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Modern Fan Deltas in the Western Gulf of Corinth, Greece

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Abstract

Rivers in the western Gulf of Corinth have built gravelly fan deltas into waters 100–300 m deep. Seismic profiles (3.5 kHz) and gravity cores show that sand-filled channels extend seaward of modern distributary mouths and lead to sandy depositional lobes in deeper water. Much of the fan delta slope is underlain by mud. Closely spaced gullies cut the interchannel ridges on either side of the main channels. Incised slope valleys occur on east-facing slopes, where the wave fetch is greatest, and may be formed by rip-current–induced turbidity currents.

Introduction

The Gulf of Corinth (Fig. 1) is a major late Cenozoic asymmetrical graben in central Greece (Brooks and Ferentinos, 1984). Active faulting on the southern side of the Gulf has resulted in at least 950 m of Pleistocene uplift of the mountains to the south (Kelletat and others 1976, 1978), which reach heights of over 2000 m. The maximum water depth of 860 m is found in the eastern part of the Gulf. The Rion Straits, 2 km wide and 70 m deep, link the Gulf of Corinth to the Gulf of Patras and hence to the Ionian Sea (Papanikolaou and others 1987). The Gulf of Corinth deepens gradually eastward from here (Fig. 2), reaching water depths of 500 m at about 30 km east of Rion. Except off deltas, where a narrow prodelta platform is developed, steep slopes lead from the coastline into deep water. The rivers draining into the Gulf have built alluvial fan–like deltas directly into deep water. Heezen and others (1966) and Anderson and Carmack (1973) have described the main features of the morphology, circulation, and sedimentation in the Gulf of Corinth and they indicate that much of the sediment in deeper water consists of turbidites deposited on coalescing submarine fans and apparently derived from the river deltas. Ferentinos and others (1988) have shown that steep fans in the central part of the Gulf are strongly influenced by gravitational mass movements.

In this study, we have examined the fan deltas in the western Gulf of Corinth, from the Rion Straits to the Erineos Delta 25 km to the east. By far the largest delta is that of the Mornos, on the northwestern side of the Gulf. A series of small steep alluvial fans have built fan deltas into the south side of the extreme western Gulf of Corinth. The Erineos is a large delta on the south side of the gulf. In the terminology of McPherson and others (1987), the smaller deltas are true fan deltas, whereas the Mornos and Erineos Deltas are braid deltas (although their channel pattern tends to be straight rather than strongly braided).

It is our purpose to describe the morphology of fan deltas at the margin of a modern rift basin and to interpret the observed sediment distribution in terms of depositional processes. Although there is currently much interest in fan deltas in the ancient geological record (e.g., Nemec and Steel 1988), almost all of the modern fan deltas that have been studied are in glacial fjords (e.g., Prior and Bornhold 1988; Syvitski and others 1986); their geologic setting is thus not analogous to most ancient fan deltas (although pro-

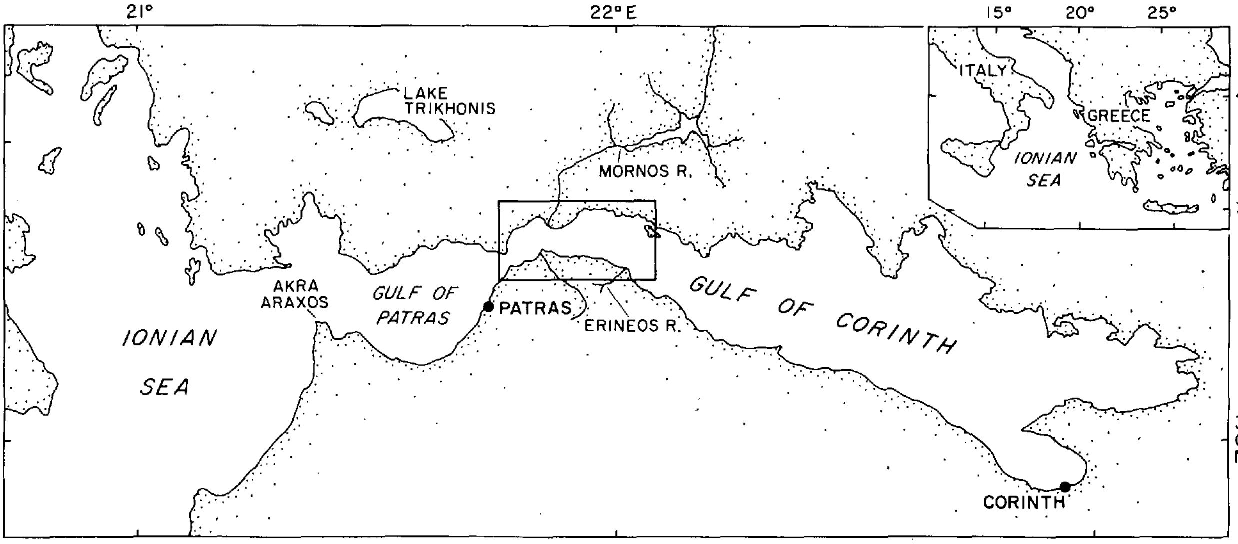

Figure 1. Map showing regional setting of the study area in the western Gulf of Corinth.

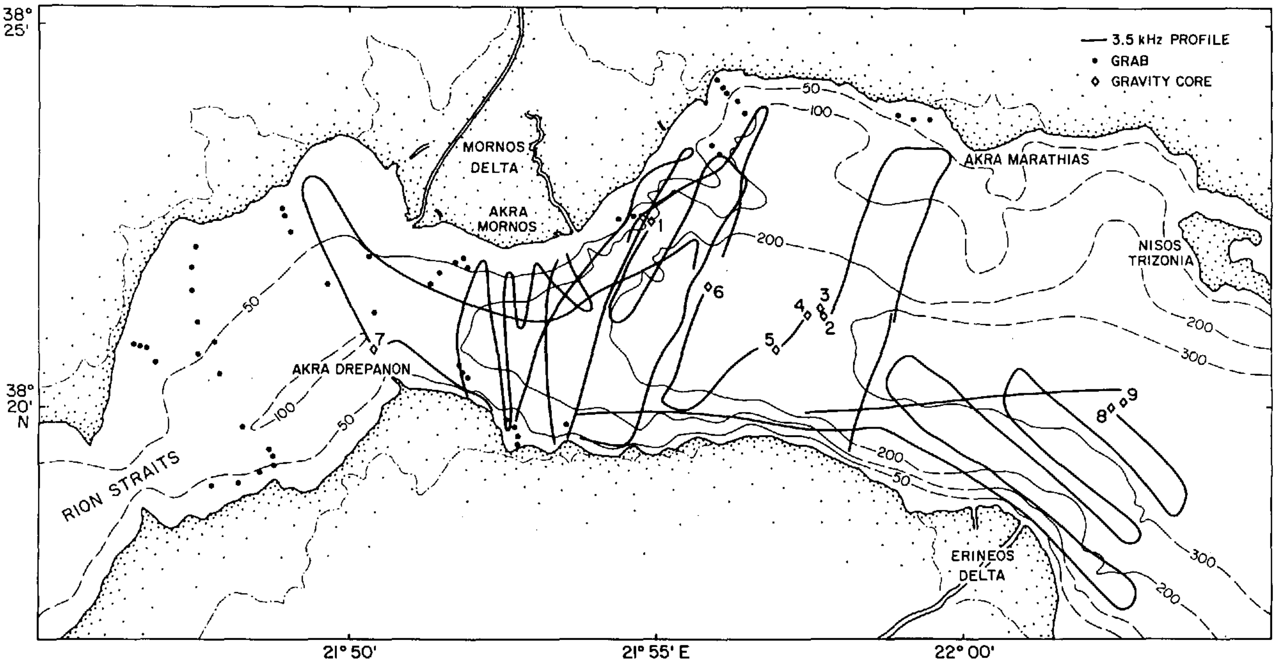

Figure 2. Bathymetric map of western Gulf of Corinth, showing location of 3.5-kHz profiles, cores, and grab samples. Dashed bathymetric contours (in meters) based on British Admiralty Chart 1676; solid contours from this study. Dashed-dotted line on land marks edge of bedrock.

cesses may be similar). This new information from the Gulf of Corinth will be of value in interpreting ancient facies distributions. Our study complements the work of Ferentinos and others (1988) in the central Gulf of Corinth, where fan deltas have built into water more than 800 m deep.

Oceanography

Present circulation is dominated by the funneling of both wind and water through the narrow Rion Straits and the adjacent western Gulf. Although mean tidal range is as little as 15 cm (Bariagin 1972), tidal currents through the Rion Strait and between Akra Drepanon and Akra Mornos reach velocities of over 100 cm/sec. The funneling also results in a highly bimodal distribution of predominant wind directions—either from the east or the WSW. Data for the University of Patras (Piper and others 1982) suggest the easterly winds are both stronger and more persistent. The fetch from the east is much greater than from the SSW, since the Rion Straits minimize the passage of waves from the Gulf of Patras.

Between 1889 and 1939, the Patras-Corinth no. 2 telegraph cable broke several times off the Mornos delta (Fig. 3) (Heezen and others 1966). Two breaks were associated with seismic activity; the remainder occurred between the months of October and early May and were probably related to sediment slumping or turbidity currents following heavy river discharge. Similar cable breaks were common off other major fan deltas in the Gulf of Corinth (Ferentinos and others 1988).

During the Pleistocene and the accompanying lowered stands of sea level extant at that era, the Gulf of Corinth would have been cut off from the open sea by Neogene bedrock ridges at the Rion Straits (−62 m) and Akra Araxos (−45 m) (Piper and Panagos 1980). Lacustrine or brackish water sediments accumulated at times of lowered sea level in the Gulf of Corinth (Heezen and others 1966; Keraudren and Sorel 1987).

Methods

The work was carried out using a fishing vessel. One sampling cruise obtained grab samples, with navigation by sextant fixes to points on shore. A second cruise collected 3.5-kHz high-resolution seismic profiles and short gravity cores, with navigation by Miniranger. The coastline and subaerial deltas were also examined in the field. Published maps based on surveys in 1934 and 1945 were used to determine changes in delta morphology.

Subaerial Deltas

The Mornos subaerial delta is a large fan-shaped body with an area of 25 km^2 and a mean gradient of 0.004 (0.2°) (Fig. 3). The Mornos River drains the southern Pindos mountains and has an average discharge of 40 m^3/sec, with the greatest flow in the winter months. Flow is now regulated by the Mornos dam, completed in 1979. The river is enclosed by dikes along its entire delta reach, and discharges on the west side of the delta (Fig. 2). The 1934 and 1945 maps show that the

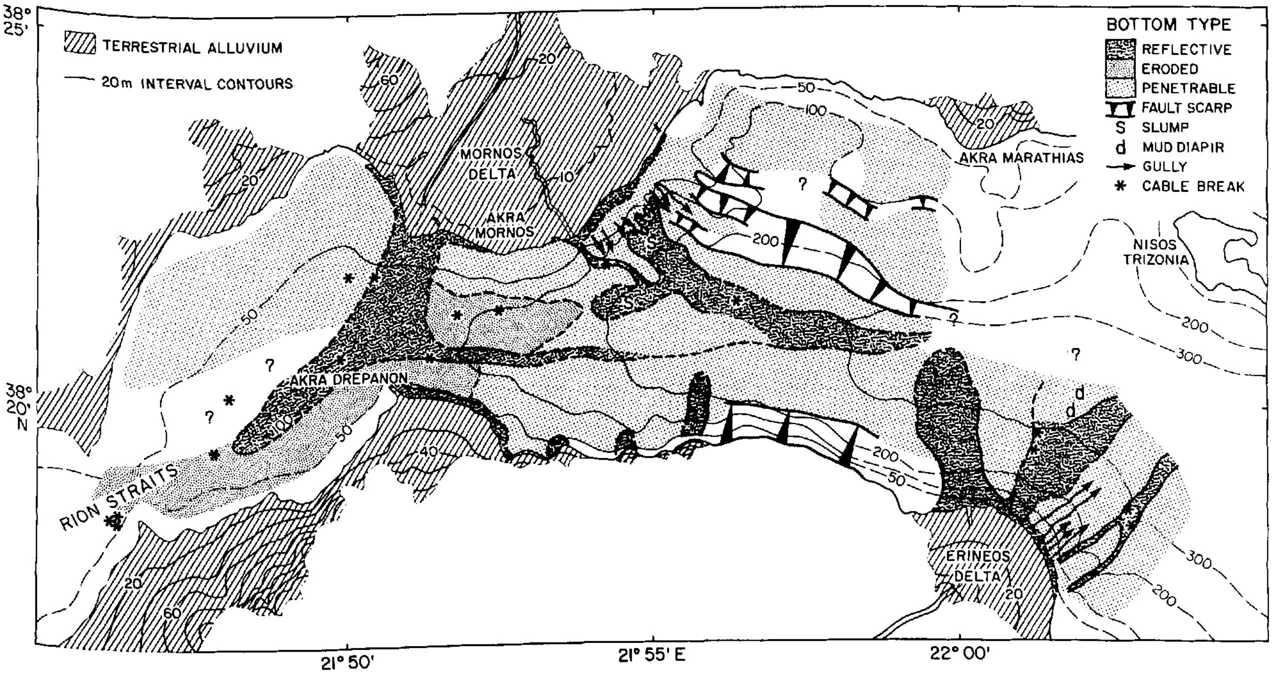

Figure 3. Interpretative map of surficial sediment in the western Gulf of Corinth, based on 3.5-kHz profiles, samples, and fieldwork on land. Map shows terrestrial fan deltas and river channels; distribution of reflective sea bed (sandy prodelta platform, sandy channels, lobes, and slumps), penetrable sea bed (mud), and eroded sea bed (eroded by tidal currents); seabed features such as gullies and mud diapirs; and the distribution of fault scarps. Area west of Akra Drepanon tentative, based only on grab samples from Piper and others 1981.

main distributary was to the central (southeastern) part of the delta, and the present river channel was a lesser distributary. There has been approximately a 150-m progradation of the modern mouth of the river since 1945.

The Mornos River has a braided gravel bed all the way to its mouth, and delivers cobbles of up to 20 cm mean diameter to the sea (Piper and others 1981). Sand and some fine gravel is moved eastward from the mouth by longshore drift, forming a series of complex spits, but there appears to be little reworking of coarser pebbles and cobbles, which accumulate as the mouth progrades. At the abandoned mouth, in the central delta, fine gravel has been reworked, along with sand, to form parallel beach ridges; wind-blown dunes have also formed. The eastern coast of the delta, exposed to winds blowing straight down the Gulf of Corinth, has a slowly eroding coastline with a steep straight pebble beach. Along the entire coast, the immediate subtidal marine zone has an ephemeral cover of fine sand or silt during fair weather, but everywhere appears underlain by gravel. The fan-like shape of the delta and the universal presence of gravel suggests that delta growth took place by gradual shifting of braided distributaries.

The alluvial fans on the southeastern edge of the Gulf of Corinth range from as steep as 0.2 (11°) to gradients of 0.04 (2°) on the large Drepanon Fan. Surface sediments comprise cobble and boulder gravel.

The Erineos subaerial delta has a gradient of 0.025 (1.4°), is almost perfectly fan-shaped, and has widespread cobble gravel. There are two major distributaries, to the northeast and northwest: channel maintenance since the 1960s has directed most flows down the northeast distributary.

Subaqueous Delta Morphology and Facies

The western Gulf of Corinth is a complex asymmetrical graben (Fig. 3). Faults are in places marked by scarps, both on land and on the sea floor; elsewhere scarps have been eroded by rivers and masked by delta progradation. The central part of the graben is bounded on its south side by a major fault scarp along the coastline that has been built over by the Erineos and Drepanon fan deltas. The northern edge of the central graben is marked by a sea floor fault scarp running down the center of the Gulf; this fault scarp is obscured both by progradation of the Mornos Delta and by more distal mud deposits (Fig. 3).

The Erineos fan delta is described in detail as an example of a larger fan delta. Except at the active distributary mouth, the delta has a narrow sandy or gravelly shelf along which coastal recession is occurring. The prodelta slope has gradients typically of 0.15 (9°) to 0.12 (7°), except near the prograding river mouth, where gradients of 0.3 (18°) occur to water depths of at least 100 m.

Four morphogeological zones are distinguished on 3.5-kHz profiles (Fig. 4). In the central part of the fan delta, zone A comprises the modern prograding sand system, with a broad valley extending from the river mouth to about 250 m water depth, where it spreads into a sandy depositional lobe. Zone B consists of thick mud sequences cut by narrow gullies on either side of the modern sandy valley. On the southeastern side of the delta, zone C comprises two larger sand-floored gullies with muddy intergully ridges. On the western side of the fan delta, zone D consists of a a former sandy valley-lobe system covered with 5–10 m of mud.

The modern sand-floored valley off the mouth of the river is incised up to 40 m below the surface of the fan (zone A in profile A–A′, Fig. 4). The sandy depositional lobe shows increasing acoustic penetration distally (e.g., profiles E–E′, Fig. 4), and has a rather rough surface. Irregular hyperbolic returns, up to 20 m high, appear to break the surface of the distal lobe (profile E–E′, Fig. 4) and are interpreted as either mud diapirs or large slumped blocks. A short gravity core (core 9; Fig. 2) shows that there is surface sand on the lobe.

The gullies of zone B are similar are spaced at approximately 100–250 m and are 5–25 m deep, decreasing downslope (compare profiles B–B′ with D–D′, Fig. 4). The larger gullies of zone C have a similar form, but are incised up to 100 m (profile A–A′, Fig. 4). In both groups of gullies, the intervening muddy ridges appear to have steadily aggraded. Individual reflectors can be traced across the ridges to the edge of the coarse sediment on the flat gully floor, in the manner of reflectors on levees (e.g., profile C–C′, Fig. 4). It is not clear whether these ridges are true levees, resulting from overbank flow of turbidity currents down the gullies; or whether they have aggraded from fall-out of surface plume sediment, with minor erosion on the gully walls maintaining the gully relief.

Zone D appears to represent an abandoned depositional lobe, covered with a surface layer of 5–10 m of mud (see NW end of profile B–B′, Fig. 4). There is no prominent channel similar to that off the modern mouth of the Erineos: rather, a flat sand sheet appears to extent offshore from the prodelta platform.

Progradation of the Mornos and Drepanon fan deltas has resulted in a constriction of the easternmost Gulf of Corinth to less than 4 km wide and about 100 m deep; this area is swept by tidal currents. The southern prodelta slope of the Mornos and the northern slope of the Drepanon have flat reflective bottoms

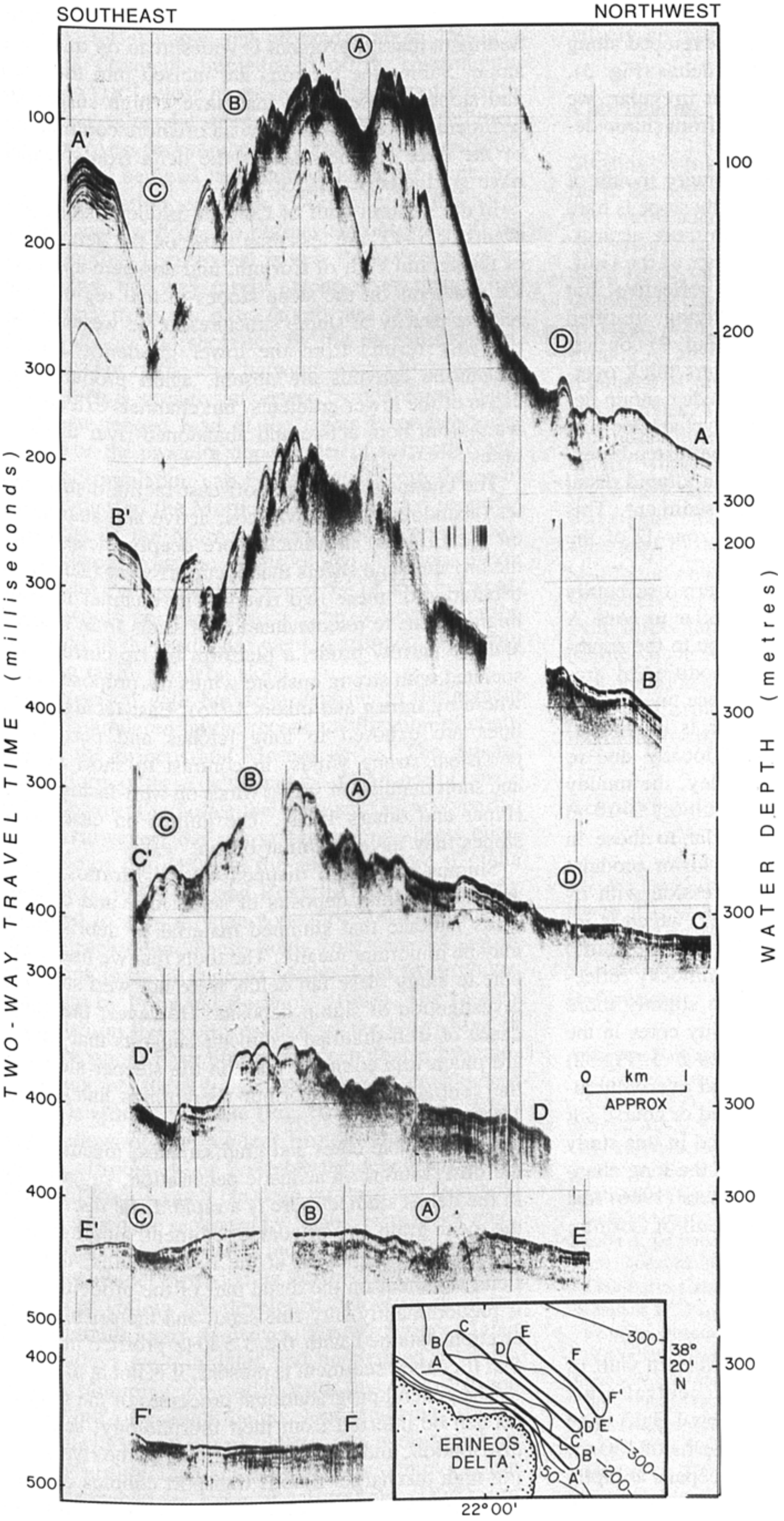

Figure 4. Series of 3.5-kHz profiles across the Erineos prodelta slope, showing division into zones A through D described in the text.

on 3.5-kHz profiles and are floored by silty sand. A 300-m-wide, 15-m-deep channel has developed along the axis of the straits between the two deltas (Fig. 3). The floor of the channel is somewhat irregular: we cannot distinguish whether this results from slump deposits or bedforms.

Seaward of the southwestern distributary mouth of the Mornos, the sea floor on the prodelta slope is hard and irregular, but passes laterally into more acoustically penetrable seabed. On the flat floor of the Gulf, seaward of the mouth, the bottom is reflective, but there is some penetration into underlying stratified sediments. A core from here (core 7; Fig. 2) consists of a surface sand bed a few centimeters thick overlying a graded sand to silt bed; both beds contain detrital wood fragments. The acoustic character and sample suggest that a surface sand sheet extends seaward of the southwestern mouths, with a rapid distal decrease in the abundance of coarse sediment. This sand sheet appears similar to that in zone D of the Erineos delta.

Seaward of the abandoned southeastern distributary mouth is a deeply incised valley, similar to zone A of the Erineos delta. The prodelta slope to the southwest of this valley is muddy, but is modified by erosion, as shown by surface and subsurface unconformities in 3.5-kHz profiles. This erosion is interpreted as partly due to tidal currents and locally due to slumping. To the northeast of the valley, the muddy prodelta slope is cut by a series of gullies, 5–20 m deep, spaced 150–200 m apart, similar to those in zone B of the Erineos delta. On the lower prodelta slope there is a broad elongated depression with irregular stratification in seismic profiles, which is interpreted as a slump scar. The valley and the slump scars lead to a broad channel with hummocky reflective fill in its proximal part, but with slightly more acoustic penetration distally. Short gravity cores in the distal part of the channel system (cores 2–5, Fig. 2) all consist of 20–40 cm of surface mud overlying alternating mud and thin graded fine sand or coarse silt beds. This valley and channel examined in this study (Fig. 3) are probably the beginning of the long channel system mapped by Heezen and others (1966) that leads to the deeper eastern part of the Gulf of Corinth.

Discussion

The morphology of fan deltas in the western Gulf of Corinth differs from those of the central Gulf (Ferentinos and others, 1988). In the central Gulf, there is a 1.5-km-wide shelf extending to depths of 150 m, with an average gradient of 6°. This steepens abruptly to a 25–40° slope, which is largely fault controlled, but which is locally the result of delta progradation. Sediment mass movement is widespread on this steep slope. Submarine canyons are incised into the shelf and slope. Those rivers that have a high suspended sediment concentration show an offshore continuation of the river channels across the delta fronts, which have gradients of 15–25°.

In the western Gulf of Corinth, prodelta slope gradients of 5–12° are less than those on the delta fronts of the central Gulf of Corinth, and nowhere approach the gradients on the steep slopes in that region. The relative paucity of slump structures in the western Gulf probably results from the lower gradients. Incised submarine canyons are absent, again probably because of the lower gradients, but channels extend seaward from both active and abandoned river distributaries.

The channels developed off east-facing distributaries (abandoned on the Mornos, active and abandoned on the Erineos) are much more deeply incised than the broader sand sheets that occur off west-facing distributaries of these two rivers. The channel incision might be due to resedimentation of sands from beaches and the narrow prodelta platform by rip currents associated with strong onshore winds (as proposed elsewhere by Inman and others 1976). East-facing coastlines are exposed to long fetches and periods of persistent strong winds, in contrast to short fetches and short duration of strong winds on west-facing coasts (Piper and others 1982). The gullies on east-facing slopes may have a similar origin.

Slumps have been mapped off the Mornos Delta, and the irregular deposits of some lobe and channel areas indicate that slumped material or debris flows may be important locally. The tools that we had available to study these fan deltas were not well suited to investigation of slump deposits. However, the abundance of well-stratified sediments suggests that slumps are much less common than on the steeper slopes in the central Gulf of Corinth (Ferentinos and others, 1988).

The available cores and grab samples, together with the observations on acoustic penetration, suggest that in the deltas studied there is a rapid distal decrease in the mean grain size of coarse sediment: although cobble gravels are present at the river mouths, the surficial sediment on the distal part of the prodelta slope is predominantly silty fine sand, and the seismic penetration obtained with the 3.5-kHz profiler indicates that if coarser sediment is present, it is not at all thick.

The general progradational processes of the fan deltas can be inferred from their morphology, sediment distribution, and casual observations of the rivers during high discharge. Floods transport cobbles or boulders (depending on delta gradient) to the shoreline, leading to significant progradation of the river. The Mornos, for example, has prograded about 150 m in 35 years. Gradients immediately off the river mouths are steep (18°), close to the dynamic angle of friction; there may either be direct flow of bedload sediment from the rivers (as postulated by Prior and others, 1987) or failure of bedload sediment on the upper slope during progradation episodes. During high discharge events, muddy discharge plumes are observed off the river mouths. Their extent is very dependent on wind conditions, but they rarely extend more than a few kilometers from the river mouth and are frequently blown against the shoreline by the prevailing wind. Thus, except in the area between Akra Drepanon and Rion which is strongly influenced by tidal flows, much of the suspended load of the rivers is probably deposited on the prodelta slope. Rates of suspended sediment accumulation can be estimated from the sediment budget of the Mornos. The suspended sediment discharge of the Mornos river (prior to regulation), extrapolated from the better-known Acheloos River (Piper and Panagos 1981), was 0.5–0.8 tons per year, which would correspond to a 2 cm/yr sedimentation rate if all of this sediment were distributed uniformly over the entire prodelta slope.

Comparison with fan delta deposits in the ancient record is hindered by the recent stabilization of channels in the Erineos and Mornos deltas. The general arcuate form of these deltas and the abundance of coarse topset sediment indicates that they are Gilbert-type fan deltas. However, the coarse prograding sheets characteristic of fan deltas in the ancient record (Colella and others 1987; Ori and Roveri 1987) are spatially restricted to a 1-km-wide zone close to one distributary on each delta. These sandy zones are not significantly incised, in contrast to the delta front chutes described by Prior and Bornhold (1988). The smaller fan deltas on the southwest side of the Gulf, west of Akra Depanon, have built very steep coarse prograding sheets, but these are generally only a few hundred meters length along strike (Fig. 3). The incised delta-front valleys off the modern Erineos and abandoned Mornos distributary, do resemble the delta-front chutes described from a small fan delta by Prior and Bornhold (1986), which are separated by "stable islands" of mud. In this respect, these deltas morphologically resemble the facies model proposed by Postma (1984) in which delta-front valleys are developed below small distributary mouth lobes. However, Postma proposed that these valleys were initiated and maintained by retrogressive slumping: no evidence for this origin is seen in the Gulf of Corinth deltas. Our study has shown that quite deeply incised valleys are widespread on the slopes of the muddier fan deltas. In contrast to fan deltas described by Prior and Bornhold (1988) and Ferentinos and others (1988), slumping appears relatively unimportant.

Conclusions

Shifting distributaries on high-bedload-discharge deltas in the active graben of the western Gulf of Corinth have prograded gravelly fan-shaped deltas across active graben-margin faults into waters 100–300 m deep. Sand-filled channels extend seaward from modern distributary mouths and lead to sandy depositional lobes in deeper water; similar features are found off old distributaries abandoned since river channels have been regulated. Cores show surface graded sands on the active lobes. Channels (both active and abandoned) are much more deeply incised on the east side of the deltas, where the wave fetch is greatest, and the incision may reflect generation of turbidity currents from wave-generated rip currents. Closely spaced gullies, separated by aggraded levee-like ridges of mud, are also found on east-facing slopes. Most of the prodelta slopes consist of muds tens of meters thick, derived from direct fall-out from surface suspension plumes. Slumps have been recognized locally, but are much less common than on the steep slopes of the central Gulf of Corinth. In places, the prodelta slopes are modified by tidal current erosion.

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