Shoreline displacement, drainage diversion in NW Peloponnese (Greece) as result of the geology, active tectonics and human activity during the last 100ky

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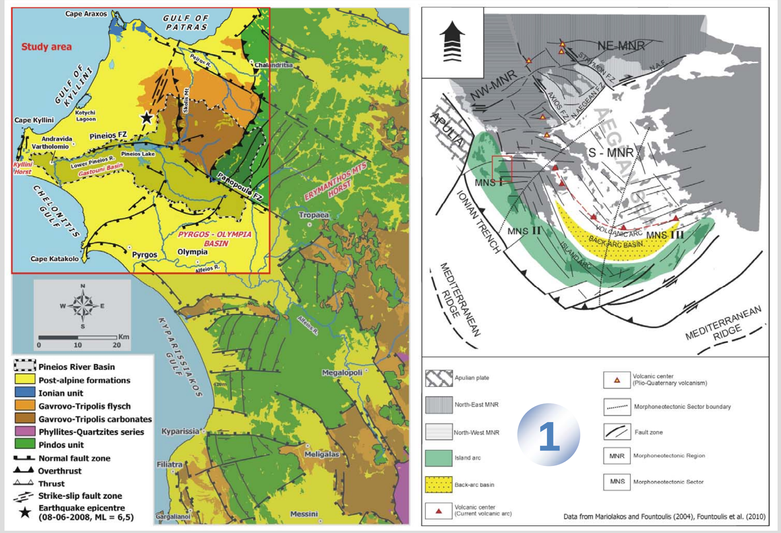
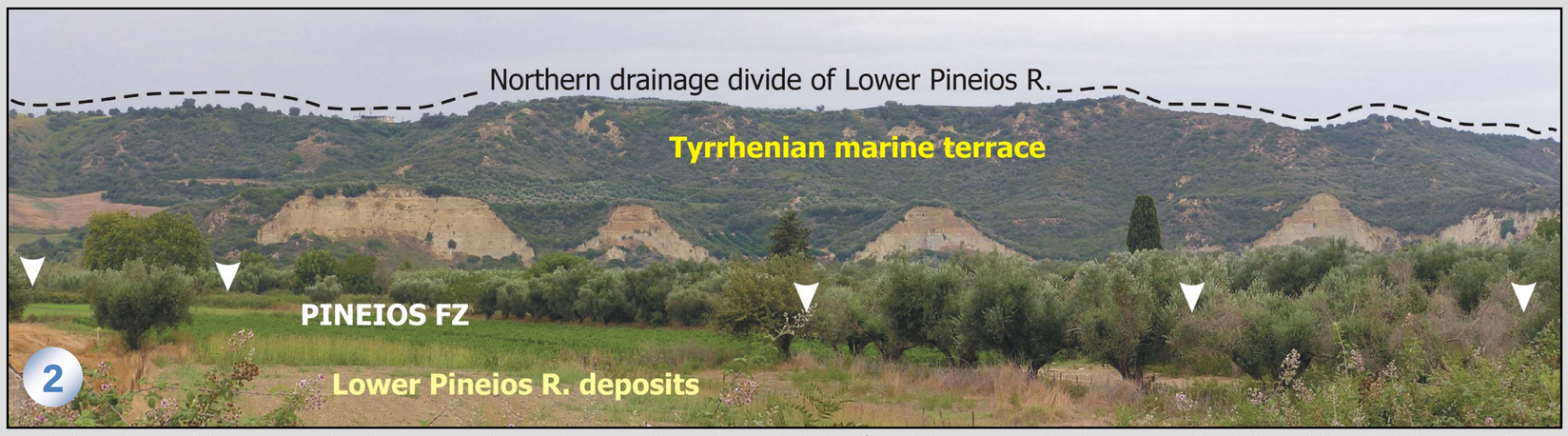
ABSTRACT
Pineios River is the 3rd longer river in Peloponnese and flows in Kyllini wider area which is located close to the Hellenic Arc system and is one of the most active areas in Greece with a great number of changes in the morphogenetic procedures taking place during the neotectonic period, as well as the last 100ky. Pineios River downstream crosses the study area and today flows out south of the Kyllini peninsula, in the Ionian Sea. The Greek historian, geographer and philosopher Strabo reported in his Geography (1st century A.D. – VIII, 3,5,1) that the mouth of Pineios River was situated during the ancient times to the north of the Kyllini peninsula and the river flowed out into the Ionian Sea southwest of the Kotichi Lagoon. Furthermore, already published data indicate that the Pineios River may have shifted north and south of the Kyllini peninsula throughout the Holocene, it was diverted southwards in the late the 18th century A.D. and the current delta has been evolving since then. The effects of the geological, tectonic and neotectonic structure and the impact of the human presence and activity on the drainage network are presented here in order to determine the causes of the diversion of the Pineios River and the shoreline displacements. For this reason, we used, analyzed and evaluated (a) geomorphological, geological, tectonic and neotectonic data of the study area, (b) historical information and archaeological findings from buried and eroded archaeological sites of the wider study area, (c) published data related to drill cores and radiocarbon dates and (d) satellite and aerial photos of different periods, as well as real-time kinematic differential GPS measurements for the definition of the current shorelineline. It is concluded that the studied shoreline displacements and drainage diversions are the result of the combination of active tectonics and human activity during the last 100 kyrs.



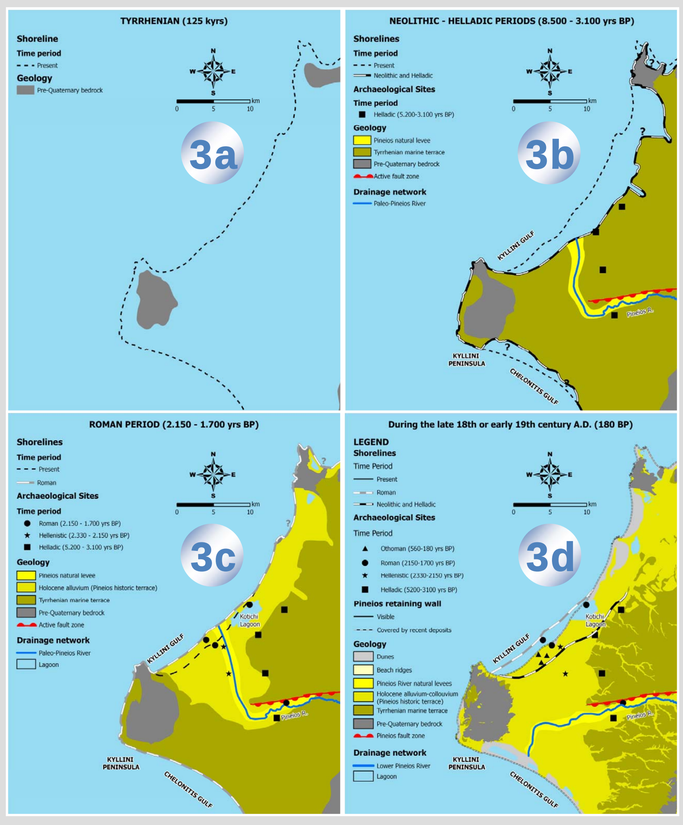


The Pineios River development and history takes place in one of the most tectonically and seismically active areas in Greece. The intense tectonic activity in the area is due to its location on the external part of the Hellenic arc and close to the convergent boundary where African plate is subducted beneath the European one as well as the diapirism of the evaporates. The recorded highest seismicity levels in Greece (Hatzfeld *et al.*, 1990, Geophys. J. Int., 101) as well as the generation of many strong earthquakes confirm the neotectonic studies, which show that the area is undergoing intense tectonic deformation.

The main neotectonic macrostructures of the wider study area are (a) the Erymanthos Mts horst, (b) the Pyrgos - Olympia basin and (c) the Kyllini horst. These structures result from ongoing vertical movements and are faulted and/or bounded by fault zones.

The geological formations can be divided into alpine and post-alpine. The alpine formations belong to Pindos, Gavrovo - Tripolis and Ionian units. The post - alpine formations belong to the Pyrgos - Olympia basin, are of Pliocene and Quaternary age and lie unconformably on the alpine basement. Their geographical distribution and the variety of facies (marine, lagoonal, lacustrine and terrestrial) clearly reflect vertical movements during the neotectonic period and ongoing active tectonics.

The most important fault zones in the study area are the Panopoulo fault zone (Panopoulo FZ), Pineios fault zone (Pineios FZ) and the strike - slip fault zone that gave rise to the Andravida earthquake (08-06-2008, ML=6,5). These major faults form several neotectonic blocks in the study area including the Gastouni graben (hangingwall of Pineios fault zone), the uplifted area of Varda (footwall of Pineios fault zone) and the Kyllini horst.



Shoreline displacements in the study area during the last 8 kyrs are always related to the the tectonic instability and the longshore redistribution of sediments from the Pineios delta.

(3b) The palaeo-delta of Pineios River was developed N of Kyllini peninsula before and during Neolithic period. The Neolithic and Helladic shoreline was located 3,5 km onshore from the present shoreline.

(3c) During the Roman period, Pineios River flowed directly S of the Kotychi lagoon forming a levee, which is now abandoned, eroded and stands as a low sea cliff. An acceleration of coastal deposition and consequently delta propagation took place. The Roman shoreline was 1,5 km seaward from the present shoreline.

(3d) During the Othoman period, Pineios occupied the channel 5 km S of Kotychi lagoon forming another levee standing well above the floodplain at the shoreline and indicating coastal retreat. This channel is now in the process of filling. The minimum age of this levee is about 200 yrs BP. The shore has retreated since Roman times.

The Pineios diversion to the south of Kyllini peninsula took place during the late 18th century. Following this diversion, the pre-18th-century-A.D. Pineios River delta shoreline in now undergoing marine transgression and intense coastal erosion, as is to be expected in a former delta now essentially starved of new sediment. The pre-18th-century-A.D. northern channels of Pineios River and few smaller streams can still be seen in their courses to the northwest, now dry. The dominant geomorphic processes in the modern delta of Pineios River have been progradation and aggradation with large volumes of river sediment.

Based on the palaeogeographic reconstructions developed by Kraft *et al.* (2005, Hesperia 74) and the late Holocene environmental changes from Kotychi Lagoon recorded by Kontopoulos and Koutsios (2010, Quatern. Int., 225) we concluded that:

a. the shoreline in the Pineios delta advanced by 3,5 km into the sea in the 6.350 yrs period from Neolithic (8.500 yrs BP) to Roman (2.150 yrs BP) period.
b. the shoreline in the Pineios delta retreated by 1,75 km in the 2.150 yrs period from Roman period (2.150 yrs BP) to present.

Based on the previous shoreline displacements we estimated:

c. a coastal progradation rate as 0,55 m/yr from Neolithic to Roman period and
d. a coastal retrogradation rate as 0,81 m/yr from Roman period to present.

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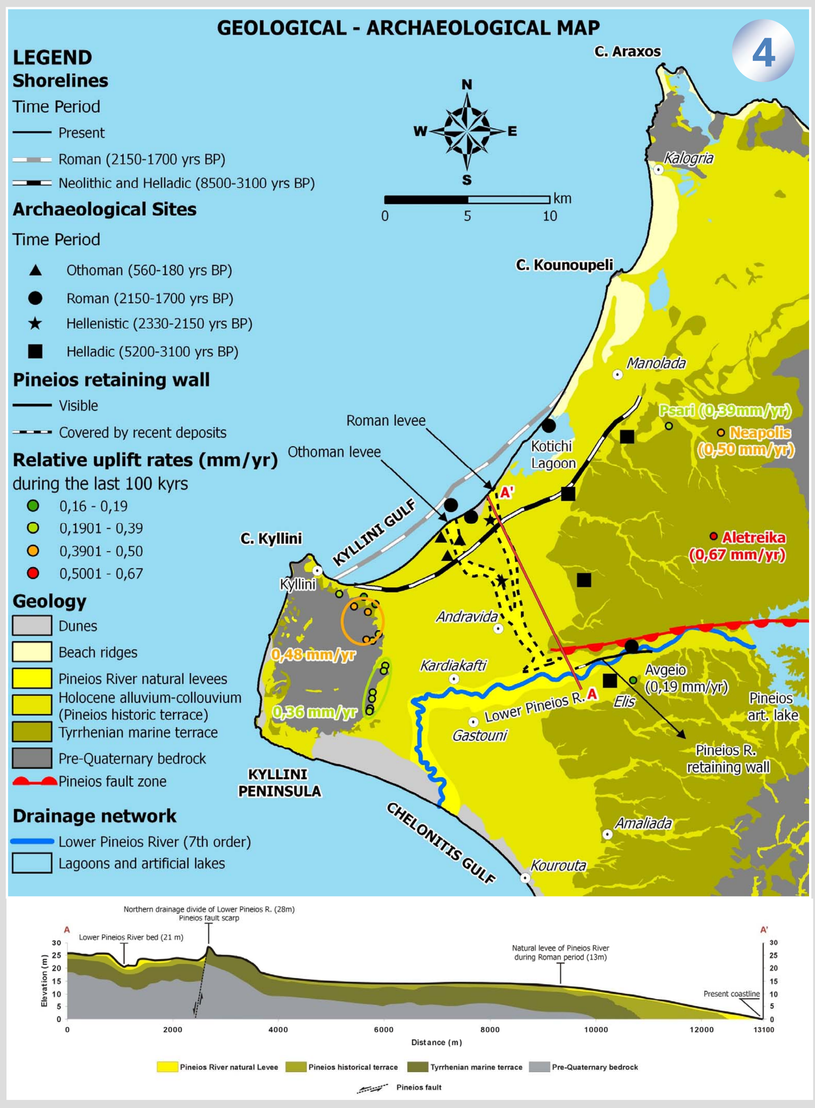
Pineios FZ is one of the most recently active structures in NW Peloponnese (Mavroulis *et al.*, 2010, 11th IAEG Congress, Auckland, New Zealand). It is located SSW of Skolis Mt, trending E-W, dipping S-wards and displaces a Tyrrhenian marine terrace forming well-preserved fault scarps and consecutive triangular facets across active hill front. The minimum fault slip rate based on the basal facet height was calculated as 0,15 mm/yr, while the maximum slip rate based on the maximum throw of the fault zone was calculated as 0,48 mm/yr (Mavroulis, *et al.*, 2010). The calculated slip rates of Pineios FZ do not differ substantially from the slip rates in other neotectonic macrostructures of Peloponnese obtained by Koukouvelas *et al.* (1996, J. Geol. Soc. London, 153) and Papanikolaou *et al.* (2007, Quatern. Int. 171-172).

One of the most characteristic effects of the Pineios FZ on the Pineios drainage network is the asymmetrical development of the western part of the Pineios drainage basin, where the Lower (alluvial) Pineios River shifts northwards and flows close and parallel to the northern drainage divide, which is formed and determined by the Pineios FZ. This asymmetry is clearly reflected in the number, size and order of the tributaries and subbasins on either side of the main river. Especially, north of the Lower Pineios River, the 1st and 2nd order drainage basins prevail, while higher order drainage basins are absent. In contradiction, the 3rd order drainage basins prevail covering an extended area south of the Lower Pineios River.



In order to determine the effect of the ongoing active tectonics on the Pineios River diversion during the late 18th or the early 19th century, we calculated relative uplift rates for several sites of the study area based on $^{230}Th/^{238}U$ dating of corals made by Stamatopulos *et al.* (1988, Geogr. Fis. Din. Quat., 11) and dating of marine deposits in Kyllini peninsula estimated by Mariolakos *et al.* (1988, Research project of the University of Athens):

a. 0,39 mm/yr for Psari area (103 kyrs)
b. 0,50 mm/yr for Neapoli area (118 kyrs)
c. 0,67 mm/yr for Aletreika area (209 kyrs)
d. 0,16 to 0,48 mm/yr for the eastern (inland) part of Kyllini peninsula (125 kyrs)

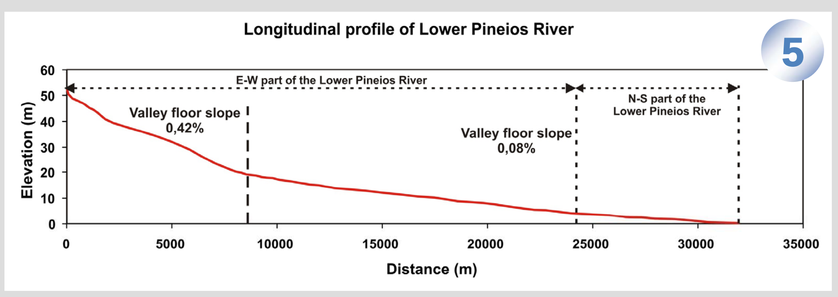
We concluded that:

a. The maximum relative uplift rate (0,67 mm/yr) characterizes an area (Aletreika) located on the footwall side and very close to the Pineios FZ.
b. The relative uplift rate of the Gastouni graben (hangingwall of Pineios FZ, 0,19 mm/yr) is less even than the lowest value of the Pineios FZ footwall relative uplift rate (0,39 mm/yr).
c. The northeastern part of Kyllini peninsula has higher relative uplift rate (0,48 mm/yr) than the southeastern part (0,30 mm/yr)
d. The maximum relative uplift rate of the footwall of Pineios FZ is significantly higher than the maximum relative rates of the eastern part of Kyllini peninsula and the Gastouni graben.

It is obvious that the western part of Pineios drainage basin is developed in an area (Gastouni graben), which is uplifted with lower relative uplift rate in comparison with the other surrounding areas. Hence, the Lower Pineios River was and is forced to flow in this graben, close and parallel to Pineios FZ.

Furthermore, the age of Pineios FZ initiation progressively decreases from E to W. A similar decrease from E to W is also observed in the throw of Pineios FZ. The throw of the western part was gradually increased until a critical point in time (probably during 18th century A.D.) when the relative uplift rate of the Pineios FZ footwall was larger than the relative uplift rate of the hangingwall. Since then, Pineios River was blocked, not able to flow N-wards and over the morphology escarpment formed by the fault and consequently enforced to shift S-wards. Moreover, the combined uplift movement of the footwall of Pineios FZ in the E and the northeastern (inland) part of the Kyllini peninsula in the W resulted in the slightly uplifted margin of the northwestern part of Gastouni graben, the block of the northwards flow of Pineios River and the initiation of the southwards flow of the river.

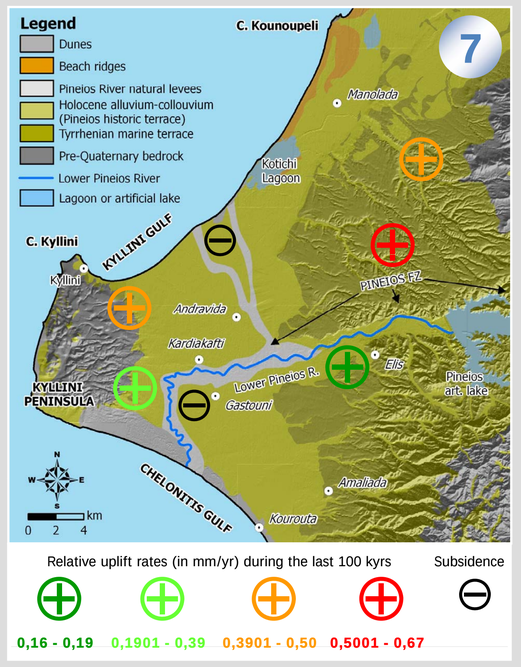
This natural trend of Pineios southward diversion during 18th century was supported and enforced by the human activity in the study area and especially by the construction of the ancient retaining wall of Pineios River (Papaconstantinou, 1991, First International Symposium on Achaia and Elis in Antiquity, Athens, Greece) during the Hellenistic period (2.330-2.150 B.C.) in order to protect the northern banks from the destructive river action.



Lower Pineios River flows between banks and on a bed composed of sediment that is transported by the river and is very sensitive to changes of the valley floor slope. Therefore, the on going active tectonics of the study area and especially Pineios fault zone causes pattern change. The most significant pattern change in Lower Pineios River due to the active tectonics of the area is the change of the valley floor slope as it is shown in the above longitudinal profile, the abandonment of its former northward courses and canals and the southward diversion.

In order to determine whether or not progradation or retrogradation took place in Pineios former and current deltas in recent years, we initially mapped the shorelines at different times in the 27-year-period from 1972 to 1999 using (a) topographic maps at 1:5.000 scale (1972), (b) aerial photos (1987, 1996), (c) satellite images (1999). Then, these data were compared with the present shoreline (2011), which was traced with the use of real-time kinematic differential GPS.

Our results have shown that both the former and the current delta fronts of Pineios River are divided into various sub-areas characterized by different type, phase and rate of shoreline displacement. Moreover, there is no systematic progradation or retrogradation in these delta fronts according to the data covering the last 40-year-period from 1972 to 2011.



CONCLUSIONS

The study area is undergoing intense and differential tectonic deformation which has continued since Pliocene.

The areas of maximum thickness are constantly subsiding during the sedimentation phase and strictly related to the Pineios delta and river sediment loads and transport. Moreover, the southern area presents higher subsidence rates than the northern one.

The study area is also divided to three subareas that uplift with different rates: (i) the footwall of Pineios fault zone (0,39-0,67 mm/yr), (ii) the Gastouni graben (0,19 mm/yr), (iii) the eastern (inland) part of Kyllini peninsula (0,36-0,48 mm/yr).

The western part of Pineios basin is corresponding to the subarea with the lowest relative uplift rate (0,19 mm/yr, Gastouni graben).

The diversion of Pineios River to the south of Kyllini peninsula during the 18th century is a case of fluvial antecedence upon the slightly uplifted margin of the Gastouni graben and is the result of the gradually increase of the throw along the western part of the Pineios fault zone during historic times marked by strong and destructive earthquakes during the late 18th or early 19th century A.D. This natural process and trend is supported and enforced by the human activity in the study area during historic times as it is revealed by significant human constructions in the area.