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Drainage evolution in a rifted basin, Corinth graben, Greece

Abraham Zelilidis *

Department of Geology, University of Patras, 26110 Patras, Greece

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Abstract

Intrabasinal basement highs and transfer faults, distance from source, and the underlying geology influence the drainage pattern and the evolution of the 41 river basins in the northern Peloponnesus. These rivers were classified as antecedent (10), multistory (17), re-established (5) and juvenile (9) drainage types. Antecedent drainage is when a river has maintained its original direction of flow across later tectonic topography. Multistory drainage consists of a re-established drainage and of a reverse drainage. Reverse drainage, when flow direction along part of a river is reversed, consists of two opposing drainage components: a misfit and a reverse element; the area between these two elements, termed "wind gap", is a dry valley. Re-established drainage is when a reverse element returns to its original flow direction. Juvenile drainage consists of small incising and headward-eroding streams. The sediments that the rivers flow across (soft uncohesive marls or coarse-grained deposits and Pre-Neogene basement with limestones), river power (strong close to the source or weak far from the source), presence or absence of transfer faults and tilted blocks due to the activity of synthetic and antithetic faults, all influence whether an antecedent drainage will remain unchanged or will be changed to a reverse drainage. When transfer faults cross-cut the area of a wind gap and the underlying sediments were soft uncohesive marls, reverse drainage changed to a re-established drainage. In other cases, where transfer faults were absent and underlying deposits were coarse-grained sediments or limestones, in the area of the wind gap, then reverse drainage remained unchanged.

Keywords: drainage evolution; multistory; antecedent; re-established; juvenile; corinth graben

1. Introduction

There is a rich literature on the drainage evolution in tectonically active areas. Mazzanti and Trevisan (1978), Burbank et al. (1996), and Alvarez (1999) studied drainage evolution on evolving fold–thrust belts and especially in transverse canyons in the Apennines. They related drainage evolution to the time of evolution, ratio of sedimentation to uplift rate and lithologies that the rivers flow across. Mather (1993) worked in Sorbas basin, SE Spain and related drainage evolution to tectonic control and sedimentological changes. Cox (1994) focused on tilted blocks to analyze drainage basin changes.

Seger and Alexander (1993) studied drainage evolution in the Corinth graben. They studied 24 drainage basins of northern Peloponnesus and classified them into four types: antecedent, reversed, capture, and juvenile drainage basins. Antecedent drainage is

* Corresponding author. Tel.: +30-61-996272; fax: +30-61-996272.

E-mail address: a.zelilidis@upatras.gr (A. Zelilidis).

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when a river has maintained its original direction of flow across later tectonic topography. Reversed drainage is when the flow direction along part of a river is reversed, caused by tectonic deformation of the river-bed. Reversed drainage consists of two opposing drainage components: a misfit and a reversed element; the area between these two elements, resulting from tectonic deformation, termed a "wind gap", is a dry valley. Capture was the term used for drainage when the flow direction of the reverse drainage elements returns to the original flow direction. Juvenile drainage basins consist of small incising and headward-eroding streams.

This paper deals with the geologic and tectonic controls on drainage evolution in extensional basins. It examines the influence of the different lithologies that the rivers flow across, the presence or absence of transfer faults and intrabasinal basement highs, variations in uplift rates, the time of evolution, and the distance from the basement. Most attention is given to the development of transverse drainages.

2. Geological setting

The Corinth graben, 100 km long and 40 km wide, is an area of rapid subsidence that separates continental Greece from Peloponnesus (Fig. 1A). According to Poulimenos et al. (1989), Doutsos and Piper (1990), and Poulimenos (1993), WNW-trend-

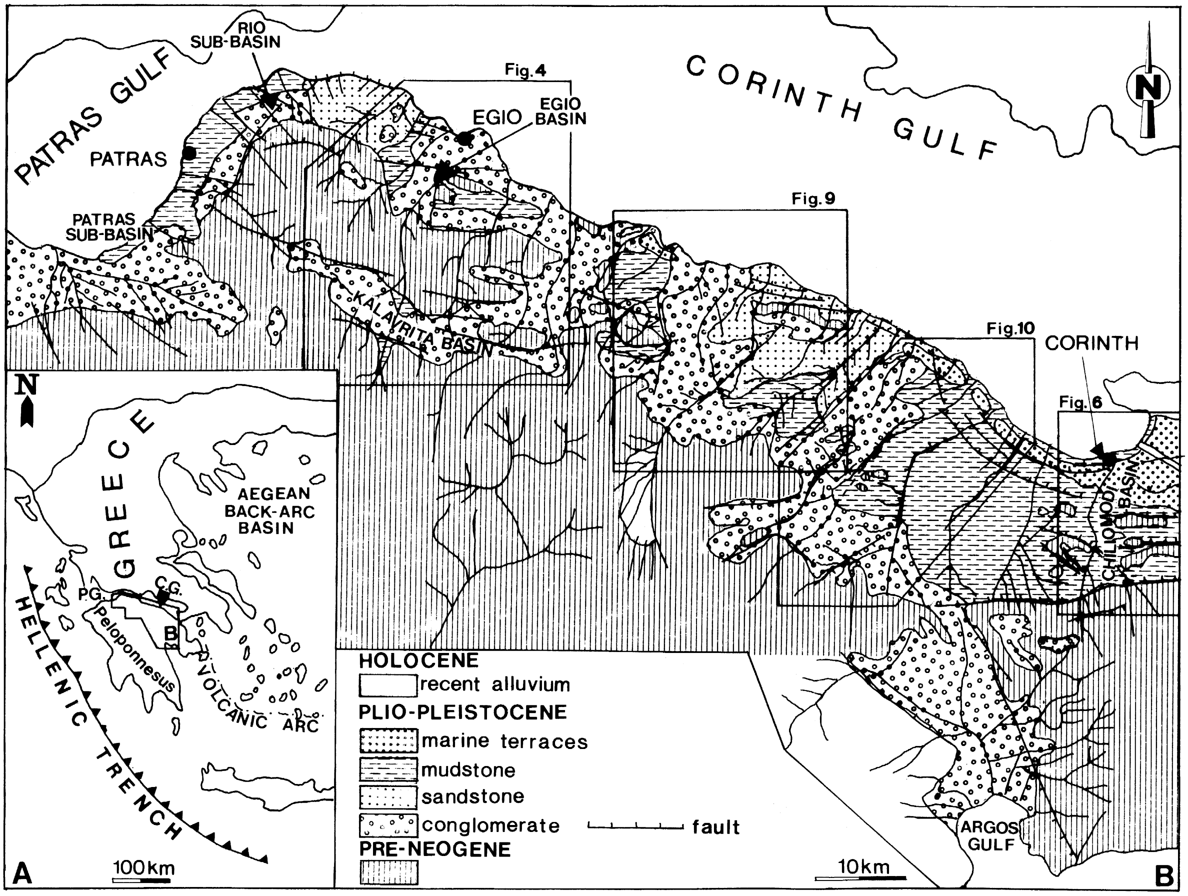


Fig. 1. (A) General map of Greece, showing location of the study area, and the Corinth (C.G) and Patras (P.G) grabens. (B) Geological map of the northern part of Peloponnesus showing the 41 rivers and the Plio-Quaternary sediment facies distribution.

ing listric faults are the master faults that influenced the basin evolution. The dominant tectonic style is characterized by the formation of asymmetric grabens bounded by listric faults. Due to the ("synthetic" or "counter") master faults that dip northwards, several tilted blocks dipping southwards were formed and a wedge-shaped terrigenous clastic sequence accumulated during tilting. Many master faults are accompanied by one to three minor faults that dip southwards, called "backward" or "antithetic faults", showing smaller displacement, which tend to reduce the structural relief. Numerous WNW-trending master faults terminate abruptly at NNE-trending "cross-faults" or "transfer faults". The synchronous activity of master (synthetic), minor (antithetic) and cross-faults (transfer) influenced the basin configuration and the depositional environments. As a result, several small sub-basins were formed at the southern margins of the Corinth graben (Poulimenos et al., 1993; Zelilidis and Kontopoulos, 1996), such as Egio and Kalavrita sub-basins (Fig. 1).

During the Late Pliocene, the marine Corinth graben was almost twice the width of the modern Gulf of Corinth. Subsequently, tectonic activity in northern Peloponnesus migrated basinwards, with the footwall of active faults uplifted and backtilted (Poulimenos et al., 1993). Tectonic activity seems to be stronger in the west than in the east. Quaternary sediments exposed in the uplifted southern part of the Corinth graben (Fig. 1B) consist, from south to north, of alluvial fan and lacustrine conglomerates near the graben margins. Fan delta conglomerates (Gilbert- or trapezoidal-types, according to Poulimenos et al., 1993; Zelilidis and Kontopoulos, 1996) and marls, deposited in the middle part of the graben. Lacustrine marls overlain by thin marine or fluvial terraces formed near the present coastline (Doutsos and Piper, 1990).

3. Depositional environments

Neogene sediments within the drainage basins are of three different facies, lacustrine–lagoonal marls, marine sandstone (forming elevated terraces), and coarse-grained braided river or fan delta deposits (Fig. 1B) (Poulimenos et al., 1989; Doutsos and Piper, 1990; Piper et al., 1990).

Lacustrine–lagoonal marls (Zelilidis, 1998a) are composed of coarsening upwards cycles with mudstone and silty sandstone beds. Near bounding faults coarse-grained massive, matrix-supported, high dipping conglomerates accumulated. Moreover, in transfer zones thick interbedded mudstone–sandstone and conglomerate beds were deposited.

Marine sandstone terraces are most common in the northeastern part of the basin (Dufaure and Zamanis, 1980; Keraudren and Sorel, 1987; Collier and Thompson, 1991; Armijo et al., 1996; Dia et al., 1997). They date from 300,000 to 80,000 years, and are subdivided into four different lithologies: (a) planar-bedded, cross-bedded and massive sandstone/conglomerates, (b) variably laminated and bioturbated siltstone/sandstones, (c) oolitic sandstones and, (d) transverse dunes.

Coarse-grained braided river deposits consist of two components: (I) proximal deposits consisting up to 90% pebbles and cobbles and (II) braided plain deposits that consist of silt and sand beds alternating with conglomerates. Fan delta facies consist of subaerial and sub-aqueous components that consist of thick conglomeratic deposits (Poulimenos, 1993; Poulimenos et al., 1993).

4. Age determination

The age of the oldest sediments in the Corinth graben is Middle to Late Pliocene lacustrine and fluvial sands and silts (Kontopoulos and Doutsos, 1985; Frydas, 1987, 1989; Zelilidis, 1998a). These are overlain by thick Quaternary conglomerates, dated as Calabrian by Symeonidis et al. (1987) using mammalian fossils. The more northerly conglomerates formed prograded sequences that have the morphology of trapezoidal- or Gilbert-type fan deltas and are interbedded with marls (Poulimenos et al., 1993; Zelilidis and Kontopoulos, 1996). The marls contain nannofossil assemblages of the NN20 and NN21 zone, corresponding to the Middle Pleistocene and Late Pleistocene isotopic stages 12 to 5, younger than 475 and 122 ka effectively (Keraudren and Sorel, 1987; Doutsos and Piper, 1990; Frydas, 1991; Fernandez-Gonzalez et al., 1994; Stamatopoulos et al., 1994; Kontopoulos and Zelilidis, 1997). The later sediments are overlain by thin marine or fluvial sandstones and/or conglomeratic terraces, dated as Late Pleistocene (Keraudren and Sorel, 1987; Piper et al., 1990; Armijo et al., 1996; Dia et al., 1997).

Uplift rates, calculated for Quaternary terraces, differ along the Corinth–Patras rift. According to Stamatopoulos et al. (1994) the uplift rate in the Patras sub-basin (Fig. 2) is about 0.8 mm/year; whereas near Patras town this is about 1 mm/year (Piper et al., 1990). The highest uplift rate was calculated in the Rio sub-basin (Fig. 2) and is about 4.5 mm/year (Kontopoulos and Zelilidis, 1997). Uplift rate for the Corinth sub-basin decreases eastwards, from 2.2 mm/year near Egio (Frydas, 1991; Poulimenos et al., 1993), to 1.5 mm/year in the central part of the basin (Doutsos and Piper, 1990), and decreases to 0.3–0.4 mm/year near Corinth town (Keraudren and Sorel, 1987; Armijo et al., 1996; Dia et al., 1997) (Fig. 2).

A relative erosion rate was calculated, between the river valley and adjacent areas, either in the area of a wind gap or on the footwall and adjacent to the active faults. The calculation of the erosion rate is based on the difference between valley and adjacent area altitudes that formed in specific time spans. Erosion rate in the area of the wind gap in the multistory drainages is calculated between 0.8 and 1.2 mm/year. Uplift rate in these rivers is about 1.5 mm/year. In the antecedent Piros drainage relative erosion rate near the coast and on the footwall of the active fault is 0.4 mm/year. Uplift rate of Piros drainage is about 0.8 mm/year. In all studied cases the ratio, erosion rate to the uplift rate is < 1.

5. Geomorphological data

In the study area, maximum altitudes reached are 2200 m. Most of the Plio-Quaternary deposits are situated between 0 and 600 m, trending in a WNW direction, parallel to trends of master faults (Fig. 1B). The continuity of the WNW direction of relief is interrupted by NNE trend, which is parallel to the direction of the transfer faults. Altitudes more than 1400 m referred to the Pre-Neogene basement and show the same directions and influence of fault activity as in the Plio-Quaternary deposits (Fig. 3).

6. Drainage patterns and their evolution

Forty-one drainage basins have been studied in this paper in order to understand why particular rivers changed course at particular times and what the role of the different types of fault is. These 41 river drainages were classified in four types (Table 1). Two of these are similar to the antecedent and juvenile types of Seger and Alexander (1993). The new types “re-established drainage” and “multistory drainage”, replacing Seger and Alexander’s (1993) capture and reverse drainage types, respectively (Figs. 1B and 3) (Zelilidis, 1998b). The new multi-

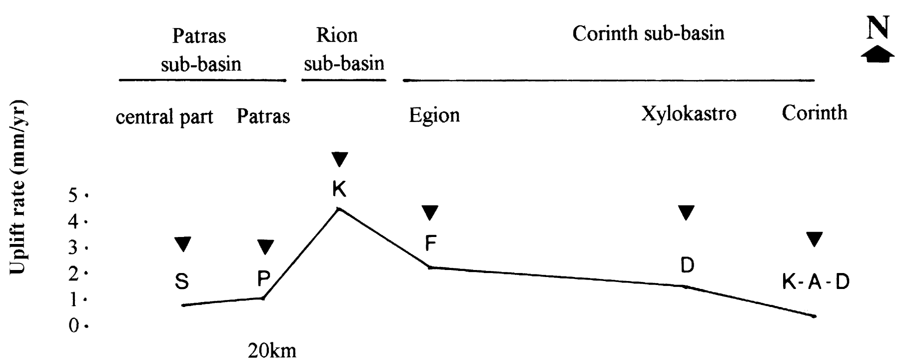


Fig. 2. Schematic section showing uplift rates along the Corinth graben. Letters correspond to data derived from S = Stamatopoulos et al. (1994), P = Piper et al. (1990), K = Kontopoulos and Zelilidis (1997), F = Frydas (1991), D = Doutsos and Piper (1990), K–A–D = Keraudren and Sorel (1987), Armijo et al. (1996), and Dia et al. (1997).

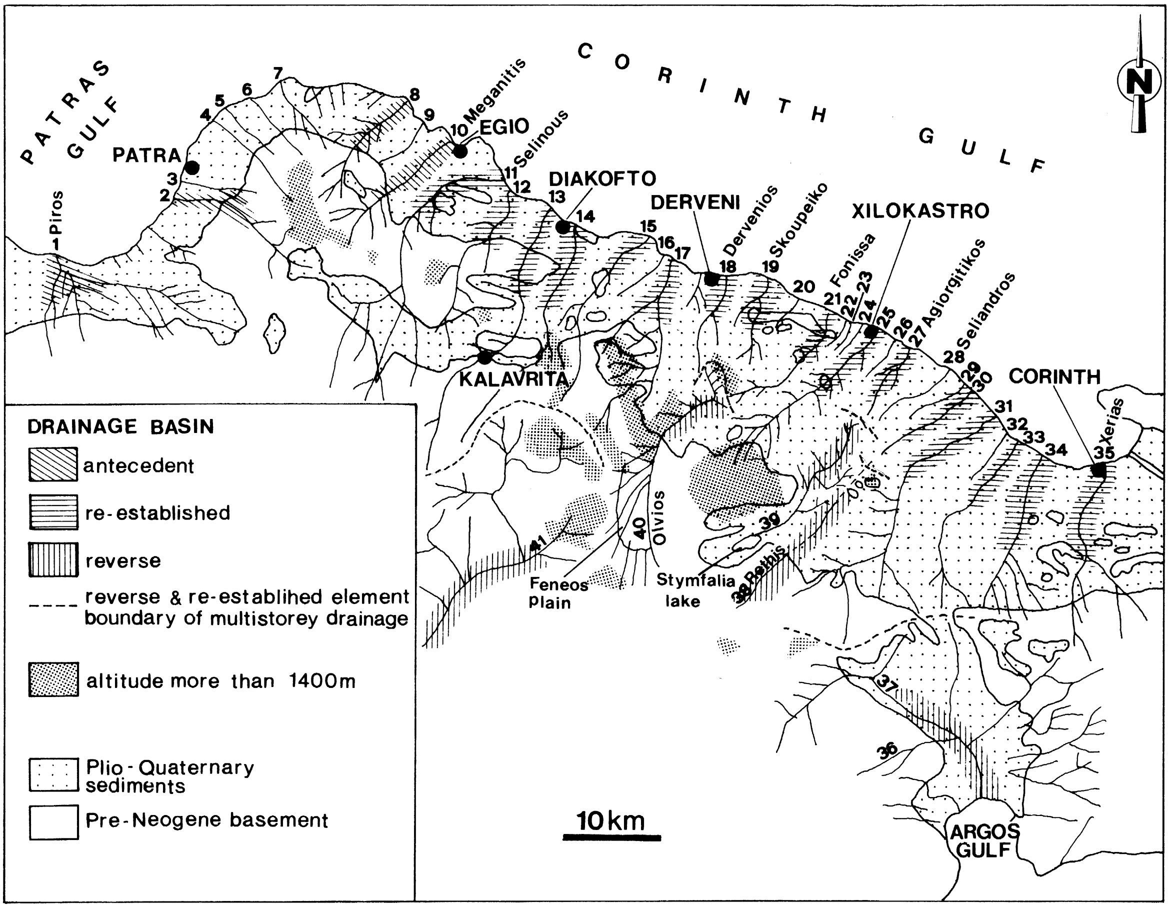


Fig. 3. General map of the study area showing the distribution of the different drainage basins and the areas higher than 1400m altitude. Numbers 1 to 41 represent the studied drainage basins. The names of the rivers that used in the text are also shown. For the rest, names corresponding to the numbers, see Table 1.

story drainage type consists of both re-established and reverse drainage. The replacement of the misfit element in the reverse drainage of Seger and Alexander (1993), with the re-established drainage of multistory drainage in this work, is based on the fact that the evolution of misfit elements is similar to the evolution of a re-established drainage.

Antecedent drainage is restricted to the western part of the basin; multistory, re-established and juvenile drainages occur in the central and eastern parts of the basin (Fig. 3).

6.1. Antecedent drainage

This is where rivers have maintained their original direction of flow across later tectonic topography. Two examples are presented: the Piros (1) and Meganitis (10) Rivers.

6.1.1. The Piros River (1)

The Piros River (1) is situated in the Patras sub-basin (Fig. 1B) and its drainage basin is within Plio-Quaternary deposits between 0 and 200 m altitude. This river evolved in a narrow basin, influenced by ENE- and WNW-trending faults (Zelilidis et al., 1988) filled with Upper Pliocene shallow marine fine-grained deposits (Zelilidis et al., 1988; Frydas, 1989). During the Early Pleistocene the basin was covered by alluvial fans (situated mostly towards the southern margins) and braided river coarse-grained deposits and lacustrine fine-grained deposits. Finally the basin was inundated during the

Table 1
Classification of the 41 studied drainage basins in north Peloponnesus, with 10 antecedent drainages, 9 juvenile, 5 re-established (2 of them with two wind gaps, and 3 of them with only one wind gap) drainages, and 17 rivers form five multistory drainages. For this classification, see also Fig. 3

RIVER DRAINAGE CLASSIFICATION

Antecedent drainage		Juvenile drainage	
Piros (1)	Xilokeras (6)	Tholopotamos (16)	Katharoneri (26)
Glaukos (2)	Volineos (7)	Agriolagado (20)	Kyrillou (29)
Diakoniaris (3)	Finix (8)	Arachovitikos (22)	Gourgouroti (32)
Charadros (4)	Tholopotami (9)	Spartila (23)	Xirias (36)
Selemnos (5)	Meganitis (10)	Kolones (24)	

Re-established drainage
took place in one step (one wind gap) and in some cases in two evolutionary steps (two wind gaps)

wind gap lithologies that the river flow across

	wind gap a (first step)	wind gap b (second step)
Selinous (11)	Pre-Neogene basement	intrabasinal high of Pre-Neogene basement
Kerinitis (12)	//	//
Ladopotamos (14)	conglomerates	
Trikalitikos (25)	intrabasinal high of Pre-Neogene basement	
Xerias (35)	marine terraces	

Multistory drainage

STEP		
1	***Misfit***	***Reverse element*** remained unchanged and formed a Reverse drainage basin
2	changed to a new misfit and reverse element	
3	changed to a re-established drainage basin	
4	in some cases re-established drainage changed again to misfit and reverse element	
5	changed again to a **re-established drainage basin**	

SYSTEM	wind gap a (second step)	wind gap b (fourth step)			lithologies of the unchanged wind gap of the first step
	wind gap lithologies that the river flows across during second and fourth step				
Vouraikos (13)	Pre-Neogene basement	Pre-Neogene basement	►	Ladonas (41)	Pre-Neogene basement
Krathis (15)	//	marine terraces			
Krios (17)	//	//			
Dervenios (18)	Pre-Neogene basement				
Skoupeiko (19)	//		►	Olvios (40)	conglomerates
Fonissa (21)	//				
Agiorgitikos (27)	marine terraces		►	Rethis (39)	lacustrine marls
Seliandros (28)	//				
Elisson (30)	marine terraces		►	Souteni (38)	Pre-Neogene basement/ conglomerates
Asopos (31)	marine terraces				
Nemeas (33)	//		►	Inachos (37)	Pre-Neogene basement
Rachiani (34)	//				

Late Pleistocene and marine fine-grained deposits accumulated (Stamatopoulos et al., 1994). The direction of the Piros River flow and the outcrops of old deposits are aligned in WNW directions, parallel to WNW directed master faults. Transfer- or antithetic-faults are few or absent. The Piros River drainage is characterized by a low Late Quaternary uplift rate (0.8–1 mm/year) and gorges less than 30 m deep.

The evolution of the Piros drainage within the Patras sub-basin is very different from the other drainages studied in the Corinth sub-basin. The fact that the Piros River flows parallel to the master faults and the absence of transfer- and antithetic-faults are the reasons that the Piros River never changed its flow direction. The fact that gorges are shallow could be related with low uplift rates.

6.1.2. The Meganitis River (10)

The Meganitis River (10) is situated between the Rion- and Corinth sub-basins (Fig. 1B) and its drainage evolution was influenced by the evolution of these two sub-basins. The upper reaches, within Pre-Neogene basement, are in an area of 600–1400 m altitudes, whereas the lower reaches are situated between 0 and 600 m altitude within Plio-Quaternary deposits. This river (Figs. 3 and 4) evolved in a narrow basin, influenced by WNW-trending faults, filled with Lower to Middle Pleistocene fluvio-lacustrine fine-grained deposits interbedded with coarse grained deposits towards the basement and fine-grained deposits towards the center of the basin (Poulimenos, 1993). All these deposits are overlain by Upper Pleistocene alluvial fan deposits. The flow direction of the Meganitis River, and the fluvio-lacustrine deposit outcrops, are aligned in a NNE direction due to the activity of many transfer faults that influenced the evolution of sub-environments. Antithetic faults are few or absent and the tectonic activity migrated northwards, towards the basin center. The Meganitis River drainage is characterized by a high Late Quaternary uplift rate (> 2.2 mm/year), and gorges up to 300 m deep with walls more than 70° steep.

The Meganitis River flow direction remained unchanged through time, in a NNE direction parallel to the transfer fault direction. This happened because the basin was narrow, the tectonic activity migrated northwards, and antithetic faults were absent. Deep and steep gorges in the Meganitis River could be related with the coarse-grained deposits that the river flows across and the higher uplift rates, in relation to the Piros River.

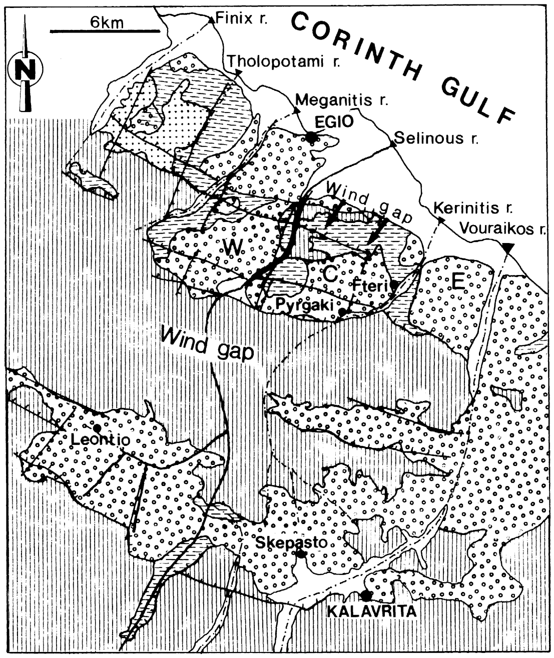


Fig. 4. Geological map, modified from Poulimenos (1993), of the western part of the studied area, showing the sediments cut by the Meganitis, Selinous, Kerinitis and Vouraikos Rivers, and the principal extensional and transfer faults. Also, the two wind gap areas are marked for the Selinous River. For location and map symbols, see Fig. 1B.

6.1.3. Interpretation of antecedent drainage basin evolution

The Piros and Meganitis Rivers represent antecedent drainage (Fig. 4) formed during the same period and flowing across analogous lithologies. The Piros River flows parallel to master faults, whereas the Meganitis River flows parallel to transfer faults. In both cases antithetic faults are absent, and for this reason the flow direction remains unchanged. The different gorge geometries relied on different uplift rates.

6.2. Re-established drainage

Two examples are presented, the Selinous (11) and Xerias (35) Rivers.

6.2.1. The Selinous River (11)

The Selinous River drainage flows across two basins, the Kalavrita and Egio basins (Figs. 1B and 4). The upper reaches of this river in the Kalavrita basin flow across Plio-Quaternary deposits (between 200 and 1000 m) and Pre-Neogene basement up to 1800 m altitude. The lower reaches in the Egio basin flow across mostly Plio-Quaternary deposits outcropping at 0–1000 m altitudes.

The Kalavrita basin is filled with Late Pliocene fine-grained lacustrine deposits (exposed thickness >100 m) overlain unconformably by Lower Pleistocene (Mountzos, 1990) alluvial fan (up to 350 m thick) and braided river (500 m thick) coarse-grained deposits. The Egio basin is characterized by the presence of interbedded fine-grained and coarse-grained Middle to Upper Pleistocene (? <450 ka according to Frydas, 1991) fluvio-lacustrine deposits (150 m thick). At the southern margins and unconformably over them, Upper Pleistocene trapezoidal-type fan deltas (500 m thick) accumulated, whereas in the north, Holocene alluvial fan deposits (up to 120 m thick) were formed.

The Selinous River (Fig. 4) during Late Pliocene–Early Pleistocene (early phases of sedimentation) formed an antecedent drainage (Fig. 5A). From the Early Pleistocene until the Late Pleistocene, two flow directions changes (reverse drainages) were indicated in the Plio-Pleistocene sediments, for the Selinous flow, in relation to tectonic activity (Fig. 5B,C). The Selinous River basin is characterized by an average 2.2 mm/year uplift rate.

The first drainage reversal took place as tectonic activity migrated northwards and the Kalavrita basin was separated from the Egio basin by uplift of a footwall block where Pre-Neogene basement (limestones) outcropped (wind gap area). The reverse element discharged into the Kalavrita basin from north to south and the misfit element discharged from south to north into the Egio basin. This reverse element drainage changed to a re-established drainage, thus returning to its original direction, probably due to the activity of transfer faults that were situated both in the central part of the Kalavrita basin and in the area of the wind gap (Fig. 5C). Due to the transfer faults the Kalavrita basin was separated into the Leondio and Skepasto sub-basins; where lacustrine deposits accumulated during the time of reverse drainage (Fig. 5B).

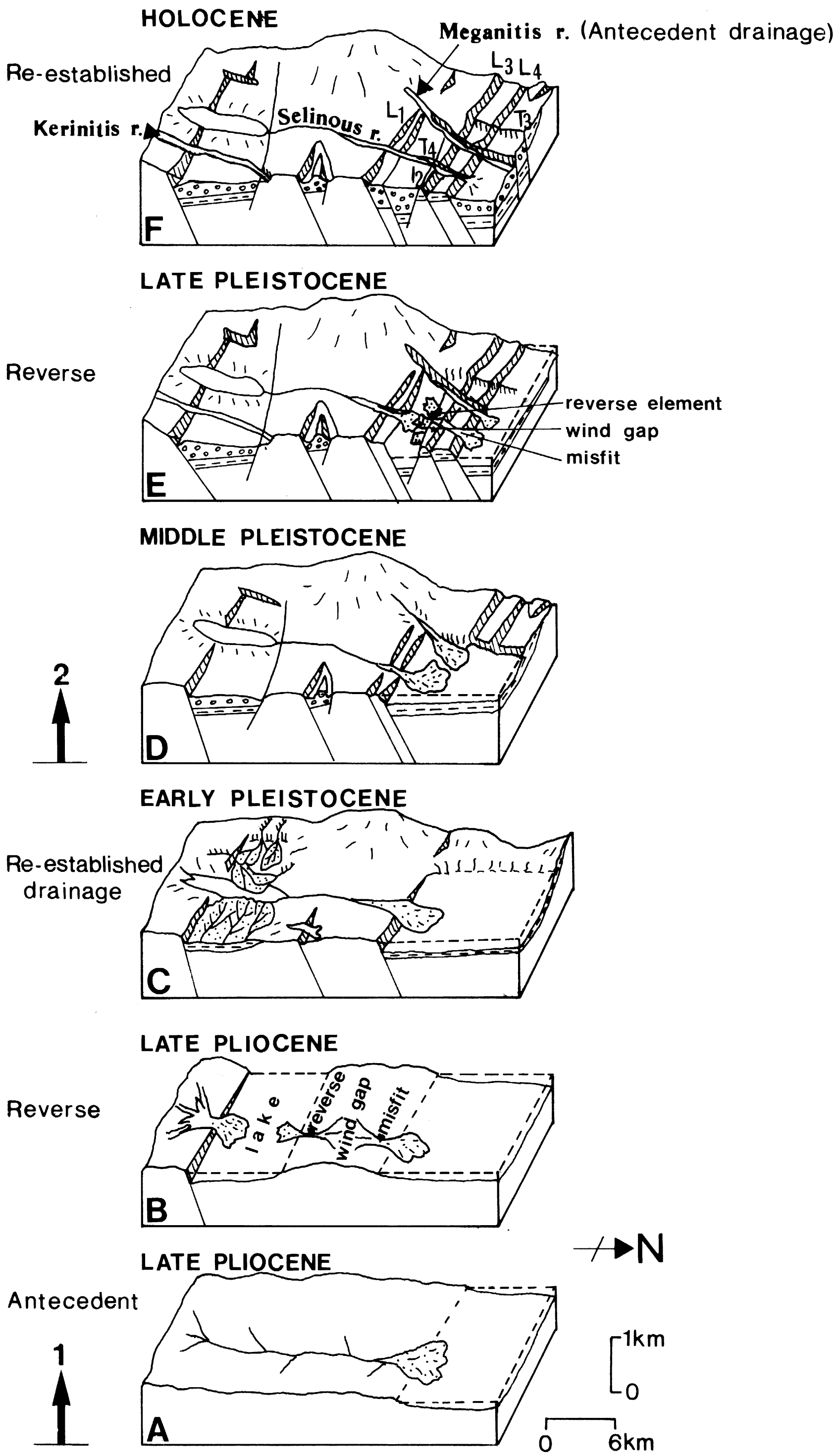
The second drainage reversal took place within the old misfit, during Late Pleistocene sedimentation of fan delta deposits within the Egio basin (Figs. 4 and 5E). Due to synchronous activity of synthetic and antithetic faults, a small sub-basin (the Pyrgaki sub-basin) was formed at the southern margins of the Egio basin, restricted basinwards by an intrabasinal basement high (Fteri intrabasinal basement high: Fig. 4). This second wind gap is underlain by Pre-Neogene limestones and Middle to Upper Pleistocene lagoonal mudstones (Poulimenos et al., 1993; Zelilidis and Kontopoulos, 1996). Sedimentological analysis of fan deltas showed that these prograded either northwards or southwards sourced from the southern margins of the basin and the wind gap, respectively. This second drainage reversal changed again to a re-established drainage (Fig. 5F) due to activity on transfer faults that separates this marginal sub-basin into three parts (W, C and E on Fig. 4) also influencing depositional environments (Poulimenos et al., 1993; Zelilidis and Kontopoulos, 1996). In both evolutionary stages gorges up to 400 m deep with $>70°$ walls were formed in the area of wind gaps.

6.2.2. The Xerias River (35)

The upper reaches of the Xerias River flow across Pre-Neogene rocks situated between 600 and 1000 m altitudes, whereas the lower reaches developed on Quaternary deposits at 0–600 m altitudes (Fig. 1B).

The Quaternary deposits consist of Middle Pleistocene fluvio-lacustrine marls (Keraudren and Sorel, 1987) and Middle to Upper Pleistocene sandy marine terraces (up to 30 m thick). Two unconformities were recognized within fluvio-lacustrine marls with up to 300 m exposed thickness (Zelilidis, 1998a).

Fig. 5. Schematic block diagrams, modified from Poulimenos (1993) illustrating the drainage evolution of antecedent Meganitis and re-established Selinous drainages, in relation to tectonic activity of WNW extensional faults (L: master faults, l: antithetic faults) and NNE transfer faults (T). Numbers on the left mark the two stages of evolution from an antecedent to reverse and finally to re-established drainage.


HOLOCENE
Re-established
Meganitis r. (Antecedent drainage)
Kerinitis r.
Selinous r.
F
LATE PLEISTOCENE
Reverse
reverse element
wind gap
misfit
E
MIDDLE PLEISTOCENE
2
D
EARLY PLEISTOCENE
Re-established drainage
C
LATE PLIOCENE
Reverse
lake
reverse
wind gap
misfit
B
LATE PLIOCENE
Antecedent
1
N
1km
0
0 6km
A

Near the bounding faults, this unit consists of coarse-grained conglomerates (up to 200 m thick). Marine terraces are developed mostly at the northern part of the Chiliomodi basin (Fig. 1B), and dated from 300 to 80 ka according to Keraudren and Sorel (1987), about 200 ka according to Collier and Thompson (1991), and from 70.2 to 385.5 ka according to Dia et al. (1997).

Basement outcrops within the Quaternary Chiliomodi basin were intrabasinal basement highs during the sedimentation and resulted from movement on antithetic and synthetic faults, which are parallel to the master bounding WNW-aligned listric fault (L1) situated at the southern margins of the basin (Fig. 6). Due to these intrabasinal basement highs, the Chiliomodi basin was separated into sub-basins. Moreover, NNE cross-faults (transfer faults) influenced the expansion and sediment thickness of the sub-basins (Zelilidis, 1998a).

The Xerias River (Fig. 6) formed an antecedent drainage during the Early to Middle Pleistocene (Fig. 7). The river was incised through the uplifted footwall of two internal sub-basins (the Athikia and Galataki sub-basins). The river flowed through shallow gorges in its lower reaches and deep gorges in the upper reaches in the Pre-Neogene basement. The shallow gorges in the lower reaches result from the soft Middle Pleistocene lacustrine sediments that the river flows across (Zelilidis, 1998a). The Xerias River drainage is characterized by low uplift rate compared with the Selinous River drainage (about 0.4 mm/year according to Keraudren and Sorel (1987) or 0.3 mm/year according to Armijo et al. (1996) and Dia et al. (1997)). During Upper Pleistocene sedimentation, marine terraces were formed on the footwall of L4 master fault (dated $< 80{,}000$ years, according to Keraudren and Sorel, 1987). Antecedent drainage remained unchanged until Holocene time (1000–2000 years BP?) (Fig. 8). Evidences for this are (1) the presence of a Holocene delta in the hanging wall of L4 fault and (2) the fact that the town of Ancient Corinth was built on the footwall of L4 fault, far from the active Xerias River delta.

The footwall of L4 fault was uplifted during the Holocene (?1000–2000 years BP) and tilted southwards (Fig. 8). Due to this evolution the pre-existing antecedent drainage changed to a reverse drainage consisting of two opposing drainage elements: a reverse drainage component and a misfit drainage component. Evidences for the change to reverse drainage are: (1) the small size of river width in the area of the wind gap (local residents stated that 100 years ago the maximum width of the river was < 4 m), (2) the presence of alluvial deposits over marine terraces in the area between the Xerias River and the Kechrees coast, and (3) the presence of a small submarine delta, indicated by contour lines in the Gulf of Kechrees.

The probable reason for uplift and backtilting of the L4 fault footwall is the strong earthquakes that took place in Corinth town during the years AD 77, 543, 580, 1858 with unknown magnitude, and 1928, with magnitude (Ms) 6.3 (Ambraseys and Jackson, 1990).

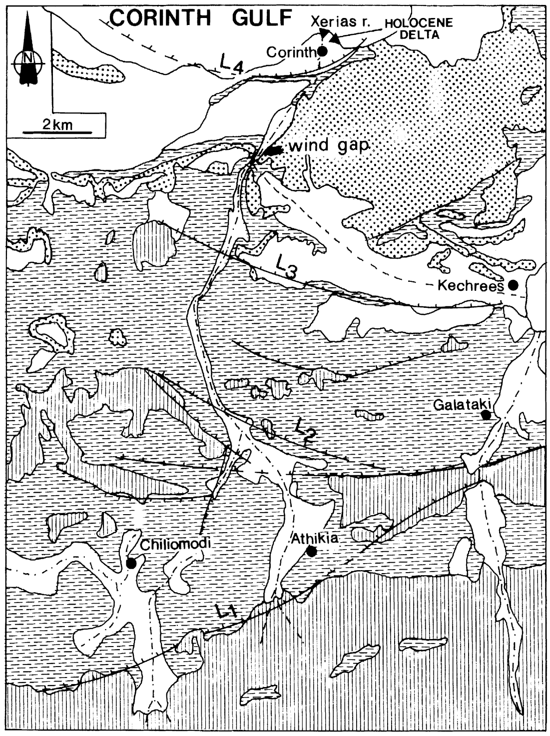


Fig. 6. Geological map of the easternmost part of the study area, modified from Zelilidis (1998a) showing the Quaternary sediment facies distribution, the principal extensional faults, the Xerias River drainage and the area of the wind gap. Numbers 1 to 4 correspond to Athikia, Galataki, Ancient Corinth and New Corinth sub-basins, respectively. For location and map symbols, see Fig. 1B.

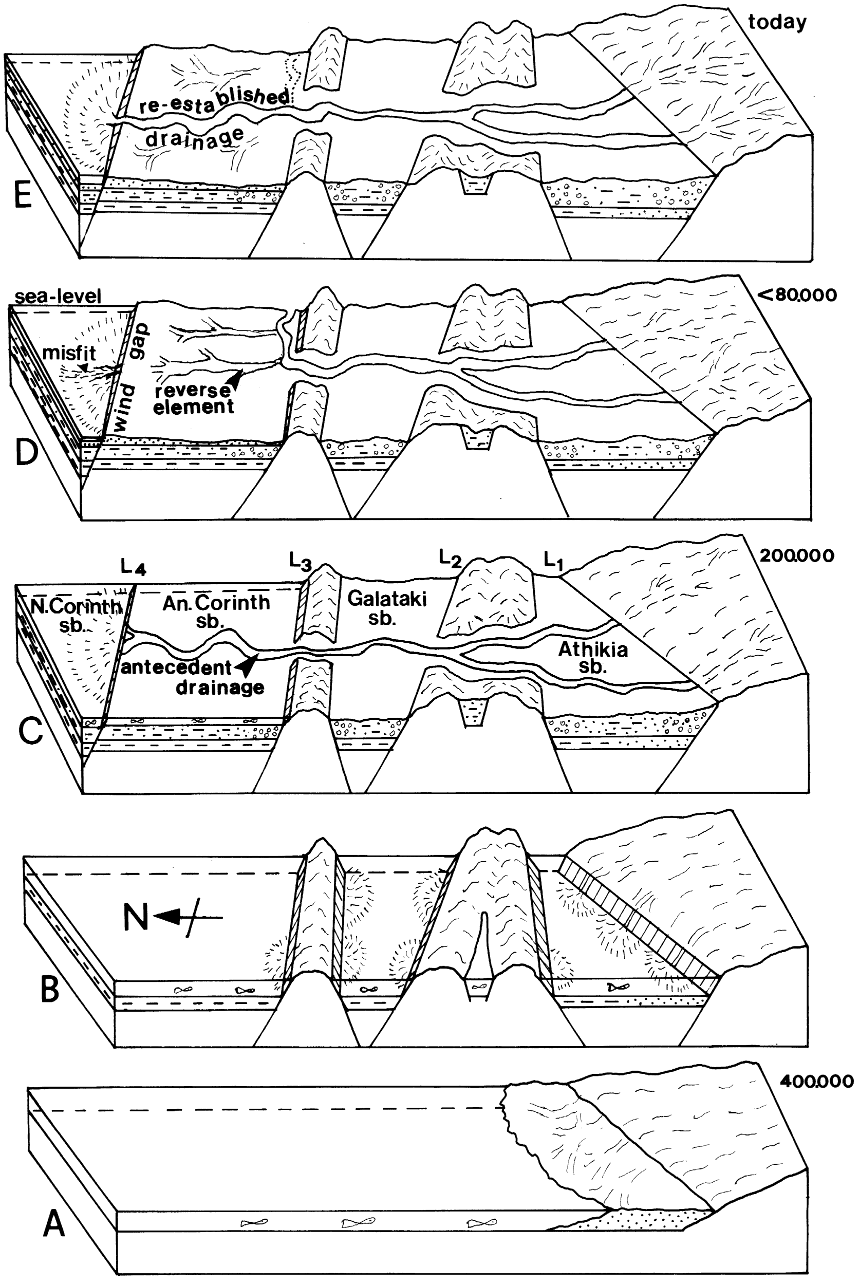


Fig. 7. Block diagrams showing the paleogeographic evolution of the easternmost part of the study area and the evolution of the Xerias drainage pattern in five stages.

The reverse element drainage occurs in the footwall of the active fault L4 that is the platform between L3 and L4 faults and that represents the wind gap (Fig. 7). The misfit drainage has its original flow direction and discharged to the Chiliomodi basin. The flow direction of the reverse element was from north to south and near the fault L3 its flow changed and was from SSW to ESE direction, paral-

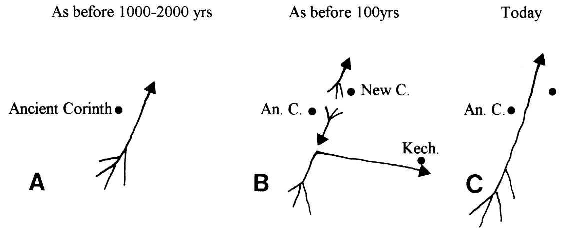


Fig. 8. Diagram showing the evolution of the Xerias drainage in three stages: (A) antecedent drainage, (B) reverse drainage, and (C) re-established drainage.

lel to L3 fault, towards the coast at Kechrees (Fig. 6). This flow direction change suggests an asymmetrical subsidence of the platform between the L3 and L4 faults. The development of the reverse drainage type indicates also a great reduction in water and sediment discharge in the original flow of the river by the reduction in catchment size.

At the present time, the Xerias River has changed to a re-established drainage because the reverse element returned to its original flow direction. Headward erosion by the misfit stream through the wind gap extended into the area of the reverse drainage and captured the stream (Figs. 7 and 8). Gorges in the area of the wind gap have increased in width, by up to 30 m, and depth, by up to 5 m, during the last 100 year, eroding the pre-existing Upper Pleistocene deposits.

6.2.3. Interpretation of re-established drainage basin evolution

The Selinous and Xerias Rivers represent re-established drainages (Fig. 3) formed at different times and flow across different lithologies, but both cases formed due to the activity of transfer faults, although the lithologies in the wind gaps are different (Pre-Neogene basement and conglomerates for the Selinous River, and marls and sandy marine terraces for the Xerias River). The fact that the Selinous River gorges are larger than those of the Xerias River is a result of the different time evolution, and that the Selinous River flows across the Pre-Neogene basement and conglomeratic deposits, whereas the Xerias River flows across marls and sandy marine terraces, and is also due to different uplift rates (Selinous drainage uplift rate is 2.2 mm/year, whereas Xerias drainage uplift is 0.3–0.4 mm/year).

6.3. Multistory drainage

This drainage consists of two drainage types, re-established drainage where rivers flow northwards and reverse drainage where rivers flow southwards. Two examples are presented (A): the Dervenios (18)–Skoupeiko (19)–Fonissa (21) rivers forming re-established drainages and the Olvios (40) River forming the reverse drainage, and (B) Agiorgitikos (27)–Seliandros (28) Rivers forming re-established drainages, and Rethis (39) River forming the reverse drainage (see also Table 1). All river drainages are between 0 and 1400 m altitudes, and the area where the rivers change flow direction is situated between 600 and 1000 m altitude. WNW-trending listric faults led to a widening and deepening of the basins. Synthetic and antithetic faults formed intrabasinal basement highs and influenced drainage basin evolution. Transfer faults are rare or absent (Figs. 9 and 10).

6.3.1. The Dervenios–Skoupeiko–Fonissa → the Olvios Rivers (Fig. 9)

During the Late Pliocene–Early Pleistocene the Olvios River formed an antecedent drainage. Later during the Middle Pleistocene, the Olvios River changed to a reverse drainage and then remained unchanged (Doutsos and Piper, 1990). The present Olvios River forms a reverse drainage with the reverse element discharging into the Feneos plain (Figs. 3 and 9). The wind gap is on thick conglomeratic deposits. One of the Dervenios, Skoupeiko and Fonissa Rivers probably was the misfit element and the other two were the old juvenile rivers of this reverse drainage. During the Late Pleistocene, these misfit and juvenile rivers formed new drainage patterns, and as the tectonic activity migrated basinwards, changed again to reverse drainages due to an intrabasinal basement high (area of the new-second wind gap) and then returned to their original flow directions, forming re-established drainage (as for the Selinous River). From this intrabasinal basement

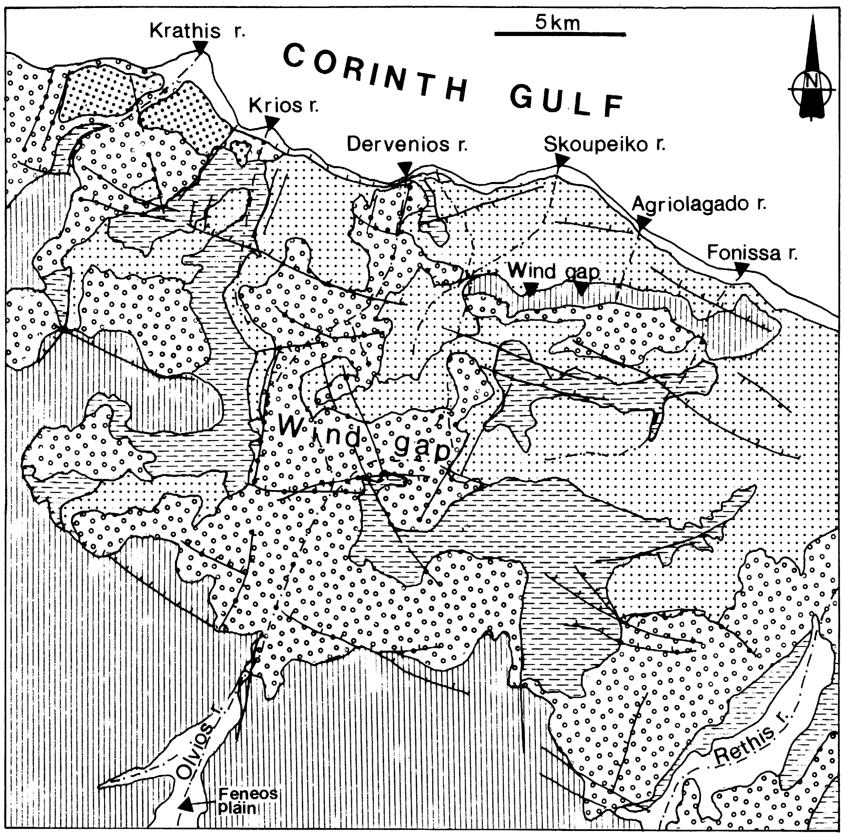


Fig. 9. Geological map of the central part of the study area, modified from Poulimenos et al. (1993), where the Krathis, Krios, Dervenios, Fonissa, Olvios and Rethis drainage basins were formed. For location and map symbols, see Fig. 1B.

high new juvenile drainages were formed (the Agriolagado River in Figs. 3 and 9).

6.3.2. The Agiorgitikos–Seliandros → the Rethis Rivers (Fig. 10)

During the Late Pliocene–Early Pleistocene, the Rethis River formed an antecedent drainage. Later, during the Middle Pleistocene, the Rethis River changed to a reverse drainage (Doutsos and Piper, 1990). The present Rethis River consists of the reverse element discharging into Stymfalia Lake (Fig. 10). The wind gap is on conglomerates and the Agiorgitikos River was the misfit element.

Later, the misfit Agiorgitikos River formed a new drainage basin during the Late Pleistocene and changed again to a reverse drainage. The second wind gap area is on lacustrine marls. The reverse element was restricted between the two gaps (the old one with conglomerates and the new one with lacustrine marls) (Fig. 10: cross-section). Human activities (an underground channel) joined the old and new reverse elements forming the present Rethis River. The new-second misfit is the Agiorgitikos River. The Seliandros River formed as a juvenile river during this second reverse drainage evolution. As the tectonic activity migrated basinwards, misfit and juvenile rivers changed again (for third time in the case of the Agiorgitikos River) to reverse drainages with backtilting of marine terraces (third wind gap area) and then returned again to their original flow forming re-established drainages (as the Xerias River re-established drainage).

According to Doutsos and Piper (1990), who studied the paleogeographic evolution of this drainage

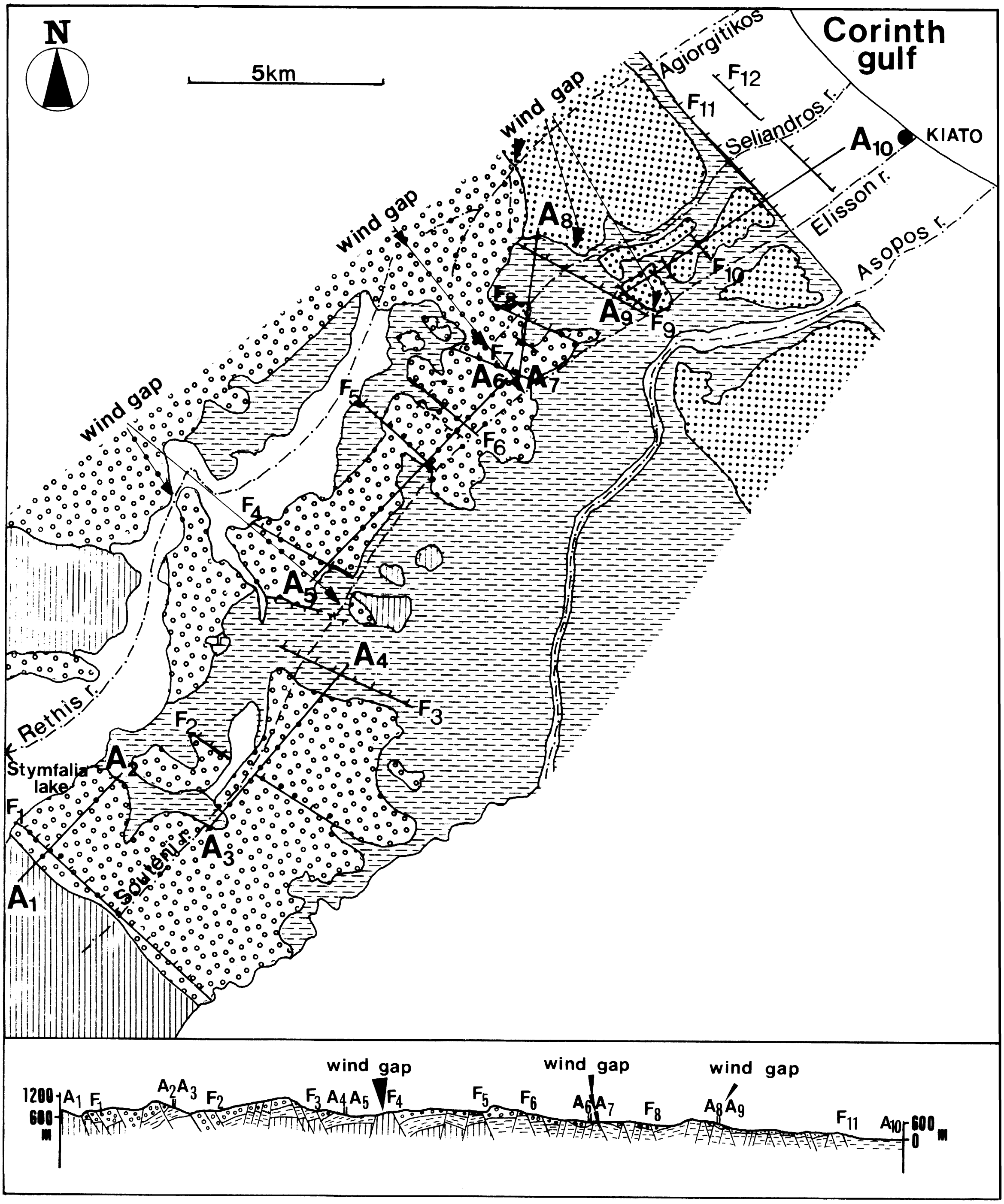


Fig. 10. Geological map and cross-section of eastern part of the studied area, modified from Doutsos and Piper (1990), where the Agiorgitikos, Seliandros, Elisson, Asopos, Rethis and Souteni drainage basins were formed. For location, see Figs. 1 and 3. Principal faults, sediment facies and the three wind gap areas are shown in the cross-section. For location and map symbols, see Fig. 1B.

area, the change of drainage basin from antecedent to reverse drainage took place during the Middle Pleistocene (the Olvios and Rethis reverse drainages). This change influenced the depositional environment evolution as the supply of conglomerates diminished the drainage reversal.

6.3.3. Interpretation of multistory drainage basin evolution

The presence or absence of transfer faults in the wind gap areas, since lithologies in the wind gap areas are the same, is probably the major reason for the different evolution of the studied drainages (Fig. 3). The wind gaps of the unchanged Olvios and Rethis reverse drainages lack transfer faults. The wind gaps of the Dervenios–Skoupeiko–Fonissa and the Agiorgitikos–Seliandros re-established drainages as cross-cut by transfer faults. Probably the different distance from the source (the first wind gap is far from the basement whereas the second wind gap is close to the basement) is also a component of this different evolution.

7. Discussion and conclusion

The change of an antecedent drainage to a reverse drainage could be related to the model of Cox (1994) where due to tilted blocks a river flow could be changed.

Intrabasinal basement highs due to that drainage patterns changed from antecedent to reverse drainage and then to a re-established drainage could be related to the barriers formed by internal thrusting in fold–thrust belts. In this study area intrabasinal basement highs formed wind gap areas and re-established drainage flow across intrabasinal basement highs forming transverse drainages. The change of drainage evolution is related mostly to the presence of transfer faults. Transverse drainage formed across anticlines, according Alvarez (1999) never formed wind gap areas and were not related with pre-existing faults crossing the anticlines. Alluvial architecture may also be related to tectonic activity influence drainage patterns as is also indicated by Mather (1993).

The 41 neighboring river drainage basins, studied in the northern Peloponnesus, are classified into four drainage types, antecedent, multistory, reverse and juvenile. Their evolution was influenced by the presence of intrabasinal basement highs and transfer faults, by the distance from the source, by the sediments traversed by the rivers, and by the uplift rate. The following factors especially influence their evolution.

1. Where the sediments traversed by the river were soft uncohesive lacustrine marls, the drainage remained stable as an antecedent-type.
2. Where the sediments were cohesive sandy marine terraces, or coarse-grained deposits, or Pre-Neogene basement and erosion was difficult, then an antecedent drainage could change to a reverse drainage.
3. In the case where the distance from the source was small and the river power was highstrong then independently of the lithologies the antecedent drainage remained unchanged.
4. In the case where the drainage changed due to the lithologies, from an antecedent to a reverse drainage, then depending on the presence of transfer faults in the area of the reverse element, the reverse drainage could be changed into a re-established drainage. When transfer faults were absent then the reverse drainage would remain unchanged. Multistory drainage results when a river drainage changed along its flow at least twice (see Table 1).
5. Independently of the lithologies, the distance from the source, the presence of transfer faults and the uplift rate, antecedent drainage might change to a reverse drainage due to the synchronous activity of synthetic and antithetic faults within the basin, forming intrabasinal basement highs, separating the drainages.
6. Due to different uplift rates along the Corinth and Patras graben, and in relation to the time of evolution and the kind of the lithologies traversed by the rivers, gorges with different geometries were formed both along the rivers or in the wind gap areas of the reverse drainages (e.g., the Meganitis, Kerinitis and Selinous Rivers with steep and deep gorges compared to the Piros and Xerias Rivers with shallow gorges).
7. Differential subsidence and uplift along a fault may influence the flow direction in the reverse drainage (e.g., the Xerias and Inachos flows changed eastwards and not westwards).

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