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QUANTIFICATION OF RIVER VALLEY MAJOR DIVERSION IMPACT AT KYLLINI COASTAL AREA (W. PELOPONNESUS, GREECE) WITH REMOTE SENSING TECHNIQUES

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Abstract: *The effects of the geological, tectonic and neotectonic structure and the impact of the human presence and activity on the drainage network of Pineios river are presented here in order to determine the causes of its diversion and the implications to the shoreline. 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) remote sensing datasets, as satellite and aerial photos of different capturing periods, as well as real-time kinematic differential GPS measurements for the definition of the current shoreline. It is concluded that the detected shoreline displacements and drainage diversions are the result of the combination of active tectonics and human activity during the last 100 kyrs.*

Key words*: Kyllini peninsula, Pineios river, RTK DGPS, river evolution, coastal erosion*

INTRODUCTION

The Pineios River development and history takes place in one of the most tectonically and seismically active areas in Greece. The intense and continuous tectonic activity in the area is highly related to its location on the external part of the Hellenic arc and adjacent to the convergent boundary where African plate is subducted beneath the Aegean as well as the diapirism of near surface evaporitic domes. The highest seismicity levels recorded in the area (Hatzfeld *et al*., 1990) as well as the generation of many historic strong earthquakes confirm the neotectonic observations, which show that the area is undergoing a complicated tectonic deformation.

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 (Fig. 1).

GEOCHRONOLOGICAL INTERPERETATION

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 Stamatopoulos *et al*. (1988) and dating of marine deposits in Kyllini peninsula estimated by Mariolakos *et al*. (1988):

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)

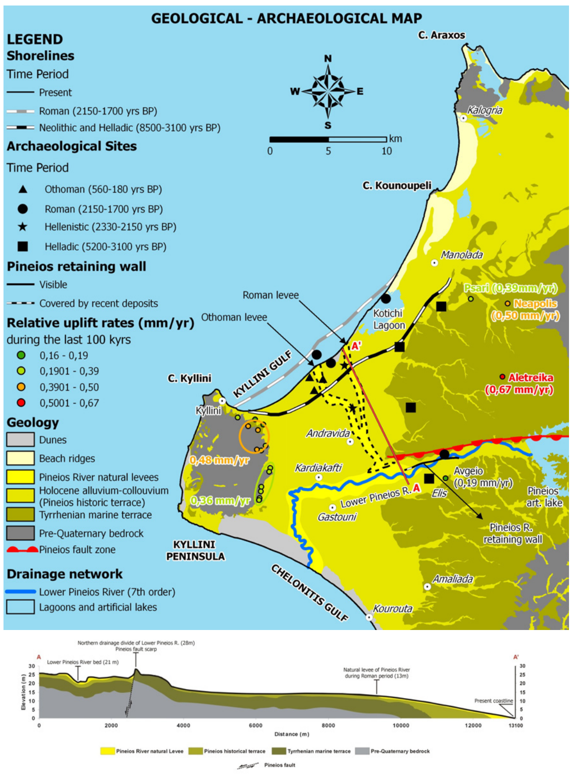

Fig. 1: Sketch map of the contemporary Pineios river deltaic area (at the hanging wall of the Pineios fault) and the former deltaic area at the footwall of the same fault. The estimated shorelines for the Roman and Neolithic periods are shown. The archaeological sites and the sampling sites of the geochronological analysis are also noted, along with the calculated uplift rates for the last 100kyrs.

The general conclusions after the interpretation of the geochronological data are:

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.

HISTORICAL COASTLINE DATA

It is more than obvious that the major percentage of the coastline displacements in the study area, during the last 8kyrs, are related to active structures and the tectonic instability as this affects the alongshore redistribution of sediments from the Pineios delta. After the organization of all the available geological and historical data we were able to estimate and reconstruct the paleo-coastline in several periods for the last 100kyrs (Fig. 2). It is quite easy to accept that during Tyrrhenian most of the area of Kyllini was under the water since the marine sediments were deposited.

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. 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. 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 in the process of filling. The minimum age of this levee is about 200 yrs BP.

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 are progradation and aggradation with large volumes of river sediment.

Based on the palaeogeographic reconstructions developed by Kraft *et al.* (2005) and the late Holocene environmental changes from Kotychi Lagoon recorded by Kontopoulos and Koutsios (2010) we note 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, which shows a coastal progradation rate of the order of 0,55 m/yr, and
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 which shows a retrogradation rate as 0,81 m/yr from Roman period to present.

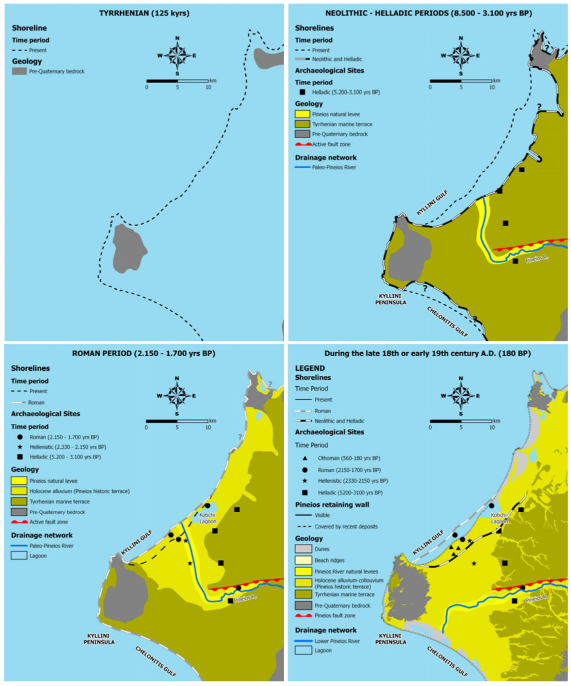

Fig. 2: Shoreline displacements in the study area during the last 8 kyrs.

REMOTE SENSING CONTRIBUTION

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) two datasets of 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.

The initial phase was to collect the available remote sensing data and create a time series of images along the contemporary coastline. The oldest data available were the topographic maps acquired from the Geographic Agency of the Hellenic Army that was also based on photogrammetry techniques on previously acquired aerial photographs.

Using 42 air photographs acquired during 1987 we generated an ortho-mosaic for the same year. During this photogrammetric procedure a high resolution (2-meters) DEM was produced, and used for the orthorectification of a 15-meter resolution Landsat-7 ETM+, panchromatic image. All the data were registered with an ortho-mosaic produced by 1996 aerial photographs (Fig. 3).

Next, by using image interpretation techniques we traced the coastline in the different periods. The difficulty was to identify the exact points of contact between the seawater and the land. This was made by equalizing the image histogram and in some cases applying a threshold value. The use of the panchromatic part of the spectrum for all the collected remote sensing data provides the homogeneity of the methodology.

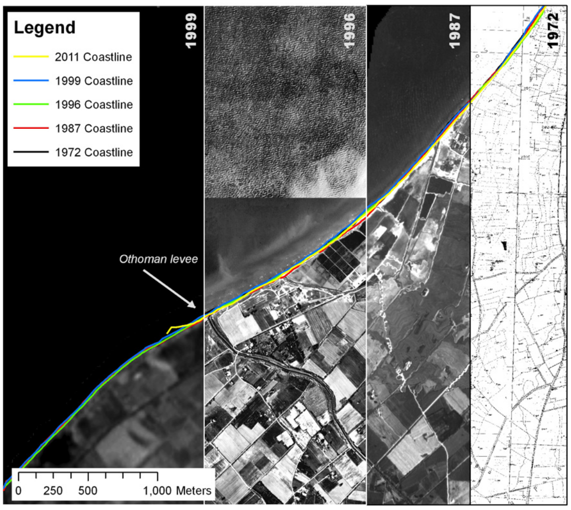

Fig. 3: Parts of the digital data used for the interpretation of recent coastline displacement.

Establishing 4 GPS bases along the shore and use the technology of real time kinematic GPS point acquisition completed the methodology. The accuracy of the present coastline was very good as the specifications of the equipment give less than 10cm (Fig. 4).

Fig. 4: Using high accurate RTK GPS measurements for the tracing of the present coastline.

The combination of all the traced coastlines on the remote sensing data with the RTK GPS recorded coastline 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 (Fig. 5). Nevertheless, there are parts of the coastline, especially where the Roman and Othoman levees used to function, that most of 50 meters of the beach have been eroded.

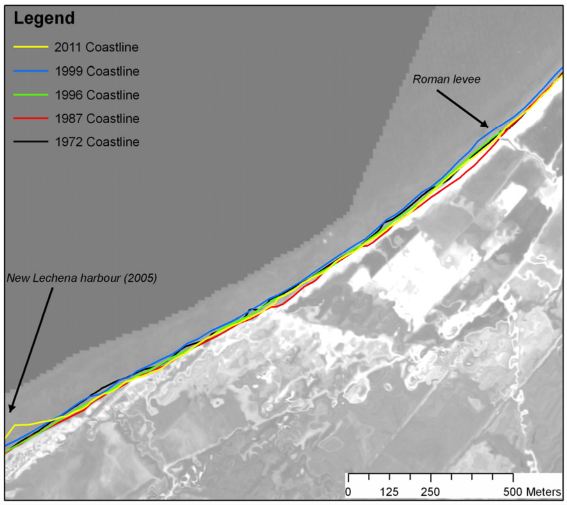

Fig. 5: Synthetic image with all the traced coastlines at a part of the study area where Pineios river used to flow into the sea before 1800's.

CONCLUSIONS

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 hanging wall. 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) during the Hellenistic period (2.330-2.150 B.C.) in order to protect the northern banks from the destructive river action.

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 (Fig. 6): (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).

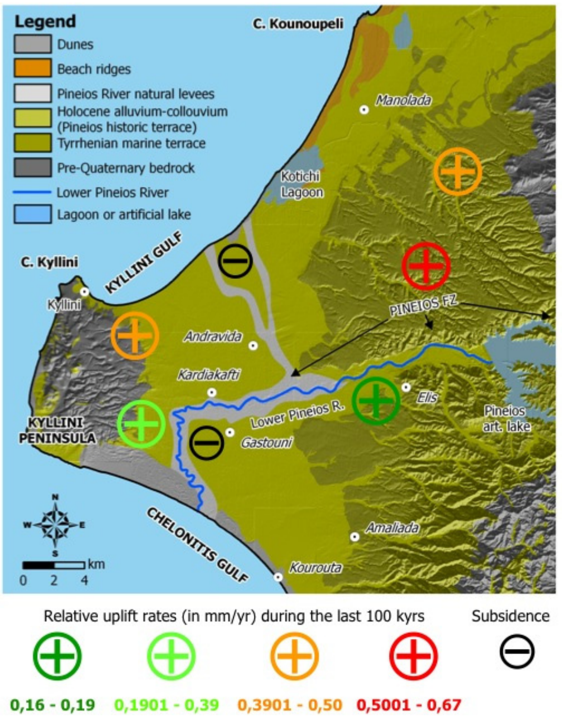

Fig. 6: Areas of uplift and subsidence around the Pineios river former and contemporary deltas.

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.

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