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Structural characteristics of two strong earthquakes in the North Aegean: Ierissos (1932) and Agios Efstratios (1968)

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Abstract—Structural analysis has been carried out on the volcanics of the island of Agios Efstratios and along the highly faulted zone of SE Chalkidiki, south and north of the North Aegean Trough, respectively (northern Greece). The areas have been affected by strong earthquakes and a comparison is made between the available structural and seismological data, together with new seismotectonic information. At Agios Efstratios, the earthquake of 1968 (M7.1) occurred on a principal displacement zone with dextral strike-slip movement, while the fault geometry of the whole area supports the view of transtensional deformation. The strong (M7.0) earthquake of 1932 at Ierissos was directly connected with an E–W-trending normal fault. Striations on the seismic fault surfaces and the corresponding fault mechanism indicate a N–S direction of active extension. The hangingwall is also affected by smaller antithetic E–W- and NW–SE-trending structures.

INTRODUCTION

The North Aegean Trough and its vicinity is one of the most seismically active areas in Greece. It is characterized by intense shallow earthquakes with magnitudes up to 7.5, many of which can be directly connected with pre-existing geological faults. Surface faulting during large shallow earthquakes is more widespread than has previously been recognized, while seismically active faults are connected with physiographic features of late Cenozoic and more specifically Quaternary displacements. For these reasons a detailed study of seismotectonic information concerning surface phenomena (seismic fault traces, scarps, etc.), fault geometry, kinematics and hangingwall deformation has been made for two poorly studied strong and destructive earthquakes in the vicinity of the North Aegean Trough. They are the 1932 (M7.0) Ierissos, Chalkidiki, earthquake in the Serbomacedonian zone, and the 1968 (M7.1) earthquake on the island of Agios Efstratios (northern Aegean) (Fig. 1).

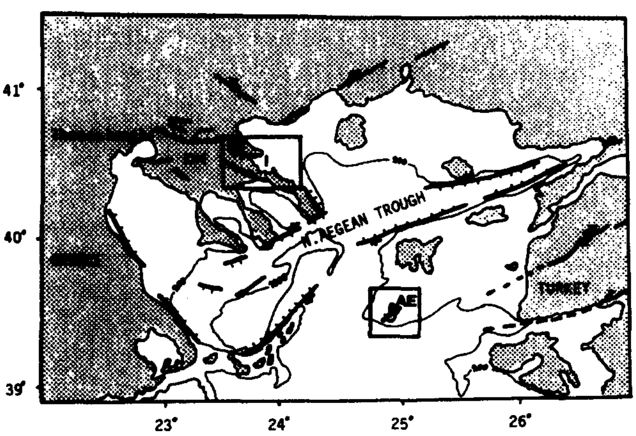

Fig. 1. A map of the northern Aegean, showing the study areas (in boxes) and the main structures (heavy lines). AE: Agios Efstratios island. CH: Chalkidiki peninsula. I: Ierissos town. ST: Stratoni Fault.

IERISSOS, CHALKIDIKI, EARTHQUAKE OF 1932

Geological and seismological information

The earthquake occurred in the southeastern part of the Chalkidiki peninsula (northern Greece). The area belongs to the Serbomacedonian zone, an old massif affected by pre-Alpine and neotectonic deformation. The zone comprises Paleozoic or older metamorphic rocks, Tertiary igneous rocks (granites, quartz–diorite porphyries, etc.) and a few exposures of post-Alpine sediments. The post-Alpine sediments are mainly in the hangingwall of the Stratoni Fault (i.e. Ierissos area) and include upper Miocene–lower Pliocene lacustrine limestones and red clays, sands and marls (Syrides 1989), as well as some conglomerates of Pleistocene age.

Neotectonic and active faults are oriented mainly in three directions (E–W, NW–SE and NE–SW) and generally show extensional features. The E–W-trending faults are pure dip-slip structures, while the NW–SE ones are oblique-slip faults with sinistral component and dominate the area (Pavlides & Kilias 1987). The wider area is seismically active; within the past 100 years, five disastrous (M6.5–7.5) earthquakes occurred along the zone in 1902, 1905, 1931, 1932 and 1978, at least two of which were associated with prominent surface faulting, the 1932 Ierissos (M7.0) (Floras 1933, Maravelakis 1933, Georgalas & Galanoloulos 1953) and Thessaloniki 1978 (M6.5) shocks (Papazachos *et al.* 1980).

On 26th September 1932 at 19:20:42 GMT, a very strong surface shock destroyed the town of Ierissos and nearby villages (latitude 40.5°N, longitude 23.9°E). The only known shock which could be considered as a foreshock was the event of 23rd April 1932 (M5.0), which was located about 45 km NW of the epicenter of the main shock. A series of aftershocks followed, the three strongest of them (M6.0, 5.7 and 6.2) occurred in 4 days between 26th and 29th of September, while a large

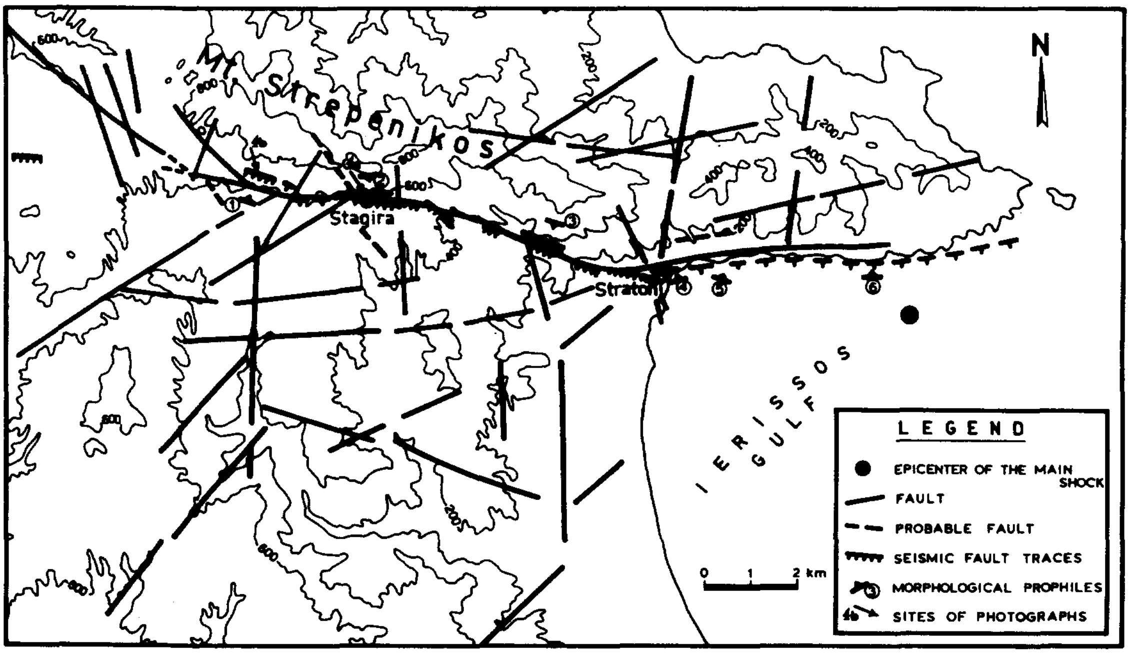

Fig. 2. A structural map of SE Chalkidiki peninsula (Ierissos–Stratoni region) showing the main seismic rupture of the 1932 earthquake, as well as the fault pattern of the wider area (heavy lines).

aftershock (M6.3) took place on 11th May 1933 (Papazachos 1982). The mean calculated seismic slip rate for the wider active zone is 0.81 cm a^{-1} (Voidomatis *et al.* 1990).

Seismotectonics

Floras (1933) in a short technical report located, with great difficulty, some surface ruptures following the earthquake, as did Maravelakis (1933) and Georgalas & Galanopoulos (1953) in a general way. To extend these early observations an attempt was made to trace the Stratoni Fault (Fig. 2) along its total length and to detect the striations directly connected with seismic displacement.

The Stratoni Fault has an E–W orientation and extends for about 15 km. It divides the area geomorphologically into two different regions (Figs. 2 and 3). The northern region is an area of high relief including Mt Strepenikos and forms an E–W footwall block whose southern slopes coincide with the Stratoni Fault. The southern region coincides with the innermost part of the Ierissos Gulf and forms the hangingwall block, which is characterized by an extensive drainage network and lower relief. It is partly covered by Neogene and Quaternary deposits and also affected by antithetic normal or oblique-slip faults. Many sites along the Stratoni Fault comprise scree and other debris deposits. Fault traces, remnants of the last earthquake, along the 15 km of the structure had been mapped in 1:5000 scale (Figs. 2 and 3). Another system of faults (second order) is directed NW–SE and NE–SW and affects mainly basement rocks. In two cases the NW–SE-trending faults divert stream flows from a W–E direction to a NW–SE one; an additional indication of recent (neotectonic) activation.

The seismogenic area forms a well-known narrow fractured zone within the Serbomacedonian massif along its western boundary, elongated in a NW–SE direction (Pavlides & Kilias 1987, Voidomatis *et al.* 1990). It is a zone of crustal weakness associated with normal and left-lateral oblique-slip faults.

The interviewing of over 30 villagers (over 60 years old) and especially some old workers of the nearest mine, gave enough data to map the seismic fault along its total length of over 15 km (Figs. 2 and 4a & b). The activated fault trends in an E–W direction and is generally a pure dip-slip structure, but in some cases it appears left-lateral oblique-slip in character (pitch between 55° and 80°). Some smaller traces strike systematically in a NW–SE direction. An interesting place with clear seismic fault traces (scarps, furrows, etc.), detected after 35 years, is shown in Fig. 4(b).

The strike of the seismic fault is consistent with the E–W to NW–SE elongation of the isoseismals (Papazachos *et al.* 1982), and the WNW–ESE elongation of the seismogenic volume of the 1932 earthquake (Voidomatis *et al.* 1990). The maximum linear dimension of the elliptical seismogenic surface is 68 km, and it has been drawn taking into account aftershocks distribution, inner isoseismal ellipses and ground and coastal deformation observed after the strong shock by Maravelakis (1933). The interview method also confirmed the existence of a weak tsunami in the Ierissos Gulf and brought additional evidence for lightening phenomena accompanying the main shock. Descriptions suggest that lightening starting at the eastern edge of the fault and propagated westwards. It is generally accepted that it defines the seismic rupture propagation.

Paleostress analysis by fault slickensides shows that the neotectonic stress pattern has a clear extensional character and has rotated from NNE–SSW to N–S since at least the late Miocene. In order to explain this

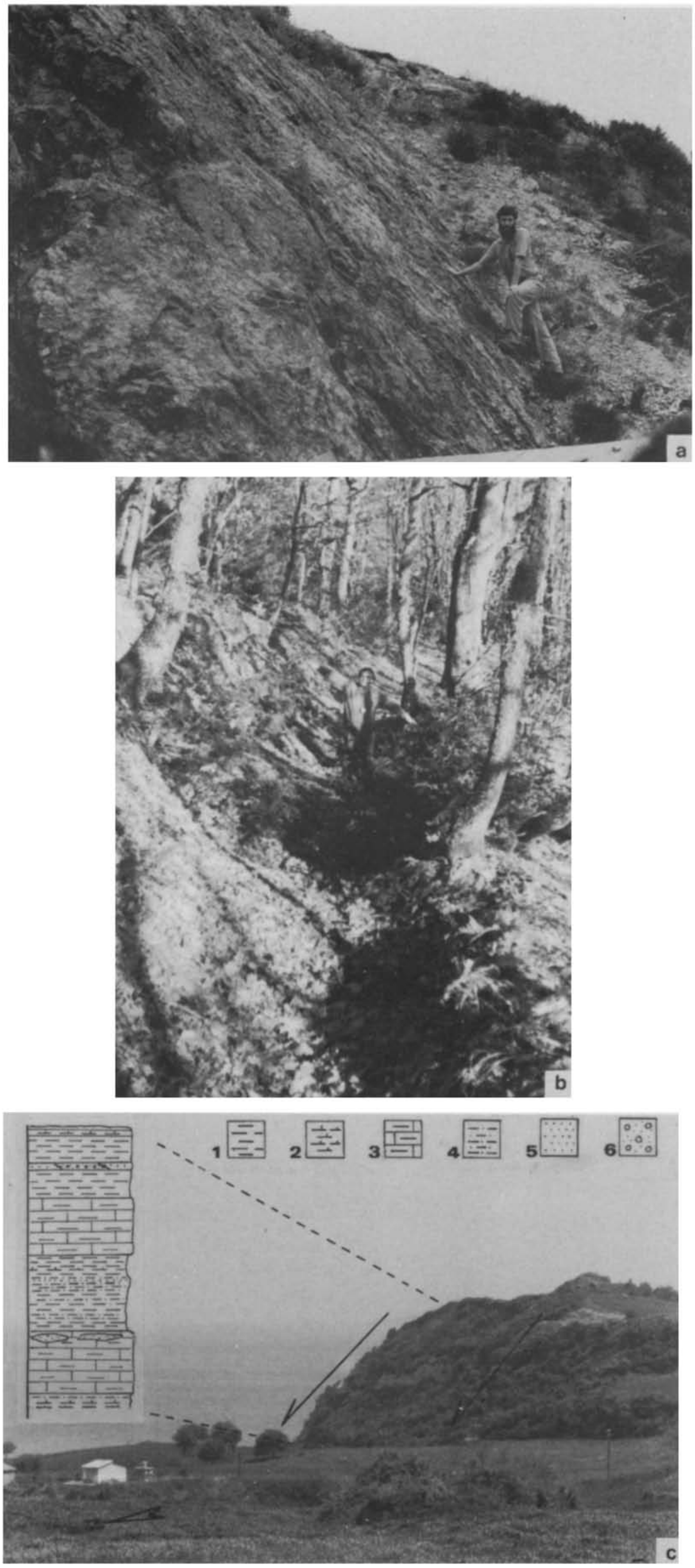

Fig. 4. (a) Outcrop photograph showing the exposed surface of the Stratoni Fault at the village Stagira, affecting the basement rocks. The slickenside is 3 m high and partly covered by scree. The earthquake of 1932 activated this part of the fault and caused an opening in the Holocene deposits of about 2 m vertical displacement and heave of more than 0.5 m. (b) A remnant fault furrow, extending in 500 m along the neotectonic fault affects basement rocks (schists, amphibolites, etc.). (c) An antithetic fault of the hangingwall block south of Ierissos town affecting Pliocene marls and limestones. The lithostratigraphic column is also shown (1, muds; 2, marls; 3, marly limestones; 4, silts–silty sands; 5, sands; 6, pebbly sands).

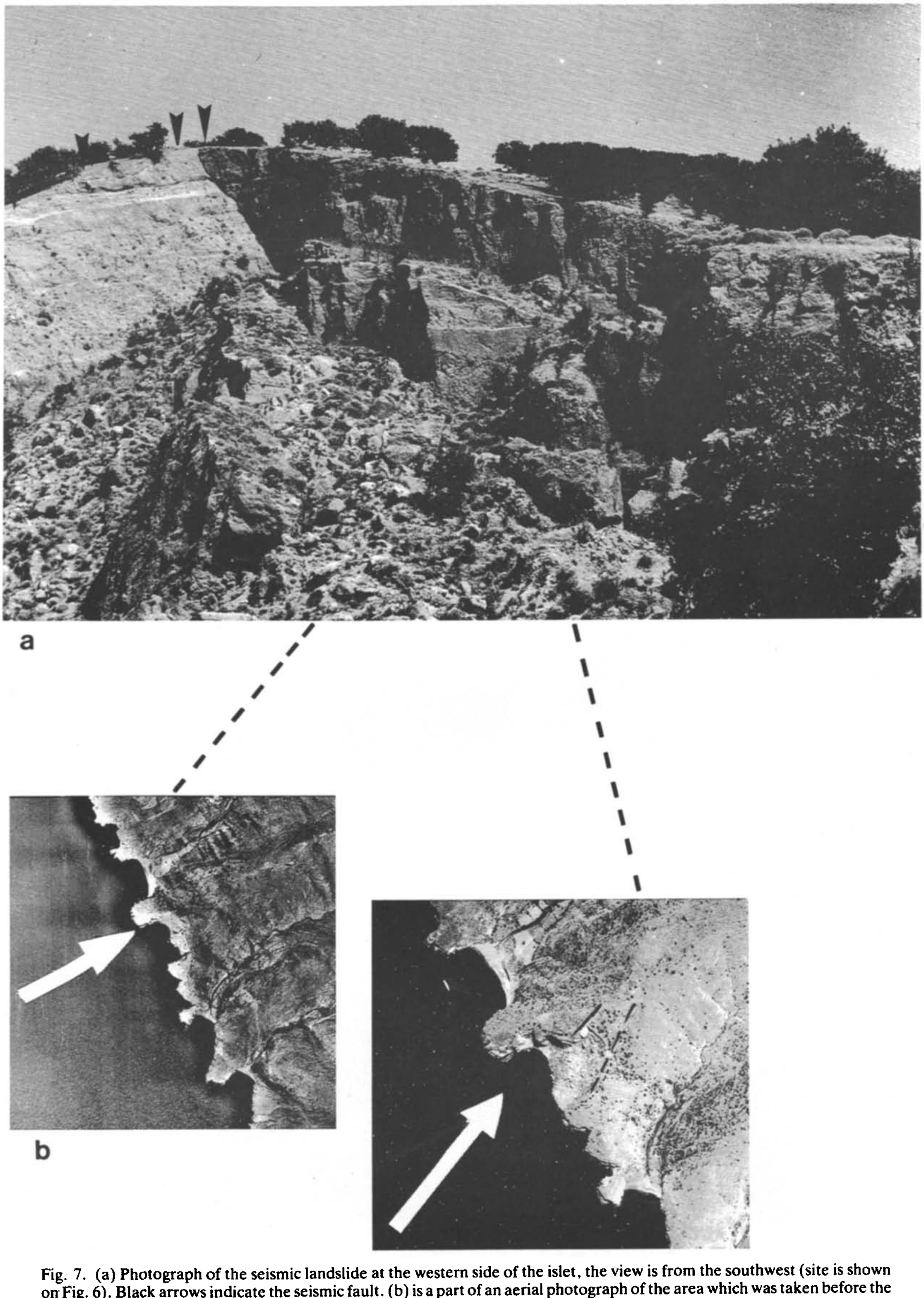

Fig. 7. (a) Photograph of the seismic landslide at the western side of the islet, the view is from the southwest (site is shown on Fig. 6). Black arrows indicate the seismic fault. (b) is a part of an aerial photograph of the area which was taken before the earthquake (1960), where there is no landslide. (c) is a later (1975) aerial photograph of the same area; the seismic landslide and the activated faults are clearly shown.

apparent counterclockwise rotation of the stress directions, Pavlides *et al.* (1988) suggested a clockwise rotation of the geological structures, based mainly on paleomagnetic data. Additional structural data (striated faults affecting mainly basement rocks and Pliocene deposits) and the calculated stress direction of the wider seismogenic area are shown in Fig. 5. They are neotectonic data describing the recent stress pattern of the area, but of general interest only. An attempt has also been made to calculate the principal stress axes of the active deformation based only on the slip vectors (striations) measured directly on fault surfaces activated during the last earthquake. The data used for this calculation are four striated surfaces undoubtedly associated with the last seismic displacement on the basement rock, and two uncertain seismic fault surfaces lying nearby. Some additional representative seismic fault surfaces have also been taken into account (Fig. 5,2a). As there is no published focal mechanism for this earthquake, this analysis must be considered as an alternative solution (Fig. 5,2c).

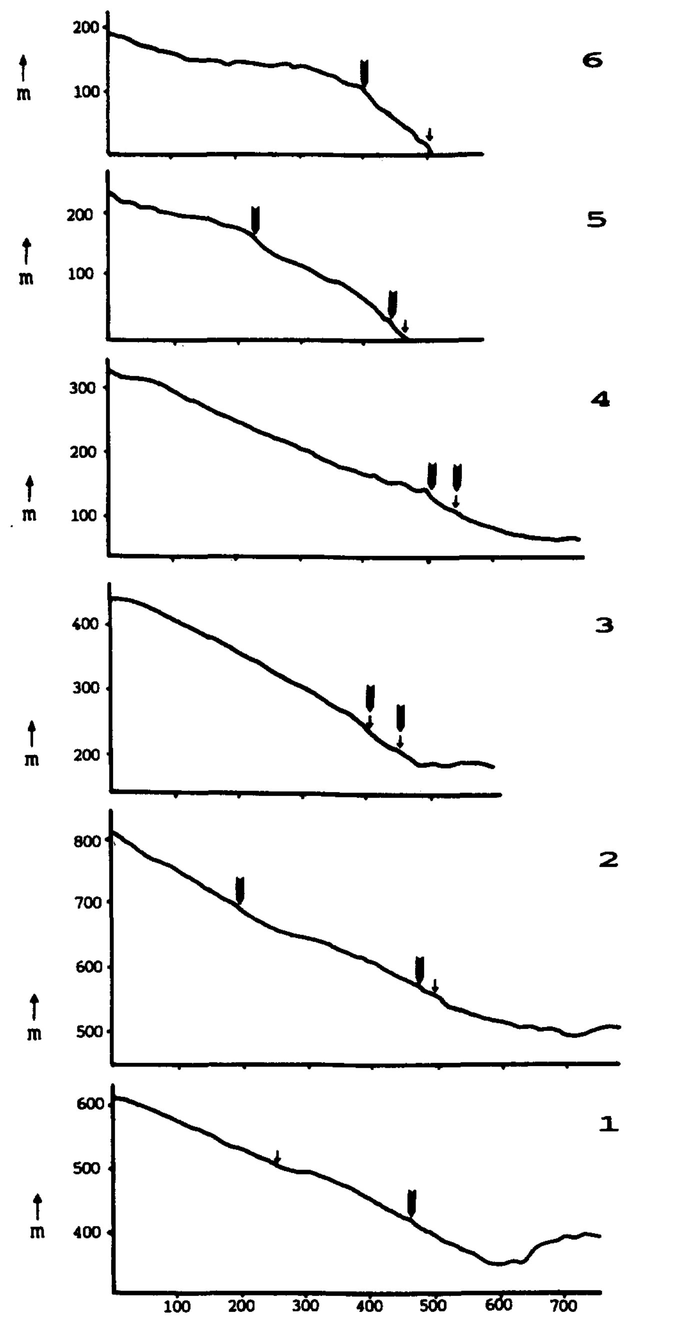

Fig. 3. Morphological profiles (N–S) along the Stratoni Fault (measurements in m). The fault is indicated by heavy arrows, while fault traces directly connected with the 1932 Ierissos earthquake are shown by smaller arrows.

AGIOS EFSTRATIOS SEISMOTECTONICS

Geological regime

The island of Agios Efstratios consists mainly of upper Oligocene to middle Miocene volcanoclastic formations, with some recent marine and lacustrine deposits, located in the northeast part of the island. The volcanoclastics, according to Latsoudas *et al.* (1983), include tuffs of acid and intermediate composition showing cross-bedding. Irregular dispersed and ungraded fragments of volcanic rocks are enclosed in the tuffs, as well as ejecta and bombs of andesitic–dacitic composition. The age of this formation, according to Fytikas *et al.* (1980), is of late Oligocene–early Miocene (17–22 Ma), similar to that of Lemnos Island to the north. The same authors divide the formation into three main units; the basal unit is clearly exposed in different tectonically tilted blocks. In the northeast part of the island (Fig. 6), they show a monocline structure with dips ranging between 50° and 10° towards WSW.

The shallow-water marine formations (yellow–white marly limestones), dip 10–15° to the ESE and are of Miocene age (Latsoudas *et al.* 1983) and unconformably overly the pyroclastics. The lacustrine Plio-Pleistocene deposits are mainly marls, but also include clays and some lignite intercalations, in the deeper members, while volcanic pebbles are rare. Alluvial deposits are very few.

All the abovementioned formations are strongly affected by neotectonic (post-middle Miocene to recent) movements. Mercier *et al.* (1989) suggest that the neotectonic regime of the island is extensional, but separated into two phases. The minimum principal stress (σ_3) of the Pliocene–early Pleistocene phase was directed NE–SW, while the σ_3 axis of the middle Pleistocene–present-day phase trends in a N–S direction.

Seismological information

The Agios Efstratios destructive earthquake of 19th February 1968 (M7.1 and focal depth 10 km) represents a major seismic slip within the vicinity of the seismically active North Aegean Trough. The main shock was preceded by two small foreshocks, on 6th February (M4.0) and 19th February (M3.5), and was followed by 60 aftershocks with magnitudes ranging between 4.0 and 5.6 in a 3 month period until April 1968 (Papazachos

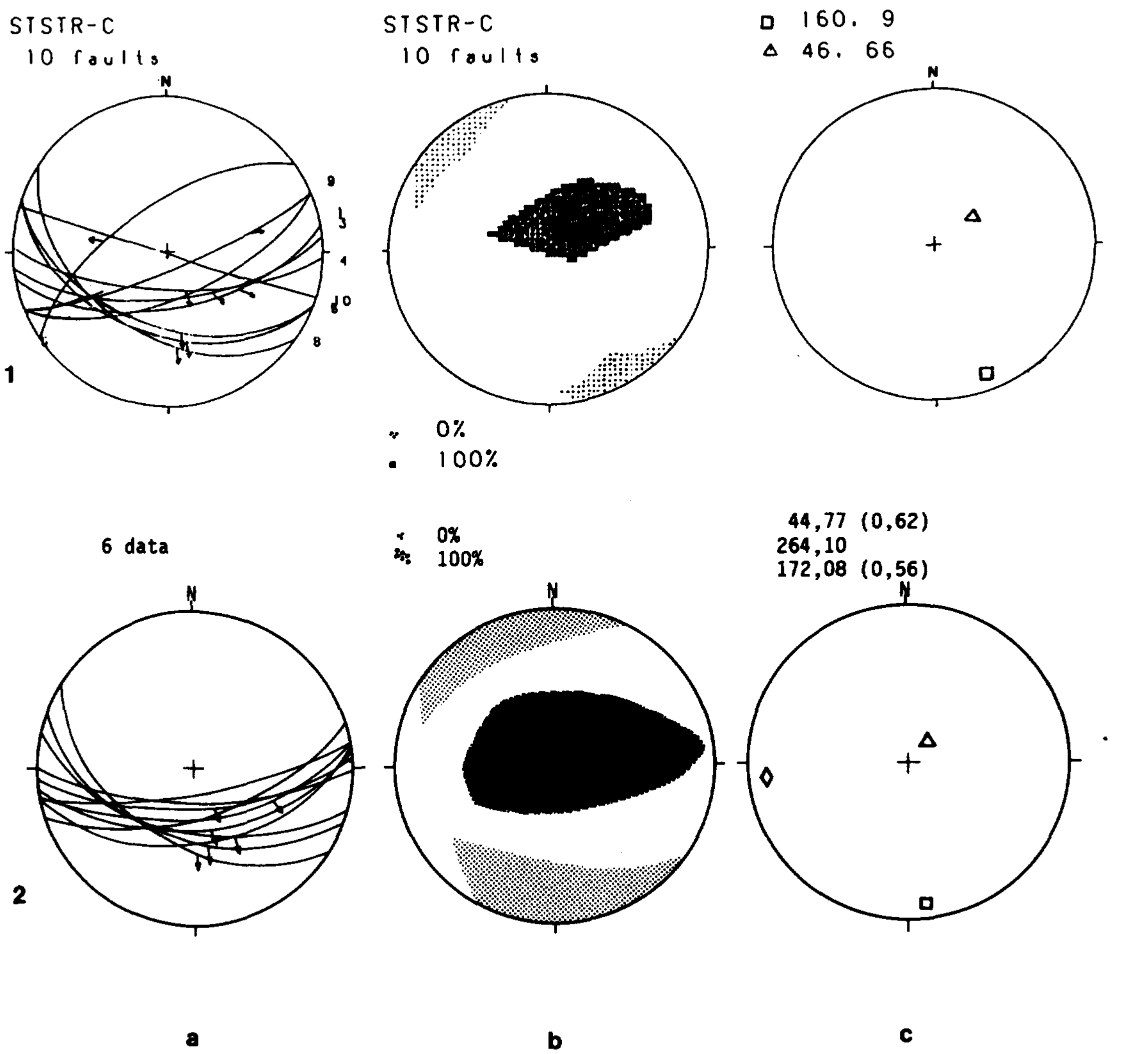

Fig. 5. Structural data of the Ierissos–Stratoni region. Line 1 shows the data used and the results obtained for the neotectonic stress pattern of the wider seismogenic area. Line 2 shows data and results of the Stratoni seismic fault. Column a: stereonets with faults as cyclographic projections and striations as arrows. Column b: the application of the right-dihedra method (Angelier & Mechler 1977), dense shading–compressional area (σ_1), light shading–extensional area (σ_3). Column c: the results of the mathematical method of Caputo & Caputo (1988) showing the position of σ_1 (triangles). σ_2 (rombs) and σ_3 (squares) principal stress axes (see also Fig. 8).

1975). The total number of aftershocks ($M \geq 2.1$) were more than 2800 (Drakopoulos & Ekonomides 1972). North (1977) located them and found that they lay on a NE–SW trend. If this trend follows the fault plane the motion must be right-lateral (McKenzie 1978).

Additional information on the fault direction comes from macroseismic data. The earthquake effects near the epicenter, shown by an elongated inner isoseismal trend, have been noted by several investigators as indicating the orientation of the fault generating the motion. The inner isoseismals (IX–VI) of the Agios Efstratios main shock clearly trend in a NE–SW direction (Papazachos *et al.* 1982). On the other hand no surface faulting associated with the earthquake was reported. Eyewitnesses, however, gave clear information on the seismic faulting, hence a search for surface fault traces at the NE edge of the island was made by J. L. Mercier (Paris—Sud), C. Simeakis (IGME—Athens) and the first author, during a short excursion in 1982. A detailed survey took place during the summer of 1988 by the present authors.

It is worthwhile recording the vivid descriptions of the villagers after 20 years, like "... we lived in dreadful havoc of the unsuspicious movement of time ..." or "... macaber cryouts ...". Other descriptions of "open faults", "stones rolling" and "pathways closing", gave more specific information concerning the surface phenomena of the earthquake. The existence of fault traces (Figs. 6 and 7), uplifted movements (about 0.5 m) on the southeast shore of the island, liquefaction phenomena and a tsunami (a 2 m wave at the shore right after the major shock) were confirmed. Precursor phenomena were also reported by the local fishermen, such as: the strong changes in speed and direction of the major sea currents, hours before the earthquake, still they remain disputable. On the other hand it was impossible to confirm the information about lightening phenomena which accompanied the major shock.

Fault geometry and deformation

Field observations, aerial photograph analysis and the reports of villagers, were used to map the main seismic fault traces on the island, as well as the principal structures affecting the volcanoclastics and recent sediments (Fig. 6). Two sets of aerial photographs at scale 1:30,000 and 1:40,000, respectively, were taken some years before (1960) and after (1975) the earthquake. These were used to detect photolineaments and geomorphic features connected with faults as well as other surface features which may have been due to the earthquake. The seismic landslide at the western part of the island was observed only on the second set of aerial photographs and was studied in the field (Fig. 7). It is directly connected with a NE–SW fault and lies within a zone where some ENE–WSW seismic fault traces were observed (see also Fig. 6).

The most fractured area of the island is in the north-east, where the Plio-Pleistocene deposits exist. The area is dominated by NW–SE normal or left-lateral oblique-slip faults, which are connected with Quaternary landslides, as well as NE–SW right-lateral strike-slip faults, occasionally displaying normal components of movement. The seismic fault traces were detected along the NE–SW right-lateral fault, mainly over a distance of 3 km. The cliffs of the north-west part of the island are very steep, with altitudes up to 250 m, due to the

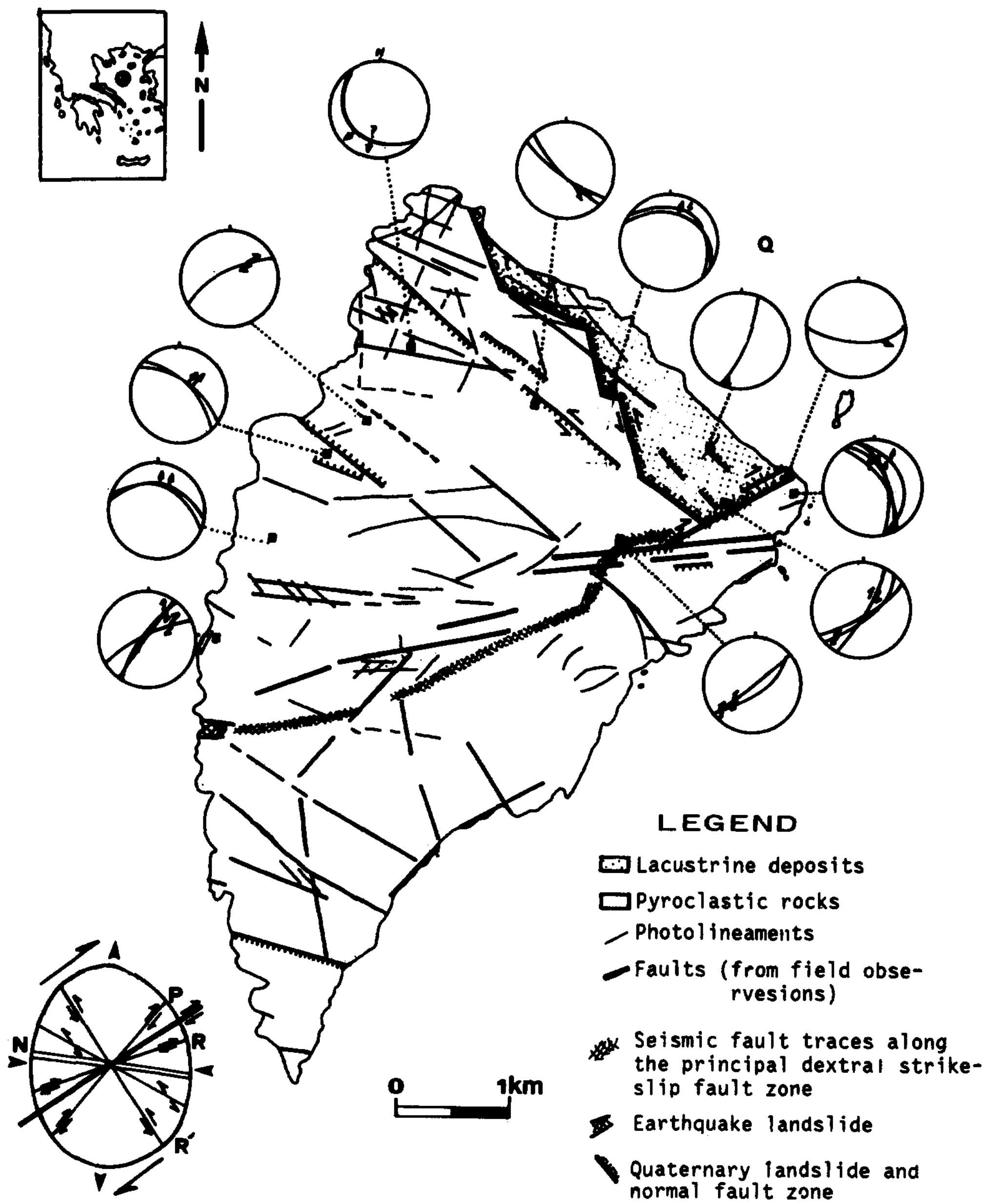

Fig. 6. Location of Agios Efstratios normal and strike-slip fault system. Small stereonets represent the measured faults (curves) with the corresponding slip vectors (arrows) of the recent (late Pleistocene) and active kinematics. Lower-left a stress ellipsoid, which emphasizes the resolved extension (N9°) and shortening (N99°) directions, and the corresponding structures; *N* : normal faults and extensional fractures, *P* and *R* synthetic shears (right-lateral strike-slip faults), *R'*: antithetic (Riedel) shears (left-lateral oblique-slip faults).

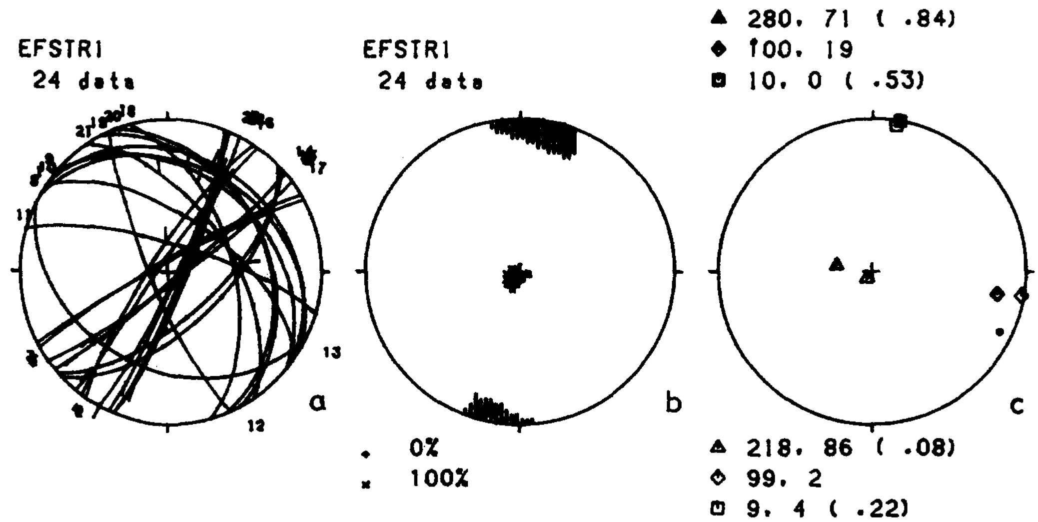

Fig. 8. Structural data of Agios Efstratios and the application of the mathematical method of Caputo & Caputo (1988). (a) Stereonet showing the measured faults (as cyclographic traces) and the corresponding striations (as arrows). (b) The right-dihedra method (Angelier & Mechler 1977), the darker areas representing the maximum probability of axes of maximum shortening, while the lighter areas represent the maximum probability axes of maximum lengthening. (c) Stereonets representing the results of the Caputo & Caputo numerical methodology, where the Conditioned Least Square Method have been applied on the right-dihedra and P–T axes pre-existing methods. Numbers up (from P–T axes method) and down (from right-dichedrons) represent the azimuth and dip of the calculated axes. △, σ_1; ◊, σ_2; and □ σ_3 stress axes. All stereonets are equal-area (Schmidt) projections of lower-hemisphere.

abovementioned gravitational-tectonic slides. While the NE–SW strike-slip faults, affecting recent sediments, form steep scarps, typical of recent (or active) deformation.

Figure 8 shows the measured striated faults from the whole area of the island, which have been used to calculate the directions of the three principal axes of the incremental strain ellipsoid. Some of the data used are directly measured on clear seismic fault surfaces or within the principal seismic fault zone (see this zone crossing the island in Fig. 6). Using the numerical methodology of Caputo & Caputo (1988), applied to the P–T and right-dihedra methods, the axis of maximum shortening (σ_1) was calculated to be almost vertical, the maximum lengthening (σ_3) to trend SSW–NNE with the intermediate axis (σ_2) trending ESE–WNW. From these data the extensional character of the neotectonic deformation on the island is obvious. However, taking into account the compressional character of the σ_2 axis and the geometry of the faults described above, where the NE–SW seismic faults form the principal right-lateral displacement zone (Fig. 6), it could be argued that the neotectonic-active deformation is characterized by an extensional strike-slip regime or more precisely that it forms under right-lateral transtensional conditions.

Seismotectonic results

Recent deformation expressed on the surface by fault systems, which may be still active, and slickensides are comparable with the active deformation at depth deduced from earthquake focal mechanism based on seismograph records, which in turn yield information on the present-day tectonic motion. A striking feature is that sometimes for the same earthquake these methods give quite different solutions. Solutions based mainly on the first motion of P waves (short period instruments) have been published for the Agios Efstratios earthquake by Delibasis & Drakopoulos (1974). They calculated the focal mechanisms for the main shock and the largest aftershocks, which indicate a significant strike-slip component (Fig. 9a). The nodal plane of the main shock is N40°, 85° dip. McKenzie (1972) gave a strike-slip solution for the same shock with a small normal component. The strike and dip of the nodal planes are N025°/75°NW and N114°/87°SW. A recent solution of Kiratzi *et al.* (submitted) based on synthetic seismograms and determined by body waveform inversion, favours the NE–SE-striking plane as the fault plane (N36.2°/81°NW) and dextral strike-slip motion. This is completely consistent with our field measurements of the major seismic faults (Fig. 9c), which strike between N20° and N60°, with a mean direction of N45° and dip 80°NW, and have dextral strike-slip movements. Taking into account the overall distribution and character of the recent and seismic structures, the active deformation picture of the seismogenic area of Agios Efstratios is typical of divergent right-lateral wrench zone (transtensional tectonics) with the NW–SE-striking sinistral oblique-slip faults standing as R' shears against the principal displacement fault zone (inset Fig. 6), with occasional E–W faults, as extensional structures.

CONCLUDING REMARKS

The Aegean and surrounding region is an area of intense seismic activity, and is characterized by extensional tectonics (McKenzie 1978, Mercier *et al.* 1989 and others). The two earthquakes studied affect regions lying on either side of the North Aegean Trough (400–1950 m deep), which takes up the dextral strike-slip

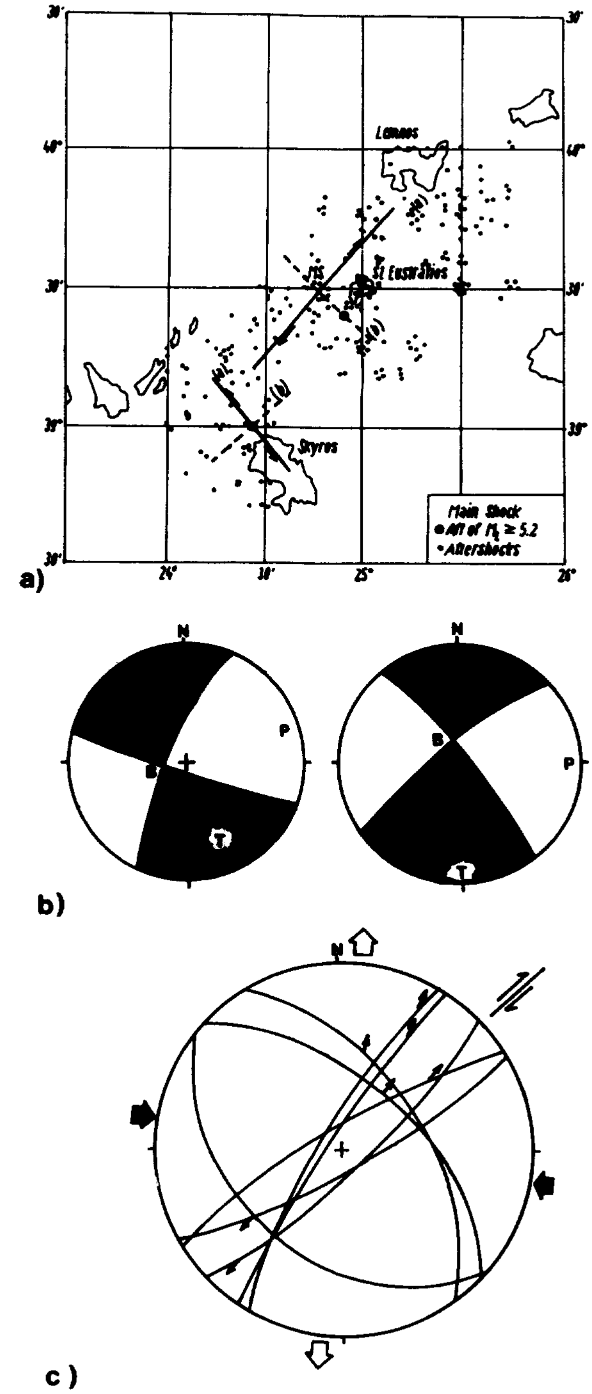

Fig. 9. Seismotectonic correlation on the 19th February 1968 (M = 7.1) Agios Efstratios earthquake. (a) Index map of the location of epicenters of aftershocks and the seismic faults deduced from focal mechanisms of the main event and the largest aftershock (Drakopoulos & Ekonomides 1972). (b) Two additional published focal solutions for the main shock (McKenzie 1972, Kiratzi *et al.* submitted). (c) Representative measurements along the seismic fault in stereographic projection.

motion of the North Anatolian Fault. Pavlides *et al.* (1990) suggest that the loading conditions for the whole area of Northern Aegean are similar to right-lateral transtension, as described by Sanderson & Marchini (1984), Biddle & Christie-Blick (1985) and others.

In the light of these ideas, the environment of two strong earthquakes within the area have been examined. The fault movements are considered to be driven by the motion of the North Aegean Trough principal displacement zone. The 1932 (M7.0) earthquake at Ierissos is directly connected with the well known E–W-trending Stratoni Fault on the basis of remnant fault traces and eyewitness information. The fault is a pure dip-slip structure, dipping steeply to the south, and was active from at least the Oligocene, while E–W and NW–SE mainly conjugate and semi-conjugate faults affect the hangingwall. This fault belongs to a fractured zone of recent crustal weakness trending NW–SE to WNW–ESE, which mainly behaves as a left-lateral oblique-slip wrench fault zone.

The main structures of Agios Efstratios Island, to the south of the North Aegean Trough, have been mapped using field data and aerial photographs. The seismic fault of the 1968 strong earthquake trends NE–SW (N045°/80°NW), and is consistent with the fault direction obtained from focal mechanism solutions (N036°/81°NW). This master displacement zone on Agios Efstratios is a secondary structure, oblique to the North Aegean Trough Fault, and forms part of a major strike-slip fault system (see also Fig. 1). The study of the geometry and kinematics of the faults leads to the conclusion that active deformation at Agios Efstratios forms under right-lateral divergent shear (transtensional) conditions.

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