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Quaternary tectonics in the Gulf of Patras, western Greece

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Abstract—Air gun seismic and 3.5 kHz profiling data from the Gulf of Patras, western Greece, show that it is occupied by a small asymmetric graben with several geometric similarities to the larger-scale graben in the Gulf of Corinth to the east. Major listric faulting characterizes the southern flank of the graben whilst the northern flank represents an associated rollover structure affected by antithetic and synthetic faulting. The present phase of subsidence is of Holocene age, but buried growth faults suggest earlier subsidence in the Gulf. The average rate of subsidence through the Holocene is estimated to be 10 mm/year.

The Gulf of Patras graben, together with the Gulf of Corinth graben and the Megara basin, represent a continuous system of WNW–ESE trending grabens in a broad zone of intense seismicity within the Aegean domain. Individual grabens are offset and are interconnected by NE–SW trending fault systems.

INTRODUCTION

THE AEGEAN domain of the eastern Mediterranean is undergoing crustal extension in a marginal basin environment behind the active subduction system of the Hellenic outer arc. This crustal extension is concentrated in several zones of graben development, both in front of and behind the active volcanic inner arc of the Cyclades.

The Gulf of Patras lies at the western end of a system of graben structures extending from the boundary of a marginal compressional zone (Brooks & Ferentinos 1984), associated with the active subduction in the Western Hellenic arc, towards the centre of the Aegean domain (Fig. 1). Offshore and onshore neotectonic studies of the two documented grabens of this system, the Gulf of Corinth basin and the Megara basin, show that they are WNW–ESE trending asymmetric grabens associated with listric normal faulting (Brooks & Ferentinos 1984, Mariolakos & Papanikolaou 1982). The grabens lie within a broad zone of high seismicity (Papazachos *et al.* 1982, Makropoulos & Burton 1980). Fault plane solutions for the central and eastern part of the Gulf of Corinth show that shallow earthquakes are associated with normal faults trending WNW–ESE and WSW–ENE (Jackson *et al.* 1982).

The purpose of this short paper is to outline briefly the Quaternary tectonics of the Gulf of Patras and its relationship to the tectonics of the other graben structures within the region. It is not intended to provide a detailed or complete account of the geology of the Gulf. The structure of the seafloor beneath the Gulf was investigated during RRS *Shackleton* cruise 1/82 using 3.5 kHz and 40 in^3 air-gun profiling systems along about 300 km of track (Fig. 2). The offshore survey has been supplemented by preliminary structural studies onshore.

GEOLOGICAL SETTING

The Gulf of Patras is flanked to the northeast by the mountains of Varasova and Klokova which reach an elevation of about 1000 m and are composed of Cretaceous limestones and Eocene flysch of the Gavrovo zone of the Hellenide orogenic belt. To the northwest, the Gulf is fringed by Quaternary deltaic deposits of the Acheloos and Evinos rivers (Piper & Panagos 1981). The southern shore of the Gulf is flanked by Plio-Quaternary deposits of shallow marine and lagoonal facies which reach a maximum thickness of 1500 m (Hageman 1979). Recent offshore drilling in the southern part of the Gulf reveals about 1800 m of Neogene and Plio-Quaternary sediments overlying Triassic anhydrites (D. Monopolis, pers. comm.).

BATHYMETRY AND SHALLOW STRUCTURE

Physiographically, the Gulf is composed of two segments, the outer trending WNW–ESE, the inner NE–SW and extending towards the Narrows at the entrance

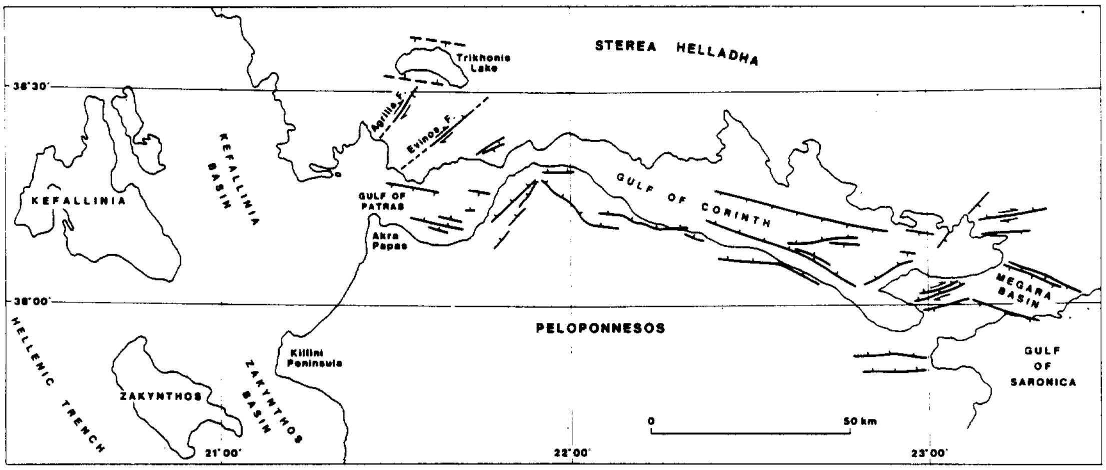

Fig. 1. The Gulf of Patras and its relationship to the Gulf of Corinth basin and the Megara basin. Fault lines for the Gulf of Corinth area are derived from Dufaure *et al.* (1975), Brooks & Ferentinos (1984) and Mariolakos & Papanikolaou (1982), and for the Megara basin from Mariolakos & Papanikolaou (1982).

to the Gulf of Corinth (Fig. 2). The outer segment is occupied by a linear trough with a length of about 22 km and a width of about 8 km. Water depths reach 135 m along the axis of the trough and shoal northeastwards towards the Narrows.

The bathymetry of the trough is controlled by extensive active faulting of WNW–ESE trend (Fig. 2). 3.5 kHz profiles 1 and 2 (Fig. 3), which cross the fault system obliquely, show normal growth faults with seabed displacements typically between 5 and 25 m. The major faulting occupies the southern flank of the trough. The northern flank is affected by antithetic and synthetic faults. Individual fault blocks are tilted towards the southern margin of the trough and display a progressive decrease of stratal dip upwards. These various structural features are evidence that the trough represents an asymmetric graben with a listric master fault (Bally *et al.* 1981, Anderson *et al.* 1983, Wernicke & Burchfiel 1983). Further, the synsedimentary nature of the faulting is indicative of continued fault activity through the Quaternary.

Two layered sequences can be identified in the 3.5

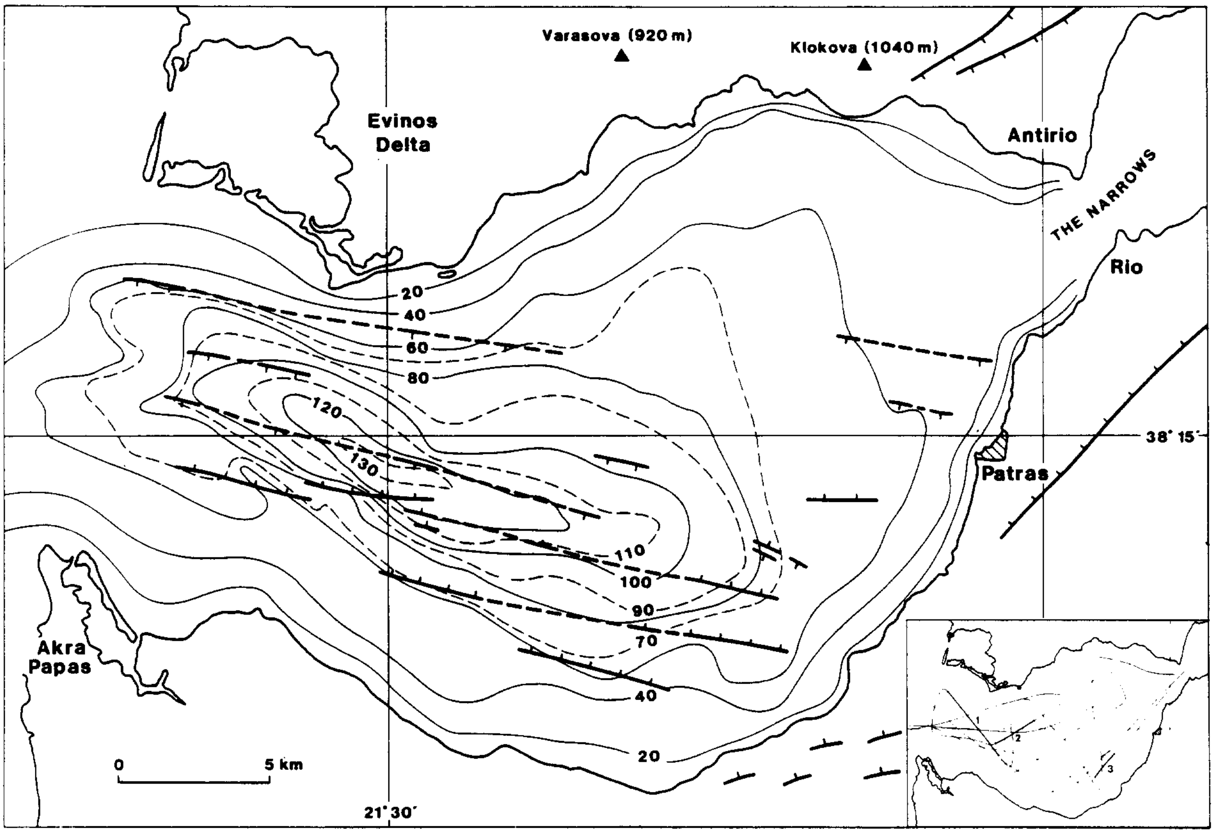

Fig. 2. Bathymetric contours (in metres) and active faults in the Gulf of Patras. (Contours in metres.) Fault lines on land after BP Ltd (1971) and Doutsos & Kontopoulos (in prep.). (Inset shows 3.5 kHz and air-gun profiling survey lines established in the Gulf of Patras during RRS *Shackleton* cruise 1/82; 1, 2 and 3 are sections of 3.5 kHz survey lines illustrated in Fig. 3.)

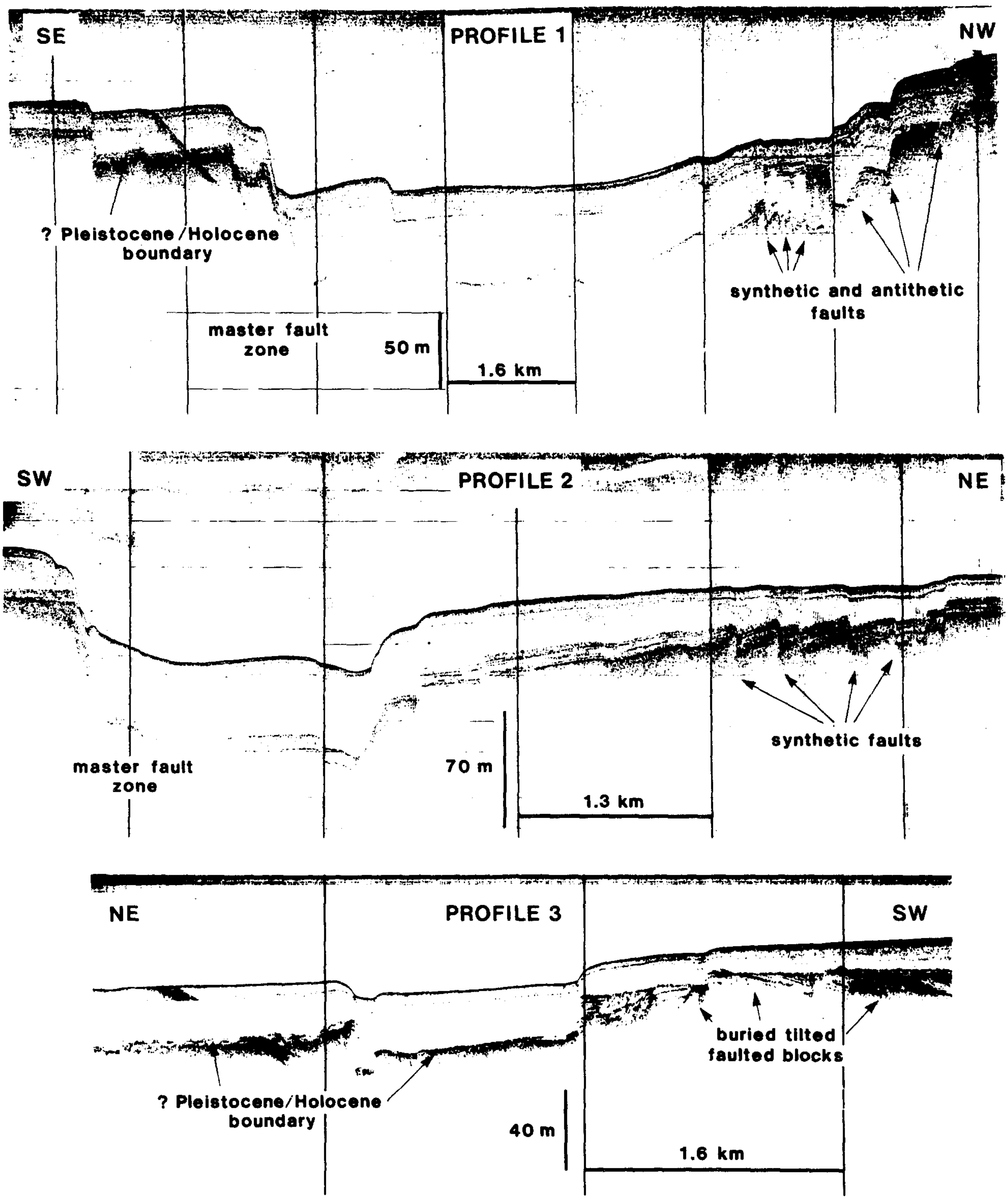

Fig. 3. 3.5 kHz profiles across the Gulf of Patras graben showing the (?)Pleistocene–Holocene unconformity and buried fault blocks. Profile locations shown as 1, 2 and 3 in Fig. 2 inset.

kHz records: the upper sequence has a transparent reflection character but the lower sequence contains strong, closely spaced, parallel or subparallel reflection events. Throughout the Gulf, the upper, Holocene sequence unconformably overlies this lower sequence which, typically, is either disposed in a series of tilted fault blocks (profile 3, Fig. 3) or affected by gentle growth folding. The lower sequence has not been dated but along the nearby shoreline, only 2 km south of profile 3, there are outcrops of Pliocene marls and Pleistocene sands and gravels and these are likely to underlie the Holocene veneer in the offshore area.

The Plio-Pleistocene sequences cropping out onshore in the southeast corner of the Gulf are affected by ENE–WSW normal faulting (Fig. 2) with displacements ranging from a few centimetres to over 10 m. This appears to be the direction of faulting against which the offshore graben terminates.

The inner segment of the Gulf represents the submerged part of a NE–SW trending graben which crops out onshore in the Rio-Antirio area (Fig. 2) (BP Ltd 1971, Doutsos & Kontopoulos in prep.). The sea bed in this part of the Gulf is not affected by active faulting. Air-gun records show growth faults to exist in the deeper parts of the Quaternary section but they do not extend to the surface. The trend of these buried faults cannot be established from existing data. They suggest that the zone of faulting has become more restricted during the Holocene. The evidence provided by buried faults for an earlier phase of subsidence is supported by the existence of a large negative Bouguer anomaly over the Gulf of Patras. This anomaly is attributed by Brooks (in prep.) to a local thickness of 2–3 km of Plio-Quaternary sediments.

To the west of the mapped limits of the trough shown in Fig. 2, in the approaches to the Gulf of Patras, is a broad area devoid of active faulting. This area, containing ill-defined zones of buried minor faults affecting the pre-Holocene sequence, extends out to the zone of active compressional tectonics in the Zakynthos and Kefallinia Channels described by Brooks & Ferentinos (1984).

By analogy with its eastern truncation at a zone of discordant structural trend, it is postulated that the graben is truncated westwards at a NE–SW fault zone lying immediately offshore from the Akra Papas to Killini coastal sector. Such a fault line, projected to the northeast, would align with the Evinos fault mapped by BP Ltd (1971) in the area north of the Gulf (see Fig. 1).

DISCUSSION

Compared with many other active basins of the Aegean region, for example, the nearby Gulf of Corinth basin and the Sporadhes basin of the North Aegean Trough, the Gulf of Patras is relatively shallow, the deepest part being little more than 100 m. The overall structural features revealed by the shallow reflection profiling are indicative that the Gulf of Patras trough was nevertheless formed by listric normal faulting and associated downbending in a similar way to the formation of the Gulf of Corinth basin and the Sporadhes basin (Brooks & Ferentinos 1980, 1984) and the Megara basin (Mariolakos & Papanikolaou 1982).

The angular unconformity observed between the Holocene and earlier sequences in the Gulf of Patras suggests that the Gulf was emergent during the late Pleistocene and that the present phase of subsidence was initiated in early Holocene times. On this assumption, the average rate of subsidence along the axis of the trough through the Holocene is about 10 mm/year, a much higher figure than those determined for the nearby Gulf of Corinth basin, namely 2 mm/year for the Holocene, 7 mm/year for the Neo-Tyrrhenian (Schröder & Kelletat 1976, Kelletat *et al.* 1976), and 5 mm/year of differential vertical movement between the sea floor and the flanking mountains from post-Calabrian to Holocene times (Brooks & Ferentinos 1984).

The average rate of sedimentation during the Holocene is estimated to be about 2.5 mm/year, which is considerably greater than the spatially averaged sedimentation rate of 0.5 mm/year for the present day Gulf determined by Piper & Panagos (1979). The estimated sedimentation rate for the Holocene of the Gulf of Patras is higher than rates determined for the nearby Gulf of Corinth basin, namely an average of 1 mm/year for turbidite sedimentation during the Quaternary (Brooks & Ferentinos 1984) and 1.5 mm/year for present day turbidite sedimentation (Varnavas *et al.* in prep.).

Two directions of major faulting with trends of WNW–ESE and NE–SW are observed in the Gulf of Patras. The full history of movement along these faults is not known, but the former set is now the more active since it controls the present day bathymetry of the Gulf. It is of interest to note that similar trends characterize the Gulf of Corinth. There also, the WNW–ESE faulting seems to be the more active as it defines the boundaries of the zone of major subsidence (Brooks & Ferentinos 1984). In both gulfs, grabens controlled by a WNW–ESE fault system terminate against NE–SW fault systems. Essentially N–S extension along the overall graben system at the present day implies a significant component of dextral strike slip along the NE–SW fault sectors. It should be noted that Mariolakos *et al.* (1982) postulated such movement along the NE–SW trending Pissia fault zone of the Perachora peninsula during the Corinth earthquakes of 1981, although a strike-slip component was not evident from focal mechanism studies of these events (Jackson *et al.* 1982). The NE–SW trending Evinos fault, however, whose extension to the southwest may truncate the Gulf of Patras graben, involves dextral strike-slip displacement (BP Ltd 1971).

The possible role of these discordant, NE–SW structures in truncating the WNW–ESE trending grabens is in delimiting individual upper crustal blocks that develop independent patterns of faulting in response to the prevailing extensional stress.

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REFERENCES

Anderson, E., Zoback, M. & Thompson, G. 1983. Implications of selected subsurface data on the structural form and evolution of some basins in the northern Basin and Range province, Nevada and Utah. *Bull. geol. Soc. Am.* **94**, 1055–1072.

Bally, A., Bernoulli, D., Davis, G. & Montadert, L. 1981. Listric normal faults. *Oceanologica Acta* (Proc. 26th Int. Geol. Congr. Geology of continental margins symposium, Paris, 1980) 87–101.

B.P. Ltd. 1971. *The Geological Results of Petroleum Exploration in Eastern Greece.* Institute for Geology and Subsurface Research, Athens.

Brooks, M. in prep. Geological interpretation of gravity anomalies in the Gulfs of Corinth and Patras, western Greece.

Brooks, M. & Ferentinos, G. 1980. Structure and evolution of the Sporadhes basin of the North Aegean trough, northern Aegean Sea. *Tectonophysics* **68**, 15–30.

Brooks, M. & Ferentinos, G. 1984. Tectonics and sedimentation in the Gulf of Corinth and the Zakynthos and Kefallinia Channels, western Greece. *Tectonophysics* **101**, 25–54.

Doutsos, T. & Kontopoulos, N. in prep. Des westliche ende der Korinth-Graben.

Dufaure, J. J., Kadjer, M. H., Keraudren, B., Mercier, J. L., Sauvage, J. & Sebrier, M. 1975. Les deformations plio-pleistocene autour du golf de Corinthe. *C.r. somm. Soc. géol. Fr.* 18–20.

Dufaure, J. J., Bosquet, B. & Pechoux, P. 1979. Contributions de la geomorphologie a la connaissance du Quaternaire continental grec, en relation avec les etudes de neotectonique. *Rev. Géogr. phys. Géol. dyn., Paris* **21**, 29–40.

Jackson, J. A., Cagnepain, J., Houseman, G., King, G., Papadimitriou, P., Soufleris, C. & Virieux, J. 1982. Seismicity, normal faulting and the geomorphological development of the Gulf of Corinth (Greece): the Corinth earthquakes of February and March 1981. *Earth Planet. Sci. Lett.* **57**, 377–397.

Hageman, J. 1977. Stratigraphy and sedimentary history of the Upper Cenozoic of the Pyrgos area (Western Peloponnesos), Greece. *Annls geol. Pays hell.* **22**, 299–333.

Kelletat, D., Kowazczyk, G., Schröder, B. & Winter, K. 1976. A synoptic view on the neotectonic development of the Peloponnesian coastal regions. *Zeit. Geol.* **27**, 447–465.

Makropoulos, K. & Burton, P. 1981. A catalogue of seismicity in Greece and adjacent areas. *Geophys. J.R. astr. Soc.* **65**, 741–762.

Mariolakos, S., Papanikolaou, D., Symeonidis, N., Lekkas, S., Karotsieris, Z. & Sideris, Ch. 1982. The deformation of the area around the eastern Korinthian Gulf, affected by the earthquakes of February–March 1981. *Proceedings of the International Symposium on the Hellenic Arc and Trench* (H.E.A.T.). **I**, 400–421.

Mariolakos, J. & Papanikolaou, D. 1982. The Neogene basins of the Aegean arc from the palaeogeographic and the geodynamic point of view. *Proceedings of the International Symposium on the Hellenic Arc and Trench* (H.E.A.T.). **I**, 383–399.

Papazachos, B. C., Comninakis, P. E., Moundrakis, D. & Pavlides, S. 1982. Preliminary results of an investigation of the February/March 1981 Alkionides Gulf (Greece) earthquakes. *Proceedings of the International Symposium on the Hellenic Arc and Trench* (H.E.A.T.). **II**, 74–87.

Piper, D. J. & Panagos, A. 1979. Surficial sediments of the Gulf of Patras. *Thalassographica* **3**, 5–20.

Piper, D. J. & Panagos, A. 1981. Growth patterns of the Acheloos and Evinos deltas, western Greece. *Sediment. Geol.* **28**, 111–132.

Schröder, B. & Kelletat, D. 1976. Geodynamical conclusions from the vertical displacement of Quaternary shorelines in the Peloponnesos, Greece. *Neues Jb. Geol. Paläont. Mh.* **3**, 174–186.

Varnavas, S., Ferentinos, G. & Collins, M. B. in prep. Dispersion of bauxitic red mud in the Gulf of Corinth, Greece.

Wernicke, B. & Burchfiel, B. 1983. Modes of extensional tectonics. *J. Struct. Geol.* **4**, 105–115.