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The geometry of fan-deltas and related turbidites in narrow linear basins

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The sediment distribution in three narrow, linear basins, two modern and one ancient, in Greece and Italy, was studied and related to changes in basin configuration. The basins are the Plio-Quaternary Patras–Corinth graben, the Pliocene–Quaternary Reggio–Scilla graben and the middle Tertiary Mesohellenic piggy-back basin. These basins were formed at different times and under different geodynamic conditions, but in each case, the tectonic evolution produced a narrow area in the basin where the water depth decreased dramatically, forming a strait with a sill. This strait divided the basin into major and minor sub-basins, and the strait has a similar impact on sedimentary environments in all three basins, even though different depositional environments were formed along the initial basin axis.

Predictions for the development of depositional environments in the two modern basins, especially in their straits, are based on the studied ancient basin. In the straits, powerful tidal flows will transport finer sediments to sub-basins and trapezoidal-type fan-deltas will gradually fill up and choke the strait through time. In sub-basins, according to basin depth, either deltaic (in the shallow minor sub-basin) or turbiditic (in the deep major sub-basin) deposits may accumulate. Moreover, an extensive shelf is likely to develop between the strait and major sub-basin. This shelf will be cross-cut by canyons and characterized by thin fine- to coarse-grained deposits. These sediment models could be applied to analogous basin geometries around the world.

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1. INTRODUCTION

In orogenic belts, narrow linear basins with steep slopes and deep water, open to the sea at both ends, are quite common and may evolve in extensional or compressional settings. The original basin, uniform in width and depth, can be separated into sub-basins due to the tectonic development of a strait. In extensional basins this strait typically results from movement on transfer faults or relay ramps (Gibbs 1984; Rosendahl *et al.* 1986; Frostick and Reid 1987; Leeder and Gawthorpe 1987), while in compressional basins it results from either movement on strike-slip faults or the presence of indentors (differential movement along the collided margins may produce different tectonic regimes along the basin margins, influencing the depositional processes; e.g. Ori and Friend 1984). However, there has been no general examination of the role of straits in such basins, regardless of their tectonic origin.

The aim of this study is to determine the depositional environments that form along the basin axes in response to the development of a narrow and shallow strait. This tectonically controlled change in basin configuration, in basins of very different origin, can influence the geometry of coarse-grained sediments derived from the adjacent margins that accumulate in the strait, and related deep-water turbidites (Zelilidis 1997). The sedimentological consequences of this type of basin evolution have been studied in three basins (Corinth–Patras graben and Mesohellenic piggy-back basin, in central Greece; and Reggio–Scilla graben, in southern Italy).

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2. STRUCTURAL SETTING OF NARROW, LINEAR DEEP BASINS

Compressional basins, whether associated with subduction or not, are common in the closing stages of oceans, and become constricted by indentors. For example, many narrow, linear sedimentary basins were formed during the development of the India–Asia collision zone. The accompanying foreland (foredeep) basins (Tadrhim, Surkhab) are characterized by marine conditions, whereas intramontane (Pamir, Karakorum, Himalaya) and piggy-back (Katmandu, Kashmir) basins are characterized by non-marine environments (Brookfield 1993). Compressional basins are widespread within the Alpine orogen and include well-known basins in Italy. The Apennine foredeep and piggy-back compressional basins (Ricci Luchi 1990; Ori and Friend 1984) to the east of the mountain divide and the extensional basins to the west (Martini and Sagri 1993) are mostly linear and narrow. Aquitanian molasse in the Rhône–Alp region in the north of the Alpine foreland basin, deposited in narrow, linear piggy-back basins during active shortening, consists of thick, shallow marine deposits, whereas narrow continental basins separated by palaeohighs were related to late Eocene–Oligocene extension in the Rhine–Bress–Rhône system (Allen and Bass 1993). The South Pyrenean Ebro foreland basin was narrow, linear, and of uniform width and depth during the late Cretaceous, but was gradually segmented into minibasins from late Eocene to Oligocene times by structural highs. It shows an upward succession from turbidites to deltaic and then fluvial facies (Puigdefabregas 1975; Teixell 1996; Nichols and Hirst 1998; Ardèvol *et al.* 2000). Many other foreland basins, such as the Alberta foreland basin (Cant and Stockmal 1993), are linear and narrow and often are filled by deep-water submarine fan deposits passing upwards to shallow-water and continental deposits, due to changes in tectonic regime and basin style.

Extensional basins may become focused into narrow rifts. The basic structural elements of individual rifts are half-grabens (Gibbs 1984; Rosendahl 1987) which may be separated, along their length, by accommodation zones or transfer faults (Frostick and Steel 1993). At each end of the rift segment there may be topographically high areas where basement rocks are shallow or cropping out. These transfer faults tend to separate one segment from another for the period during which they are active (Frostick and Reid 1990). Published examples where extensional basins display this evolution include the Red Sea rift and the Gulf of Suez where two transfer zones have modified the original basin configuration (Gawthorpe and Colella 1990), the North Sea rifted basins (Spencer and Larsen 1990), and sedimentary basins in Madagascar (Morondava, Majuanga, Diego; Wescott 1988). Segmentation of such linear narrow basins has also been reported from the Karoo Supergroup (Nyambe 1999) and many of the Neogene and Quaternary basins of southeastern Spain, such as the Sorbas-Tavernas basin (Dabrio 1990; Haughton 2000). The Sorbas-Tavernas late Miocene basin is characterized by the deposition of turbidites (Cronin 1995) in basins with different geometry that evolved from open marine conditions to restricted and finally to ponded basins (Haughton 2000).

Narrow linear basins are also common in strike-slip settings. The Queen Charlotte strike-slip basin, western Canada, of which the fill consists of synextensional volcanics and clastics formed in a graben and half-graben (Dietrich *et al.* 1993), and the Alboran pull-apart basin in southeast Spain (Van der Straaten 1990), are both linear, narrow basins with narrow and shallow ends (straits).

The aspects that have influenced basin evolution in all basins described above, together with the three basins examined in this study, are: (1) the basin configuration—all are narrow and linear basins; (2) their evolution through time—all basins have changed from being relatively uniform in width and depth along their axes, to non-uniform troughs with laterally varying dimensions; and (3) the changes in depositional environment that they display, either through time as the basin changed from uniform to non-uniform morphology, or along the axis when the basin is non-uniform.

3. CORINTH–PATRAS GRABEN

3.1. Structural evolution

The Corinth–Patras basin is a late Pliocene to Quaternary WNW trending extensional basin that extends for 130 km across the Greek mainland. It formed by late Cenozoic back-arc extension behind the Hellenic trench (Figure 1A; Doutsos *et al.* 1987; Chronis *et al.* 1991). During the Pliocene, extension formed the Corinth–Patras basin, and the resulting WNW-directed basin was relatively uniform in width and depth along its axis (Figure 1B). Determination of the amount and timing of cumulative vertical displacement along the major extensional faults reveals that the graben depocentre migrated northwards throughout the Quaternary (Doutsos and Poulimenos 1992). This depocentre migration was accompanied by rapid uplift of the southern side of the basin (0.6 cm/yr according to Kontopoulos and Zelilidis (1997); up to 1000 m according to Doutsos and Piper (1990); and up to 1700 m above present sea-level, according to Seger and Alexander (1993)). Holocene net vertical slip on the central graben of the Patras sub-basin is about 3–5 mm/yr, and on its northern and southern margins is about 12 mm/yr (Chronis *et al.* 1991).

WNW-trending faults are clearly segmented along strike and most are characterized by variable displacement. Such differences are accommodated by NNE-oriented transfer faults, which permit abrupt changes in depositional conditions along the WNW-trending downthrown blocks (Poulimenos 1993). Transfer faults resulted in the formation of small sub-basins at the southern margins of the basin (Poulimenos 1993; Poulimenos *et al.* 1993).

The Corinth–Patras basin was separated into two WNW-trending sub-basins (Corinth and Patras sub-basins, 90 km and 30 km long and up to 30 km and 20 km wide, respectively) due to a NE-trending rifted sub-basin (Rion sub-basin, 15 km long and up to 3 km wide; Figures 1B, C and 2). Both basins (Corinth and Patras) show high rates

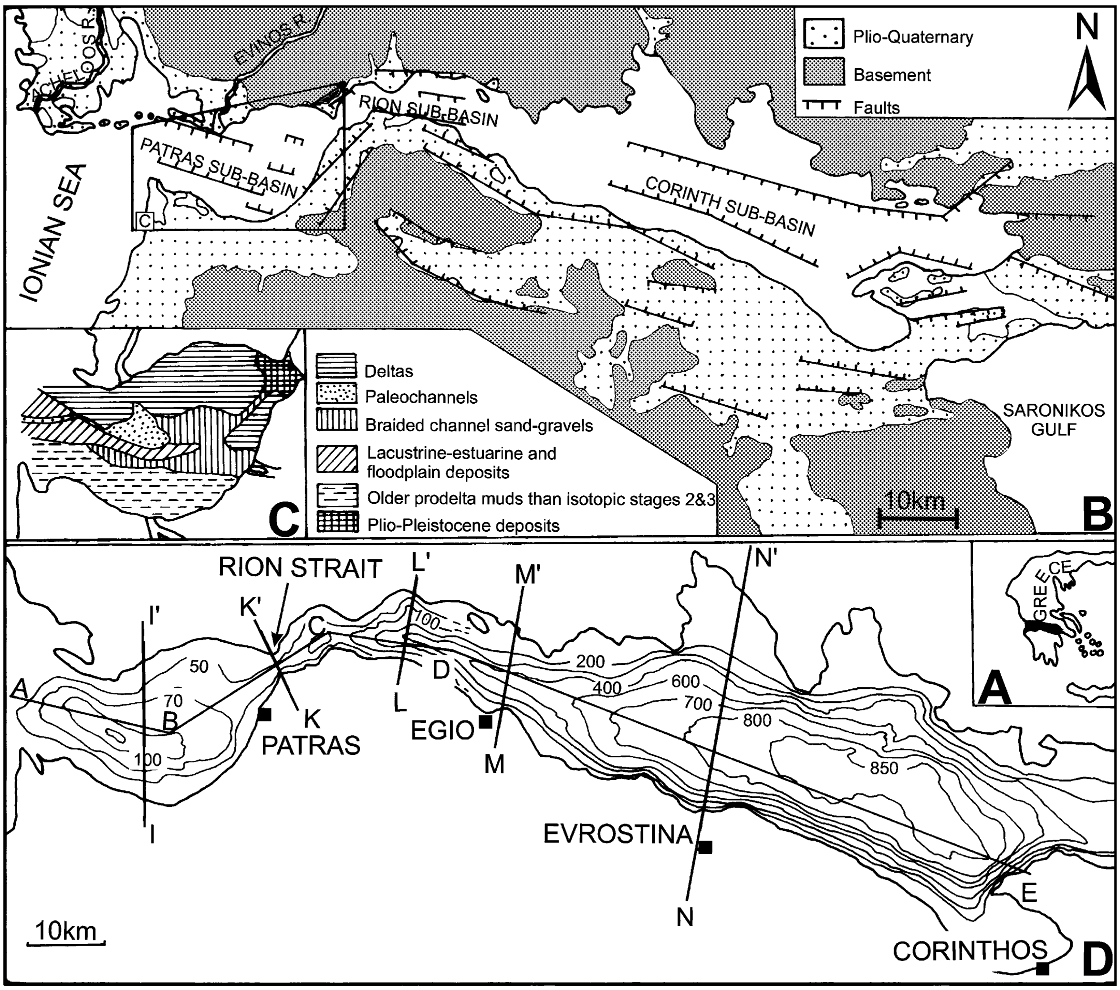

Figure 1. **(A)** Sketch map of Greece: black area indicates the studied area (shown in B and C). **(B)** Geological map of the Corinth–Patras graben, showing the Post-Miocene sediment distribution, the principal extensional faults, and the three sub-basins (Corinth, Patras and Rion). **(C)** Sediment facies distribution in the Patras sub-basin during isotopic stages 2 and 3 (modified from Chronis *et al.* 1991). **(D)** Recent Corinth–Patras basin configuration showing the present basin bathymetry.

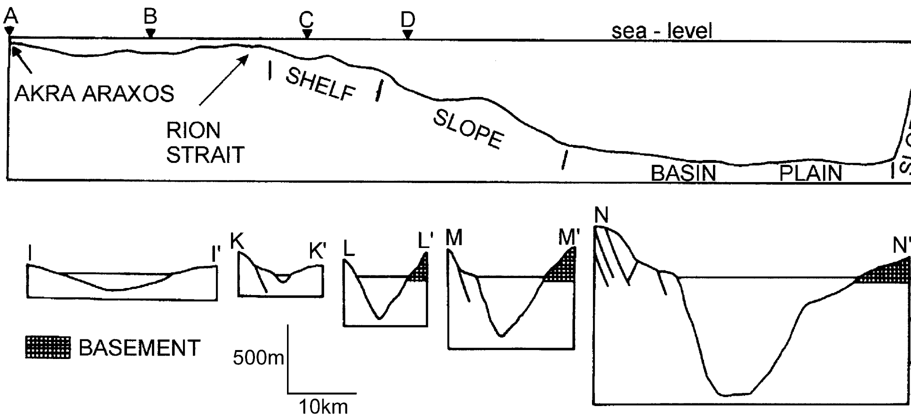

Figure 2. Cross-sections along (A–E) and across (I–I′, K–K′, L–L′, M–M′, N–N′) the Corinth–Patras graben showing the basin geometry. For locations see Figure 1D.

of subsidence along the southern, more active margins (Brooks and Ferentinos 1984; Melis *et al.* 1989). The Rion graben (Figure 1B) formed due to movement on pre-existing NE–SW-trending faults reactivated in the Pliocene (Doutsos *et al.* 1985). Changes in predominant stress directions at this time led to the Rion graben acting as a transfer zone between the extending Patras and Corinth graben (Doutsos *et al.* 1988; Melis *et al.* 1989). Due to the above-mentioned different fault trends in the area of the Rion sub-basin, the Corinth–Patras basin locally became very narrow and shallow, forming the Rion Strait which influences sedimentological evolution of the whole basin (Figures 2 and 3).

Moreover, the combination of major extensional fault activity and migration of this activity northwards, together with the different uplift rate along the southern margins of the basin and the presence and activity of transfer faults, also influenced the evolution of the drainage systems and rivers that discharged into the basin (Zelilidis 2000).

3.2. Stratigraphic and palaeogeographic evolution

Pliocene muddy deltaic, shelfal and marginal marine deposits are exposed on the uplifted southern margins of the basin. During the Quaternary the basin was deeper, forming at times a lake, at times a marine seaway, connected both at Akra Araxos and Corinthos (Figures 1 and 2). Fan-delta deposits fed by small rivers pass basinwards into turbidites in the deep areas. Large rivers produce mixed sand-mud deltas. At present the basin is open only at the western end, in Akra Araxos, and is subdivided into two sub-basins (Corinth and Patras) connected by the Rion Strait (Figure 1D; Piper *et al.* 1990). The Corinth sub-basin is characterized by an asymmetric bathymetry, deepening southwards (Figure 3). The slopes in the south are 30–40° and in the north 10–20°. Narrow shelves and slopes characterize the margins, dissected by canyon systems (Heezen *et al.* 1966; Brooks and Ferentinos 1984; Ferentinos *et al.* 1988; Higgs 1988). The gentler slopes in the Patras sub-basin compared with the Corinth sub-basin, have resulted in much of the sand load of the rivers being trapped on subaerial deltas (Piper and Panagos 1981) or in the coastal zone (Piper *et al.* 1982) while fine-grained sediments have accumulated in the central part of the sub-basin at a rate of about 0.5 mm/yr (Figure 1C; Piper 1980).

Strong tidal flows have been measured in the Rion Strait (up to 1.5 m/s) and in the Patras sub-basin (0.4–0.7 m/s), despite the small regional tidal range (0.1–0.4 m/s) (G. Ferentinos, personal communication).

3.3. Special sedimentological characteristics

The Quaternary fan-deltas were built out into lakes and formed in restricted and protected sub-basins (Egio and Evrostina regions), and are characterized by the absence of toe-sets (trapezoidal-type fan-deltas after Poulimenos

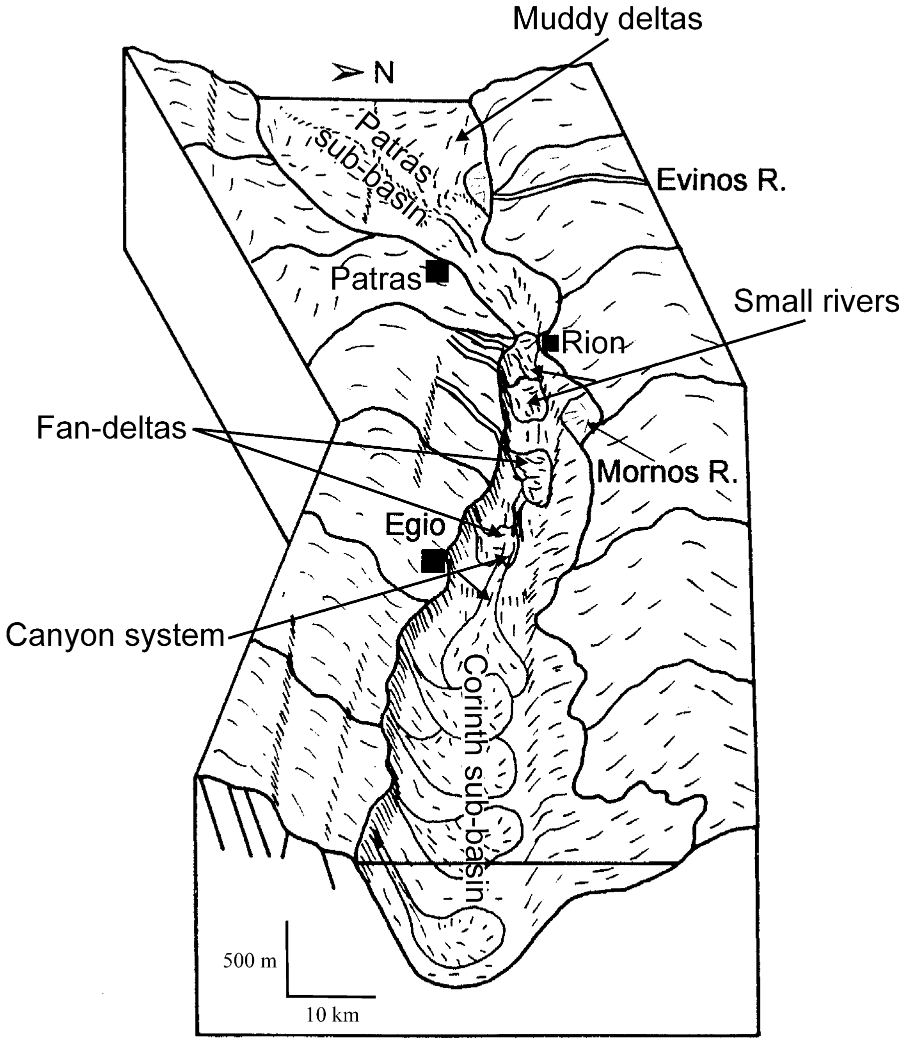

Figure 3. Morphological sketch showing the distribution of depositional environments in the present Corinth–Patras graben. Note also the narrow shelves on the southern margins of the Corinth sub-basin.

et al. 1993; Zelilidis and Kontopoulos 1996). The absence of toe-sets distinguishes trapezoidal- from Gilbert-type fan-deltas, and according to Poulimenos *et al.* (1993) and Zelildis and Kontopoulos (1996) this feature is controlled by basin geometry. These sub-basins formed at the margins of the main Quaternary Corinth sub-basin and are narrow and restricted basinwards, in the direction of the progradation, due to an intrabasinal basement high. Toe-sets cannot be formed and powerful underflows bypassed the narrow sub-basins, transporting fine-grained sediments to the central Corinth sub-basin. Location of powerful underflows was controlled by transfer fault activity. Fan-deltas that formed in open conditions are Gilbert-type.

Modern trapezoidal-type fan-deltas, deposited in marine conditions, are also observed in the western part of the Corinth sub-basin (Figure 3; Papatheodorou 1991). These fan-deltas derived from the southern margins, prograded in a NNE direction, and were eroded by channels with WNW trend, parallel to the basin axis (Heezen *et al.* 1966; based on echo soundings and sediment cores). These channels formed due to powerful underflows from Rion Strait to the Corinth sub-basin. Fan-deltas within the eastern Corinth sub-basin show an abrupt break in slope and form Gilbert-type fan-deltas.

According to Ferentinos *et al*. (1988) sediments are transported by processes such as debris/mud flows, liquefied flows and high density turbidity flows, from the narrow shelves down the slopes of the Corinth sub-basin to the basin floor, where they build deep-water fan aprons. According to Brooks and Ferentinos (1984), the ability of modern turbidity currents in the Corinth sub-basin to seek out the lowest bathymetric points across slopes of typically less than 0.1° implies very low viscosity. The turbiditic succession in the deep basin floor (>1000 m thick) is intercalated with debris flows and comprises two sequences. The lower sequence is interpreted as being more distal and the upper sub-sequence as more proximal, indicating that the basin floor, which is now about 40 km long and 14 km wide (Brooks and Ferentinos 1984), or 50 km long and 5 km wide (Heezen *et al.* 1966), must have been significantly wider, during Pliocene to Pleistocene times. The turbiditic succession contains several minor angular discordances, exhibiting onlapping relationships, and these are attributed to episodes of synsedimentary tectonic deformation of the sea floor (Brooks and Ferentinos 1984). Most of the sediments deposited on the slope of the southern Corinth sub-basin, according to Heezen *et al.* (1966), are removed by mass transportation processes to the Corinth basin floor. A general narrowing in size of the basin with time was also suggested by Higgs (1988).

The western part of the Corinth sub-basin was rapidly filled by deltas constructed on both northern and southern margins (Figure 3). At lowstands of sea-level the Mornos Delta closed the Rion Strait. The eastern end of the Corinth sub-basin was subsiding less rapidly and the Isthmus of Corinth has blocked connection to Saronikos Gulf (Aegean Sea) since isotopic stage 2 (Doutsos and Piper 1990). The Rion Strait is now characterized by no sedimentation, whereas the Patras sub-basin is dominated by large muddy deltas (Figures 1B and 3).

3.4. Discussion of basin evolution

The Corinth–Patras graben was initially a narrow, linear basin, broadly uniform in width and depth along its axis and displaying similar depositional environments along the basin axis, and was supplied mainly from southern sources. Through time and due to the formation of a transfer zone, the basin was separated into two sub-basins by a strait that formed in the transfer zone (Figure 3). In the major Corinth sub-basin turbidites accumulated, at a depth of more than 800 m, whereas on the southern margins and in narrow protected sub-basins, trapezoidal-type fan-deltas were formed. In the minor Patras sub-basin deltaic deposits have infilled the basin, to a depth of less than 150 m. Moreover, in the Rion Strait there is little or no sediment accumulation due to powerful tidal flows, which transport sediment to both sub-basins. Between this strait and the major sub-basin there is a gently dipping shelf cross-cut by canyons (Heezen *et al.* 1966), where trapezoidal-type fan-deltas, derived from the southern margin have prograded basinwards, in a NNE direction.

4. REGGIO–SCILLA GRABEN

4.1. Structural and palaeogeographic/stratigraphic setting

The Tyrrhenian and Ionian Seas are connected by the Straits of Messina (Figure 4A and B), which is a structural depression between Calabria and Sicily in southern Italy. The present basin configuration is a result of active tectonics, with persistent reactivation of normal faults with high dip-slip rates that have caused rapid changes of palaeobathymetry (Figure 4D).

Work on the Messina and Reggio sub-basins (Bousquet *et al.* 1980; Sauret 1980; Ghisetti 1981; Barrier 1986; Montenat *et al.* 1987) shows that the recent physiography of these sub-basins results from gradual uplift of the margins of a former wide basin. The major faults that are still active are oriented NW–SE. Displacement on these faults is up to 1100 m, with most slip occurring prior to 700 ka. These active faults formed small grabens and horsts during the Pleistocene.

According to Bousquet *et al.* (1980), the Messina Strait was characterized by extension during the Plio-Pleistocene transition, by weak compression during the end of early Pleistocene and finally by extension from the mid-Pleistocene to Holocene. Early E–W extension was gradually replaced by ENE–WNW extension. Ghisetti (1981), studying the deformation of the Plio-Pleistocene deposits, suggested one simple tectonic regime characterized by E–W extension.

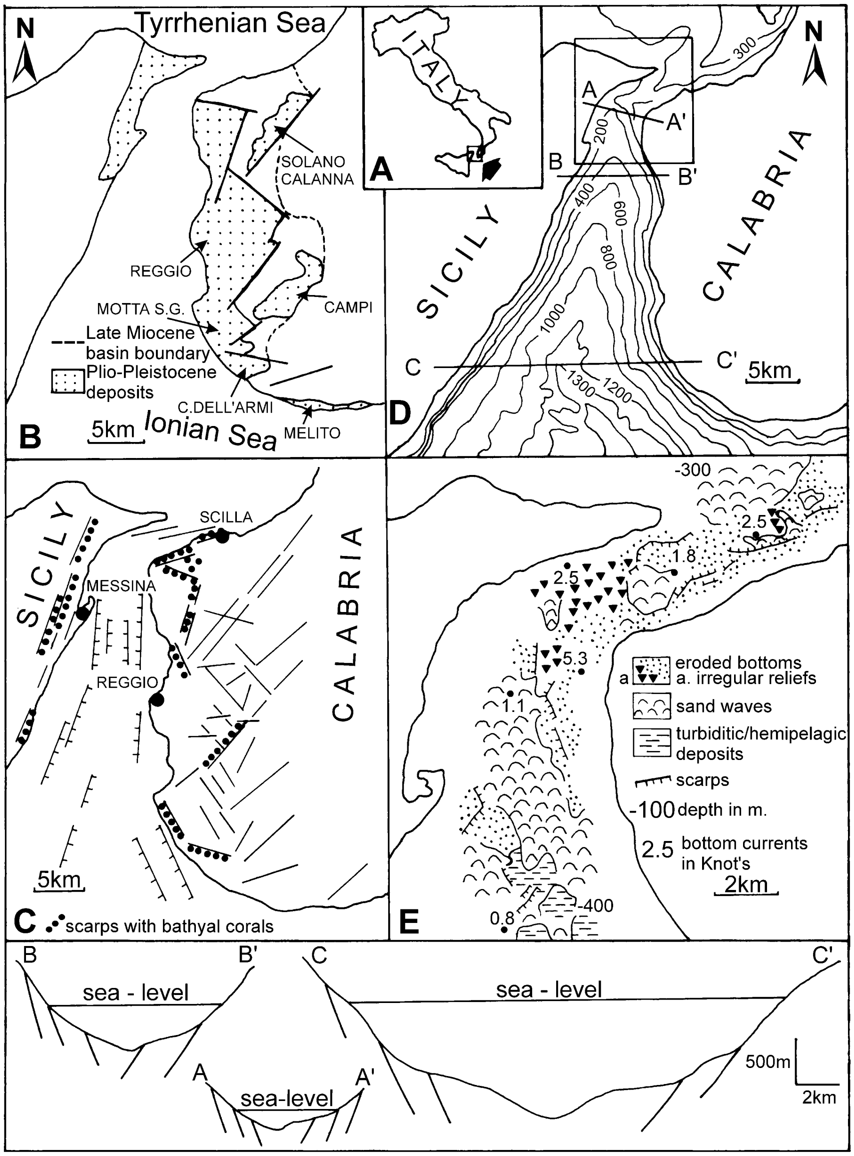

Figure 4. **(A)** Sketch map of Italy showing the studied area (black box marked with arrow). **(B)** Geological map of Scilla–Reggio graben showing the post-Miocene sediment distribution (Barrier 1986). **(C)** Structural map of Reggio–Scilla graben (Montenat and Barrier 1985). **(D)** Reggio-Scilla basin configuration showing the present-day basin bathymetry (Selli *et al.* 1978). **(E)** Present sediment facies distribution in a small area around the Strait of Messina (Selli *et al.* 1978) (for location see D). Cross-sections A–A′, B–B′ and C–C′ show the basin geometry (for locations see D).

According to Sauret (1980) and Barrier (1986), small shallow basins to the north and south characterized the early Pliocene Reggio–Scilla basin, and the strait was closed. Gradually the Tyrrhenian and Ionian seas were connected by the development of a wider, deeper basin (Figure 4B). From late Pliocene to Holocene the basin was gradually restricted to the present basin configuration by strong uplift of the margins (Figure 4B).

The Reggio–Scilla basin is a Pleistocene NNE-trending rift, 60 km long, that has now been separated into two NNE-trending rifted sub-basins (Reggio and Scilla) by the WSW-trending rifted Messina sub-basin. The Reggio sub-basin (40 km long and up to 25 km wide) is the deeper (up to 1500 m), whereas the Scilla sub-basin is shallower (up to 1000 m basin depth; Figure 4D). The Messina sub-basin is narrow (about 3 km wide) and shallow (minimum of 75 m water depth). Due to the different trend of the Messina sub-basin, the Reggio–Scilla basin in this region is very narrow and shallow, forming the Messina Strait, which has strongly influenced regional sedimentation patterns.

4.2. Sedimentologic evolution

In its early evolution (Pliocene), the basin was much like the early Corinth–Patras basin, with a more uniform geometry along its axis in width and depth. The sedimentation rate was higher in the eastern parts of the basin (Calabrian peninsula) due to strong subsidence.

Ancient (middle Pleistocene) 'Ghiaie di Messina' fan-deltas, here interpreted as trapezoidal-type fan-deltas, were associated with strong currents passing through the strait. Gilbert-type (?) fan-deltas that accumulated at the margins of the Messina basin during the Pleistocene were the sedimentary response to rapid uplift of the margins. These fan deltas prograded basinwards, perpendicular to the basin axis from both coastlines towards the strait (Sauret 1980; Barrier 1984).

The Messina Strait is now characterized by sea floor erosion and an absence of sediment cover, irregular relief and strong currents that go through the strait, transporting fine-grained sediments into both the Reggio and Scilla sub-basins (section A–A′ Figure 4D and E). Currents are between 1.8 and 5.3 knots (0.9–2.7 m/s) and reverse direction every six hours. Currents are up to 3.5 m/s in lower depths and up to 1.2 m/s in 300 m water depth (Selli *et al.* 1978).

In the Reggio sub-basin (Figure 4E), which is characterized by irregular and narrow shelves, marine turbidites (Figure 5) have accumulated on the abyssal plain (>1400 m water depth) and sand dunes occur in the transitional

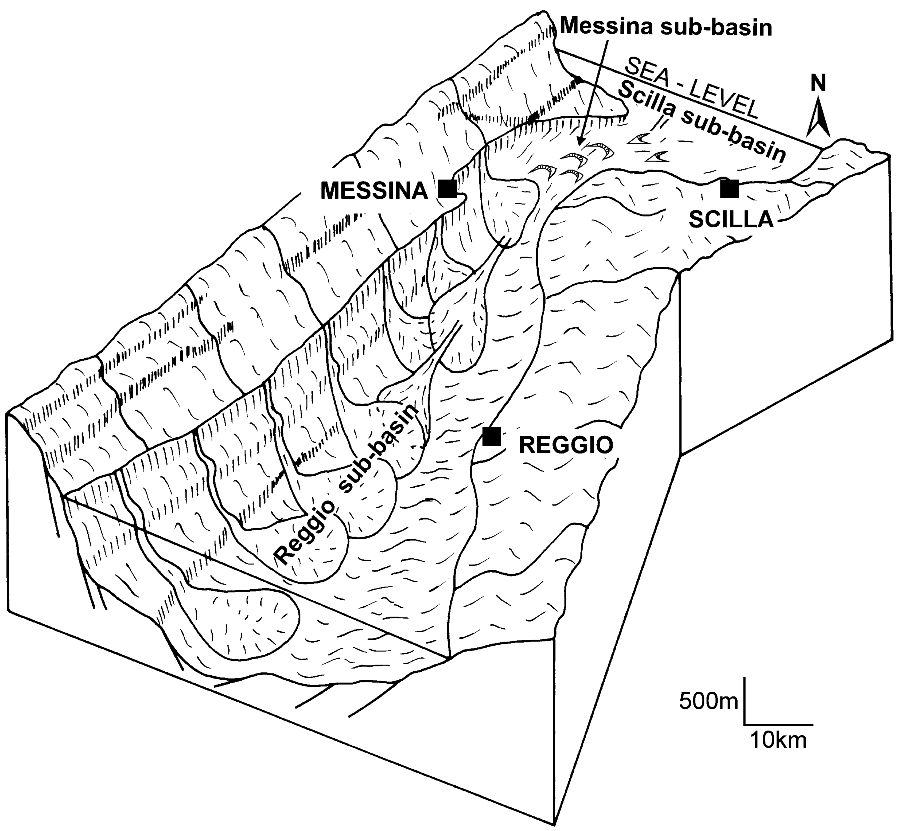

Figure 5. Morphological sketch showing the Reggio–Scilla basin configuration and the probable depositional environment development, based on the block diagram of Montenat *et al.* (1987) and a comparison with the Corinth–Patras basin.

zone from the basin floor to the strait (section C–C′, Figure 4D and E) (Selli *et al.* 1978). Bottom currents in the beginning of the turbidite zone are up to 1.1 knots (0.6 m/s). Clasts in the sand dunes are either pyroclastic or bioclastic, derived from the adjacent margins (Montenat *et al.* 1987) but probably also result from currents that transport sands from the strait through the canyons (section B–B′, Figure 4D and E). Dunes, mainly as ripples and megaripples (up to to 10 m high and 50 m long) are active (high migration speed) influencing the basin morphology and producing an unstable sea floor (Colella 1990, 1995). Montenat *et al.* (1987) show that modern fan-deltas lacking bottomsets are forming in the transitional zone (Figure 5).

4.3. Discussion of basin evolution

The Reggio–Scilla graben seems to have experienced a similar evolution to the Corinth–Patras graben. It was a linear basin displaying broadly uniform width and depth and similar depositional environments along the axis. Through time the basin was separated into two sub-basins by a shallow strait developed at a transfer zone (Figure 5). In this new basin geometry, different depositional environments formed along the basin axis. Strong currents resulted in erosion within the strait. Turbidites accumulated in the deeper major sub-basin, and sand dunes accumulated in the transitional zone from the strait to the basin floor. In the transitional zone, trapezoidal-type fan-deltas derived from both the adjacent margins also formed, and prograded in WNW and ESE directions.

5. MESOHELLENIC PIGGY-BACK BASIN

5.1. Structural setting

The Mesohellenic trough is a NNW-trending intermontane basin (Figure 6A), located at the contact between the Apulian and Pelagonian zones (Doutsos *et al.* 1994). It developed from middle Eocene to middle Miocene time as a piggy-back basin (Robertson 1994) along the eastern flanks of a giant pop-up structure (Doutsos *et al.* 1994). This structure consists of west-verging, foreland-propagating thrusts within the Apulian plate, and of east-verging back-thrusts within the Pelagonian plate. The Mesohellenic trough is bounded at its western edge by an upthrust fault, the 'Apulian' thrust (Figure 6B). Flexural subsidence near the Apulian thrust attains a maximum of 4 km, diminishing eastwards. The northern continuation of the trough is situated in Albania, whereas the southern part lies below Plio-Pleistocene alluvial sediments of the Thessalian plain. At the northern and southern terminations of the trough, two small indentors (Figure 6B) induced tectonic escape toward the central part of the basin until the middle Miocene, when the convergence wrenching at the indentors was gradually replaced by post-orogenic collapse. Near the two indentors the basin narrowed considerably and basin depth decreased dramatically. The indentors themselves, according to Doutsos *et al.* (1994), represent structural elevations, as higher tectonic units (ophiolites) are eroded or never thrust over them, whereas thrusting mainly induces uplift in the areas of the indentors.

This contractional Mesohellenic basin, according to Doutsos *et al.* (1994), shows several similarities with piggy-back basins described from the Pyrenean Chain (Roure *et al.* 1989; Munoz 1992), from the Venezuelan Andes (Molnar and Lyon-Caen 1989) and from the Lesser Antilles Forearc (Westbrook *et al.* 1983).

A gulf was formed, due to activity on the Krania thrust, during middle to late Eocene in the Krania area. During the latest Eocene–early Oligocene (Figure 6B) the Mesohellenic trough was a NNW–SSE elongated basin (Doutsos *et al.* 1994) with uniform width (about 25 km) and basin depth along the basin axis. During late Oligocene–early Miocene times, the impact of the southern indentor (Apulian indentor after Doutsos *et al.* 1994) changed the basin configuration in the south. Near the town of Kalabaka (Figure 6B, section C–C′) the basin was only about 2 km wide and became very shallow, forming the Kalabaka Strait. Thus the basin became subdivided in two sub-basins by this strait. The northern (Pentalophos) sub-basin was the major sub-basin (Figure 6B, section C–C′), whereas the southern (Thessalian) sub-basin (Figure 6B, section D–D′) was much shallower and was the minor sub-basin.

From four boreholes drilled in both sub-basins (Alexiadis 1995), the thickness, lithology and age of the sediments were estimated (see Figure 6 for the location of these boreholes). These boreholes show that the maximum thickness in the central part of the Thessalian plain is less than 1000 m, and in the eastern part of the Pentalophos

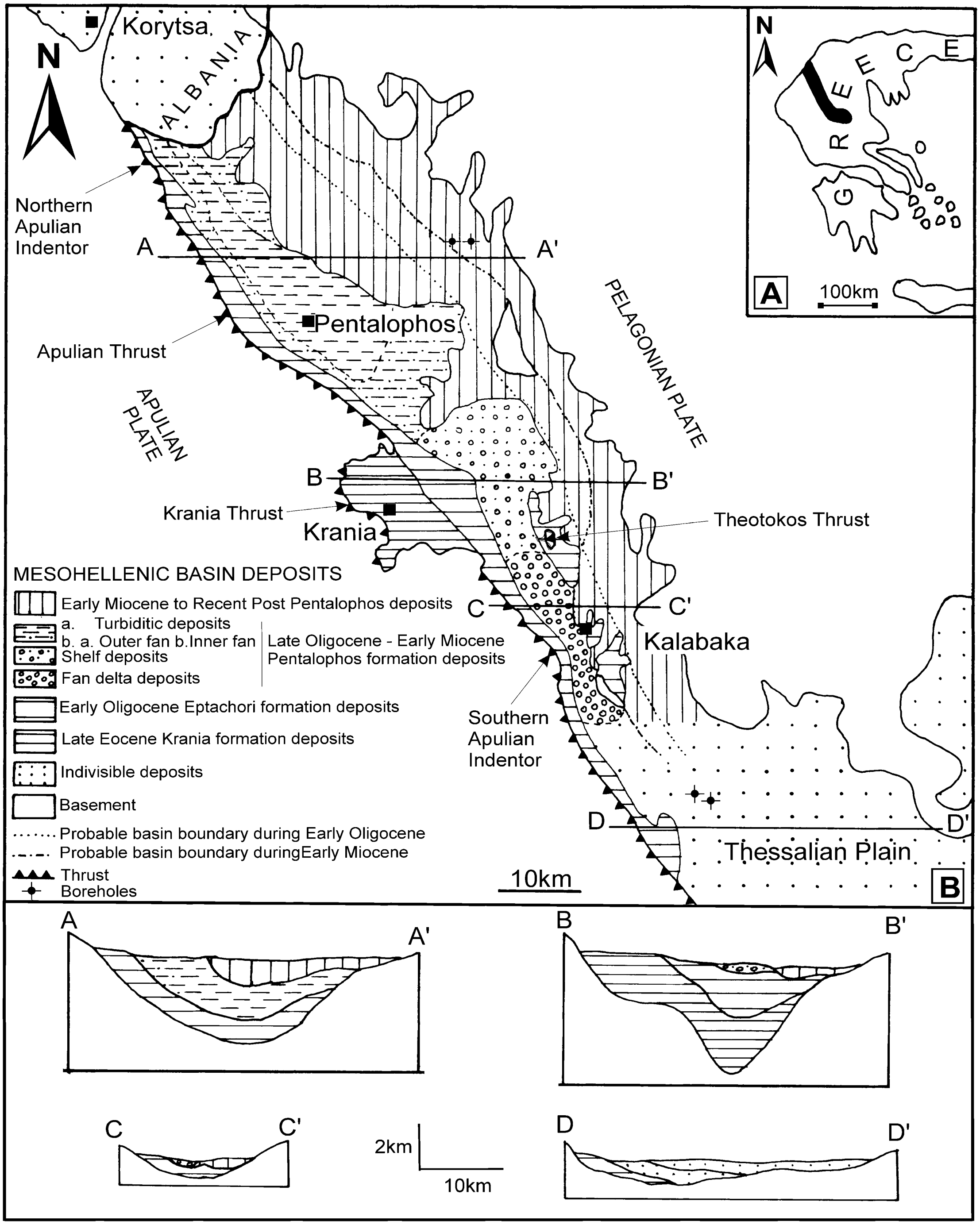

Figure 6. **(A)** Sketch map of Greece showing the studied area (black area). **(B)** Geological map of the Mesohellenic piggy-back basin, showing the late Eocene–late Miocene sediment facies distribution. Early Miocene to Recent Post Pentalophos deposits correspond to the Tsotyli, Ondria etc. Formations. Cross-sections A–A′, B–B′, C–C′, D–D′ show the facies distribution and the geometry of the basin based on field and seismic data (for locations of the cross-sections see B).

sub-basin it is also less than 1000 m (from seismic data the thickness of sediments in the main Pentalophos sub-basin is more than 4500 m, according to Kontopoulos *et al.* 1999). The age of sediments in both these boreholes is early Miocene (Aquitanian to Burdigalian).

5.2. Palaeogeographic/stratigraphic evolution

Submarine fans accumulated in the middle to late Eocene basin that formed in the first stage of the Mesohellenic basin development. The latest Eocene to early Oligocene uniform basin was characterized by deltaic and fan-delta deposits adjacent to the western margins and later by turbiditic deposits formed in a foredeep (Doutsos *et al.* 1994; Zelilidis *et al.* 1997; Zelilidis and Kontopoulos 1997; Kontopoulos *et al.* 1999; Zelilidis *et al.* 2002; Avramidis *et al.* 2002). Late phases of the basin (late Oligocene) were characterized by different depositional environments along the basin axis due to the change in basin geometry, caused by the indentor activity (Figures 6 and 7). Trapezoidal-type coarse-grained fan-deltas were deposited near the town of Kalabaka (Zelilidis and Kontopoulos 1996; Gilbert-type fan-deltas, according to Ori and Roveri 1987), where the basin was very narrow (Kalabaka Strait; Figures 6B and 7); these rest unconformably on submarine fan deposits. Submarine fans continued to accumulate in remaining parts of the basin. During the early Miocene, and due to continuing indentor activity, the fan-deltas were uplifted and sub-aerially exposed. Along the basin axis northwards the fan-delta deposits pass laterally through thick shelf sediments that accumulated on a gentle dipping platform, up to 12 km wide, while submarine fan deposits were formed in the central part of the Pentalophos sub-basin.

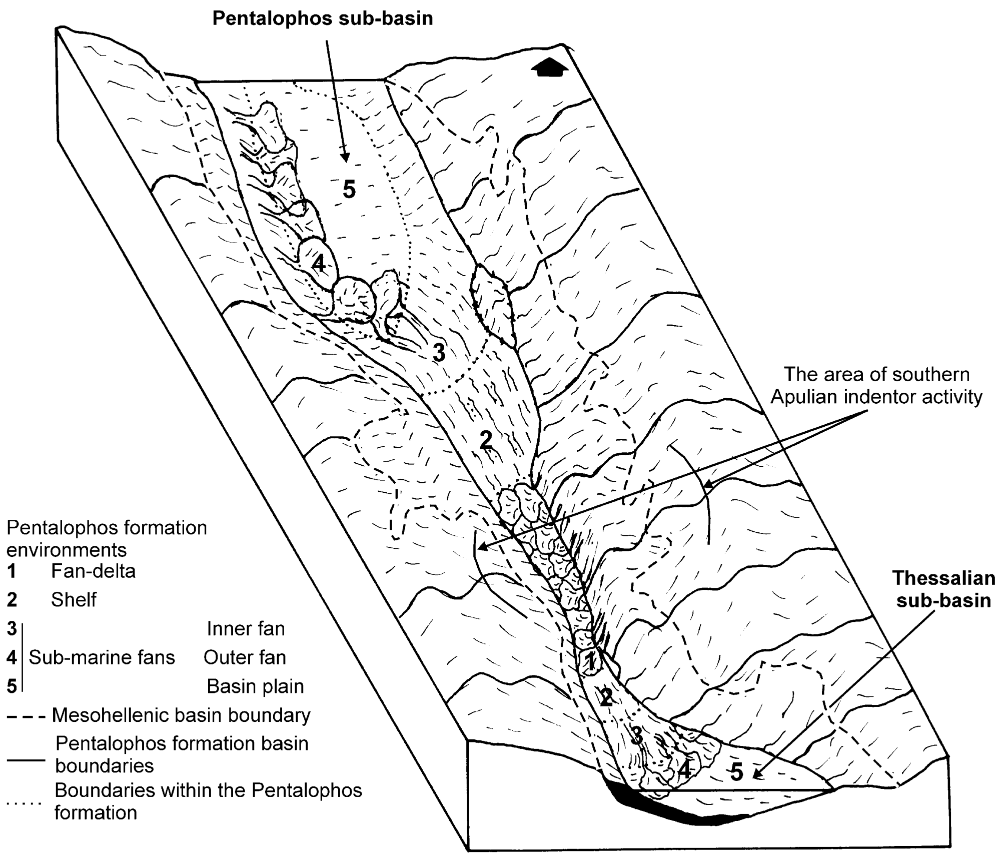

Figure 7. Morphological sketch showing the Pentalophos Formation sub-environments in the Mesohellenic piggy-back basin during late. Oligocene–early Miocene time. Distribution of depositional environments is based on Figure 6.

5.3. Special sedimentological characteristics

Sediments accumulated in the Mesohellenic basin consist, from base to top, of 1300 m of late Eocene submarine fan deposits formed in a small basin in the Krania area (Krania Formation, bounded westwards by the Krania thrust). These are followed unconformably by 900 m of latest Eocene deltaic deposits, and coeval fan-delta deposits up to 2000 m thick which rest directly on the basement outside the Krania sub-basin (bounded to the west by the Apulian thrust, renamed the Eptachori Thrust by Kontopoulos *et al.* 1999). These deltaic and fan-delta deposits are followed by an Oligocene–Miocene succession up to 3500 m thick, with submarine fan deposits (Eptachori, Pentalophos and Tsotyli Formations) (Figure 6B; Brunn 1956). In the southern part of the basin, the Pentalophos and Tsotyli Formations consist of trapezoidal-type fan-delta (Zelilidis and Kontopoulos 1996) and Gilbert-type fan-delta (Ori and Roveri 1987) deposits respectively, related to the uplift of this area due to the presence of the southern indentor (Doutsos *et al.* 1994).

These trapezoidal-type fan-deltas, up to 350 m thick, formed during late Oligocene time and were derived from the eastern margin, and prograded westwards (Zelilidis and Kontopoulos 1996). This type of fan-delta records the input of coarse sediment into a restricted basin. The absence of the bottomsets in the fan-deltas formed in the strait is attributed to narrowing of the basin and the strong currents that were focused through a shallow strait, transporting finer sediments into the deeper parts of the basin. These strong currents may be responsible for the 'channel-like' sedimentary structures that were developed within the foresets of the trapezoidal-type fan-deltas (Zelilidis and Kontopoulos 1996).

Continuing activity of the indentors during early Miocene caused further uplift so that fan-deltas were exposed to subaerial influence and a wide, gently dipping shelf was formed in the northern periphery of the fan-deltas. Shelf deposits, unconformably overlying submarine fans, are mostly fine-grained sediments, although in places coarse-grained deposits are formed, that are interpreted to have been deposited in canyons. Within the fine-grained deposits coal beds, up to 1 m thick, were formed. Laterally from the shelf deposits were inner fan deposits that pass northwards to outer fan deposits (Figure 6B, section A–A′, Figure 7; Zelilidis *et al.* 2002).

Most of these fans are formed in small, tectonically controlled basins; so are Types I and II, according to the classification of Mutti (1985). In such basins relatively small volumes of coarse-grained sediments, chiefly fan-delta deposits, may accumulate along narrow and irregular shelves. Different turbidite stages within the same formation indicate a rapid lowering of sea-level, followed by a gradual re-establishment of shelf deposition (Zelilidis and Kontopoulos 1997; Zelilidis *et al.* 1997). The turbidites of the Mesohellenic basin appear to have formed in conditions analogous to those in the Corinth–Patras basin.

6. BASIN CONFIGURATION IN THE THREE STUDIED BASINS

The three basins studied are all narrow and linear, and changed configuration through time. Tectonic activity in basins of very different origin may result in the development of straits/sills separating sub-basins of varying depth. The strait may thus connect a deep major sub-basin with a shallower minor sub-basin (Figure 8; Zelilidis 1997).

In the three studied examples, the ratio of the width in the strait to the width of the sub-basins is about 1:10; the ratio of the depth in the major sub-basin to the depth in the strait is >1:15, and this ratio between the minor sub-basin and the strait is >1:2.

In the major sub-basins (Figures 3, 5 and 7), which are characterized by narrow and irregular shelves, turbidites accumulated in the central part (basin floor) derived from the steep margins or along the basin axis from the strait. Between the strait and the basin floor there is a transitional zone where fine- to coarse-grained deposits can accumulate. This transitional zone includes shelf and slope environments. The shelf is cross-cut by canyons, which transport sediment from the strait to the basin floor.

The minor sub-basins are characterized by extensive river-dominated deltaic sedimentation (Figure 3), with coarse-grained deposits around the periphery, and fine-grained deposits in the central part of the sub-basin. Moreover, relatively small volumes of sediment are transported from the strait to the basin.

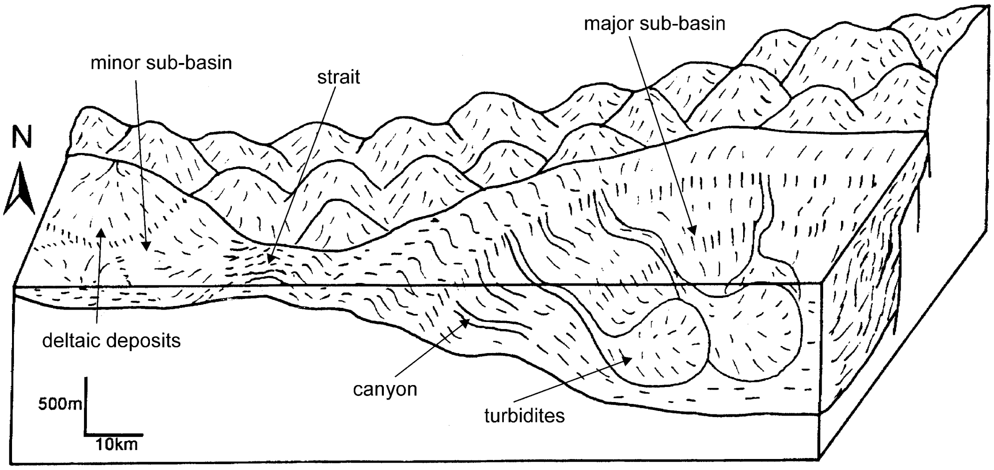

Figure 8. Morphological sketch showing the basin configuration and the depositional environments likely to be formed in a basin following the development of a strait. This strait can separate the original basin into two sub-basins, one major and one minor.

The straits are characterized either by coarse-grained sediments accumulated in steep active margins (Figure 7) or even by no sedimentation (Figures 3 and 5). Strong tidal currents within the straits transport sediment to the sub-basins and erode the sea floor. Coarse-grained sediments accumulate as trapezoidal-type fan-deltas where toe-sets are absent and currents may form scours, 'channel-like' structures, within the foresets (see Zelilidis and Kontopoulos (1996) for the Mesohellenic piggy-back basin). Clasts are derived from the adjacent steep margins. Sediment progrades basinwards perpendicular to the basin axis. A subaerial platform is narrow or absent.

7. DISCUSSION AND CONCLUSIONS

Despite the fact that different tectonic regimes have influenced the three studied basins, and they have evolved over different time intervals, they display broadly similar basin evolution and configuration: (1) the basin was narrow, linear and uniform in width and depth along its axis when it formed; (2) the basin was tectonically separated through time into two different sub-basins (major and minor) connected by a strait; (3) the basin depth and width in the strait decreased dramatically; (4) the major sub-basin is significantly deeper than the minor sub-basin; (5) the major sub-basin has narrow shelves and turbiditic deposits accumulated on the basin floor; (6) shallow-water or terrestrial coarse-grained sediments are deposited in the strait and pass laterally into shelf deposits and deep-water submarine fans (in the major sub-basin) or into the deposits of large river deltas in the minor sub-basin.

We can thus predict that in the two recent basins (Corinth–Patras and Messina), where the straits are currently characterized by a lack of sedimentation, coarse-grained trapezoidal-type fan-deltas may develop, as observed in the Mesohellenic basin. The absence of bottomsets is the result of strong currents, which transport finer sediments into the two sub-basins. Subaerial platforms will be narrow or absent, and clasts will be derived from the adjacent pre-existing coarse-grained deposits and basement. Moreover, in the two recent basins, an extensive shelf is likely to develop between the strait and major sub-basin. This shelf will be cross-cut by canyons and characterized by thin fine- to coarse-grained deposits. In the shallow sub-basins, river-dominated thick deltaic deposits can be formed, interbedded with fine-grained deposits transported from the strait. In the major sub-basin the deposition of turbidites will continue. The evolution described assumes no subaerial exposure of the strait by eustatic sea-level fall.

In general, along-axis changes in basin morphology and dimensions will cause different depositional environments to be formed along the basin axis, independent of the basin genesis. Straits/sills will separate the basin into two or more sub-basins. In the straits, powerful tidal flows will transport finer deposits to sub-basins and trapezoidal-type fan-deltas will gradually fill up and choke the strait through time. In sub-basins, according to basin depth either deltaic (in the shallow minor sub-basin) or turbiditic (in the deep major sub-basin) deposits may accumulate.

Knowledge based on the evolution of the strait formed in the Mesohellenic basin, enables us to recognize three stages of strait evolution. (1) During the first stage, when the basin changes from a uniform to a non-uniform configuration with the development of a strait, the strait is characterized by an absence of sedimentation due to the strong currents passing through it. (2) In the second stage, the strait gradually fills up with coarse-grained trapezoidal-type fan-deltas. The fact that coarse-grained deposits accumulate in the strait may relate to the active tectonic influence in this part of the basin, and the pre-existing coarse-grained deposits in the periphery of the strait. (3) Gradually, from the second to the third stage, the strait will become narrower due to the progradation of the fan-deltas. Finally, the strait will be closed and fan-deltas will be exposed to subaerial influence. Currents in the strait may cut into the existing foresets forming scour fields, 'channel like' structures, within them. These channels will be perpendicular to the dipping foresets and parallel to the basin axis. In the periphery of the fan-deltas and towards the major sub-basin a gently sloping shelf environment will be formed.

Placing the two modern basins in the above scenario it seems that the Rion Strait is still in the first stage (characterized by no sedimentation in the strait), whereas the Messina Strait seems to belong to the second stage, because trapezoidal-type fan-deltas have started to fill up the strait.

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