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Extensional tectonics of northwestern Macedonia, Greece, since the late Miocene

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Abstract—Tectonic field studies in the Florina-Ptolemais basin (northwestern Greece) were carried out in an attempt to define the regional stress tensors in selected areas affected by Neogene and Quaternary faulting, using recently proposed quantitative methods. The analysis allows us to distinguish two extensional phases in the area: a late Miocene–Pliocene one with a NE–SW average direction of extension; and a Pleistocene–Recent one with a NW–SE direction of extension. We conclude that the principal stress axes σ_2 and σ_3 were interchanged in passing from one phase to the other. These results are reasonably consistent with results of studies carried out in other parts of the Aegean area, especially the south Aegean back-arc domain.

INTRODUCTION

A NEW interpretation of the neotectonics of the Aegean region has been developed from numerous recent local (Mercier *et al.* 1979, Angelier 1979a, Jackson *et al.* 1982) and regional (McKenzie 1978, Dewey & Sengör 1979, Le Pichon & Angelier 1979, Mercier 1981, Jackson & McKenzie 1983, Lyberis 1984) studies. According to the converging views of these workers, the Aegean region and surrounding areas (Hellenic back-arc area, central-northern Aegean and the greater part of continental Greece and West Turkey) have been subjected to widespread extensional tectonism since the middle or late Miocene (Serravallian–Tortonian) (Le Pichon & Angelier 1979). The principal manifestation of this is the large-scale normal faulting in the area. However, the neotectonic and seismotectonic evidence for extension in the north Aegean is not fully explained by the subduction of the Mediterranean plate beneath the Aegean plate, because the subducted slab does not extend beyond the active volcanic arc of the South Aegean.

The area of the present study is located in northwestern Macedonia (northern Greece) near the Greek–Yugoslavian border, between the outer compressional zone and the inner extensional zone of the greater Aegean area. This region and surrounding areas (continental northwestern Greece, southern Yugoslavia and eastern Albania) have been less well described and understood from the tectonic point of view, than the rest of the Aegean domain and western Turkey (McKenzie 1978). For northwestern Greece and Albania in particular, where both thrust and normal faults exist, McKenzie (1978) suggested the concept of mantle 'blobs' (cold mantle detaching from the lower half of the lithosphere) in order to give an initial explanation for the tectonism of the area.

In this paper we present some field observations on late Miocene–Pliocene and Quaternary tectonic features in the Florina-Vegoritis-Ptolemais Graben (northwestern Macedonia) and attempt to determine the mean principal stress directions by tectonic analysis of fault populations using the methods proposed by the 'French school of neotectonics' (Carey & Brunier 1974, Mercier 1976, Angelier & Mechler 1977, Carey 1979, Angelier 1979b, 1983). Our purpose is to provide new data on the tectonics of this part of the greater Aegean area and to contribute to an understanding of the geotectonic regime.

GEOLOGY OF THE STUDIED AREA

Field observations on faulting, geomorphology and stratigraphy have been carried out mainly in the Florina-Vegoritis-Ptolemais Graben (Fig. 1). This is a large basin, filled with Neogene–Quaternary sediments, which has developed between the mountains of Voras-Vernon to the east and Vermion-Askio to the west, and extends from the Bitola plain (Yugoslavia) in a SSE direction to the hills of the Kozani area. It is almost 100 km long and about 15–20 km wide.

The pre-Neogene rocks of the basin and the surrounding area belong to the North Pelagonian geological zone, which consists of Palaeozoic metamorphic rocks (the crystalline basement), Mesozoic carbonate cover and ophiolites. The metamorphic rocks and the Mesozoic cover of Mt Voras form a megascopic anticlinal dome whose axis plunges gently SE, and the rocks of Mt Vernon form thrust sheets emplaced westwards. This megastructure is the result of two folding phases which acted during the Tertiary (late Eocene to early Miocene) (Mountrakis 1982, 1984).

The Neogene–Quaternary sediments, which fill the basin, overlie unconformably both the Palaeozoic metamorphic rocks and the Mesozoic crystalline limestones and can be divided into three lithostratigraphic formations as follows. The lowest, known mainly from boreholes and a few outcrops (e.g. at Vegora), consists of basal conglomerates, containing pebbles of metamorphic rocks, which pass transitionally upwards into

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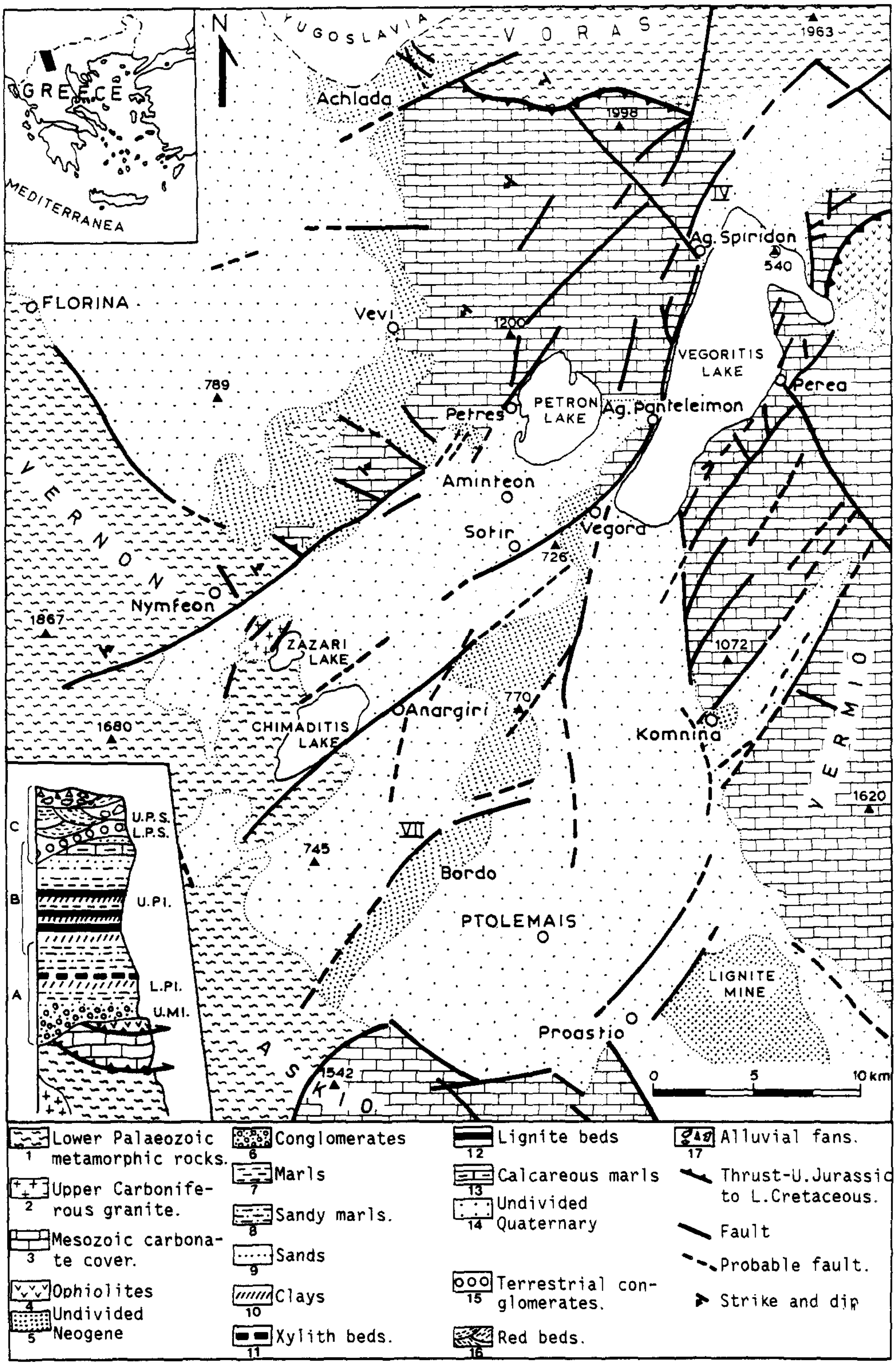

Fig. 1. Tectonic map and stratigraphic section of the Florina-Vegoritis-Ptolemais region (northwestern Macedonia, Greece). A, B, C, are lithostratigraphic Neogene–Quaternary formations (see detailed description in the text). U.P.S., Upper Pleistocene Series; L.P.S., Lower Pleistocene Series; U.Pl., Upper Pliocene; L.Pl., Lower Pliocene; U.Mi., Upper Miocene. Units 6–13 are of Neogene age and units 14–17 are of Quaternary age. Data concerning marginal bedrock have been taken from Brunn (1982) and Mountrakis (1984). Fault lines have been completed or re-estimated on the basis of LANDSAT and aerial image analysis as well as on new field observations.

marl, sandy marl, sand, clay and lignite (xylith type) layers. The age of this formation has been defined by fossils as late Miocene (Pontian *sensu lato*) to early Pliocene (Velitzelos & Petrescu 1981).

The middle formation is argillaceous and contains some thick lignite beds, which are under continuous and intensive exploitation. The lignite beds alternate with clays, marls, sandy marls, sands and lacustrine calcareous marls. Pollen analysis and a microfauna study (Van de Weerd 1979, Ioakim 1984) have given an early Ruscinian age for the lower members of the formation and a late Ruscinian one for the upper beds (Koufos

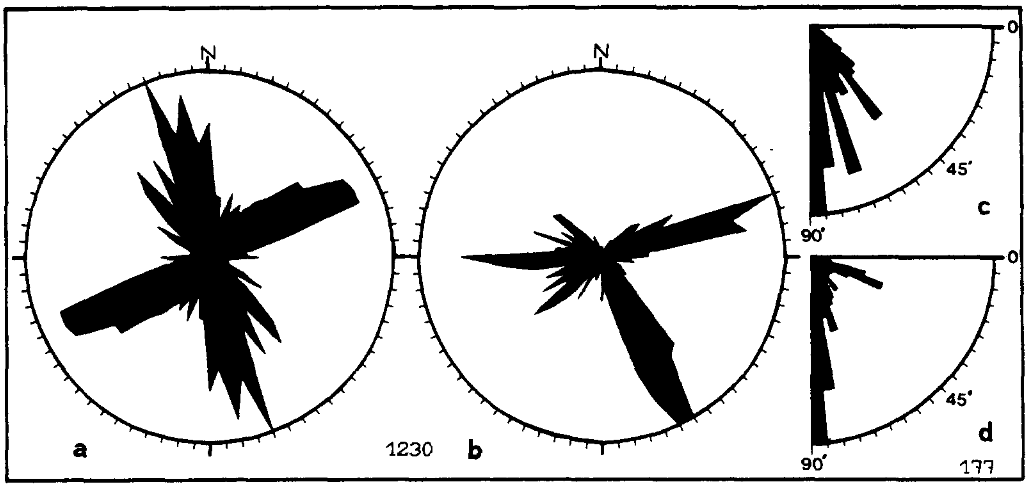

Fig. 2. Distribution in the Florina-Ptolemais area of Late Cainozoic fault strikes (a); dip directions (b); dips (c); (1230 measurements); and pitches of striations (d); (177 measurements). (a) and (b) are rose diagrams graduated in 5° intervals; (c) and (d) are circular histograms, labelled in degrees.

1982). Thus the middle formation is considered to be of Pliocene age (MN-14, MN-15 and MN-16?, European mammalian zone classification, Mein 1975).

The upper formation consists of terrestrial and fluvioterrestrial conglomerates, and lateral fans and alluvial deposits, and represents the Quaternary sedimentation in the basin according to macrofaunal evidence.

The rocks of all three formations are of continental origin and were mainly deposited in a lacustrine environment, so dating the tectonic events is less precise than in the rest of the Aegean region, where the equivalent formations are mainly marine.

Geomorphologically, the principal large basin of Florina-Ptolemais is subdivided by ridges and hills into several sub-basins trending NE–SW, almost perpendicular to the main direction of the large basin. These features, as well as the symmetrical position of the four lakes in the area (Vegoritis, Petron, Zazari and Chimaditis), are tectonically controlled. Some very important normal faults, striking NE–SW and up to 30 km long, created the sub-basins in Quaternary times as will be shown below.

Numerous large normal faults cut both the pre-Neogene formations and the unconformably overlying Neogene–Quaternary sediments. Statistical analysis of the strikes of 1230 faults (mesostructures) measured in the Florina-Ptolemais basin and its margins showed two main fault systems in the area, the first with a NW–SE strike and the second with a NE–SW strike (Fig. 2). Most of these faults exhibit clear dip–slip movements. As the geological map (Fig. 1) suggests, the large NW–SE normal faults are difficult to locate as they are covered by the sediments of the basin and can be detected mainly by boreholes, whereas the NE–SW faults appear to dominate the area and control its structure and geomorphology. Some of the largest faults in the area are (Fig. 1): (a) Petron-Nymfeon, which strikes N30°E, dips SE and is more than 30 km long; (b) the main Vegoritis fault, which strikes N40°E, dips SE, crosses the villages of Ag. Spiridon, Ag. Panteleimon and Vegora, and is about 20 km long; (c) Chimaditis-Anargiri, which strikes N30°E, dips NW and is more than 10 km in length; and, finally, (d) the group of parallel NE–SW normal faults of the Mt Vermio-Komnina valley and Ptolemais-Proastio subsidence, which extend for over 50 km.

Field observations show that the faults affecting the Neogene–Quaternary sediments of the basin coincide with or have similar directions to the faults affecting the pre-Neogene rocks, mainly the Mesozoic limestones of the basin margins. Figure 3 shows such an example in the Komnina valley. Some of the normal faults affecting the Mesozoic limestones and Palaeozoic metamorphic rocks of the basin margins, continue into the basin sediments. They were initially created during pre-Neogene times (Mountrakis 1982, 1984) and were probably reactivated by the neotectonic deformation. Thus, we can conclude that the neotectonic faults observed in the sediments of the basin follow pre-existing structures.

TECTONIC ANALYSIS OF FAULTS

An attempt was made to determine the stress pattern of the area by microtectonic analysis, and to define mathematically the main characteristics of the stress tensor from conjugate or semi-conjugate fault populations. The methods used have been presented and described in detail by Carey & Brunier (1974), Carey (1979), Angelier & Goguel (1979), Angelier (1979a,b) and attempts have been made to improve them using computer-based inversion processes (Etchecopar *et al.* 1981, Angelier *et al.* 1982, Michael 1984). The methods have also been extended to apply to earthquake focal mechanisms (e.g. Gephart & Forsyth 1984).

The theoretical basis of the method was first given by Bott (1959). For a highly fractured medium where deformation takes place by small displacements of rigid blocks along pre-existing fault-planes, the assumption has been introduced that the slip marked by striations is parallel to the tangential stress applied to each fault. This

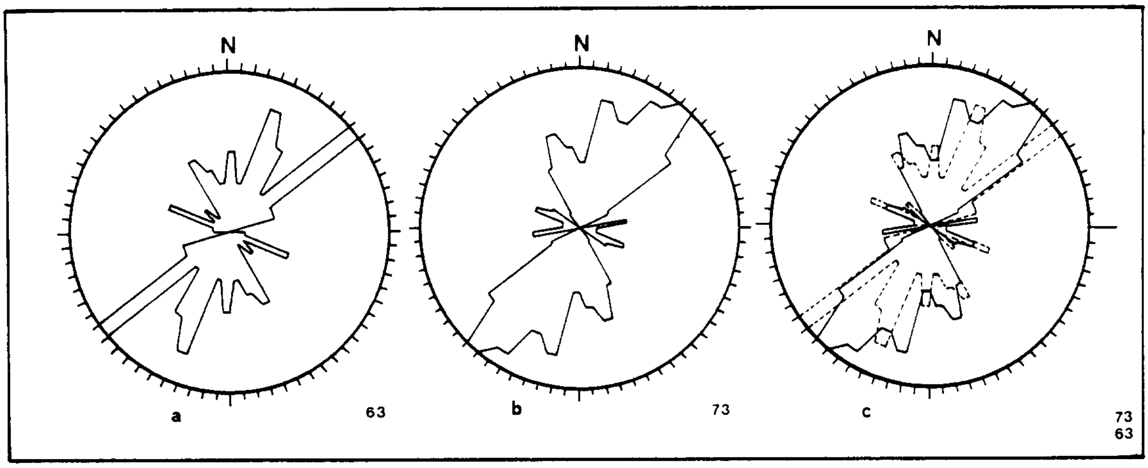

Fig. 3. Rose diagrams of fault strikes in the Komnina valley. (a) Faults observed only in the marginal limestones (63 measurements). (b) Faults affecting only the Plio-Pleistocene sediments of the valley (73 measurements). (c) The two sets of data combined.

assumption is valid only if all the slip events are independent and represent the same stress tensor; that is the studied fault population corresponds to a single tectonic event, governed by a single regional stress tensor (Angelier 1979b). Field measurements include strikes and dips of a population of fault planes and the pitches of the striations on them.

These methods have been applied, and the limitations established, in numerous field studies, particularly in Greece, by the above mentioned workers and other investigators (e.g. Mercier *et al.* 1979, 1983, Lyberis *et al.* 1982, Angelier *et al.* 1982, Lyberis 1984).

To calculate the mean stress axis we use here a numerical procedure which minimizes the function (Angelier 1977, 1979a),

$$F = \sum_{k=1}^{k=N} (s_k, \tau_k)^2,$$

or for very small angles

$$F = \sum_{k=1}^{k=N} \sin^2 \left(\frac{s_k, \tau_k}{2} \right),$$

where N is the number of measured faults (local population), s is the unit vector in the direction of the observed striation and τ is the tangential stress vector resolved on the fault plane (Fig. 4).

The results of our microtectonic analysis of recent fault movements, concentrated in the young sediments of the basin, have been thoroughly checked for agreement with the geometry and senses of neotectonic movement on the major faults of the area, which control the large-scale topography and tectonics of the region.

We measured more than 200 striated faults, in 12 independent groups and at 10 sites, in the Plio-Pleistocene sediments and in the Mesozoic limestones of the basin margins. The results of the computations are shown in Table 1 and Fig. 5 and are significant for understanding the neotectonic evolution of the area.

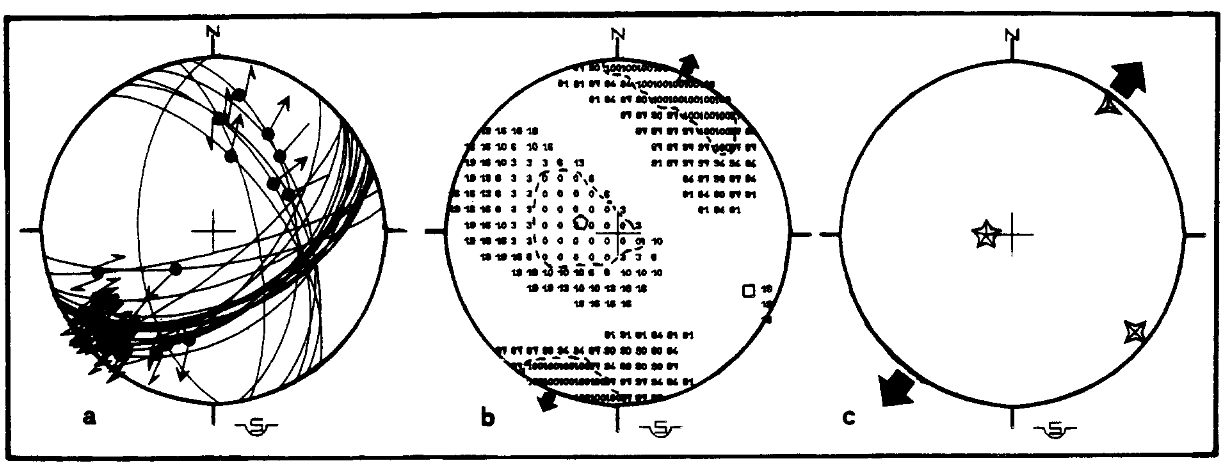

Fig. 4. Local fault populations of the Florina-Ptolemais area analysed by Angelier's methods (1979a,b, 1983); equal-area lower hemisphere projections (N = North). (a) Measured fault planes as great circles and striations as arrows. (b) Application of the right dihedrons method (Angelier & Mechler 1977), indicating common directions of compression (lower frequencies) and extension (higher frequencies). Barycentres of confidence regions are pentagons for compression, squares for intermediate, and triangles for extension axes. (c) Determination of principal stress axes by computing the 'mean stress tensor'; σ_1 is shown as a five-branch star, σ_2 as a four-branch star and σ_3 as a three-branch star, where σ_1 is maximum compressive stress, σ_2 intermediate and σ_3 minimum stress. Large solid arrows indicate the direction of extension (site IVb).

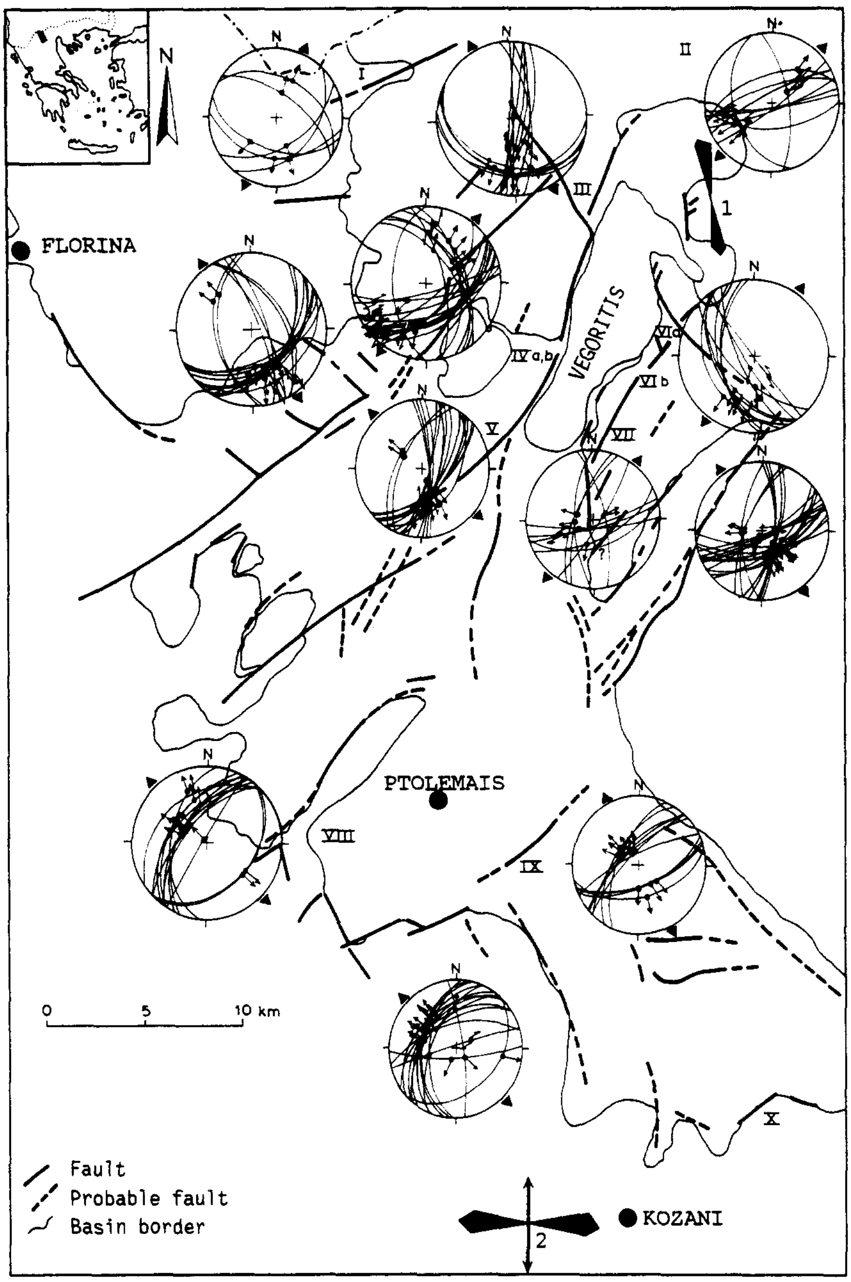

Fig. 5. Neotectonic map of the area studied, including the sites of field observations, the equal-area projections of measured striated faults and the resulting directions of extension indicated by arrows. Large black arrows (sites 1 and 2) show the orientations of the minimum principal horizontal stress after *in situ* measurements.

Table 1. Summary of the results of the tectonic analysis for northwest Macedonia. See maps of Figs. 1 and 5 for village names and sites (columns 2 and 3). No. obs. = number of measured striated faults. N designates a normal fault mechanism. The last column indicates the quality of the computed fault mechanism, which mainly depends on the geometry of the tectonic elements (A, excellent; B, good; C, poor)

No.	Region	Site	Co-ordinates	No. Obs.	Azimuth and plunge of stress axes (degrees) σ_1		σ_2		σ_3		Mechanism	Direction of extension	Quality
1	Achlada	I	40°51′–21°37′	6	253	80	122	7	31	8	N	NE–SW	B
2	NE of Vegoritis	II	40°50′–21°56′	10	301	86	131	4	41	1	N	NE–SW	B
3	N of Ag. Panteleimon	III	40°47′–21°45′	13	189	52	71	19	329	31	N	NW–SE	A
4	Ag. Panteleimon	IVa	40°43′–21°44′	18	217	62	65	25	329	11	N	NW–SE	A
5	Ag. Panteleimon	IVb		32	268	78	128	9	37	8	N	NNE–SSW	A
6	Vegora	V	40°41′–21°43′	23	229	53	22	34	121	13	N	NW–SE	A
7	Perea	VIa	40°45′–21°50′	39	107	88	234	1	324	2	N	NW–SE	A
8	Perea	VIb		10	71	51	312	22	208	31	N	NE–SW	C
9	Maniaki	VII	40°41′–21°47′	10	326	77	138	13	228	2	N	NE–SW	B
10	Bordo hill	VIII	40°32′–21°37′	14	67	63	211	22	307	14	N	NW–SE	B
11	Ptolemais	IX	40°29′–21°43′	14	172	71	68	5	336	19	N	NNW–SSE	A
12	Kozani	X	40°20′–21°49′	17	222	80	46	10	316	1	N	NW–SE	B

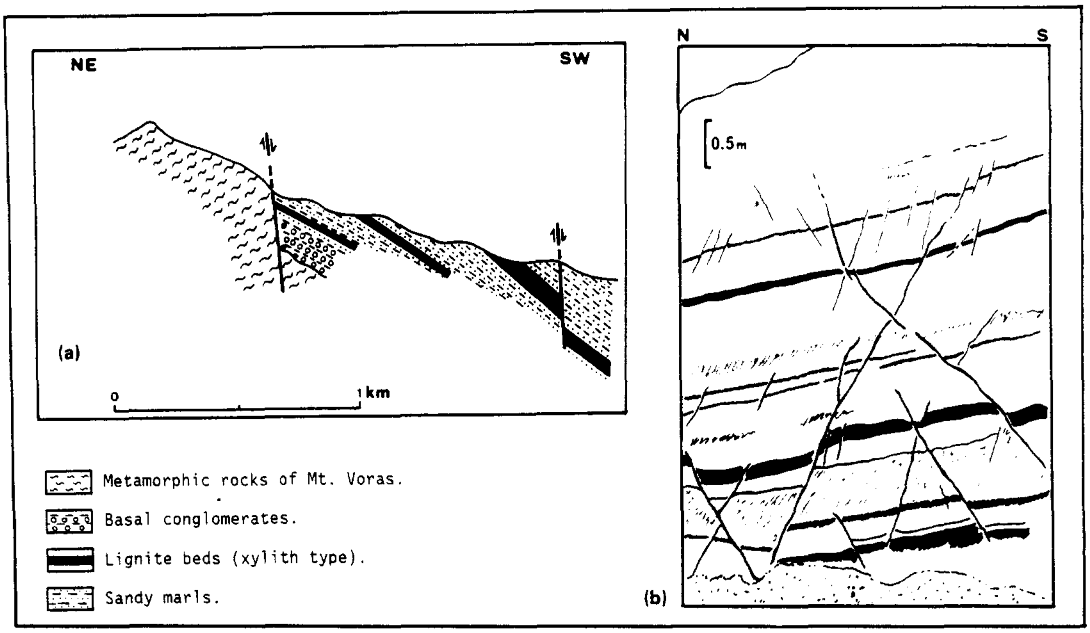

Fig. 6. Sketches from field observations. (a) Cross-section of the Achlada lignite mine (site I) including two of the measured faults (modified scheme from Maratos 1960). (b) Conjugate group of small normal faults in the Pliocene marls and lignites of the Ptolemais mine (site IX). Note the X pattern formed by crossing conjugate faults.

The critical observations which led to the determination of the age of the faulting are as follows.

(1) Six striated faults were observed in the lignite mine of the village of Achlada, a few hundred meters from the Greek–Yugoslavian border (Fig. 6). They strike mainly NW–SE to E–W and affect only the sediments of the first (lower) formation (Upper Miocene–Lower Pliocene).

(2) Successive fault movements were inferred from limestone slickensides (73 measurements) along the main Vegoritis fault (in the villages of Ag. Spyridon and Ag. Panteleimon) at the foot of Mt Voras (sites II, III and IV, Table 1). Two superimposed sets of striations were noted. Although not accurately dated, their chronological order was established by the superposition of slickensides on fault planes and by the development of tectonic striations on thin calcite fillings of faults. Only the relative ages of the latest fault reactivations can be discerned by this means.

The key to an approximate absolute chronology lies in movement along the main fault of the Vegoritis graben where it extends into the sediments of the Ptolemais basin, cutting all the Neogene and Lower Quaternary formations (site V, Table 1). The fault affects the total thickness of the Upper Miocene–Lower Pliocene and Pliocene layers (lower and middle formations), and the Quaternary conglomerates (Upper Villafranchian). The latter are well dated because they include a vertebrate fauna (Velitzelos & Schneider 1973).

(3) There is evidence of recent tectonic movements along the fault zone on the southeastern side of Lake Vegoritis (site VIa, Table 1). The relative age of faulting was mainly established by the superposition of slickensides. The very thin striations on some polished fault surfaces clearly show the most recent tectonic event to have involved normal movement. These fault surfaces are covered by unconsolidated terrestrial material, probably of Würmian or Post-Würmian age, which seems to be affected by some very small NE–SW faults, as a result of very recent reactivation of the major fault.

Evidence of earlier tectonic events is found in the same area (sites VIb and VII, Table 1) and also of the younger tectonic movement in the Kozani area (site X, Table 1) in the southern part of the basin.

(4) Consolidated Upper Pliocene and Lower Pleistocene dunes are often faulted. For example, some striated normal faults were measured on the Bordo hill (central part of the Ptolemais basin), as well as on the ridge at the Ptolemais lignite mine, indicating Quaternary tectonic events (Table 1, sites VIII, IX, Fig. 6). In addition to being deformed on a broad scale, the terraces of the basin are cut by faults which are generally normal and strike NE–SW and which created alluvial terraces of late Quaternary age. Also the young ridges and subbasins trend in the same direction, providing additional evidence for the late Quaternary tectonism.

Thus, taking into account both the geometry of the fault pattern and the chronology of events established for the Vegoritis-Ptolemais basin, we must conclude that the development of the basin had begun prior to the late Miocene. Also the fault geometry and calculated fault mechanisms allow us to deduce the existence of large scale extensional tectonism in the area since the late Miocene at least. From the analyses of fault groups (fault mechanisms of Table 1) and slickenside lineations we have reconstructed the orientations (trends and plunges) of the principal stress (or strain) axes. The main result is that there were two different extensional phases in the area (Figs. 5 and 7).

CONCLUSIONS

Taking into account both the age of the earliest deposits in the basin and the known age of onset of

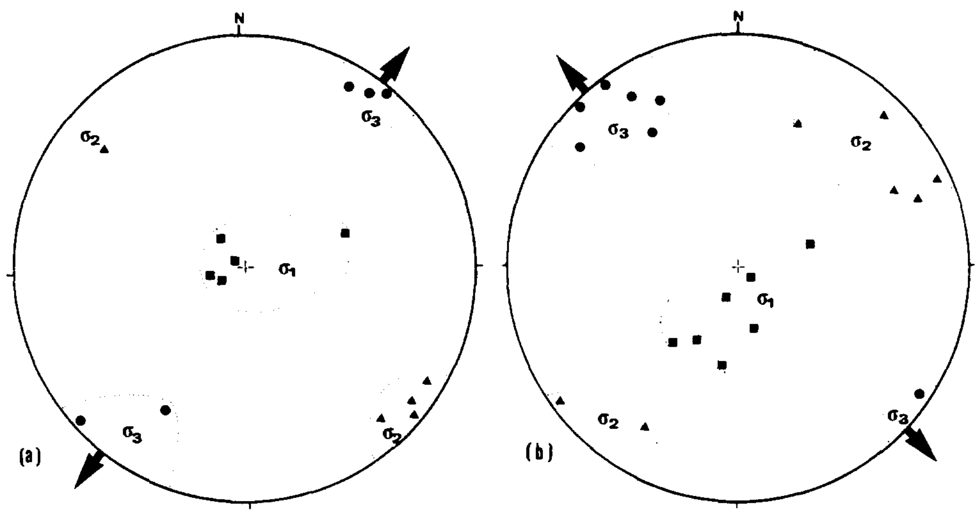

Fig. 7. Equal-area (lower hemisphere) projections of the principal stress axes (σ_1, σ_2, σ_3) computed from local fault data from the Florina-Ptolemais area (given in Table 1). (a) Stress axes of the late Miocene–Pliocene tectonic phase. (b) The corresponding phases for the Quaternary period.

neotectonic activity in the greater Aegean area (Drooger & Maulenkamp 1973, Angelier 1979a, Le Pichon & Angelier 1979), a post-Middle Miocene age could be considered as the most acceptable one for the initial creation of the Florina-Ptolemais basin. The chronology of faulting was established mainly by using stratigraphic data of the basin sediments, as well as by taking into account geomorphological and structural criteria for successive fault movements. The first significant point is that west Macedonia (Greece) is under widespread extension, which is related to normal block-faulting and which has operated since the late Miocene.

Using the methods of quantitative stress analysis of 'right-dihedrons' and 'mean stress tensor' (Angelier 1979a,b, 1983), and assuming that the stress tensor is nearly constant for all events in the same tectonic phase, it was possible to provide a quantitative interpretation in terms of stresses from the striations observed on the fault planes. At least two extensional phases have been distinguished. The first, acting during the late Miocene–Pliocene, involved NE–SW extension; the tensional axes (minimum principal stress σ_3) are almost horizontal and trending NE–SW, the compressional axes (maximum principal stress σ_1) are vertical and the intermediate axes (intermediate principal stress σ_2) trend NW–SE. The second phase is of Quaternary age and involved NW–SE extension; the tensional axes (σ_3) are almost horizontal and trending NW–SE, the compressional axes (σ_1) are almost vertical and the intermediate axes (σ_2) trend NE–SW.

These results are in close agreement with those of Mercier *et al.* 1979, Angelier 1979a, Angelier *et al.* 1981 and Lyberis 1984, for other parts of the Aegean area.

It is worth noting that the positions of the σ_2 and σ_3 axes were interchanged when the stress field changed, while the compressional axes remained vertical (Fig. 7).

The Quaternary stress pattern in the Florina-Ptolemais basin is comparable to the pattern of active stresses (*in situ* stress measurements, Paquin *et al.* 1982) in the same area (Fig. 5). Thus, a stress field could be proposed for west Macedonia based on our neotectonic data and on *in situ* stress measurements.

Another interesting point is that the Quaternary tectonism is still active today, as indicated by recent sediments being affected by the newest faults, although no significant historical earthquakes are known in the area or have been recorded instrumentally.

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