Tectono-sedimentary processes along an active marine/lacustrine half-graben margin: Alkyonides Gulf, E. Gulf of Corinth, Greece

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ABSTRACT

The Alkyonides half-graben is separated from the Gerania Range to the south by active faults whose offshore traces are mapped in detail. The East Alkyonides and Psatha Faults have well-defined, Holocene-active tip zones and cannot be extrapolated from the onshore Skinos Fault into a single continuous surface trace. During the late Quaternary, catchments draining the step-faulted range front have supplied sediment to alluvial fans along a subsiding marine ramp margin in the hangingwall of the Skinos Fault, to shelf ledge fans on the uplifting footwall to the East Alkyonides Fault and to the Alepochori submarine fan in the hangingwall of the latter. During late Pleistocene lowstand times (c. 70–12 ka), sediment was deposited in Lake Corinth as fan deltas on the subsiding Skinos shelf ramp which acted as a sediment trap for the adjacent 360 m deep submarine basin plain. At the same time, the uplifting eastern shelf ledge was exposed, eroded and bypassed in favour of deposition on the Alepochori submarine fan. During Holocene times, the Skinos bajada was first the site of stability and soil formation, and then of substantial deposition before modern marine erosion cut a prominent cliffline. The uplifting eastern shelf ledge has developed substantial Holocene fan lobe depositional sequences as sediment-laden underflows have traversed it via outlet channels. We estimate mean Holocene displacement rates towards the tip of the Psatha Fault in the range 0.7–0.8 mm year⁻¹. Raised Holocene coastal notches indicate that this may be further partitioned into about 0.2 mm year⁻¹ of footwall uplift and hence 0.5–0.6 mm year⁻¹ of hangingwall subsidence. Holocene displacement rates towards the tip of the active East Alkyonides Fault are in the range 0.2–0.3 mm year⁻¹. Any uplift of the West Alkyonides Fault footwall is not keeping pace with subsidence of the Skinos Fault hangingwall, as revealed by lowstand shelf fan deltas which show internal clinoforms indicative of aggradational deposition in response to relative base-level rise due to active hangingwall subsidence along the Skinos Fault. Total subsidence here during the last 58 kyr lowstand interval of Lake Corinth was some 20 m, indicating a reduced net displacement rate compared to estimates of late Holocene (<2000 yr) activity from onshore palaeoseismology. This discrepancy may be due to the competition between uplift on the West Alkyonides Fault and subsidence on the onshore Skinos Fault, or may reflect unsteady rates of Skinos Fault displacement over tens of thousands of years.

INTRODUCTION

The morphology and topography of active rift-basin margins are controlled by normal faults, whose displacements determine regional patterns of subsidence and uplift. Rapid gradient changes ensure that sediment
eroded from uplifted bedrock is quickly deposited in adjacent areas undergoing subsidence. A fault-line bajada (base-of-slope) results, marked by the accumulation of coarse sediment in coalesced alluvial fans, fan deltas, talus cones and submarine fans (see review by Gawthorpe & Leeder, 2000). Such deposits contain valuable evidence for:

1. evolution of the faults responsible for topographic differentiation;
2. space and time history of rates of erosion and deposition;
3. palaeoclimate and history of sea- or lake-level changes.

In addition, similar deposits in the stratigraphic record form important hydrocarbon reservoirs in 'syn-rift' plays or define regionally important water aquifers.

In this contribution, we examine the evolution of the active faulted margin to one of the world’s most rapidly extending half-grabens, that of the southern shoreline of the Alkyonides Gulf in the E. Gulf of Corinth, Greece (Fig. 1). Our studies here are predicated on previous broad-scale geophysical surveys that include this area (Perissoratis et al., 1986; Sakellariou et al., 1998), the description and analysis of active faulting that accompanied the 1981 Gulf of Corinth earthquake sequence (Jackson et al., 1982; Taymaz et al., 1991; Papatheodorou & Ferentinos, 1993; Armijo et al., 1996; Hubert et al., 1996), studies of palaeoseismicity along the same faults (Pantosti et al., 1996; Collier et al., 1998) and studies of onshore parts of the basin margin (Leeder et al., 1991; Collier et al., 1992; Roberts, 1996). This previous work established the broad half-graben structure to the Gulf, the nature of the coastal range front and bajada and its relationship to faulting, the distribution and magnitude of active uplift and subsidence, palaeoseismic events back to 2000 BP and the development of drainage catchments in bedrock of variable erodability.

Important unanswered questions relate to the relationship of the onshore to the offshore record of tectonics and sedimentation during Quaternary highstands and lowstands. In particular, the relationship between the 1981 onshore and offshore faulting has been hitherto neglected but is particularly important in constraining dynamic (Armijo et al., 1996; Hubert et al., 1996) and conceptual (Roberts, 1996) fault modelling. It is the purpose of the present paper to outline the late Quaternary evolution of the southern faulted margin, making use of new offshore geophysical data. In particular, we assess the varied sedimentary response to sea-level change in coastal

![Fig. 1. Location maps, general bathymetry and topography for the Gulf of Corinth according to previous workers (partly after Papatheodorou & Ferentinos, 1993; Armijo et al., 1996; Lymperis et al., 1998). Note the north-throwing active normal fault array that defines the southern Gulf margin. The box around the Alkyonides Gulf indicates the 1996 marine geophysical and sedimentological cruise study area, new results from which constrain the structural geometry of this key location (see Fig. 3 and subsequent figures for newly mapped faults). Epicentres for the 1981 earthquake sequence are shown (after Taymaz et al., 1991), the most easterly of which is associated with a south-throwing antithetic fault. Other antithetic faults occur in and along the northern basin margin (e.g. Lymperis et al., 1998; Piccardi, 2000), but these are not shown here for clarity.](image-url)
CHAPTER 1

DEPOSITS AND SEDIMENTATION PROCESSES

METHODOLOGY

A marine geophysical survey and gravity coring programme undertaken in the Alkyonides Gulf during June 1996 was designed to elucidate the problems identified above. Positioning of the survey vessel, M.V. Vasileos G of Patras, was controlled by a Trimble 4000 differential geographical positioning system with a base station located onshore, using NORCOM software. A total of 154 km of single-channel sparker seismic data were acquired using a 700 J sparker source, Kemo VBF21-M amplifier and four hydrophone receiver spread. Data were band-pass filtered (high pass, 70 Hz; low pass, 1100 Hz); 125 km of 3.5 kHz pinger data were also acquired, and 23 gravity cores up to 2.65 m in length, together with numerous grab samples, were taken. Seismic line spacing (see Fig. 2 for coverage) in the detailed study area considered in this paper was generally 1.5–2 km for the sparker profiles and 1–1.5 km for pinger lines.

Published results from the cruise have so far highlighted palaeoenvironmental and sediment budget studies (Collier et al., 2000). These tested rival Quaternary climate models, supporting a cool wet winter scenario with enhanced catchment erosion rates for the last glacial period, and establishing the first direct evidence for earlier suggestions (Piper & Panagos, 1979; Richter et al., 1979) that the Gulf of Corinth was nonmarine (Lake Corinth) during glacial lowstands when sea-level fell below the level of the Rion sill, approximately −70 m, at the western entrance to the Gulf from the Ionian Sea (see also Perissoratis et al., 2000).

In the current offshore study, we have carefully mapped bathymetry, morphology and seismic stratigraphy for all seismic lines (about 150 km in total) that straddle the faulted coastal margin to the Alkyonides Gulf. In order to constrain onshore Holocene sedimentation rates, we have mapped alluvial fan deposits and obtained new 14C dates from palaeosol horizons.

BASIN MARGIN MORPHOLOGY AND FAULTING

New bathymetric and geophysical data (Figs 2 and 3) reveal the 219 km² Alkyonides Gulf to be an asymmetric half-graben with a steep (30–50°) southern, step-faulted margin. The majority of the basin floor defines a wide, gently south-sloping (3–6°) hangingwall ramp. The embayed and often linear shorelines of the northern margin reflect prominent anti-tectonic faulting. The Alkyonides Gulf is separated from the main Corinth Gulf by a prominent faulted Mesozoic basement horst (Figs 2 and 3) that lies above sea-level as the Alkyonides Islands. The southerly connection between the two Gulfs is via a narrow fault-bounded channel. Onshore, the southern tectonic margin is best defined to the west by the impressive double escarpment in Mesozoic basement formed by the active Pisia and Skinos Faults and to the east by the Psatha Fault (Jackson et al., 1982). The tip zone of the Psatha Fault runs offshore onto a narrow shelf as a series of spays.

We have mapped two kinds of offshore fault (Fig. 3) from our seismic lines. 1 Major, steep (30–50°), linear escarpments with acoustically opaque reflectors (Type 1 of Papatheodorou & Ferentinos, 1993) are indicative, although not necessarily

Fig. 2. Map of detailed study area to show 1996 offshore geophysical survey lines. Also shown are offshore faults associated with the Strava graben, as mapped by Papatheodorou & Ferentinos (1993), and onshore fault breaks associated with the 1981 earthquake sequence and other onshore faults and scarps, as mapped by Jackson et al. (1982) and the authors.
diagnostic, of Mesozoic basement in fault footwalls. Further evidence for faulting as the origin of these escarpments comes from their position ‘on-trend’ from onshore faulted basement ridges and/or their sharp contacts with stratified Quaternary sediments that exhibit normal and reverse drag features and evidence for stratal thickening and facies changes towards the fault trace. We are unable to determine fault displacements in this kind of fault because of the lack of recognizable stratigraphic offsets between footwall and hangingwall deposits. The extrapolation of ‘top basement’ obtained in fault hangingwalls at the limit of penetration of our sparker source indicates >1 km of total displacement on the largest offshore structures.

2 The second type of fault cuts the offshore basin fill either as relatively minor structures or defines the tip zones to some of the major structures noted previously. In both cases, the faults may cause seabed subsidence and cut stratified late Quaternary sediment, thus making possible the determination of local displacements. Significantly, in most shallow water areas (<60 m depth), we see displacement of a very strong sub-bottom reflector under a few metres of surficial sediment (Fig. 4). We interpret such features to be faulted last glacial lowstand land surfaces overlain by Holocene sediment. Because we know from previous studies in the area (Collier et al., 2000; Perissoratis et al., 2000) that late Pleistocene Lake Corinth, whose water surface was at a depth of ~70 m

Fig. 3. Alkyonides Gulf bathymetry (in metres) and faults mapped from geophysical data of the 1996 cruise, together with previously known onshore faults and topography (in metres). Major right-stepping offshore faults of the southern Gulf margin are emphasized. Intrabasinal faults have a lower line weight. The exact relationship between the tips of the Strava and West Alkyonides Faults is not established. The Kaparelli Fault is an antithetic structure (see Jackson et al., 1982).
Fig. 4. Details of interpreted traces, together with one original record, from 3.5 kHz pinger profiles to illustrate the nature of evidence for Holocene movements on tip splay to the East Alkyonides (maximum 2.5–3 m displacement) and Psatha (maximum 8–10 m displacement) Faults. Both faults show clear displacements of prominent reflectors interpreted as last glacial maximum lowstand land surfaces. The solid and broken vertical lines on the original trace are position lines.

with respect to modern sea-level, gave way to marine conditions at about 12 ka, we may use the displacement of such chronostratigraphic markers as indicative of active (i.e. Holocene-active) faulting.

Two major offshore structures, the West and East Alkyonides Faults (nomenclature after Lymeris et al., 1998), dominate the topography of the offshore southern Gulf margin (Fig. 3). The >15 km long E–W-trending West Alkyonides Fault lies on the same trend as the eastern termination to the active Strava Fault as mapped by Papatheodorou & Ferentinos (1993), but the lack of seismic lines over intervening ground means that we cannot be sure of the exact relationship between the two structures. The submarine scarp, in sharp contact with the near-horizontal Alkyonides basin plain (see discussion below and Fig. 7), has a relatively gentle slope (up to 30°) with two to three prominent slope concavities, possibly related to erosion by mass wasting. We cannot directly observe whether the offshore fault has been active in the Holocene because Holocene chronostratigraphic markers cannot be traced between hangingwall and footwall. It should be noted that the West Alkyonides Fault
lies seawards and in the hangingwall to the active onshore Skinos Fault which ruptured in 1981 (Fig. 3). The magnitude of bed rotations in the hangingwall of the West Alkyonides Fault can be fully explained by subsidence on the onshore Skinos Fault. Evidence from coastal morphology and the subsurface seismic stratigraphy of the coast and coastal shelf presented below supports the inference that the fault has been relatively inactive in the late Quaternary, subsiding under the influence of the active onshore Skinos structure.

The East Alkyonides Fault is a 10 km long, Holocene-active (Figs 3 and 4), right-stepping structure that carries on deformation to the NE of the tip to the West Alkyonides Fault. Along most of its length, the fault line is a steep (up to 50°) linear scarp up to 250 m high with an abrupt basal contact with the Alepochori submarine fan. The NE tip to the fault in Psathia Bay (Fig. 4) is noteworthy for its termination in complex ‘horsetail’ spays, some of which exhibit Holocene growth faulting, and ~3 m displacements of a prominent subsurface reflector which, following our previous discussion, we interpret as the last glacial maximum lowest land surface (Fig. 4). Longer term footwall uplift on the East Alkyonides Fault is indicated by three onshore raised coastal terraces, the oldest recognizable at about +35 m elevation. This contains a coral fauna that has been U-series dated from oxygen isotope Stage 5, probably 5e (Leeder et al., 1991; Collier et al., 1992).

The right-stepping geometry of the offshore fault system continues to the NE with the Psathia Fault, the well-defined onshore coastal trace of which has clear evidence for Holocene footwall uplift in the form of a prominent uplifted, 2.0 m high, solution notch (Leeder et al., 1991). Offshore (Fig. 4), the western extremity of the fault ends rapidly in Holocene-active spays that displace both the seabed and the prominent subsurface reflectors deduced to be the pre-12 ka land surface, the latter by 8–10 m, before deformation is transferred westwards to the East Alkyonides Fault.

**ACTIVE SUBAERIAL RANGE FRONT AND DRAINAGE CATCHMENTS**

On a large scale, the topography reflects the influence of footwall uplift by the coastal fault system on the development of the E–W-trending Gerania Mountains whose drainage divide reaches 1300 m elevation (Figs 3 and 5). Traced eastwards, the divide progressively lowers onto the 400 m high incised and tilted (~1.4°) surface to the inverted Megara Basin (Fig. 3), finally rising onto the old footwall uplands, the present-day Pateras Mountains, to that basin (Bentham et al., 1991). The sinuosity (S) of the range front along the Skinos Fault, the ratio of local fault length (11 km) to contour length, varies only slightly (S = 1.92 ± 0.34) at different altitudes, and is generally greater than values determined from other active range fronts worldwide (Bull & McFadden, 1977; Rockwell et al., 1985).

Slopes vary along the active range front according to the type of bedrock present. Extensive outcrops of highly fractured and altered Mesozoic serpentinite are characterized by gentler, often smooth, slope profiles. Mesozoic limestone bedrock provides the most spectacular relief, with well-bedded and karstified outcrops defining near-vertical cliffs. The presence of numerous talus cones of limestone debris along the base of these cliffs emphasizes the role of parallel slope retreat by earthquake-induced collapse failure, causing toppling down chute-like gullies. This encourages the vertical retreat of the footwall uplands and the persistence of steep rock faces above and behind active fault scarp. Finally, slopes developed in the soft and well-layered Plio-Pleistocene sediments of the inverted Megara Basin reflect the development of dendritic drainage systems (Fig. 6), deeply incised gorges and bedland-type terrains. Here, there is also a preponderance of vertical cliff retreat due to rockfall and subsequent removal of debris by undercutting ephemeral streams.

Over 20 major drainage catchments (Figs 5 and 6) have developed along the active range front since its initiation. Catchments 5–18 (Fig. 6), draining limestone and serpentinite basement of the Gerania Range bounded by the Skinos and Pisia Faults, are usually steep (mean slopes, 12–22°) and elongate in plan, typical of such features along active footwalls (Leeder & Jackson, 1993). The present distance of drainage divides (2–4.5 km) from the active fault line indicates the extent of drainage divide migration and catchment erosion. The most westerly catchment (A in Fig. 5) is relatively large, draining the tip zone to the Skinos Fault and the overlapping ledge between this and the higher Pisia Fault. Today, this drainage exits to the Gulf via the west end of the Skinos Peninsula. Streams draining catchments B and C (Fig. 5) cut into Plio-Pleistocene sediments of the Megara Basin, have shallower slopes (3–4°) than those mentioned previously and are palmate in plan view with dendritic network patterns. Here, footwall divide migration and volume of material removed have been substantially greater (maximum of 7.5 km in catchment B).

**ALLUVIAL FANS AND COASTAL PLAIN**

The onshore hangingwall to the Skinos Fault comprises a bajada of largely to partly eroded and incised alluvial fans (labelled A–G in Fig. 6) interspersed with base-of-scarp talus cones. The fans to the west around Skinos grade into a low-lying and gently sloping coastal plain. The morphology and sedimentology of the ephemeral streamflow deposits of the fans have been described previously (Leeder et al., 1991; Collier et al., 1998). New light is shed here on a prominent palaeosol noted briefly in the earlier study by Leeder et al. (1991) in the subsurface deposits...
of composite fan F/G. This mature, red–brown, ferralitic palaeosol is up to 30 cm thick and is overlain by up to 6 m of younger alluvium with thinner and more discontinuous light brown palaeosol horizons. It has developed over a large part of alluvial fan F/G and evidently dates a long period of stabilization due to low sediment supply to the fan surface. Disseminated soil organic carbon, concentrated from a 1 kg sample in the top indurated 10 cm of the palaeosol, gave an AMS radiocarbon date (analysis by ß Analytic Inc.) of 7620 ± 40 BP. Because this is a mean age, the onset of soil formation and carbon sequestration could clearly have been appreciably (perhaps thousands of years) earlier. The palynological results of Collier et al. (2000) lead us to propose that the age is in fact consistent with fan stabilization due to early Holocene climatic amelioration, and contemporaneous with the late stages of the early Holocene marine transgression which accessed the Gulf of Corinth at c. 12000 BP. This was followed by the development of extensive mixed-Mediterranean forest cover that would have caused reduction of runoff and sediment supply, perhaps assisted by channel incision. The overlying wedge of younger Holocene alluvium indicates renewed fan deposition that must have coincided with a marked change in catchment hydrological and runoff characteristics, perhaps aided by human interference. In support of this, a prominent, but less mature, palaeosol within the younger deposits of fan D (sampled at −4 m depth) has yielded an AMS radiocarbon age on disseminated organic carbon of 2550 ± 40 BP, consistent with a local pause in upper Holocene (Classical Greek period) deposition.

The volume of upper Holocene sediment produced by erosion (largely of serpentine) in catchments 15–18, which fed composite fan F/G (Fig. 6), may be computed by extrapolating the 6 m deposit close to the fan toe to the fan apex. Estimating the volume as that portion of
a partial conical segment of the 1.3 km radius fan, and assuming a porosity of 30%, gives a value for the solid volume of $6.0 \times 10^{-3}$ km$^3$. This corresponds to a mean sediment yield for the past 7.6 kyr of about $6.0 \times 10^5$ kg km$^{-2}$ year$^{-1}$, corresponding to a mean annual catchment denudation rate (ignoring chemical denudation) of 0.26 mm year$^{-1}$, a figure comparable to previous erosion estimates from related catchments in the general area (Leeder et al., 1991; Collier et al., 1995).

As noted previously (Leeder et al., 1991), the entire present-day footwall-sourced bajada along the western subsiding shelf is currently subject to marine erosion and exhibits fan margin cliffs up to 17 m high. The maximum fanward extent of this erosion, up to 150 m, may be estimated by smoothly projecting fan surface slopes down to modern sea-level. This also provides an estimate of the maximum extent of a seaboat coastal erosion (ravinement) surface (see Fig. 10 below). A consequence of the erosion is that several fan surfaces (most notably fan D) are prominently incised and terraced by their drainage channels upstream from the coastal cliffline.

**COASTAL SHELF MARGIN**

Our offshore surveys reveal that there are three subdivisions to the 18 km$^2$ coastal shelf in the detailed study area (Fig. 7).

Subdivision 1 in the west (Fig. 7) forms a prominent ledge or ramp between the active onshore Skinos Fault and the offshore West Alkyonides Fault. The ledge occurs in the hangingwall to the former structure and is fed from elongate, steep catchments in the footwall to the Skinos Fault (Fig. 6) that drain serpentinite and limestone bedrock, delivering mostly coarse-grained pebble to cobble sediment. It comprises a 0.75–2.25 km wide platform with a concave slope at mean values of 2.7°–2.9°. The gentle slope of the shelf is significantly less than that of onshore alluvial fans (9°–13°) and is comparable to that of the coastal alluvial plain around Skinos. The slope ends in a prominent abrupt convex break at the crest of the footwall to the West Alkyonides Fault (highlighted by ‘LIP’ in Fig. 7), reached at an average depth of ~85 m. The generally concave slope of the shelf is
broken periodically by the occurrence of seabed mounds (four in all) which may be mapped out as lobate features in three dimension (although our line spacings do not allow detailed bathymetric profiling) and which evidently define the traces of lowstand fan deltas (Figs 8 and 9). The features ramp gently seawards, their crests peaking at about two-thirds the distance from the shoreline, at depths of c. 60 m. Seawards, the slope is then asymptotic, extending almost to the marked bathymetric gradient of the shelf edge. The western ledge ends at the longitude of the complex three-way transfer zone between the onshore Skinos and offshore East and West Alkyonides Faults noted previously. It is marked by a major erosional feature, 75 m deep and 450 m wide offshore, and on trend NE from the deep coastal lagoon of Mavrolimni (Fig. 7). It is possible that this and a similar example a few kilometres NE (see below) have been excavated, perhaps by slumping, along offshoreshore-trending fault splays associated with fault tip zones.

Subdivision 2 (Fig. 7) forms a narrow up-losing shelf ledge situated in the active footwall to the offshore East Alkyonides Fault. This portion of the shelf is fed by runoff from large catchments draining the soft and easily erodible Plio-Pleistocene sediments of the inverted Megara Basin fill (Figs 5 and 6). It comprises a 0.45–1.0 km wide platform of convex or concave aspect at slopes ranging typically from 2.3° to 3.8°. The gentle slope of the ramp is comparable to values (around 2.8°) from the narrow uplifted onshore coastal plain around the village of Alepochori. The ledge ends abruptly in a prominent abrupt convex slope break (shelf edge lip, Fig. 7) at an average depth of 45 m. The ledge is broken by a prominent channel towards its SW end and three major convex-up lobate features (see Fig. 10) which may be mapped out in three dimension and evidently record actively accreting shelf ledge fans. The WSW–ENE channel (Fig. 7) is partly cut in bedrock and is 250 m wide and 25 m deep. The fan lobes are asymmetric, each steeper to the NE, and are cut by prominent leveed channel features up to 10 m deep, also asymmetric to the NE (Fig. 10). The lobes evidently define the traces of Holocene highstand depositional activity with preferential deposition due either to the influence of right-turning Coriolis forces on freshwater sediment-laden plumes, or of wave action on such plumes driven by prevailing long-fetch westerly winds. Present-day observations in the area during high stream discharges resulting from winter storms support the notion that sediment delivery across the shelf is via suspension-laden underflows whose surface traces disappear from view offshore at the shelf edge break. These underflows are the main source of sediment for the Alepochori submarine fan noted below.

The third subdivision marks the zone between the footwall of the NE extremity of the East Alkyonides Fault and the hangingwall to the onshore Psatha Fault.
It defines a broad 2.5 km wide ramp that slopes 1.2°–2° seawards. The ramp is broken by numerous small fault splays from the tip zone of the East Alkyonides Fault, some of which break surface or cause surface depressions and mounds (see Fig. 4). Apart from these, the surface of the ramp is featureless and uniform. It is thought that little sediment currently reaches this offshore shelf: longshore drift from the Alepochori beachface is hindered by sheltering around the faulted Psatha basement high, and sediment from onshore catchments is trapped on alluvial fans and coastal wetlands behind a prominent storm beach/barrier.

**OFFSHORE BASIN FLOOR**

The morphology of the offshore submarine basin floor (Fig. 7) adjacent to the East and West Alkyonides Faults is dominated by two features.

1. In SW areas, a prominent basin plain of area 24.5 km² has developed whose featureless floor is virtually horizontal at an average water depth of 360 m. The contact between this basin plain and basement outcrops along the footwall to the West Alkyonides Fault is usually very sharp, with no trace of significant base-of-slope fans other than a small development in the extreme SW. Evidently, during the late Quaternary, sediment supplied to the coast from catchments 9–18 in the uplifting Gerania Mountains (see Figs 6 and 7) has been largely trapped in alluvial fans and fan deltas developed on the relatively wide shelf ramp between the Skinos and West Alkyonides Faults, causing sediment starvation of the base-of-slope basin plain.

2. By way of contrast, the base-of-slope in NE areas adjacent to the East Alkyonides Fault is marked by a prominent concave sloping surface that rises up to 90 m from the basin plain (Fig. 7). Prominent subsurface reflectors define a continuous accumulation of base-of-slope sediment in a wedge-shaped body, which we name the Alepochori fan. The fan, of area 11.4 km², has evidently been fed by multiple channel sources identified (see previous discussion) along the uplifting footwall to the East Alkyonides Fault. These channels are the seaward outlets to drainage from catchments 1–8, mostly draining the easily erodible Neogene sedimentary infill to the uplifting Megara Basin (Fig. 6). Maximum relief on the base-of-slope fan occurs seaward of the drainage outlets and shelf ledge channels leading from the largest catchments 1–3.

**SEISMIC AND SEQUENCE STRATIGRAPHY OF LOWSTAND AND HIGHSTAND FANS**

**Morphology of lowstand fans and fan deltas, subsiding west shelf ledge**

Our geophysical surveys reveal a highly distinctive subsurface structure for lowstand fan deposits beneath a continuous veneer of Holocene highstand ‘drapes’ that typically averages 3 m thick (Fig. 8). The lowstand fans are defined by wedge-shaped accumulations that thin to zero thickness downslope to the lip of the shelf margin. The axis of maximum thickness of the deposits lies exactly under a seabed bathymetric high whose cuspite crest is at approximately –65 m as described in the previous section. Internal clinoforms define the subsurface expression of the wedges. These have developed in a very characteristic way (Fig. 8), showing both upslope (landward) onlap of the ‘topsets’ onto a prominent underlying surface of parallel or strong single reflectors, progradational downlap of bottomsets onto the same surface and aggradation and slope accentuation of foresets.

The parallel reflectors that underlie the wedge-shaped unit offshore are interpreted to be deposits formed under marine conditions during the last interglacial highstand (OIS 5). Micropalaeontological evidence indicates that, during the last lowstand, the Gulf of Corinth became fresh, maintaining a surface level to Lake Corinth at the c. –70 m elevation of an entrance sill at Rion in the west (Collier et al., 2000). Our interpretation (Fig. 11) of the offshore lowstand wedges (lobate in plan view) relies upon their particular combination of progradational and aggradational geometry: they clearly do not simply reflect progradational onlap of lowstand fan deltas, such as that documented from distal hangingwall ramps by Collier et al. (2000). Instead, they are interpreted to represent the adjustment of an actively prograding system under conditions of high sediment supply (Leeder et al., 1998; Collier et al., 2000) to the situation where, although absolute basin water level is approximately constant, relative base-level is locally rising due to subsidence. Reflectors progressively onlap landwards in response to aggradation of the clinoform. Similar geometries are predicted by theoretical and conceptual studies of fan deltas at actively subsiding coastlines (Fig. 11; see Dart et al., 1994; Gawthorpe et al., 1994; Hardy et al., 1994; Hardy & Gawthorpe, 1998). The maximum magnitude of the relative base-level rise due to subsidence was about 20 m, being the approximate maximum vertical extent of clinoform crestal deposits from the very earliest lowstand deposits of the clinoforms at the shelf edge ‘lip’, now in c. –85 m water depth. Little trace of lowstand base-of-slope fans or talus cones occurs along the submarine basin plain margins adjacent to the offshore fault. Evidently, the relative rise in base level due to hangingwall subsidence on the onshore fault was sufficient to cause sediment trapping on the shelf and deep water sediment starvation (Fig. 11).

In summary, during lowstand times, streams with high sediment transport capacity during wet winter runoff (Leeder et al., 1998; Collier et al., 2000) would have been free to exit the steep bajada adjacent to the active fault line and footwall escarpment. It is presumed that any toe-cut cliffs developed during highstand were degraded by slope-wash and collapse during lowstand. The lowstand
Fig. 8. Detail of interpreted sparker seismic trace, together with critical part of the original record (boxed area of interpreted sketch, enlarged below), to show lowstand coastal clinoforms traced from sparker line SPK 9. See text for discussion. The solid and broken vertical lines on the original traces are position lines.
streams would then have flowed out from the steep highstand bajada onto the more gentle slopes of the shelf ledge to deposit sediment as coastal fan deltas along the margins of Lake Corinth (Fig. 11).

**Active fans and channels on the uplifting NE shelf ledge**

As noted previously, the NE uplifting shelf ledge slopes gently seawards at about the same gradient as the narrow Alepochori coastal plain seawards of a 12 m raised late Pleistocene cliffline. It is separated from the latter by a low modern cliffline often fronted by uplifted beachrock. Strike seismic sections (e.g. Fig. 10) reveal that the three morphological fan lobes present are Holocene-active features. As previously noted, the two NE fan lobes are both markedly asymmetric being greater in both relief and extent to the NE, one with a well-defined concave levee, the other defining a convexo-concave surface. Subsurface (Fig. 10), the lobes show well-defined underlying reflectors that thin laterally away from the fan lobe axes and downlap onto a prominent underlying reflector. Maximum Holocene sediment thickness above this lower reflector, inferred to be a lowstand land surface, is 26 m. The lower side of the fans is marked by prominent surface and subsurface infilled channels. One channel cuts through at least 35 m of fan deposits, including the Holocene, and seems to be currently infilling. The buried channels commonly occur at the base of the Holocene sequence and are presumably glacial lowstand features cut when the Alepochori shelf was exposed.

**DISCUSSION: TECTONO–SEDIMENTARY INTERACTIONS**

In our introduction, we highlighted the role that sedimentary deposits laid down close to major basin-bounding faults could play in deciphering fault evolution, space and time history of rates of erosion and deposition and the history of sea- or lake-level changes. The integration of onshore data with new offshore data presented above from the eastern Gulf of Corinth enables us to shed the following light on these problems.
Fault mapping and status of the South Alkyonides Fault System

Following the 1981 Corinth earthquake sequence and the pioneering observations of faulting and interpretations of surface deformation by Jackson et al. (1982), subsequent workers have extrapolated the active Skinos Fault smoothly offshore a few kilometres east of Mavrolimni (location in Fig. 7) and then onshore again to join up with the outcrop of the Psatha Fault on the south side of Psatha Bay (e.g. Armijo et al., 1996; Hubert et al., 1996; Roberts, 1996). This extrapolation has led Roberts (1996) to view the whole zone of faulting as a continuous ‘system’ (the South Alkyonides Fault System, SAFS) stretching from Perachora to Psatha, a distance of some 35 km, made up of a number of fault ‘strands’ (e.g. Perachora, Pisia, Skinos, Psatha strands). The fact that the 1981 ruptures only occupied part of the total system length has led to suggestions that the SAFS behaves in a noncharacteristic manner during rupture evolution (Roberts, 1996). Our mapping of distinct offshore faults with well-defined, Holocene-active, tip zones, together with previous mapping of the offshore Strava Fault to the west (Papathedorou & Ferentinou, 1993), contradicts such previous continuous extrapolations from the onshore. It suggests that individual fault ‘strands’ are viable and active fault segments in their own right, when deformation is viewed on a Holocene timescale. In support of this, it is noteworthy that the surface breaks and earthquake hypocentres attributed to northerly displacements in the 1981 earthquake sequence (Jackson et al., 1982; Taymaz et al., 1991) involve perhaps only three out of the total of five Holocene-active structures that make up the putative SAFS (Strava, Pisia, Skinos Faults). In view of the fact that considerable strain continues to be taken up in the area (Davies et al., 1997), this implies that significant strain may be accommodated on the remaining structures (Psatha, East Alkyonides Faults).

Rates of fault displacement

Displacements of prominent reflectors, interpreted as pre-12 ka lowstand land surfaces at the tip of the active Psatha Fault, are ~ 8–10 m (Fig. 4), giving a maximum mean displacement rate for the past 12 kyr in the range 0.7–0.8 mm year\(^{-1}\). The +2 m raised solution notches along coastal outcrops of the fault plane indicate that this total displacement may be partitioned into 0.2 mm year\(^{-1}\) of footwall uplift over this time, about 20–30% of the total displacement.

Corresponding Holocene displacements of lowstand surfaces at the tip of the active East Alkyonides Fault...
Fig. 11. N–S sketch to illustrate the relationships between lowstand fan deltas and onshore alluvial fans along the shelf ledge adjacent to the active Skinos Fault (see Figs 6–8 for context). Inset definition diagrams illustrate lowstand clinoform geometry relative to the absence (A) or presence (B) of relative water level change due to subsidence. See text for discussion.

(Fig. 4) are ~ 2.5–3.0 m, giving a mean displacement rate in the range 0.2–0.25 mm year⁻¹. The corresponding mean long-term footwall uplift for the whole fault, gained from the +35 m elevation of onshore oxygen isotope Stage 5e terrace (Leeder et al., 1991), yields comparable values, although we cannot be sure if (i) the relative displacements have been constant over time; and/or (ii) the Holocene displacement rates determined for the fault tip may be extrapolated along the whole structure.

**Step faulting and sedimentary sequences**

A prominent feature of the western part of the study area is the down-to-the-north sequence of step faulting involving the Pisia, Skinos and West Alkyonides Faults. The ramps developed in the hangingwalls to each of these structures define prominent geomorphic features and are the site of sediment deposition: on alluvial fans in the case of the Pisia Fault, on alluvial fans and fan deltas in the case of the Skinos Fault and on submarine basin plains in the case of the West Alkyonides Fault. The aggradational lowstand fan delta wedges developed on the shelf hangingwall ramp to the Skinos Fault (Figs 8 and 11) enable us to deduce the following.

1. That hangingwall subsidence of the Skinos Fault has long been (at least since Lake Corinth lowstand began about 70 000 yr) predominant over any uplifting tendency expected if the offshore West Alkyonides Fault was active.

2. The approximate amount of hangingwall subsidence at the tip zone of the Skinos Fault experienced during the lengthy lowstand interval of Lake Corinth between 70 and 12 ka (Collier et al., 2000), and hence the minimum estimates of medium-term displacement rates. We assume that deposition began at maximum lowstand, with deposits now at ~ 85 m water depth as the oldest OIS Stage 4 fan deltas and shoreline deposits (Figs 8 and 11). The shoreline deposits subsequently aggraded to the present depth of the seaward clinoform crest below the Holocene sediment drape at about the present...
depth of —65 m. This implies maximum subsidence of approximately 20 m over the time interval involved, at a mean rate of 0.32 mm year⁻¹. Depending on the magnitude of associated footwall uplift (unknown in this case), this displacement rate is at the lower end or much less than estimate ranges (0.7–2.5 mm year⁻¹) of historical (1600–20 WP) displacements from surface trenching in adjacent fan D (Collier et al., 1998).

Although we can deduce relative late Pleistocene inactivity on the West Alkyonides Fault compared to the Holocene-active Pisia and Skinos Faults, we can at present make no suggestions as to the relative age of initiation of the step-faulting sequence, such as whether the locus of active faulting may be migrating southwards, away from the offshore fault.

**Lowstand vs. highstand shelf sediment trapping or shelf bypass?**

Here, we highlight tectonic, sea-level and drainage catchment controls upon the extent of shelf trapping vs. shelf bypass on structurally active rift margins (Fig. 12).

Step-faulted margins, such as that of Pisia–Skinsos, with a relatively inactive seawards fault like the West Alkyonides Fault, are able to trap both lowstand and highstand sediment supplied from the hinterland on a relatively wide shelf ledge that does not become completely emergent during lowstands. In addition to this topographic control by the pattern of faulting, trap efficiency is also high because the hinterlands comprise a mixture of highly to moderately mechanically resistant rock types (limestone and serpentinite, respectively) which break down to mostly pebble and boulder grades during weathering. These give little opportunity for prolonged suspended transport in sediment underflows, and the majority of sediment is deposited within fan delta complexes as bedload: the end result is a sediment-starved fault scarp and base-of-slope with little development of submarine fans.

By way of contrast, margins like the Alepochori shelf, bounded by single active offshore faults, are continually being uplifted, in this case producing a narrow, shallow shelf that becomes emergent and bypassed during lowstands. At such times, sediment-laden fluvial discharge...
will be directly channelled over the shelf lip onto the steep footwall scarp and hence down to the base-of-slope where sediment is deposited to form submarine fans. A major factor contributing to the efficiency of bypass would have been the high sediment yield experienced under cool, wet, winter climates (Leeder et al., 1998; Collier et al., 2000) from large catchments developed in a hinterland of easily erodable, relatively fine-grained Neogene sediment (predominantly muddy silt to granule grades). Significant deposition by suspension-rich underflows is also evident during highstands on this shelf, leading to the formation of active Holocene shelf lobes exhibiting geometries resulting from shear due to prevailing winds and/or Coriolis forcing of the sediment-laden plumes. The likely strength of the underflow currents responsible and the narrowness of the shelf must also result in significant bypass even in today’s highstand environment, a supposition supported by occasional observations of storm drainage entering the shelf as visible plumes which stop abruptly at the shelf margin.

CONCLUSIONS

The Alkyonides half-graben is bounded to the south by a number of active fault segments. The East Alkyonides and Psatha Faults have well-defined, Holocene-active, tip zones. During the late Quaternary, catchments draining the step-faulted footwall uplands supplied sediment to the hangingwall of the Skinos Fault, to shelf ledge fans on the uplifting footwall to the East Alkyonides Fault and to the Alepochori submarine fan in the hangingwall of the latter. During late Pleistocene lowstand times (70–12 ka), sediment was deposited in Lake Corinth as fan deltas on the subsiding Skinos shelf ramp which acted as a sediment trap for the submarine basin plain. At the same time, the uplifting eastern shelf ledge was exposed, eroded and bypassed in favour of deposition on the Alepochori submarine fan. During Holocene times, the Skinos bajada was first the site of stability and soil formation, and then of substantial deposition before modern marine erosion cut a prominent cliffline. Even though actively uplifting, the eastern shelf ledge has developed substantial Holocene fan lobe depositional sequences as sediment-laden underflows have traversed it. Mean Holocene displacement rates at the tip of the Psatha Fault are in the range 0.7–0.8 mm year$^{-1}$. Raised Holocene coastal notches indicate that this may be partitioned into about 0.2 mm year$^{-1}$ of footwall uplift. Holocene displacement rates at the tip of the active East Alkyonides Fault are in the range 0.2–0.25 mm year$^{-1}$. Any uplift on the footwall of the West Alkyonides Fault is exceeded by subsidence on the Skinos Fault, because lowstand shelf fan deltas show internal clinoforms indicative of aggradational deposition during conditions of relative net base-level rise (due to active hangingwall subsidence along the onshore Skinos Fault). Total subsidence over the last 58 kyr lowstand interval is some 20 m, indicating a reduced displacement rate compared to estimates of late Holocene (<2000 BP) activity from palaeoseismology. This may record the interaction of footwall uplift on the West Alkyonides Fault and hangingwall subsidence on the Skinos Fault. Alternatively, it may indicate unsteady rates of fault displacement over periods of $c. 10^4$ years.

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