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A MODEL FOR TECTONIC SUBSIDENCE OF THE ALLAI ARCHAEOLOGICAL SITE, LOKRIS, CENTRAL GREECE

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ABSTRACT

The Neolithic site of Allai located in the seismically-active Lokris (central Greece) is today partially submerged. A stabilistic view to explain this submergence is to invoke metre-size sea-level rises in Holocene times, caused by the latest global deglaciation. Here, we present a tectonic (mobilistic) hypothesis based on geological data and recent developments in numerical modelling of co-seismic deformations in the surrounding area of normal faults. Our calculations show that Allai suffered co-seismic subsidence of about 30 cm, twice in last 4000 years, and about 45 cm of cumulative post-seismic subsidence. The site is also subjected to horizontal-axis rotations as it is located within a rigid block between two synthetic normal faults, the Atalanti Fault and the fault along the northern coast of the Malesina peninsula. Assuming a total rotation of 0.07 degrees the sea trangression over the Theologos coastal area is found to be 870 metres.

KEY WORDS: Earthquake deformation, block rotation, modelling, sea-level, Lokris, Allai.

1. INTRODUCTION

The Allai archaeological site in the Lokris area of Greece (Figure 1) is one of the few sites in the country with documented Neolithic occupation (Coleman, 1993). It is found in the Theologos Bay area (38°40'N, 23°10'E; Figure 2a) and its classical-age acropolis is only 3-4 m above sea level (information from the web page of the Allai project at *http://halai.fac.cornell.edu/*). The Neolithic remains are found at about the same elevation or a few decimetres below sea level today, indicating a considerable amount of sea-level rise (perhaps more than 10 m) since 8000 BP. The site has not had continuous occupation throughout history, and perhaps this may have been due to sea-level changes, which may have influenced settlement patterns in ancient Lokris (the biggest hiatus occurs between the Neolithic and Archaic-age remains, a period of approximately 4000 years). In particular, the occurrence of the submerged, northern fortification wall of the acropolis was noticed by previous workers who have proposed alternative hypotheses. For example, Rondoyianni, (1984) has suggested that the observed submergence may be of tectonic origin, although she did not provide any estimates of vertical displacement. In contrast, Stiros (1985) suggested that eustatic sea-level rise of the order of a metre per millennium is responsible for the submergence.

The Lokris region has undergone NE-SW extension since Pliocene times (5-2 Ma) that is estimated at about 20% (Roberts and Jackson, 1991) and taken up by seismic slip along large, normal fault segments (e.g., Ganas and White, 1996). Allai is found on the hangingwall area of an active fault, the Atalanti fault segment whose seismic behaviour has been examined by Ganas *et al.*, (in press). Our field mapping in the Malesina peninsula area has also indicated the existence of a coastal active fault, striking almost parallel to the Atalanti fault but with much less throw (fault Co in Figure 1). A proximal offshore fault is also shown in the IGME, (1989) map but its exact position and activity are both uncertain, so it will not be considered in our analysis. In view of these new data we have attempted to quantify the amount of tectonic deformation experienced by the region around Allai.

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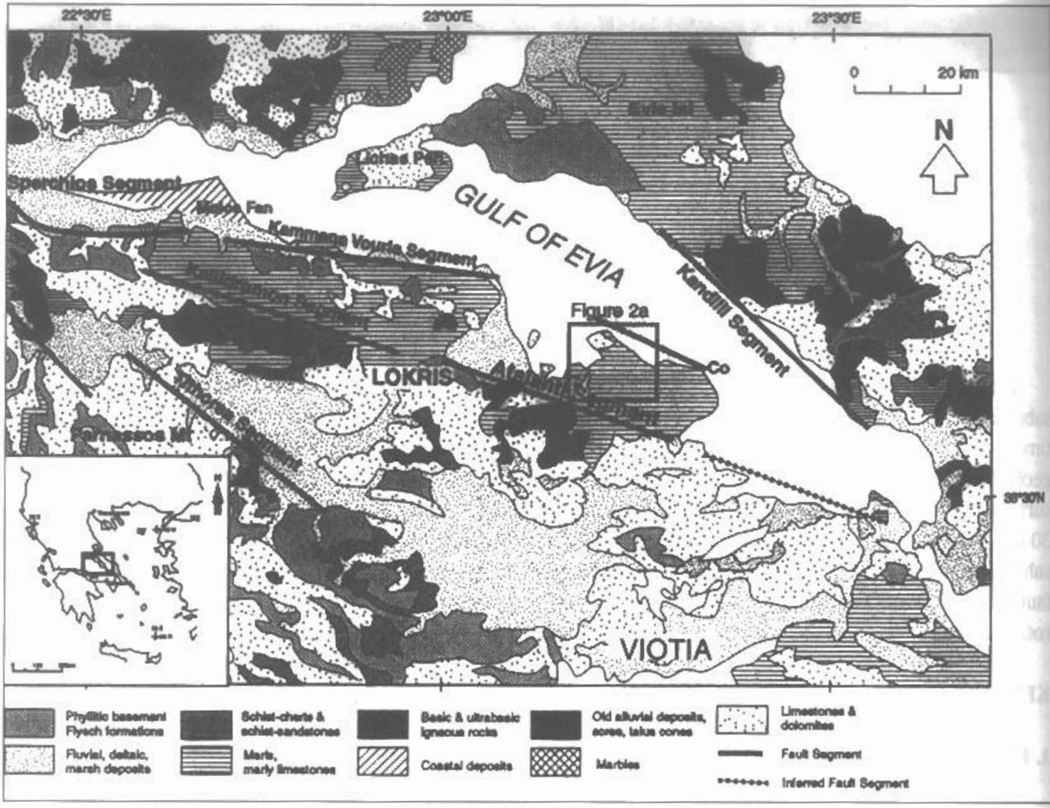

Figure 1: Geological map of the Lokris area (central Greece) adapted after IGME (1989). Active faults are after Ganas and White, (1996) and Ganas *et al.*, in press. Fault named Co refers to an active coastal fault mapped during this study.

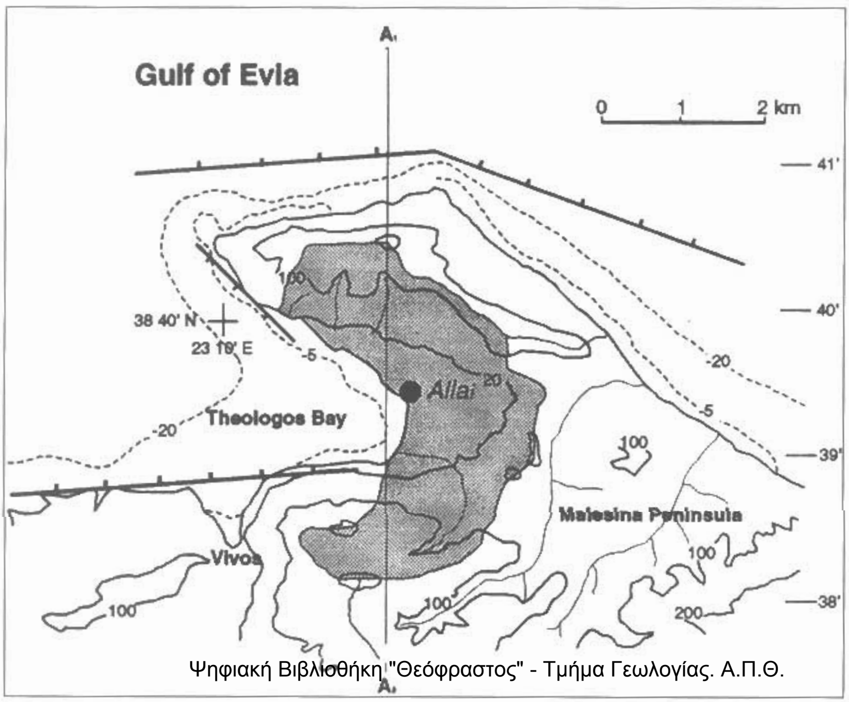

Figure 2: Topographic map of the north-western part of the Malesina peninsula, also showing the location of Allai. The two faults to the west and south of Allai are inactive. Shaded area depicts the extent of the Allai catchment.

Our modelling approach consists of two steps. First we calculate rotations of a horizontal line due to earthquakes along the two parallel normal faults, adapted to our field data. Secondly, we estimate the amount of tectonic subsidence in Allai from numerical modelling of earthquake deformation. Then, simple trigonometry is applied to calculate the amount of sea incursion on to the Theologos coastal plain during the last 4000 years. If sea levels in the Aegean are still rising (e.g. Lambeck, 1996) then our results may help discriminate between tectonic and glacio-eustatic effects.

2. MODELLING OF EARTHQUAKE-CONTROLLED SUBSIDENCE

The tectonic subsidence model makes two basic assumptions : (i) there have been two large earthquakes ($M \geq 6.5$) along the Atalanti Fault segment in the last 4000 years (ii) there have been two earthquakes ($M \geq 5.8$) along the coastal (Theologos Bay) fault. No regional effects (uplift/subsidence) are considered because their rates are infinitesimal to the north of the Gulf of Corinth (Armijo *et al.*, 1996). The Atalanti fault has ruptured in 1894 (Skouphos, 1894) during an earthquake sequence that included a M6.9 event (Ambraseys and Jackson, 1990) and on the basis of geological data (mean slip rate) Ganas *et al.*, (in press) have suggested a mean recurrence interval of 2500 years. This repeat time requires the previous event along the Atalanti Fault to have occurred around 400-600 BC. However, no geological evidence has been found so far for any previous event along the Atalanti fault. On the other hand, there have been no large instrumental events along the coastal fault (see for example the Ambraseys and Jackson, 1990 catalogue), although, a number of historical events may have occurred with the most possible candidates the 106 AD Opus event (intensity VII after Bousquet and Pechoux, 1977) and the 18/3/1874 (M 6.0 after Stiros, 1985) offshore event. The fault is not associated with significant footwall relief (about 220 m from HAGS, 1: 50 000 "Livanates" sheet) and is younger than the Atalanti Fault. It is reasonable to assume that its seismogenic potential is smaller than that of the AFS, and we accept a coastal uplift of 1m from this fault.

The geometry of the model is illustrated in Figure 3a. Allai (Figure 2) is located 6 km to the north of the N290-striking Atalanti Fault segment and 2 km to the south from the N270-striking coastal fault. The width of the crustal block (the Malesina peninsula) between the two faults is 8 km, or about half the size of the brittle layer, so we can treat this area as a rigid block (Westaway, 1991), rotating clockwise in accordance with the "domino-model". Our field mapping shows that no other active faults, synthetic or antithetic exist within that block.

In Figure 3a, from the right triangle OAB we can calculate the tectonic slope created in the Allai area due to the combined co-seismic (two 1 m slip events) and postseismic vertical displacement (2 m) along the Atalanti Fault. This is equal to:

$$\sin \phi_{AT} = 4m/6000m = 0.0006 \text{ or } \phi_{AT} = 0.0381° \quad \textbf{(1)}$$

Similarly, from the right triangle OCD we calculate the slope produced by earthquake deformation (1 m coastal uplift) along the coastal active fault :

$$\sin \phi_{CO} = 1m/2000m = 0.0005 \text{ or } \phi_{CO} = 0.0286° \quad \textbf{(2)}$$

The total angle of southern slope produced during the last 4000 years in the Allai area due to earthquake activity is then :

$$(1) + (2) : \phi_{TOT} = 0.0667° \text{ or } 0.07° \quad \textbf{(3)}$$

From numerical modelling (Ma and Kusznir, 1995) we can estimate the total amount of subsidence in the Allai area the last 4000 years. Ma and Kusznir (1995, Figure 4a) computed co-seismic and post-seismic vertical displacements of horizontal surfaces in the vicinity of 55°-dipping active normal faults, 48 km long. Co-seismic subsidence for Allai (distance 6 km; Figure 4b) is predicted to be 0.44 m per event and post-seismic displacement about 0.40 m per event (Ma and Kusznir, 1995, their Figure 7).

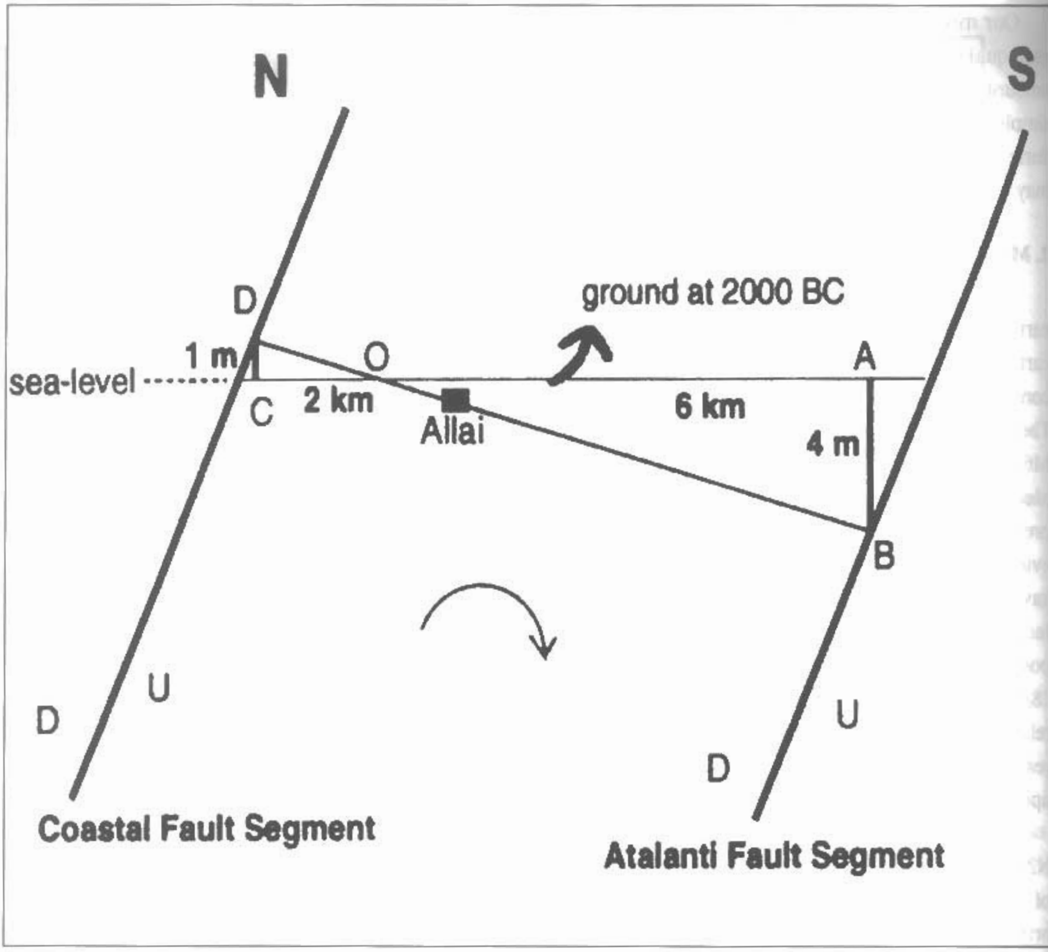

Figure 3a

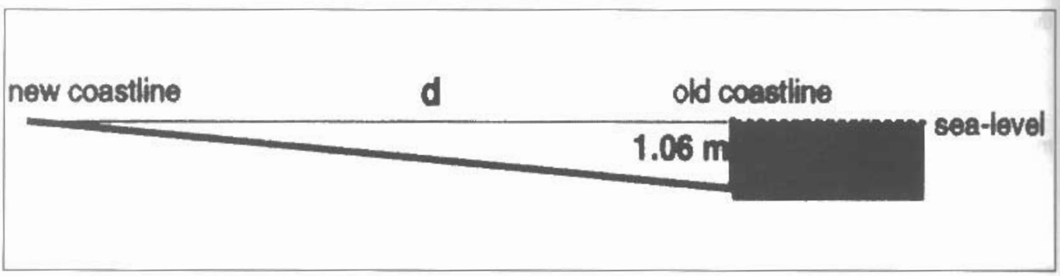

Figure 3b

Figure 3: Graphs showing the block model geometry (a) and cross-section (b) for the Allai subsidence during the last 4000 years. The cross-section is oriented N-S and the position of the 2000BC coastline near Allai is also shown. Symbols U and D mean Up and Down block movement, respectively. See text for discussion.

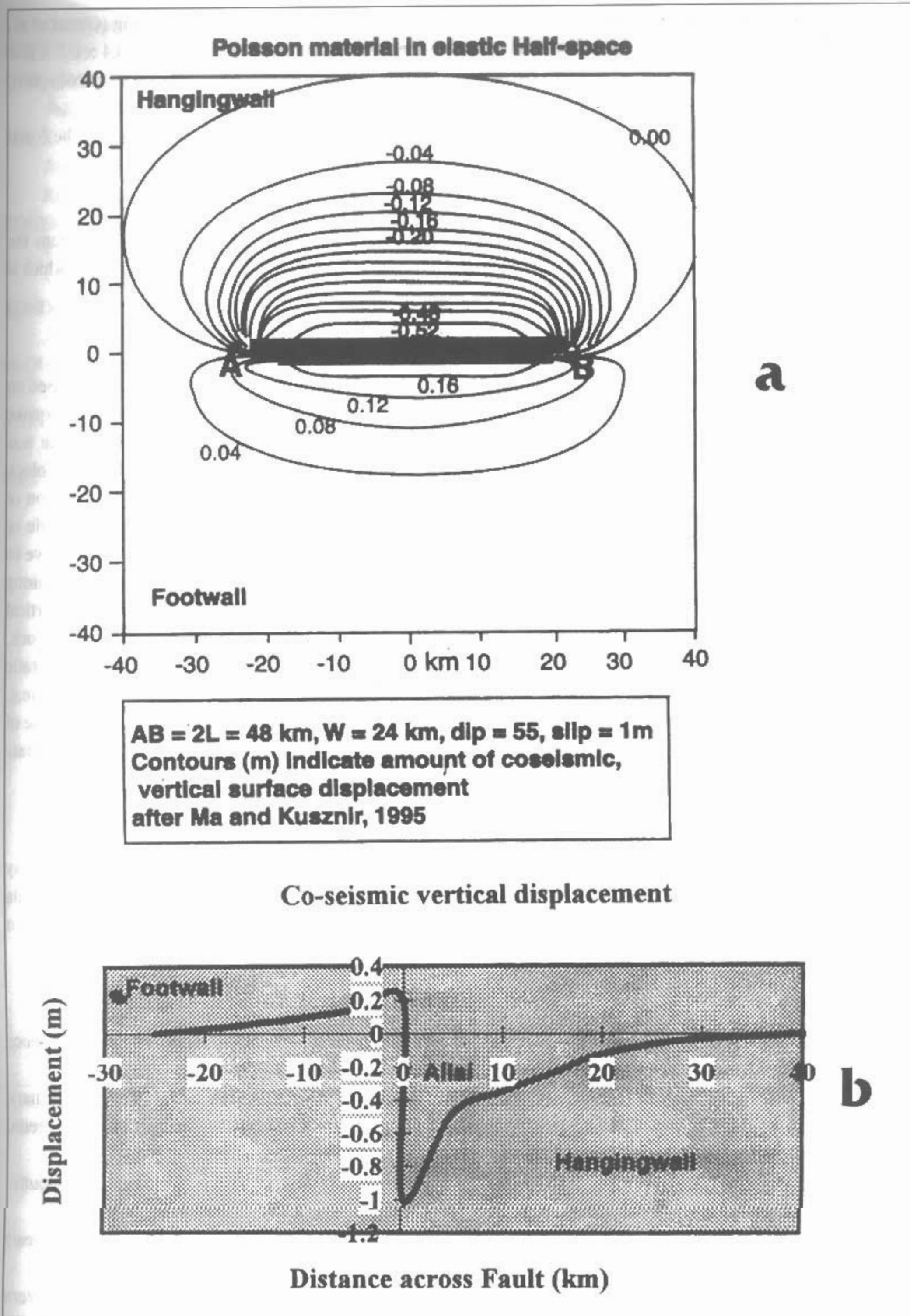

Figure 4: Map (a) of vertical co-seismic displacements in the vicinity of an inclined normal fault (AB) and cross-section (b) through the mid-point of AB according to Ma and Kusznir (1995).

These figures have to be reduced to about 70 % because the Atalanti Fault is 34 km long (Ganas *et al.*, in press). Therefore, cumulative subsidence of the Allai area amounts to (0.44 x 0.7 x 2 + 0.4 x 0.7 x 2) = 1.16 m. The influence of movements along the coastal fault is minimal in the Allai area (≤ 10 cm of uplift), except for contributing to the tilting of the Malesina block towards the south.

The amount of sea incursion in the Theologos Bay area during the last 4000 years can then be found (net tectonic subsidence 1.06 m ; Figure 3b) :

$$d = 1.06m/\tan \phi_{TOT} = 1.06m/\tan(0.07°) = 867 \text{ m.} \quad \mathbf{(4)}$$

This amount should be regarded as a maximum estimate because it does not take into account the effects of sedimentation inside the Bay, as well as minor undulations in sea-bottom topography (which is here assumed flat).

3. DISCUSSION-CONCLUSIONS

This study presents a model of tectonic subsidence for the Allai archaeological site (Figure 2) based on the most recent geological (Ganas *et al.*, in press) and numerical modelling data on earthquake deformations (Ma and Kusznir, 1995). An amount of 1.06 m of cumulative tectonic subsidence was estimated for the Allai coastal region during the last 4000 years together with a tectonic slope due to block tilting towards the south of 0.07 degrees. These estimates imply a maximum amount of sea incursion of about 870 metres during historical times, which would have had important consequences on the life of ancient populations in this area as deprived them of fertile coastal plains. The model is more sensitive to the large events along the Atalanti Fault segment rather than the smaller events possibly occurring along the coastal fault. This is because the former determines almost exclusively the amount of vertical displacement at Allai, whereas the latter mainly contributes to the southern tilt of the Malesina rigid block.

Our modelling spanning the time period of 2000 BC until today does not consider glacio-eustatic effects in accordance with Flemming and Webb (1986; their Figure 11). However, other workers (e.g. Lambeck, 1996) have suggested a steeper sea-level curve which for the Gulf of Evia region implies a rise of about 3-4 metres during the last 6000 years. In the latter case, our results may be used to discriminate between eustatic and tectonic contributions on sea-level.

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