TECTONICS AND SEDIMENTATION IN THE GULF OF CORINTH AND THE ZAKYNTHOS AND KEFALLINIA CHANNELS, WESTERN GREECE

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ABSTRACT


Single-channel seismic reflection profiling data are presented from the Gulf of Corinth and from the continental margin outside the Gulf of Patras. Different tectonic styles are exhibited in the two regions. The Gulf of Corinth is occupied by a complex asymmetrical graben structure with major faults trending nearly perpendicular to the local tectonic zones of the Internal Hellenides. The Gulf is interpreted to have formed during the Quaternary in response to approximately north–south extensional stress. The deep floor of the Gulf is underlain by a sequence of turbidites up to 1 km thick affected by normal growth faulting that extends up to the sea floor.

The sea areas inside the Ionian Islands of Zakynthos and Kefallinia (Zakynthos and Kefallinia Channels) occupy a broad structural depression that trends parallel to the local tectonic zones of the External Hellenides and is situated on the continental side of the Strophades continental margin rise. The Channels contain local NW–SE trending structural basins (Zakynthos and Kefallinia basins) whose geometry is controlled by reverse faults or thrusts with associated diapirism in Triassic evaporites. Hydra Bank is interpreted as a tilted fault block with a diapiric core and its faulted western margin can be traced into the zone of thrusting and diapirism in southeast Kefallinia at the boundary between the Ionian and pre-Apulian (Paxos) zones of the External Hellenides. The Zakynthos and Kefallinia structural basins are filled with a variety of sediments including prodeltaic deposits (in front of the modern delta complex of the Acheloos river), slumped masses and debris flow deposits and, in the Zakynthos basin, occasional turbidites.

The boundary separating zones of extensional and compressional focal mechanisms for shallow earthquakes crosses the Gulf of Patras, the inner part of which exhibits WNW–ESE trending graben tectonics apparently related to the Gulf of Corinth tectonic province. Onshore neotectonic studies around the Gulf of Patras are required in order to understand the nature and cause of the westward tectonic transition from WNW–ESE graben structures in the Gulfs of Corinth and Patras to NW–SE oriented zones of subsidence with associated compressional tectonics and diapirism in the Zakynthos and Kefallinia Channels.
INTRODUCTION

The seismic data that form the basis of this paper were collected during RRS "Shackleton" cruise 1/82 to the eastern Ionian Sea, Gulf of Patras and Gulf of Corinth (see Fig. 1), in January-February 1982. The major geological objective of this multidisciplinary research cruise was a study of the differing neotectonic environments within an E–W zone of high seismicity extending from the interior of the Aegean domain to its margin with the African plate, i.e. from the eastern end of the Gulf of Corinth to the northwestern Hellenic trench.

During the past ten million years or so, the Aegean area has undergone major crustal extension (Angelier, 1977; Le Pichon and Angelier, 1979). The associated neotectonic deformation is complex, involving discrete phases of deformation and regional variation in the type of deformation. According to Mercier et al. (1979), a normal regime involving a western marginal zone of compression (associated with subduction of the African plate beneath the Aegean area) and an internal zone of extension is interrupted by discrete regional compressive phases evidenced by the widespread occurrence of minor reverse faults, notably of early Pliocene and early Quaternary age, in the central and northern Aegean area. This view has been challenged recently by Jackson et al. (1982b) who suggested that the reverse faults may represent merely local accommodation structures in rotated fault blocks formed in an extensional regime rather than the products of regional compression.

Onshore neotectonic studies and earthquake focal mechanisms suggest that the Gulf of Corinth is currently in extension and that the continental margin adjacent to the northwestern Hellenic trench is in compression. Seismic sections illustrating the contrasting tectonic and associated sedimentary environments in these two areas are presented in this paper.

The Gulf of Corinth cuts across the NW–SE regional trend of the Hellenide (Alpine) mountain chain and overlies the Pindus, Parnassos and Othris isopic zones of the Internal Hellenides. The Gulf has been formed by very recent subsidence, and focal mechanism studies (Papazachos, 1976; McKenzie, 1978) show that it is associated with approximately north–south crustal extension. Very large vertical movements are involved, with over 3000 m of relief between the deepest parts of the Gulf and the peaks of flanking mountains in the northern Peloponnnesos and Sterea Helladha (Fig. 1).

The offshore islands of Kefallinia and Zakynthos (Zante) lie respectively north-west and southwest of the entrance to the Gulf of Patras and are separated from the mainland by narrow stretches of water referred to here as the Kefallinia and Zakynthos Channels (Fig. 1). This offshore region overlies the Apulian, pre-Apulian (Paxos) and Ionian zones of the External Hellenides and has been interpreted as an area of compressional tectonics on the basis of focal mechanism studies (McKenzie, 1978), analysis of faults in local Neogene and Quaternary sediments (Mercier et al., 1976) and offshore seismic surveys (Monopolis and Bruneton, 1982).
These two marine areas of contrasting tectonics have not previously been investigated in detail. Two small-scale reproductions of deep seismic sections from the eastern end of the Gulf of Corinth were presented by Myrianthis (1982). The sections show that the Plio-Quaternary locally has a maximum thickness of over 1 km but they do not resolve the seismic character of the sedimentary infill or the pattern of synsedimentary tectonics affecting the sediment pile. Published data from the Kefallinia and Zakynthos Channels are restricted to one short deep reflection profile from Zakynthos Channel (Monopolis and Bruneton, 1982). The two areas were investigated during RRS “Shackleton” cruise 1/82 by means of gravity and magnetic surveying and by single-channel and multichannel seismic profiling. About 2000 line km of single-channel seismic profiling were obtained and representative seismic sections are presented here to form a basis for discussion of major structural basins in the two areas and of sedimentary processes operating within them. The sections illustrated were obtained using a 40 inch$^3$ air-gun source (with waveshaping) together with a 16-element, 30 m long hydrophone streamer. The recordings were bandpass filtered in the 150–400 Hz range.
Heezen et al. (1966) recognised three distinct physiographic provinces in the Gulf of Corinth: shelf, slope and floor, the latter being subdivided into a rise and an abyssal plain. The slope along the southern margin of the Gulf is much steeper (30°–40°) than that along the northern margin (10°–20°) giving the Gulf a distinct bathymetric asymmetry. The narrow shelves and the slopes around the margins of the Gulf are dissected by canyon systems associated with the mouths of major rivers and these feed deep-sea fans that spread out on to the floor of the Gulf. The abyssal plain occupies the central area of the Gulf and is very flat at a depth of about 850 m; the plain has a length of about 40 km and a maximum width of about 14 km (see Fig.2).

Onshore zones of normal faulting lie parallel to the northern and southern coastlines of the Gulf (I.G.M.E. 1:50,000 geological map series) and these show a pattern of repeated movements through the Plio-Quaternary (Dufaure, 1977; Dufaure et al., 1979). The region is seismically very active and destructive earthquakes in 1981 were associated with movements along normal faults at the eastern end of the Gulf (Jackson et al., 1982a).

The marine seismic surveys show offshore faults trending WNW–ESE, parallel or subparallel to the long coastlines of the Gulf (see Fig. 2). The northern and southern limits of the deep floor are fault-controlled and the overall structure of the Gulf is a complex asymmetrical graben whose geometry varies significantly along the length.

Fig. 2. Outline structural map of central and east-central parts of Gulf of Corinth.
Fig. 3. Seismic section SSE-NNW across Gulf of Corinth (for location, see Fig. 2). X = basal reflector beneath turbidite sequence.
Fig. 4. Seismic section NE-SW across Gulf of Corinth (for location, see Fig. 2). L = listric growth fault; X = basal reflector beneath turbidite sequence.
of the Gulf. Representative seismic sections are illustrated in Figs. 3 and 4 and simple structural interpretations are shown in Fig. 5. The steep southern slope of the Gulf is the site of major normal faulting, though with the limited penetration and non-migrated nature of the single-channel data it cannot be determined whether this major faulting is planar or listric. Fault $L$ in Fig. 4 is a major listric normal growth fault with a maximum throw exceeding 400 m that cuts obliquely across the abyssal plain and locally subdivides the Gulf into two half-grabens (see Fig. 2). Away from the major faults, the sediments beneath the abyssal plain have been deformed by antithetic and synthetic normal growth faults, with some tilting of individual fault blocks. Extension of growth faulting up to the sea bed gives evidence of active synsedimentary tectonism. This type of deformation is very characteristic of an active extensional regime (see, e.g., Brooks and Ferentinos, 1980).

Based on reflection character, the top seismic unit beneath the floor of the abyssal plain, reaching a maximum thickness of about 1000 m, is interpreted as a turbidite sequence with intercalations of debris flow deposits. The turbidites, which form the vast bulk of the graben fill, are characterised by closely-spaced and laterally

Fig. 5. Simple structural interpretations of seismic sections from Gulf of Corinth. a. Seismic section of Fig. 3. b. Seismic section of Fig. 4.
persistent parallel or subparallel reflectors. The sequence contains several minor angular discordances exhibiting onlapping relationships, and these are attributed to episodes of synsedimentary tectonic deformation of the sea floor. The almost perfectly flat nature of the floor represents a nearly perfect dynamic balance between the rates of deformation and deposition. Concentration of turbidite deposition in the low points of the abyssal plain bathymetry tends to erase subtle relief features caused by incipient tectonic movements of the sea floor. The ability of the turbidity currents to seek out the lowest bathymetric points across slopes of typically less than 0.1° implies that the currents exhibit very low viscosity.

Interpretation of deposits beneath the floor of the Gulf as turbidites and interbedded debris flow deposits is in line with the findings of Heezen et al. (1966) who obtained seven piston core samples up to 9 m in length from the various physiographic provinces of the Gulf. They found evidence of slumping in core material from the rise and abyssal plain, and obtained sands and silts of assumed turbiditic character from the abyssal plain. Further, Heezen et al. attributed the many recorded instances of breakage of submarine telegraph cables laid along the length of the Gulf to the action of slumps and turbidity currents.

The reflection character of the turbidite sequence varies both vertically and laterally. The lower part of the sequence generally has a more transparent aspect and an absence of strong internal reflectors (see Figs. 3 and 4). The upper part of the sequence contains more closely spaced and stronger reflectors. Within distinctive packets of reflectors there is a general tendency for reflection strength to reduce laterally from north to south across the Gulf and this may represent the transition from the more proximal to the more distal zone of turbidite deposition. On this basis it would be predicted that the dominant source areas for the turbidites lie at the northern margin of the Gulf, though it should be noted that Heezen et al. tentatively suggested a southwestern or western source for the surface layers they sampled.

The lower, more transparent part of the turbidite sequence beneath the abyssal plain can in some transects be traced up to surface under the northern slope where it is deformed by tilting and faulting and disrupted by rotational slides and slumps. The extension of this lower turbidite sequence under the northern flank of the Gulf clearly indicates that the abyssal plain has previously been wider, by up to 4 km, than at the present day and that it has subsequently been constricted by differential movements along the northern margin. The transparent character of the lower sequence under the plain is then conveniently interpreted as the most distal turbidite facies represented in the Gulf, associated with a period when the abyssal plain was significantly wider and the turbidite source area consequently more distant than at the present day.

The intercalated debris flow deposits can be recognised in the seismic sections by several factors including a hummocky top surface (represented by a hyperbolic pattern of reflections), an absence of coherent internal reflectors, typical occurrence at the foot of slopes, and shallow channelling of low aspect ratio into underlying
sediments as observed on sections parallel to the base of slopes.

In the absence of deep drilling the age range of the turbidite sequence cannot be established directly. South of the Gulf, shallow marine marls and fluvi-lacustrine sequences of Pliocene and Calabrian age pass upwards into terrestrial sand and gravel sequences of later Pleistocene and Holocene age (Kelletat et al., 1976). Quaternary deposits north of the Gulf are restricted to local alluvial fan sequences which in almost all cases lie directly on pre-Neogene rocks. Initial subsidence of the Gulf may be synchronous with deposition of shallow marine and lacustrine sequences to the south but the main subsidence and associated uplift of flanking mountains, marked by a sequence of terrace deposits, is of post-Calabrian age. Thus the turbidite sequence is assumed to be entirely of post-Calabrian age and a lower seismic unit (see Figs. 3 and 4, reflector X) flooring the turbidites and approaching the sea bed under shelf areas of the Gulf may represent shallow water Calabrian deposits.

Based on the assumption of a post-Calabrian age for the main subsidence of the Gulf, the average rate of differential vertical movement between the subsiding Gulf floor and uplifting flanking mountains is about 5 mm/yr and the average rate of turbidite sedimentation is about 1 mm/yr (100 cm/1000 yr).

KEFALLINIA AND ZAKYNTHOS CHANNELS

Within the region of the Kefallinia and Zakynthos Channels three distinct physiographic provinces can be recognised (see Fig. 6): (a) a shallow water area, underlain by a thick deltaic sequence, extending from the modern delta of the Acheloos river out into the outer part of the Gulf of Patras and the eastern half of the Kefallinia Channel; (b) shallow and narrow shelves fringing the Peloponnesos coast and the east coasts of Kefallinia and Zakynthos; and (c) two narrow, elongate depressions, one in the Zakynthos Channel reaching water depths of 520 m and one in the Kefallinia Channel with water depths reaching 340 m, separated by a NNW–SSE trending ridge passing through Hydra Bank.

A thick sequence of Neogene and Quaternary sediments, locally exceeding 1000 m, is preserved onshore in structural basins in the northwest Peloponnese and on the islands of Kefallinia and Zakynthos. A wide variety of sedimentary facies is represented, from open marine, through lagoonal to lacustrine and alluvial, with marked differences of detailed stratigraphy across the region. Extensive drilling onshore and offshore shows parts of the region to be underlain by thick Triassic evaporites and the Neogene and Quaternary sequences are locally deformed by diapirism, notably on the Killini peninsula of the western Peloponnese (Kowalczyk and Winter, 1979) and in the southeast of Zakynthos (Sorel, 1976; Dermitzakis, 1978). Mercier et al. (1976) claimed that reverse faulting in Plio-Quaternary sequences on Kefallinia provides evidence that the area has been in NE–SW compression since early Pliocene times.
Multichannel seismic reflection surveys (Monopolis and Bruneton, 1982) show the local offshore area to be underlain by a Plio-Quaternary sequence estimated to be up to 5000 m thick disposed in a broad structural depression affected by major faulting and large-scale diapirism. The Plio-Quaternary sequence thins rapidly westwards on to Miocene and earlier rocks along a structural high extending along the outer part of the shelf from Zakynthos to the Strophades Islands and known as the Strophades rise (Le Quellec et al., 1980; Lyberis and Bizon, 1981). The major structural depression continues to the south inside the Strophades rise into the
Fig. 7. Seismic section SW-NE across Zakynthos basin, northern part of Hydra Bank and Kefallinia basin (for location, see Fig. 6).
Fig. 8. Seismic section WNW-ESE across Zakynthos basin, Hydra Bank and Kefallinia basin (for location, see Fig 6). D = sites of major diapirism.

Fig. 9. Simple structural interpretations of seismic sections from Zakynthos and Kefallinia Channels. a. Seismic section of Fig. 7. b. Seismic section of Fig. 8.
Fig. 10. a. Seismic section obliquely crossing the northern part of Zakynthos basin showing major slumping and associated slide scar. b. Seismic section across the flank of the Kefallinia basin showing a deformed deltaic foreset at the outer margin of the Acheloos delta complex. Deformation probably results from incipient diapirism. c. Seismic section across the shallow water area of the Acheloos delta complex showing a sequence of deltaic foresets that have accumulated in a subsiding environment (for location, see Fig. 6).
Fig. 11. Seismic section across deeper part of Zakynthos basin between Zante harbour and Killini peninsula (for location, see Fig. 6).
Kefallinia–Zakynthos plateau (see Fig. 1) which is underlain by thick Plio-Quaternary sediments (Hinz, 1974; Vittori et al., 1981).

Air-gun records collected during “Shackleton” cruise 1/82 do not penetrate the full thickness of the Plio-Quaternary sequence but show the upper part to be disposed in a series of synclinal basins coincident with bathymetric depressions. Figs 7, 8 and 11 show seismic sections illustrating the varying geometry and different sedimentary facies of the synclinal basins occupying the Kefallinia and Zakynthos Channels. Simple structural interpretations of the seismic sections of Figs. 7 and 8 are shown in Fig. 9.

The type of sediment occupying these synclinal basins varies across the region. In sections extending from the north of Zakynthos towards the Acheloos delta (Figs. 7 and 8) the bulk of the sequence is represented on seismic records by thick units with laterally-persistent parallel, subparallel or divergent internal reflectors bounded by planes of slight angular discordance. These units are interspersed with thin debris flow deposits and slumped masses, often very large, accumulating in the bottoms of basins with associated slide scars at a higher level on the basin flanks (see Fig. 10a).

The layered parts of the sequence in the Kefallinia structural basin can in some cases (Figs. 10b, c) be traced laterally into deltaic foresets of the Acheloos delta complex and may therefore represent foundered and tectonised prodeltaic deposits.

Further south, a seismic section across the Zakynthos structural basin between Zakynthos harbour and the Killini peninsula (Fig. 11) shows a faulted syncline with flanks assumed, on the basis of nearby onshore exposures, to be composed of Pliocene deposits. The axial part of the basin is filled with an assumed Quaternary sequence largely composed of slumped material and debris flow deposits with occasional thin units exhibiting good parallel internal reflectors, of possible turbiditic origin.

Air-gun seismic records from the Kefallinia and Zakynthos Channels contain abundant evidence of diapirism occurring along zones that can in some cases be traced onshore into areas of outcropping Triassic evaporites. The most spectacular example is represented by Hydra Bank (Fig. 8) which is interpreted to contain a core of evaporitic material. The bank has undergone local uplift of about 1 km relative to the floors of its flanking basins. The diapirism represented by the Bank and by the adjacent anticlinal structure to the northeast (see Fig. 8) are strikingly similar to examples of diapirism from other parts of the western Hellenic arc (e.g., Vittori et al., 1981, fig. 10E) and other parts of the world (e.g., the Sigsbee Knolls region of the Gulf of Mexico: Worzel and Burk, 1979, figs. 2 and 3).

The western margin of Hydra Bank appears to be a major fault but the sediments are steeply draped over the eastern margin without any obvious faulting (Fig. 9). This type of asymmetry is exhibited to some degree by most of the diapirs recognised in the present study and suggests that the diapirs are on the sites of reverse faults, as suggested by Monopolis and Bruneton (1982, fig. 4c), or thrust ramps.
The close association between major faulting and diapirism is well shown in Fig. 7 which illustrates a complete section through the northern part of the Zakynthos Channel basin whose margins crop out on Zakynthos and Kefallinia respectively (see Fig. 6). Outcrops of the western margin on Zakynthos show Neogene unconformably overlying Palaeogene and Cretaceous strata without any faulting. The faulted eastern margin of the basin at Hydra Bank aligns with the zone of thrusting in southeast Kefallinia at the boundary between the Ionian and pre-Apulian (Paxos) zones of the External Hellenides, and the Bank is therefore taken to mark the offshore extension of the Ionian thrust front.

DISCUSSION

The new offshore data from the Gulf of Corinth show it to be occupied by a complex asymmetrical graben structure indicative of recent north-south crustal extension. No evidence of extensional tectonics is found in the offshore region of the Kefallinia and Zakynthos Channels at the continental margin, the major fault line along the western side of Hydra Bank being interpreted as a reverse fault or thrust ramp and correlated with the Ionian thrust front cropping out nearby in southeast Kefallinia. Much of the neotectonic deformation of local Neogene and Quaternary sequences in the Kefallinia and Zakynthos Channels is related to diapirism that is assumed to be activated by the regional compressional stress.

An unresolved problem is the nature and underlying cause of the westward transition from east-west trending graben tectonics in the Gulf of Corinth to NW-SE trending basins and rises and associated zones of reverse faulting and diapirism at the continental margin. A difficulty with the marine geophysical data is that the east-west trending normal faults located in the central and eastern parts of the Gulf of Corinth cannot be traced through the narrow and shallow straits separating the Gulf of Corinth from the Gulf of Patras. The shallow waters there, and in the Gulf of Patras, lead to rather poor seismic records but these nevertheless reveal the existence, in the Gulf of Patras, of a small-scale, WNW-ESE trending half-graben.

The Gulf of Patras may therefore represent an incipient Gulf of Corinth situation which could develop in due course into a major, complex asymmetrical graben with an increased rate of subsidence creating a zone of deep water, as in the Gulf of Corinth. However, a negative Bouguer gravity anomaly of about 40 mGal overlies the Gulf of Patras, suggesting that it contains a very thick fill of young (? Pliocene) sediments. Thus the Gulf might in fact represent a Gulf of Corinth situation in which a recent reduction in the rate of subsidence has led to the sedimentary infilling of a pre-existing zone of deep water.

The boundary between compressional and extensional focal mechanisms for shallow earthquakes trends NNW-SSE across the Gulf of Patras (Ritsema, 1973; Mercier et al., 1979) so that the inner part of the Gulf, at least, appears to belong to
the same extensional regime as the Gulf of Corinth. Immediately to the west, in the outer part of the Gulf of Patras, the shallow sea floor is underlain by thick sediments of the Acheloos delta complex. These sediments are remarkably untectonised and appear in general to have suffered only subsidence and gentle tilting to the northeast. Further west is encountered the first zone of diapiric structures and, beyond these, the Kefallinia structural basin (see Fig. 6). In order to understand the nature and cause of the lateral structural transition from the Gulf of Corinth regime to the Zakynthos and Kefallinia Channel regime, a major effort of onshore neotectonic analysis is required in the Neogene and Quaternary sequences of coastal areas around the Gulf of Patras.

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