

This is a 25 km long ENE–WSW-striking fault zone that transects the Internal Hellenide zones of Almopia and Paikon close to and parallel the Greek–FYROM border (Fig. 3). Its geometry and kinematics have been described by Pavlides *et al.* (1990). It is noteworthy because it abruptly ends the prolongation of Mt Voras to the south and forms the large inter-mountain Almopia or Aridea basin. The zone consists of three segments; from west to east, these are the Loutraki, Promachi and Theriopetra faults, which are about 8–10 km long and dip steeply south, producing an asymmetric or half-graben development.

The Northern Almopia fault zone originated as an old strike-slip fault in Tertiary times, and was reactivated as a normal fault in neotectonic times (Mountrakis 1976; Pavlides *et al.* 1990). Thermal springs and Quaternary travertine outcrops have been mapped along the fault. The fact that these travertines were later affected by ENE–WSW-striking, south-dipping normal faults, with similarly orientation to the Loutraki fault segment of the Northern Almopia fault zone, suggests that neotectonic reactivation has taken place. The latest reactivation of this fault zone is normal, and defines a NNW–SSE extension axis (T).

Kerkini fault zone

The 45 km long east–west-striking Kerkini fault zone runs along the southern slopes of the east–west-elongated Mt Kerkini and forms an elongated narrow valley filled with Quaternary fan deposits. It has been characterized as an active fault using stratigraphic and geomorphological data (Psilovikos & Papaphilipou 1990) (Figs 3 and 8a). This is the dominant morphotectonic feature of northernmost Central Macedonia, and consists of two main fault segments named the Kastanousa and Poroia–Petritsi segments, respectively; those both abruptly downthrow the southern slopes of Mt Kerkini (Fig. 8b) forming a right-stepping geometry.

The 18 km long Kastanousa segment dips steeply southwards, and, together with smaller antithetic faults, bounds a narrow valley filled with Quaternary proluvial and alluvial sediments dipping gently southwards. To the west the fault joins an ENE–WSW-striking fault that extends towards Lake Doirani. The Kastanousa fault segment contains at least two more subparallel strands towards the centre of the valley, as defined by geophysical surveying along cross-section 1 (Fig. 8a) (G. Vargemezis, unpubli. data). The southernmost of these strands might be considered as the westward extension of the Poroia–Petritsi segment. The small fault scarps, and small parallel exposures of Holocene alluvial sediments that form the east–west strike, imply recent reactivation of the fault.

The eastern fault segment, the Poroia–Petritsi segment, is about 24 km long and juxtaposes the Strymon basin sediments against the metamorphic rocks of the Serbo-Macedonian massif that makes up Mt Kerkini. This segment clearly truncates the NE–SW- to ENE–WSW-striking faults that obliquely cut the mountain chain north of Petritsi village. In addition, the River Strymon possibly represents a cross-cutting feature, and consequently a possible barrier to the fault. This fault seems to have been bypassed by the fault reactivation as the fault trace continues eastwards without any deflection or change.

The kinematics of the fault zone are well defined along both segments, as indicated in Figure 8c, and define a NNE–SSW extensional stress field. It should be noted that there is an almost complete lack of recent seismic activity along most of this fault. Small-magnitude seismic activity in the wider region is concentrated further south towards the fault edges, close to Lakes Doirani and Kerkini, showing a more or less north–south extension (T) (see Fig. 3). However, few seismological data are available for this fault zone.

Anthemountas fault zone

This 40 km long zone is one of the most spectacular in Central Macedonia; it bounds the narrow

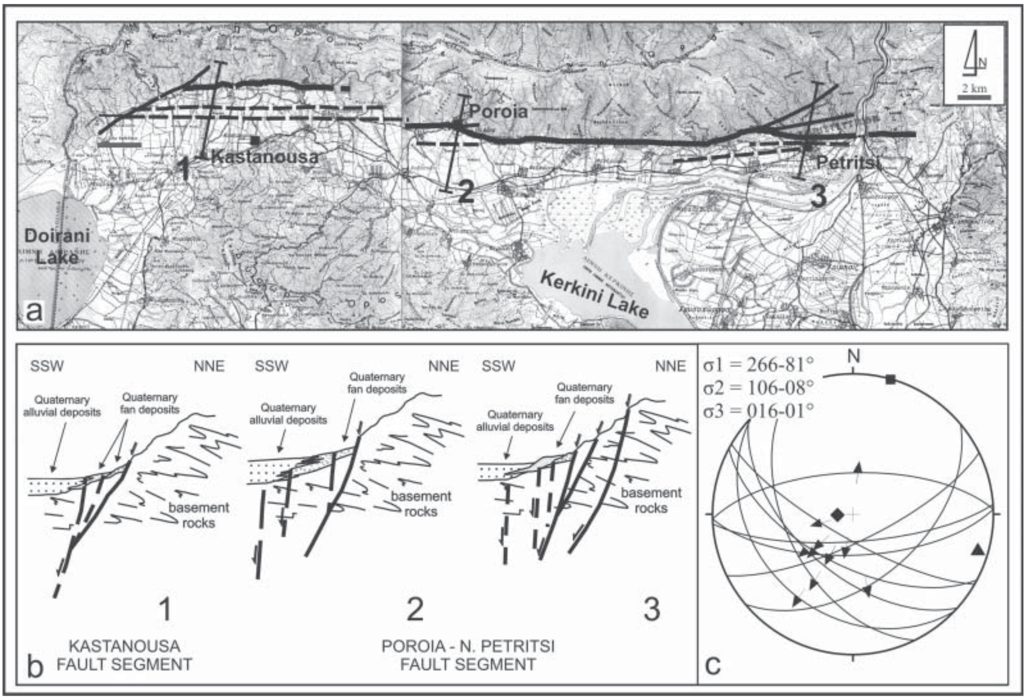

Fig. 8. (**a**) Detailed mapping of the Kerkini fault zone. Continuous bold line traces the boundary fault; dashed lines indicate the covered or less well-defined faults. (**b**) Schematic cross-sections of various parts of the fault zone. The Quaternary sediments are coarse-grained fanglomerates, fine-grained fanglomerates and floodplain deposits prograding from the mountain slope towards the basin. (**c**) Stereographic projection of the latest movement of the fault zone as recorded at the different fault segments and the calculated stress axes, as defined using the program by Duyster (1999). ◆, σ_1; ▲, σ_2; ■, σ_3.

east–west-striking Anthemountas basin to the south (Mountrakis *et al.* 1996*b*) (Fig. 3). The zone can be divided into two fault segments based on the geomorphological features and different lithology of the rocks that it separates. In particular, the segment running from the Thermaikos Gulf eastwards for about 30 km reveals an almost rectilinear strike and separates Neogene sediments of the footwall from Holocene alluvial and coastal deposits of the hanging wall. The other fault segment is about 20 km long and curves concavely northwards. The basement rocks of the mountainous terrain are exposed along this segment, and a Late Pleistocene terrace system, consisting of the older Pleistocene sediments, has formed in the hanging wall. The two segments form a right-step overlapping geometry, with the western one providing the most evidence of recent reactivation, as indicated by the distribution of the small recorded earthquakes.

The fault zone possibly extends westwards into the Thermaikos Gulf, and further west may join the Northern Pieria fault zone (see below). The 1759 earthquake (M ~ 6.5), reported to have destroyed a large part of the city of Thessaloniki (Papazachos & Papazachou 2003), could be related to reactivation of this part of the Thermaikos Gulf fault zone. However, because information is limited, this is uncertain. The database of the seismological network does not indicate any significant seismic activity along this fault.

The fault-slip data of the fault zone define an extensional stress regime with the least principal stress axis (σ_3) oriented NNW–SSE (Fig. 9a). This fits with the extension axes as defined by the focal mechanisms of small earthquakes along the zone (Fig. 9b).

Northern Pieria fault zone

The ENE–WSW-striking Northern Pieria fault zone (Figs 3 and 10a) lies in the northernmost Pieria region and downthrows low-mountainous to hilly terrain over about 20 km. It is a wide zone of faults several kilometres long and dipping steeply northward, thus forming the Aliakmonas basin. Among these, the 10 km long Vergina–Palatitsa, Neokastro and Kolindros faults are the most prominent. The faults of this zone affect Mesozoic rocks and Neogene sediments and are marked by continuous or discontinuous linear fault scarps. In addition, several possible fault lines representing concealed faults have been mapped basinwards, e.g. NW of Meliki village and these control the course of the River Aliakmonas. Small landslides have occurred along the faults affecting the Neogene sediments (e.g. Agathia fault).

Dip-slip slickenlines along the faults described above indicate that normal reactivation characterizes the fault zone, defining NNW–SSE extension axes (T) (Fig. 10b). These kinematics fit well with the focal mechanisms of the small earthquakes along this zone (Fig. 10c).

The Northern Pieria fault zone exhibits morphotectonic similarities to the western part of the Anthemountas zone, suggesting a link, or at least simultaneous evolution.

Western Macedonia

Western Macedonia (Fig. 3) lies west of the Voras, Vermio and Pieria mountain chains, and is separated from Thessaly to the south by the River Aliakmonas. This is a mountainous terrain interrupted by the Grevena, Florina, Ptolemais, Kozani–Ag. Dimitrios and Serbia basins. The Grevena basin is filled with molasse-type sediments of the Mesohellenic Trough, whereas all of the other basins contain Neogene and Quaternary sediments.

The fault pattern of Western Macedonia differs from that of Central Macedonia and Thrace, because the most prevalent faults of several kilometres length strike not east–west but rather NE–SW to ENE–WSW, cutting the NW–SE orogenic fabric of the Hellenides at high oblique to orthogonal angles. These Late Tertiary strike-slip faults were reactivated as normal faults in the Quaternary (Mountrakis 1983). The fault pattern of Western Macedonia includes NNW–SSE-striking faults of several kilometres that follow the orogenic fabric and bound the Grevena, Kozani–Ag. Dimitrios and Florina basins, without, however, affecting the Quaternary sediments. These faults exhibit a normal reactivation that defines a NE–SW extension axis (T), suggesting that they were mainly reactivated during the Pliocene within the previous NE–SW extensional stress field. The east–west-striking faults exposed in the pre-Neogene basement appear, in conjunction with the NE–SW- to

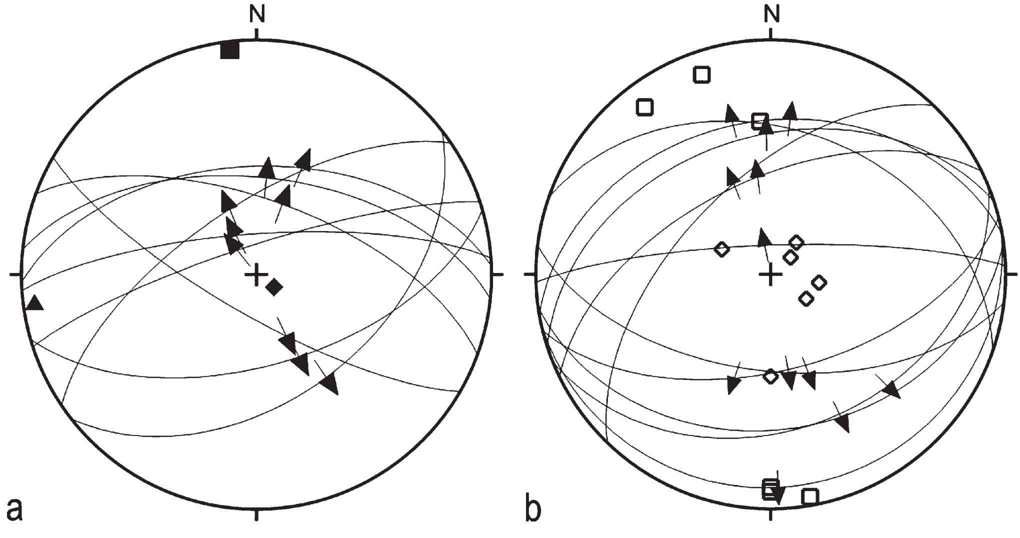

Fig. 9. (**a**) Stereographic (equal area, lower hemisphere) projection of the fault-slip data of the latest movement of the Anthemountas fault zone and the calculated stress axes σ_1, σ_2, σ_3, using the program by Duyster (1999). σ_1 (◆) = 126–82°, σ_2 (▲) = 263–05° and σ_3 (■) = 353–04°, (**b**) Stereographic projection (equal area, lower hemisphere) of the focal mechanisms of the small earthquakes that occurred along the western segment of the Anthemountas fault zone.

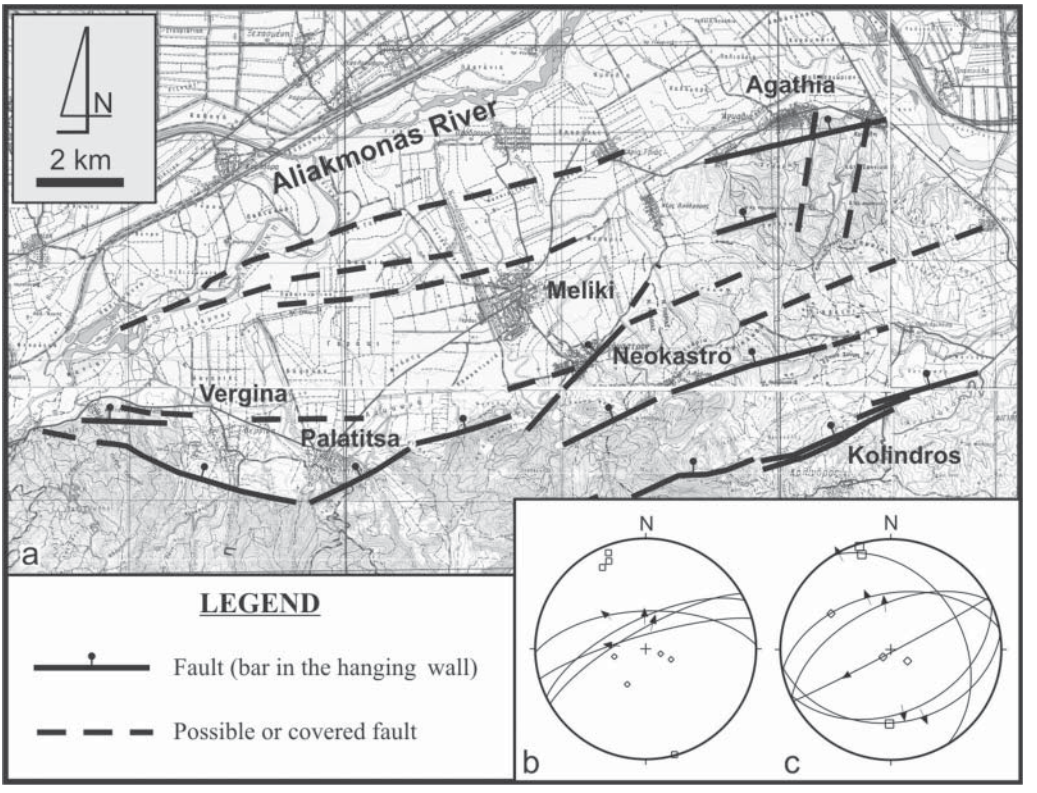

Fig. 10. (**a**) Fault map of the Northern Pieria fault zone, (**b**, **c**) Stereographic projections (equal area, lower hemisphere) of the latest movement of the zone (**b**) and the focal mechanisms that occurred along the fault zone (**c**). ◇, shortening (P) axis; □, extension (T) axis.

ENE–WSW-striking faults, to indicate oblique left-lateral normal movement. They also affect the Quaternary sediments forming isolated small faults between the NE–SW- and NNW–SSE-striking faults. In the latter case, they are steep-dipping to vertical, indicating normal movement, and possibly originated along similarly striking neotectonic joints (Tranos & Mountrakis 1998).

In general, the most numerous faults exposed in Western Macedonia are: (1) the ENE–WSW-striking Aliakmonas fault zone and the nearby east–west-striking Chromio–Vari, Pontini–Pilori and Feli faults; (2) those of the Vegoritis–Ptolemais fault system; (3) the east–west-striking Ag. Dimitrios (or Koilada–Kremasti–Kapnochori) fault. The faults in the Aliakmonas zone were investigated after the 1995 Kozani–Grevena earthquake (see Pavlides *et al.* 1995; Mountrakis *et al.* 1996*c*, 1998; Chatzipetros *et al.* 1998). The Vegoritis–Ptolemais fault system was described by Pavlides (1985) and by Pavlides & Mountrakis (1987). Here, we focus mainly on new structural and seismological data.

Aliakmonas fault zone

The 70 km long ENE–WSW-striking Aliakmonas zone consists of several subparallel faults that strike ENE–WSW to NE–SW, parallel to the River Aliakmonas (Fig. 3). These faults cut Mts Vourinos and Vermio and extend into Central Macedonia, where they join the ENE–WSW-striking Northern Pieria fault zone. The great length of the Aliakmonas zone and the linking of the recent 1995 Kozani–Grevena $M = 6.6$ earthquake with a reactivation of the fault suggests that this is the most significant fault zone in Western Macedonia. The most important segments are the Rimnio–Kentro, the Serbia–Velventos and the Polifitos–Polidendri faults.

Rimnio–Kentro fault segment. This 30 km long ENE–WSW-striking fault dips NNW and affects the Lower–Middle Miocene molasse sediments and the ophiolitic complex of Mt Vourinos.

The 1995 Kozani–Grevena earthquake was related to this fault segment. Just after the earthquake many seismic fractures along the fault were observed to cut much younger formations such as the Upper Pliocene–Pleistocene sediments that rest unconformably on the molasse. Thus, the fault has been considered ‘seismic’ (Mountrakis *et al.* 1998). It is characterized by rectilinear fault scarps, most clearly seen between Paleochori and Sarakina villages, and intense liquefaction phenomena were also observed in a broader area near Rimnio village (Pavlides *et al.* 1995; Mountrakis *et al.* 1996*c*, 1998; Chatzipetros *et al.* 1998). The latest reactivation of the fault, as defined by the slickenlines and the sense-of-slip indexes measured along its surface, suggest a normal movement defining a NNW–SSE extension axis (T) similar to that defined by the fault-plane solution of the 1995 Kozani–Grevena earthquake (Mountrakis *et al.* 1998). Towards its western end the fault splays into several smaller subparallel faults that mainly dip NNW.

Serbia–Velventos fault segment. This is 24 km long, strikes ENE–WSW and dips steeply (*c.* 60–80°) NNW, running from Rimnio to Servia village, and also probably extends eastwards as far as Velventos village. The fault forms a 10 km long rectilinear steep mountain slope about 200 m high, along which the Triassic–Jurassic marbles of the Pelagonian zone are separated from the Neogene lacustrine sediments. Because of the abruptness of the mountain slope, talus formations were also deposited, indicating recent vertical movement. Eastwards, the fault is shifted southwards beside Serbia village, where it again forms a rectilinear mountain slope. Here, the fault forms an analogous abrupt fault scarp, along which a cemented tectonic breccia is cut by corrugated slickensides that exhibit striations indicating normal reactivation. However, this fault was not reactivated during the 1995 Kozani–Grevena earthquake (Mountrakis *et al.* 1998).

Polyphytos–Polydendri fault. This 20 km long fault, which forms the easternmost segment of the Aliakmonas fault zone, cuts across the Vermio–Pieria mountain chain and reaches the Pieria fault zone to the east. On a larger scale, the fault west of Polydendri village seems to be subdivided into branches with slightly different orientations.

Closely related to the main Aliakmonas zone are three smaller faults, Chromio–Vari, Pontini–Pilori and Feli, which are found in its hanging wall. These faults strike east–west and cut Mt Vourinos, forming narrow valleys filled with Plio-Pleistocene sediments (Mountrakis *et al.* 1996*c*, 1998). Chromio–Vari is a 16 km long fault zone consisting of two parallel faults that form a right-overlapping geometry. The Pontini–Pilori fault runs close to Pilori and Pontini villages and to the east cuts across Mt Vourinos, forming a tongue filled with molasse-type sediments of Mid-Miocene age. This indicates that the fault is a pre-existing structure, which was reactivated in the Plio-Quaternary. The seismic ruptures along it during the 1995 Kozani–Grevena earthquake confirm a recent reactivation of the fault (Mountrakis *et al.* 1998).

The kinematics of these faults were described in detail by Mountrakis *et al.* (1998) as normal faults defining a NNW–SSE extensional stress regime similar to that defined by the focal mechanisms of the 1995 Kozani–Grevena earthquake sequence.

Vegoritis–Ptolemais fault system

This is 40 km long and consists of an array of NE–SW-striking (40–60°) faults that affect the pre-Alpine and Alpine basement, forming the large Neogene and Quaternary Vegoritis–Ptolemais basin (Figs 3 and 11a) (Pavlides 1985; Pavlides & Mountrakis 1987). The larger faults of this system are the SE-dipping Nimfeo–Xino Nero–Petra fault and the NW-dipping Proastio–Komnina–Mesovouni fault, believed to be the main boundary faults of the depression. Within the depression, other subparallel synthetic or antithetic faults have been mapped (e.g. the Emporio–Perdika, Chimaditis, Peraia–Maniaki and Vegora faults).

The Nimfeo–Xino Nero–Petra and Proastio–Komnina–Mesovouni boundary faults are the main faults of the system and are described below.

Nimfeo–Xino Nero–Petra fault. This is a 30 km long, NE–SW-striking fault that dips steeply SE and bounds the Ptolemais–Vegoritis depression, as it delimits the Neogene and Quaternary sediments and the pre-Alpine and Alpine basement (Mountrakis 1983). It is best exposed between Nymfeo and Aetos villages, where it forms a rectilinear mountain slope up to 400 m high, to the NE it has affected the Neogene sediments of Xino Nero village, depressing them by about 100 m (Mountrakis 1983).

Proastio–Komnina–Mesovouni fault. This 30 km long fault zone forms the southeastern borders of the Ptolemais basin and consists of two subparallel fault segments: the 10 km long Proastio

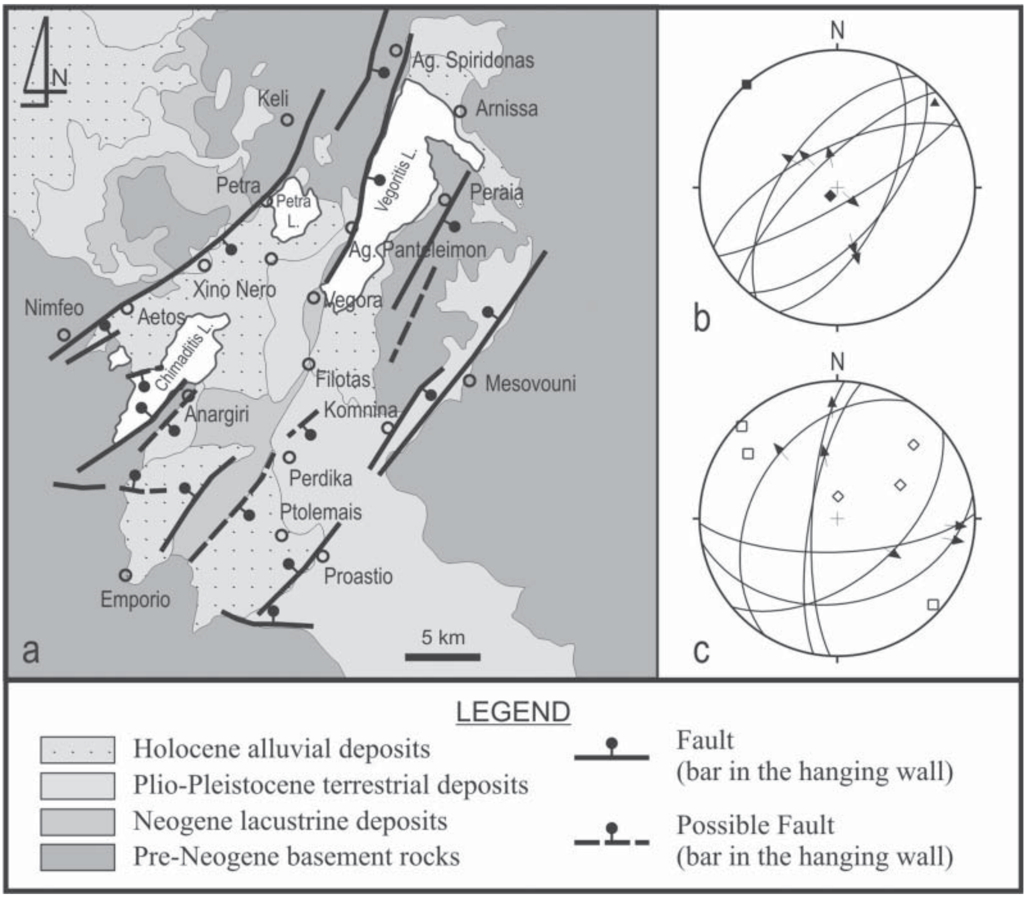

Fig. 11. (**a**) Generalized tectonic map of the Vegoritis–Ptolemais fault system, (**b**, **c**) Stereographic projections (equal area, lower hemisphere) indicating (**b**) the latest movement of the large faults of the fault system and the contemporary stress axes (◆, σ_1; ▲, σ_2; ■, σ_3) and (**c**) the focal mechanisms that occurred within or near the basin. ◇, shortening (P) axis; □, extension (T) axis. Both projections indicate the same extensional stress field with the least principal stress axis oriented NW–SE.

fault and the 20 km long Komnina–Mesovouni fault (Fig. 11a), both of which dip steeply NW. The Proastio fault mainly affects the Upper Villafranghian Proastion Formation, which consists of conglomerates, forming a rectilinear fault scarp within these sediments. The Komnina–Mesovouni fault cutting the Triassic–Jurassic Pelagonian marbles forms a narrow valley filled with Quaternary sediments.

The latest formed slickenlines and microstructures, widely accepted as sense-of-shear indicators along these faults, define an extension stress field with a NW–SE least principal stress axis (Fig. 11b). This extension is also indicated by the trend of the extension axes (T), as defined by the focal mechanisms of earthquakes that have occurred within, or close to, the Vegoritis–Ptolemais fault system (Fig. 11c), e.g. the M = 5.4 earthquake of 9 July 1984.

Ag. Dimitrios or Koilada–Kremasti–Kapnochori fault

This is an east–west-striking fault that to the south bounds the Neogene–Quaternary Kozani–Ag. Dimitrios basin; this constitute the southern part of the larger Ptolemais basin. Steep slope escarpments and a concave mountain slope characterize the fault towards the north, for a length of about 12 km. Recently formed slickenlines along the fault define a normal reactivation with a left-lateral component that exhibits a NNW–SSE to north–south extensional stress field (Fig. 12).

Discussion

Both the geological and seismological data indicate that seismic activity in Northern Greece is concentrated along normal faults of several kilometres that stand either alone or as segments of larger fault zones. In Eastern Macedonia and Thrace, the main faults are the east–west-striking Kavala–Xanthi–Komotini, Maronia–Alexandroupolis, Drama–Prosotsani, Serres–Nea Zichni and Ofrinio–Galipsos fault zones. They are typically about 30 km long, except for the 120 km Kavala–Xanthi–Komotini and the 10 km Ofrinio–Galipsos fault zones. However, the Kavala–Xanthi–Komotini fault zone is a composite of four fault segments that strike either WNW–ESE or ENE–WSW with lengths of about 30 km.

In Central Macedonia, intense recent seismicity has promoted study of the majority of the east–west-striking active faults. However, in the present work, we found that there are some other very important east–west-striking fault zones, such as the Kerkini, Anthemountas and Northern Pieria faults, that might contribute to the recent seismic activity. Several microearthquakes recorded along the Northern Pieria and Anthemountas zones indicate geometry and kinematics similar to the latest movement of these faults, indicating that both fault zones should be considered in the seismic hazard assessment of the city of Thessaloniki.

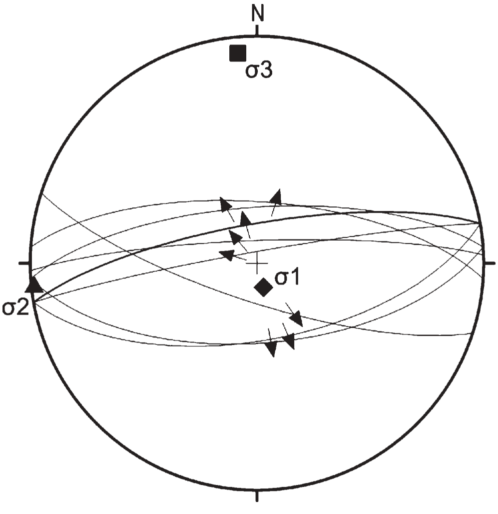

Fig. 12. Stereographic projections (equal area, lower hemisphere) of the latest movement observed along the Ag. Dimitrios or Koilada–Kremasti–Kapnochori fault. The stress field having σ_1=165–81°, σ_2=264–01°, σ_3=355–08° has been calculated using the program by Duyster (1999).

In Western Macedonia, the main active faults are the Aliakmonas fault zone and the Vegoritis–Ptolemais fault system, which strike NE–SW to ENE–WSW. The east–west-striking faults that prevail in Central Macedonia and further east are fewer and shorter in Western Macedonia. These are the Feli, Chromio–Vari, Pontini–Pilori and Ag. Dimitrios faults. However, they could also contribute to the seismic activity of the area, as indicated by the 1995 Kozani–Grevena earthquake sequence (Mountrakis *et al.* 1996*c*, 1998; Papazachos *et al.* 1998*a*).

The rupture zones in Northern Greece require re-examination in the light of new data concerning the active faults and the surprisingly low recent seismicity. Thus, we try to estimate the expected magnitude of an earthquake using the scaling law suggested by Papazachos (1989) for the region of Greece. The fault length (L) can be related to the magnitude (M) of the earthquake by the equation.

$$\log \mathrm{L} = 0.51\mathrm{M} - 1.85. \qquad (1)$$

Thus, taking into account the 30 km length of the ruptures in most fault zones, we estimate a maximum probable earthquake magnitude of 6.5. The few strong earthquakes that have been reported in the region of Eastern Macedonia–Thrace, for example the 1784 Komotini earthquake (M = 6.7), correspond to this rupture length. However, several of the 30 km long fault zones of Serres–Nea Zichni and Drama–Prosotsani consist of fault segments of *c.* 10 km length, similar to the length of Ofrinio–Galipsos fault zone. In this case, the maximum expected earthquake magnitude is 5.6.

Recent results (Papazachos *et al.* 2006) show that for events in the range M = 6.0–7.5 (including the faults studied here) the surface length is on average 30–50% smaller than the true subsurface length. This indicates that the maximum probable magnitude can be up to 0.4 units larger that estimated from the observed fault length using equation (1). However, the fault structures studied here are well developed and in most cases correspond to faults that have been reactivated several times, thus revealing the total subsurface length on the surface. As a result, application of equation (1), where L represents the observed fault length, should not lead to a systematic underestimation of the maximum probable earthquake magnitude for these faults.

The earthquake magnitudes to be expected from reactivation of the Kerkini and Anthemountas fault zones, which consist of segments varying from 18 to 24 km and from 20 to 30 km, respectively, are 6.0–6.3 for the former and 6.2–6.5 for the latter. If the entire 45 km long Kerkini fault zone ruptured, the fault magnitude there could reach 6.8. Such magnitudes are in good agreement with those of several strong historical earthquakes in Central Macedonia (Papazachos & Papazachou 2003), particularly along the Serbo-Macedonian massif during the instrumental era, with the latest being the 1978 Thessaloniki earthquake of M = 6.5. The total rupture of the 20 km long Northern Pieria fault zone could produce an earthquake of up to M = 6.2, but ruptures of its 10 km long fault segments are more likely, which would produce earthquakes of magnitude not exceeding 5.6.

In Western Macedonia, although the Aliakmonas fault zone and the Vegoritis fault system have been more or less modified by the recent stress regime, these are the main structures along which the recent seismic energy is concentrated. The 1995 Kozani–Grevena earthquake of M = 6.5 was caused by the reactivation and rupture of the 30 km long part of the total 70 km long Aliakmonas fault zone. Taking into account the 30 km length and using equation (1), we estimate a magnitude of 6.5, similar to that of the 1995 earthquake.

The Vegoritis–Ptolemais fault system appears to differ from the others described above, in which the strain is localized longitudinally. All the faults in this system exhibit recent activity, similar geometric or kinematic characteristics, and similar morphotectonic features. It thus seems that the strain is not concentrated along the NE–SW-striking boundary faults, but is distributed among most of the faults in the system. The earthquake magnitude to be expected from reactivation of the Vegoritis–Ptolemais faults, whose lengths vary from 10 to 30 km, could be 5.6–6.5.

Conclusions

The large fault zones of Northern Greece are the 70 km long Aliakmonas zone in Western Macedonia, the Southern Mygdonia and Kerkini fault zones in Central Macedonia, and the Kavala–Xanthi–Komotini fault zone in Eastern Macedonia and Thrace. These faults bounded and influenced the late Tertiary basins of Northern Greece and show clear evidence of Neogene tectonic movements and, therefore, could be considered as pre-existing large structures. These inherited structures were reactivated as normal faults in Quaternary–Recent times, producing the historical and recent earthquakes.

On a very large scale, the fault zones are interlinked and delineate major tectonic structures. One such major tectonic structure is that formed by the linkage of the NE–SW-striking Aliakmonas and the east–west-striking Kavala–Xanthi–Komotini fault zones, which form en echelon bridge structures through the east–west- to WNW–ESE-striking Northern Pieria, Anthemountas, Southern Mygdonia and Sochos fault zones. Another characteristic, although interrupted, structure of the same type is that formed by the Kerkini, Northern Almopia and Vegoritis fault zones. These inherited major structures, along which strike-slip slickenlines have been recorded, could initially represent indent-linked strike-slip faults, similar to those that characterize the brittle deformation of intracontinental regions (Woodcock 1986; Woodcock & Schubert 1994). This hypothesis is supported by the following: (1) late- to post-orogenic brittle deformation related to large strike-slip faults has been reported in Western Macedonia, e.g. in the Mesohellenic Trough (Doutsos 1994; Zelilidis *et al.* 2002; Vamvaka *et al.* 2004), in Thessaly (Mountrakis *et al.* 1993), and in Central Macedonia and Eastern Macedonia–Thrace (Pavlides & Kilias 1987; Tranos 1998; Tranos *et al.* 1999); (2) most of these fault zones exhibit strike-slip movements that precede normal reactivations (Pavlides & Kilias 1987; Tranos 1998; Tranos *et al.* 1999; Mountrakis & Tranos 2004; Tranos & Mountrakis 2004); (3) most of the fault zones bound older late Tertiary sediments; (4) they do not represent neotectonic faults related to the contemporary stress regime, as they do not reveal a single uniform reactivation, but are instead inherited structures related to the general fault pattern of the area; (5) the maximum extension defined by the focal mechanisms and the fault-slip data varies even in adjacent areas, and seems to be related to the orientation of the inherited older structures.

The stress regime in Northern Greece is extensional with the least principal stress axis (σ_3) oriented north–south during the Quaternary. However, a significant variation around this orientation is well known from both earthquake focal mechanisms (Figs 2 and 3) and fault-slip data (Fig. 3). In Eastern Macedonia and Thrace focal mechanisms are too few to precisely define the trend of the extension axes. However, such fault-slip data as have been obtained from the active faults show that the extension in the area trends from NNW–SSE (340°) to NE–SW (40°). In Central Macedonia focal mechanisms are more numerous and indicate that the commonest trend of extension is NNW–SSE (*c.* 355°), although the extension axes (T) reveal a significant variation around this trend even in adjacent areas. This change of trend of extension, as mentioned by Le Pichon *et al.* (1982) and others (Pavlides 1985; Mercier *et al.* 1987, 1989; Papazachos *et al.* 1992, 1998*b*; Papazachos & Kiratzi 1996; Tranos & Mountrakis 1998), has been confirmed. This swing of the extension in Central Macedonia and Eastern Macedonia–Thrace is also shown by the present fault-slip data, although with a much smaller variation than that obtained using earthquake focal mechanisms. In Western Macedonia, the trends of the extension, as defined by the focal mechanisms and the fault-slip data, are concentrated along NW–SE to NNW–SSE orientations. As a result, a change in the trend from Eastern Macedonia–Thrace to Western Macedonia is well established, but this change concerns the near-stress field imposed by the geometry of the large inherited faults. Although the origin of this change in trend could be attributed to the tectonic stresses related to the arc-shape of the Hellenic subduction zone, we suggest that fault pattern variations as determined by the large inherited fault zones that transect the region of Northern Greece are in fact the most influential factor in this change. A similar swing of the trend of the least principal stress axis (σ_3) has also been defined in Northern Greece from the neotectonic joints, and has also been attributed to the pattern of fault differentiations (Tranos & Mountrakis 1998; Tranos 1998).

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