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Active faulting in multi-fractured seismogenic areas; examples from Greece

by

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with 7 figures and 1 photo

Summary. Reappraisal of existing data and evidence derived from new geological investigations illustrates the often complex association between fault geometry and seismic activity that characterise five seismically active areas of mainland Greece. Morphotectonic, structural, seismotectonic and image analysis carried out in the area of the 1978 Thessaloniki (M 6.5) earthquake highlights the multi-fractured character of this seismogenic zone, previously interpreted as having a relatively simple seismotectonic setting in which E-W trending active fault zones accommodate N-S extension. The seismically active areas of South Thessaly, activated during the 1954 Sophades and 1980 Volos earthquakes, northeastern Gulf of Corinth, activated during the 1981 Gulf of Corinth earthquakes, and Kalamata, southern Peloponnesse, activated during the 1986 Kalamata earthquake, exhibit similar complex fault rupture patterns that reflect the structural heterogeneity of the seismogenic zone. This heterogeneity generates a variety of geometrical barriers to seismic rupture propagation and leads to complex fault geometry and kinematics.

Introduction

Although active faults have generally been regarded as discrete, well defined structures that are reactivated by individual earthquake events, recent studies of the geometry of neotectonic and active faults, together with detailed investigations of earthquake surface breaks, highlight the frequent complexity of fault rupture patterns (e.g. SLEMMONS & DEPOLO 1986, SCHWARTZ & COPPERSMITH 1986, BRUHN & PARRY 1987, MA et al. 1989, CRONE & HALLER 1991, STEWART & HANCOCK 1991, PAVLIDES & SOULAKELLIS 1991, DIMITROPOLOUS & LAGIOS 1991). These studies, undertaken both in the Aegean region and other seismically active terrains, demonstrate that earthquakes are often associated with 'multi-fractured' fault zones, that is, belts of multiple, intersecting faults that give rise to an often diverse pattern of fault movement. Although particularly well documented from active strike-slip fault zones (e.g. SCHWARTZ & COPPERSMITH 1986, BARKA & KADINSKY-CADE 1988), the multi-fractured character of oblique-slip or normal fault zones may also be recognised, particularly with regard to Aegean normal fault zones which may be linked directly or indirectly with strike-slip movements (DEWEY & ŞENGÖR 1979, PAVLIDES et al. 1990). Thus in the Aegean region, moderate to large magnitude earthquakes

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Fig. 1. Location of the four seismically active zones of mainland Greece examined in this paper: 1) Thessaloniki (Macedonia, northern Greece); 2) South Thessaly (central Greece); 3) Eastern Gulf of Corinth; and 4) Kalamata (southern Peloponnese).

(> M 6.0) commonly involve the failure of a number of multiple fault structures, with the result that various segments of the same fault zone may be in motion simultaneously during an earthquake event. The resulting complex rupture patterns contrasts with faulting during moderate magnitude earthquakes in other regions, such as China (MA et al. 1989) and western U.S.A. (DEPOLO et al. 1991), which tends to cause relatively simple surface rupture, complex rupture patterns in these areas generally being most associated with large magnitude events (M 7.0).

Seismological analysis of recent earthquakes provide further evidence of the complex behaviour of active faults. Instead of being single events, some earthquakes are multiple events, that is, a series of earthquake ruptures nucleating close together in time on separate but often contiguous fault surfaces. In the Aegean region, for example, the 1969 Alasehir and 1970 Gediz earthquakes (EYIDOĞAN & JACKSON 1985), the 1954 Sophades earthquake (AMBRASEYS, pers. commun.) and the 1978 Thessaloniki earthquake (CARVER & BOLLINGER 1981) are all interpreted as multiple earthquake events. Furthermore, the nucleation and propagation of earthquake ruptures has been shown to be strongly influenced by fault geometry, with the majority of earthquake ruptures terminating in areas of complex faulting. Fault geometry, itself a product of the inhomogeneous nature of the upper crust, is, therefore, an important control of earthquake behaviour. For this reason, it is necessary to gain a greater understanding of continental fault structures, particularly relating the nature of fault segmentation to the regional stress regime and the character of the seismogenic zone within which earthquakes nucleate and propagate. This paper reassesses the seismotectonic and structural characteristics of a number of recently activated seismogenic fault zones in mainland Greece in order to clarify the role of fault geometry in determining the earthquake rupture pattern.

Thessaloniki seismogenic zone

The Thessaloniki seismogenic zone, where two destructive earthquakes have occurred this century (1902 and 1978), constitutes part of a longer seismically active belt trending NW-SE along the line of the Serbomacedonian massif, an ancient crystalline massif affected by Alpide deformation but also cut by numerous neotectonic faults. These faults, generally reactivated older structures, strike mainly NW-SE and, to a lesser degree, N-S and NE-SW. Seismically the Serbomacedonian belt is very active, with some faults within the belt exhibiting slip rates as high as 1 cm/year (Voidomatis et al. 1990), although faults in other parts of the belt appear inactive. Morphotectonic features such as bedrock scarps and escarpments, offset stream channels and young superficial scarplets are well developed along the most active faults within the belt. According to the classification of Matsuda (1975), the mean slip rate of 0.8 cm/yr. across the whole belt and the nature of the tectonic landforms present within it nature of the would correspond to that expected of a High Activity Fault (type A fault, that is, with a slip rate between 0.1 – 1 cm/yr.), although the well defined geomorphic expression of some faults may suggest Very High Activity (AA) class.

The Thessaloniki seismogenic zone constitutes a relatively small Neogene-Quaternary basin, the Mygdonia Graben, that lies along the edge of the old crystalline massif (Fig. 2a). Numerous recent investigations of this area have permitted a steady increase in the understanding of the tectonics of this zone, evolving from a simple model of a fault-bounded graben to a more complex model of a multi-fractured angular crank-shaped depression. These studies, the majority of which were initiated following the 1978 Thessaloniki earthquake, have incorporated geological mapping, satellite image analysis and morphotectonic studies, as well as geophysical, geodetic and seismotectonic surveys.

Although the generally accepted interpretation of the Thessaloniki earthquake has been of E-W trending normal faults reactivated in response to regional N-S directed extension, some workers suspected a more complex earthquake pattern (e.g. Carver & Bollinger 1981). Fault-plane solutions of the mainshock (M 6.5) and the largest foreshocks during the 1978 event (Papazachos et al. 1980, Carver & Bollinger 1981, Soufleris et al. 1982) are compatible with E-W striking normal faults, but an earlier fault-plane solution of Papazachos et al. (1979), subsequently revised by the same investigators, indicated that the seismic motion involved sinistral strike slip along a NW-SE striking fault. Because the earthquake was a double event, the determined fault-plane solution related to the first of these events. An additional complication was that the seismic expression of the reactivated fault was much longer than its surface trace, extending northwest along pre-existing structures. Furthermore, the epicenres of foreshocks were not distributed along an E-W trend, but instead followed an arcuate belt that was subparallel to and 3 – 6 km north of the surface ruptures, and expressed as a series of spatially distinct clusters of seismicity (Fig. 2b) (Carver & Bollinger 1981, Soufleris et al. 1982).

In addition to the reactivated fault, several other faults exist within the seismogenic zone, some of which may have a different geometry and kinematics. For example, detailed seismological investigation of the fault-plane solutions of small earthquakes within the zone undertaken six years after the 1978 sequence demon-

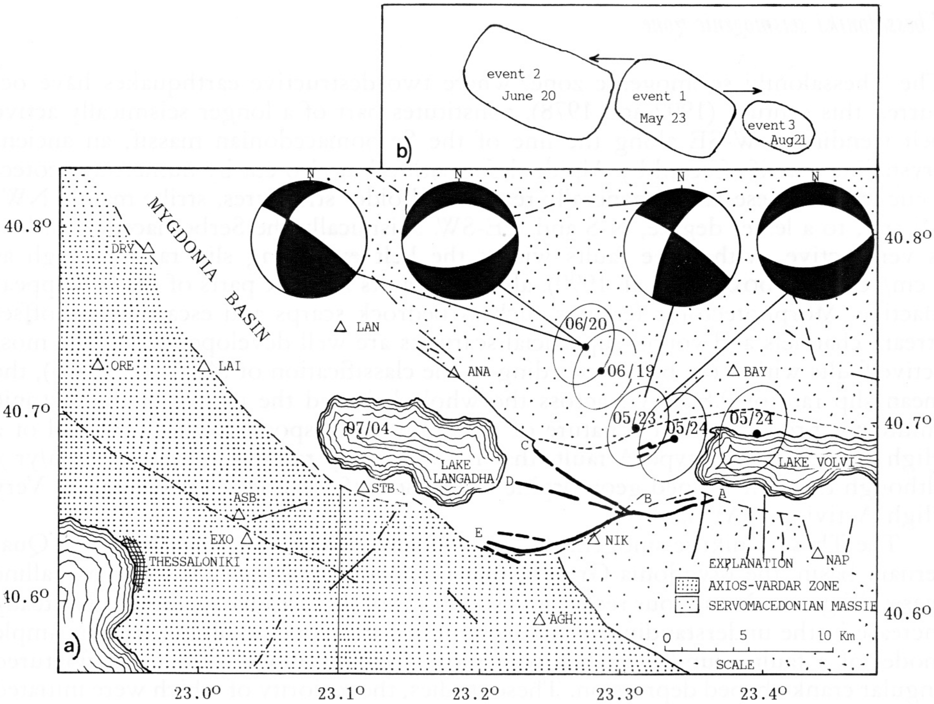


Fig. 2. (a) Epicentres (ellipses show 90% confidence limits) of the four larger shocks of the 1978 Thessaloniki earthquake sequence. Focal plane solutions for strike-slip and dip-slip events from PAPAZACHOS et al. (1979) and (1980), respectively. Triangles show position of the seismograph network. Heavy lines denote surface rupture traces, thin lines denote surface faults (after CARVER & BOLLINGER 1981). (b) Schematic distribution of the foreshock and aftershock clusters (SOUFLERIS et al. 1982).

strates a complex fault pattern (HATZFELD et al. 1986). The orientations of fault planes determined from their analysis conform to three main kinematic sets; (1) NW-SE striking faults with components of normal and sinistral slip, (2) NNE-SSW striking faults exhibiting dextral strike slip and (3) E-W striking normal faults. These three sets can also be distinguished from structural and morphotectonic analysis, together with a fourth set of faults that strike NE-SW. The set of faults striking NW-SE form the structural boundaries of the Langada sub-basin, western part of the Mygdonia Graben, and are well defined geomorphologically, in contrast to NNE-SSW striking faults which have no geomorphic expression (Fig. 3a & b).

An ongoing morphotectonic study of the area indicates that the main fault that bounds the southern margin of the graben is divided into two sets of fault scarps developed in both bedrocks and superficial deposits, one set possessing a rounded and degraded scarp form and the other having a fresher, steeper morphology. In particular, in the area between the two lakes scarps are either well rounded or remain well defined. It is likely that steep scarps reflect active faulting or fluvial downcut-

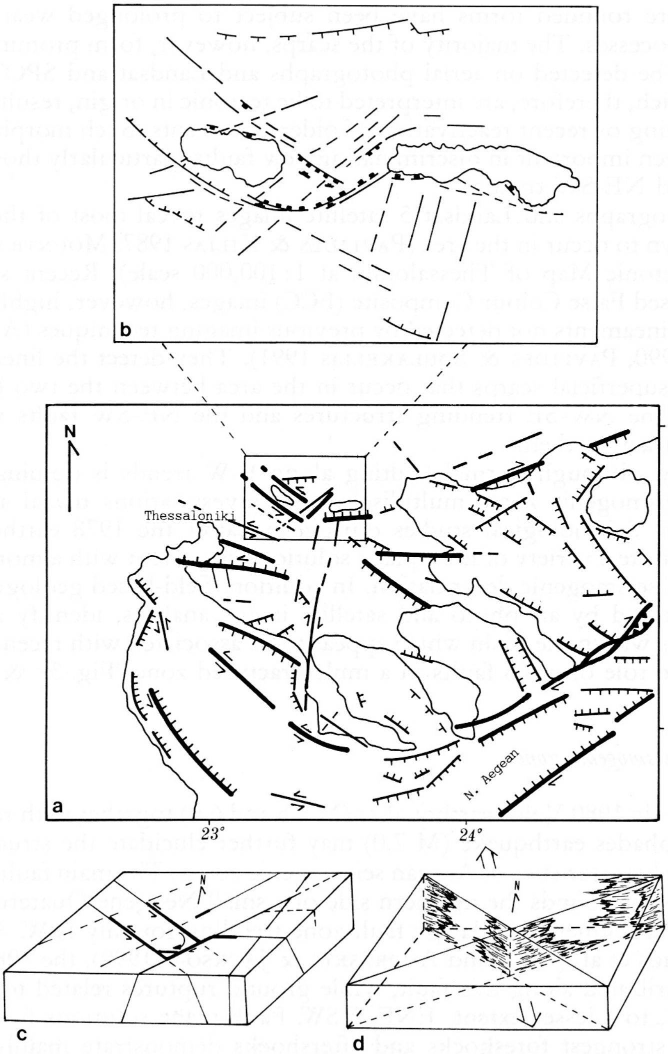


Fig. 3. (a) Fault pattern of the Thessaloniki region with a box denoting the seismogenic zone of the 1978 earthquakes. Heavy lines mark major fault zones while normal faults are shown by lines with ticks on downthrown side. Lines with arrows represent strike slip faults, with arrows showing sense of fault movement. Data from Pavlides & Kilias (1987), Pavlides et al. (1990), Pavlides & Soulakellis (1991).
(b) Fault pattern within the Thessaloniki seismogenic zone showing reactivated faults and seismic ruptures (lines with solid boxes on downthrown side), prominent faults (lines with ticks on downthrown side) and lineaments (lines only).
(c) Schematic block diagram illustrating the inferred multi-fractured nature of the Thessaloniki seismogenic zone showing neotectonic and seismically reactivated faults (heavy lines).
(d) Multiple fracture model (modified from Ma et al. 1989) showing a cross-fault geometry in which some sections are ruptured seismically and adjacent sections remain locked (shaded areas). Arrows show inferred direction of extension.

ting, while more rounded forms have been subject to prolonged weathering or surface wash processes. The majority of the scarps, however, form prominent lineaments that can be detected on aerial photographs and Landsat and SPOT satellite images, and which, therefore, are interpreted to be tectonic in origin, resulting either from fresh faulting or recent reactivation of older lineaments. Such morphotectonic surveys have been important in discriminating new faults, particularly those following NW-SE and NE-SW trends.

Aerial photographs and Landsat 5 satellite images reveal most of the tectonic structures known to occur in the area (PAVLIDES & KILIAS 1987, MOUNTRAKIS et al., unpubl. Neotectonic Map of Thessaloniki at 1:100,000 scale). Recent studies on digitally processed False Colour Composite (FCC) images, however, highlight additional tectonic lineaments not detected by previous imaging techniques (ASTARAS & SOULAKELLIS 1990, PAVLIDES & SOULAKELLIS 1991). They detect the linear pattern of most of the superficial scarps that occur in the area between the two lakes, and highlight both the NW-SE trending structures and the NE-SW faults which are observed to cut across them.

In summary, although normal faulting along E-W trends is dominant in the Thessaloniki seismogenic zone, multidisciplinary investigations reveal a complex tectonic pattern. Seismological studies during and after the 1978 earthquake sequence demonstrate a variety of fault-plane solutions consistent with a more complicated pattern of seismogenic deformation. In addition, field-based geological investigations, supported by air photo and satellite image analysis, identify additional structural trends within the basin which appear to be associated with recent faulting, highlighting the role of cross faults in a multi-fractured zone (Fig. 3c & d).

South Thessaly seismogenic zone

Data from the July 1980 Volos earthquakes (M 6.5 and 6.0) together with reappraisal of the 1954 Sophades earthquake (M 7.0) may further elucidate the structural and seismotectonic characteristics of Aegean seismogenic zones. The main fault activated in the former event bounds the northern side of a small Neogene-Quaternary basin and is probably a segment of a larger fault zone trending roughly E-W. As is clear from PAPAZACHOS et al. (1983) and AMBRASEYS & JACKSON (1990), the 1980 seismic sequence is distributed along this fault, while ground ruptures related to it mainly strike E-W and, to a lesser extent, ENE-WSW. Fault-plane solutions for the main shock and the strongest foreshocks and aftershocks demonstrate mainly E-W to ENE-WSW trending, dip-slip fault planes, consistent with striated fault surfaces measured in the field. Palaeostress reconstructions from the structural analysis of striated fault planes yield principal stress directions for the Mid Pleistocene to Present-day stress regime in good agreement with those derived from fault plane solutions, with a tensile ($\sigma 3$) axis trending N-S to NNE-SSW (CAPUTO & PAVLIDES 1991).

While the above stress determinations reflect the regional stress regime, a second or third order stress field has also been determined in which extension is directed WNW-ESE. This local stress field is associated with minor neotectonic structures trending mainly NE-SW, and with some of the 1980 earthquake ground ruptures which in places strike ENE-WSW to NE-SW and which have a weak sinistral

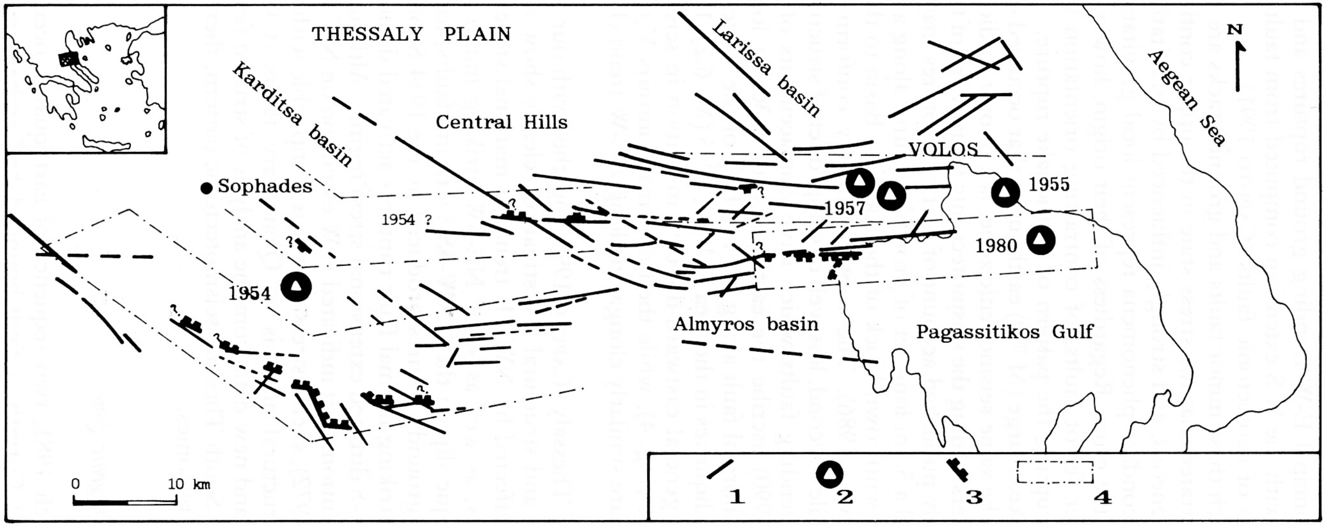


Fig. 4. South Thessaly fault pattern showing faults (1), epicentres of mainshocks from recent earthquakes (2), coseismic fault ruptures (3) and areas of possible seismogenic fault zones activated during the 1954 (Sophades), 1955 (Volos), 1957 (Velestino) and 1980 (Volos) earthquakes (4). Data from Papazachos et al. (1983), Papastamatiou & Mouyaris (1986a, b), Ambraseys & Jackson (1990), Caputo (1990), Caputo & Pavlides (1991) and new field and remote sensing observations. Inset map shows position in mainland Greece.

component of movement. These features indicate a conflicting sense of movement to that exhibited by the principal E-W trending ground ruptures and neotectonic faults, being incompatible with the N-S extension computed from fault-plane solutions and structural analysis of neotectonic faults (CAPUTO 1991).

The mechanism by which these minor faults and ground cracks are generated is not clear. It is well demonstrated that the stress state in the upper continental crust is characteristically heterogeneous, and strongly influenced by gravitational forces, and it may be that these secondary phenomena represent local gravitational effects in the uppermost levels of the crust. Regardless of their origin, however, they are evidence for a second order set of faults, of contrasting orientation to the main seismogenic structures, disrupting the pattern of earthquake rupture.

The Sophades earthquake, a large (M 7.0) earthquake that occurred on April 30, 1954 at the western end of the same seismogenic zone, is a poorly studied event but one that is important in understanding the seismotectonic framework of the Thessaly seismogenic zone. A recently published account of surface ruptures mapped immediately after the event reveal a 5 km long set of ground ruptures along a NNW-SSE trending fault and in the downthrown block of the Karditsa Basin to the northeast (PAPASTAMATIOU & MOUYARIS 1986). The ruptures mainly conform to oblique (sinistral) dip-slip faults, while a second, less well developed set of structures indicate pure dip slip along E-W trending faults which have displacements of 10–70 cm. AMBRASEYS & JACKSON (1990) ascribe the earthquake to a 30 km long NW-SE striking major seismogenic normal fault along the foothills of the western Thessaly (Karditsa) plain. Recent earthquakes in the area in 1954, 1955 (Ms 6.2), 1957 (Ms 6.5 and 6.7) and 1980 reveal a general eastward-directed migration in seismic activity within the seismogenic zone (Fig. 4), while the isoseismal contours V to IX of the 1954 and 1957 earthquakes are similarly elongated along a E-W trend (PAPAZACHOS et al. 1982).

The neotectonic map of Thessaly (CAPUTO 1990) together with our own photogeological, morphotectonic and structural investigations clearly show a large E-W trending active fault zone affected by NW-SE trending marginal structures of the Karditsa and Larissa Basins, as well as some NE-SW striking minor faults. The sinistral component of oblique slip on the NNW-SSE striking faults, together with the similar character of the ground ruptures produced by the 1954 Sophades earthquake, as well as the E-W striking normal fault ruptures activated during the same event, is consistent with a N-S directed extensional stress regime. Although conflicting with early fault plane solutions that indicated E-W extension on NW-SE striking normal faults (MCKENZIE 1972), such a stress regime is compatible with the state of stress determined from structural analysis of Quaternary faults (CAPUTO 1990, CAPUTO & PAVLIDES 1991) and new data from the analysis of striated fault surfaces. The principal feature of the South Thessaly seismotectonic pattern, therefore, is the cross-cutting nature of the tectonics.

Eastern Gulf of Corinth seismogenic zone

During February and March 1981, two sequence of earthquakes occurred in the eastern part of the Gulf of Corinth, a fault-bounded half-graben separating the

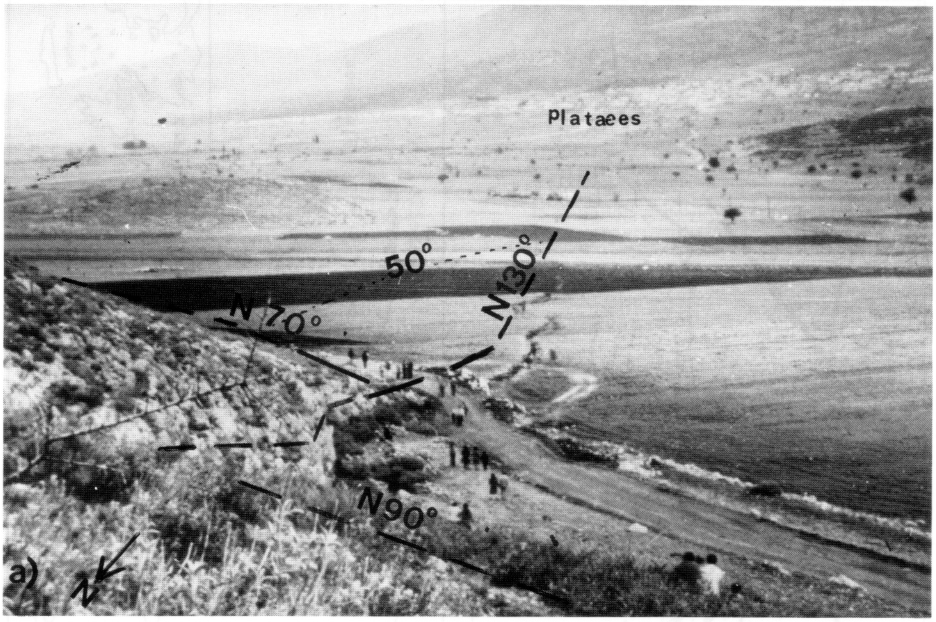
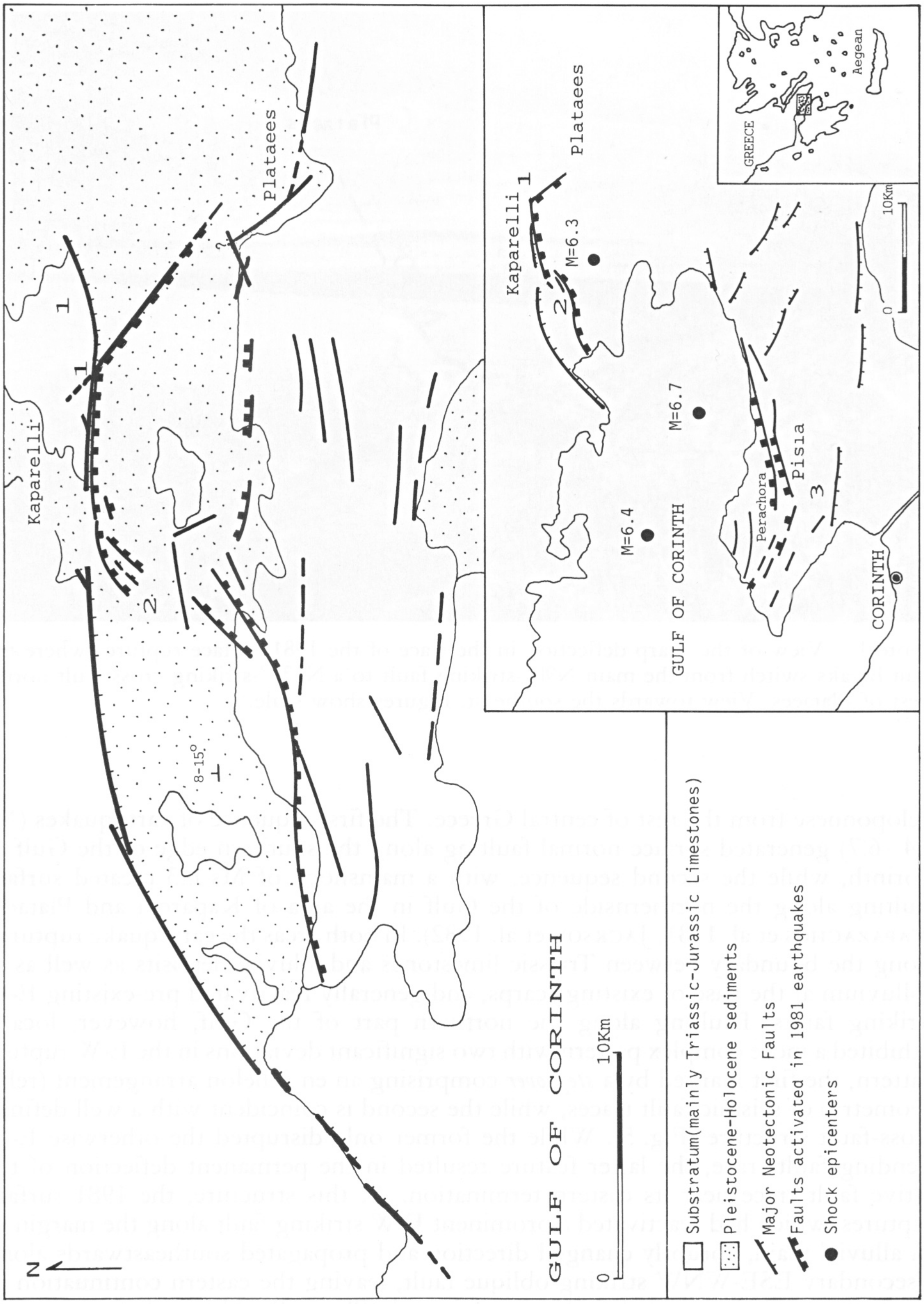


Photo 1. View of the sharp deflection in the trace of the 1981 surface ruptures where the fault breaks switch from the main N90°-striking fault to a N130°-striking cross fault northwest of Plataees. View towards the southeast. Figures show scale.

Peloponnese from the rest of central Greece. The first sequence of earthquakes (Ms 6.4–6.7) generated surface normal faulting along the southern edge of the Gulf of Corinth, while the second sequence, with a mainshock of Ms 6.3 created surface faulting along the northernside of the Gulf in the area of Kaparelli and Plataees (Papazachos et al. 1981; Jackson et al. 1982). In both areas the earthquake ruptured along the boundary between Triassic limestones and alluvial deposits as well as in colluvium at the base of existing scarps, and generally reactivated pre-existing E-W striking faults. Faulting along the northern part of the Gulf, however, locally exhibited a more complex pattern with two significant deviations in the E-W rupture pattern, the first marked by a *step-over* comprising an en échelon arrangement (relay geometry) of seismic fault traces, while the second is coincident with a well defined cross-fault structure (Fig. 5). While the former only disrupted the otherwise E-W trending fault trace, the latter feature resulted in the permanent deflection of the active fault trace near its eastern termination. At this structure, the 1981 surface ruptures, which had reactivated a prominent E-W striking fault along the margin of an alluvial plain, abruptly changed direction and propagated southeastwards along a secondary ESE-WNW striking oblique fault, leaving the eastern continuation of the E-W striking marginal fault unreactivated (Photo I). Although Stewart & Hancock (1991) interpreted this structure as a minor accommodation structure in


Kaparelli
Plataees
1
2
8-15°
GULF OF CORINTH
0 10Km
N
Substratum(mainly Triassic-Jurassic Limestones)
Pleistocene-Holocene sediments
Major Neotectonic Faults
Faults activated in 1981 earthquakes
Shock epicenters
Kaparelli
Plataees
M=6.3
M=6.7
M=6.4
GULF OF CORINTH
Perachora
Pisia
3
CORINTH
0 10Km
GREECE
Aegean

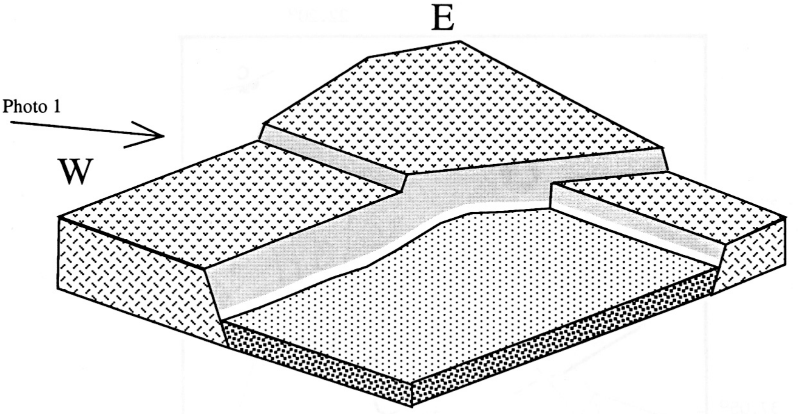


Fig. 6. Block diagram of the inferred geometry of the eastern end of the Kaparelli fault. The discoloured strip along the fault scarp base denotes portion of the fault reactivated during the 1981 earthquakes. Only the section of the main fault in the hangingwall (left) of the cross-fault was reactivated, with the footwall portion (right) remaining undisturbed.

the hangingwall of the fault (a hangingwall cross-fault), it is here interpreted as a cross fault since it can be traced into the footwall of the marginal fault (Fig. 6).

Kalamata seismogenic zone

The Messinia Gulf, an area cut by numerous prominent neotectonic faults and affected by a number of strong earthquakes in the past, represents another example of a multi-fractured seismically active zone. The zone was most recently reactivated during the September 13, 1986 (Ms 6.2) Kalamata earthquake resulting in a number of detailed seismotectonic and geological investigations. According to Mariolakos (1989) the area comprises a system of grabens bounded by cross faults. The predominant fault trends are NNW-SSE to ENE-WSW and also NW-SE to E-W. Based on fault plane solutions, geological data, field observations of seismic ruptures and aftershock distributions, Papazachos et al. (1988) proposed the seismogenic fault was a NNE-SSW striking and WNW-dipping normal fault with a listric geometry. The pattern of the aftershocks reveals an irregular spatial and temporal distribution,

Fig. 5. (a) Simplified seismotectonic map of the eastern Gulf of Corinth highlighting major faults and the position and magnitudes of the mainshocks of the 1981 Gulf of Corinth earthquakes, and (b) more detailed geological map of the Kaparelli–Plataees area on the northern side of the gulf. Data from Papazachos et al. (1983), Jackson et al. (1982), together with field data from Rodogianni & Simeakis (personal communiation) and the Geological map of Greece, 1:50 000 Kaparelli sheet. The maps show the positions of three significant deviations in surface rupture traces from a general E-W trend; occuring as a cross-fault intersection (1), a marked step-over zone (2), and an angular fault bend (3).

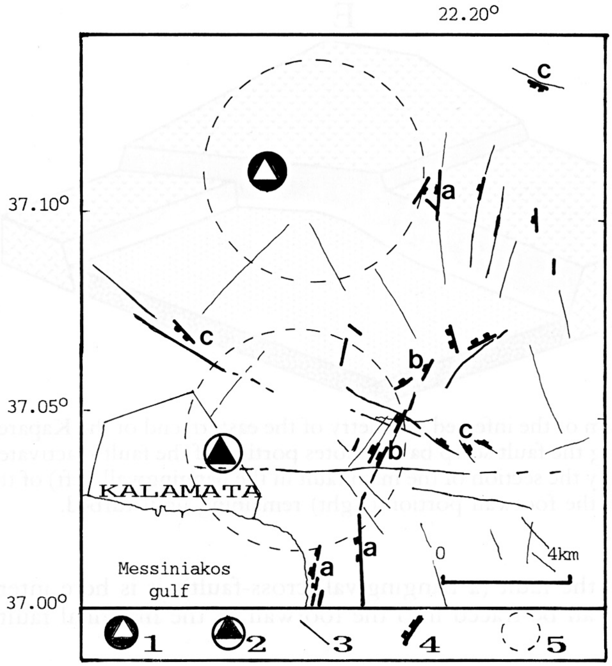


Fig. 7. Seismotectonic map of the area of the 1986 Kalamata (southern Peleponnese) earthquake showing the position of the mainshock (Ms 6.2) (1), and the principal aftershock (Ms 5.4) (2). Also shown are faults (3), surface ruptures from the 1986 events (4), and aftershock clusters (5). The surface ruptures are divided into a number of sets related to their orientation; (a) N-S, (b) NNE-SSW, and (c) NW-SE. Data from Papazachos et al. (1988), Mariolakos et al. (1989) and Fountoulis & Grivas (1989).

occurring as two distinct aftershock clusters (Fig. 7) rather than a continuous belt of seismicity (Tselentis et al. 1989, Lyon-Caen et al. 1989). In addition, a wide variety of fault plane orientations and inclinations were determined from minor faults activated during the aftershock sequence (Tselentis et al. 1989). Analysis of the northern aftershock cluster reveals the existence of faults of two different trends and which dip at four contrasting inclinations, while the southern cluster is characterised by more regular faulting activated later during the aftershock sequence.

Independent data from geophysical profiles (Dimitropolous & Lagios 1991), air-photo analysis and geological investigations (Fountoulis & Grivas 1989) detect another prominent set of NW-SE to E-W trending faults in the seismogenic zone around the vicinity of Kalamata in the southern aftershock cluster. This strengthens the suspicion that at least two faults were activated during the 1986 earthquake sequence (Dimitropolous & Lagios 1991), necessitating a reappraisal of the interpretation of a the 1986 event involving reactivation of a NNE-SSW striking normal fault in favour of one invoking the multiple reactivation of cross faults.

Discussion and conclusions

The main purpose of this paper has been to illustrate the intricate fault geometry of seismogenic zones in mainland Greece and demonstrate the consequent complexity of earthquake ruptures. New geological observations, together with reassessments of existing studies, highlight the role of composite fault structures being reactivated as multiple fault strands in a number of recent Greek earthquakes. This, together with the wider recognition that heterogeneities within the uppermost levels of continental crust may give rise to a range of "fault geometrical barriers' which control fault rupture and arrest, lead to the recognition of multi-fractured seismogenic zones being an important facet of seismic risk evaluation. In this respect, a number of noteworthy observations arise from investigations in the Aegean region which may find wider application.

(1) The geometry of seismic fault traces and the architecture of the underlying fault zone is commonly more complex than generally described.

(2) Fault-plane solutions of earthquakes only partially describe the geometry of seismogenic faults. They appear, for example, to indicate the sense of fault movement at deeper levels, giving a mean sense of fault kinematics rather than describing the overall rupture pattern.

(3) The main fault ruptures generated by earthquakes follow prominent faults with more or less uniform strike, but locally geometrical barriers may deflect rupture propagation to varying degrees. Examples of such geometrical barriers in the seismogenic zones investigated are the intersection of contrasting fault sets, releasing bends or branch lines, minor bends in fault strike, step-over zones and intersections between reactivated faults and pre-existing cross faults. The result of these barriers is to produce a multi-fractured seismogenic zone characterised by a diverse pattern and sense of fault movements.

(4) Because of the difficulty in correlating surface rupture characteristics with those at depth as determined from fault plane solutions, it is likely many barriers do not extend very deep into the crust. Similarly there is the likelihood that some disruptions of fault geometry may reflect deeper discontinuities not apparent at the surface.

(5) Finally, this study illustrates how structural and morphotectonic investigations of active faults can provide useful information on earthquake behaviour, particularly with regard to assessing likely rupture nucleation and propagation characteristics, as well as defining those fault segments which are likely candidates for reactivation. It is in this way that such studies may contribute to assessments of seismic risk within seismically active areas such as the Aegean region.

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