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Comment to "*Relative sea level fluctuations in aegean coastal areas from middle to late holocene by Kosmas Pavlopoulos*"

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1. Introduction

In the light of current and predicted future accelerated sea-level rise it is important to understand the past sea-level history of a particular area and to identify the various factors affecting sea-level changes. A number of models reconstructing past sea-level changes exists. The models, however, require continuous adjustment and confrontation with field data. In a recent paper, Pavlopoulos [1] presents such a comparison of observed rates of sea-level rise with the glacio-hydro-isostatic models of Lambeck [2] and Lambeck & Purcell [3] for six Aegean coastal areas (Lafrouda, Palamari, Marathon Plain, Vravron, Istron, and the areas of Mykonos, Delos and Rhenia).

In addition the paper by Pavlopoulos [1] presenting the sea-level curve of the past 6000 years of four Aegean coastal areas collected from literature is also of importance for archaeologists who work in these coastal areas and need to interpret their findings within a context of sea-level and coastal changes. Such a synthesis can be of great use for archaeologists who rely on publications produced by sea-level specialists. However, in contrast to the title, Pavlopoulos [1] does not discuss relative sea-level fluctuations and does not analyze all available information about old sea levels as stated in the objective of the paper. The author only presents a calculation of the rate of sea-level rise in mm/a with very little information about the sea-level index points and without any evaluation of the possible sources of error in the interpretation of the sea-level data. His calculated rate of sea-level rise is then compared with those from the glacio-hydro-isostatic models of Lambeck [2] and Lambeck & Purcell [3]. Depending on a higher or lower rate between the calculated and the modelled rate, the author concludes uplift or subsidence of the coastal area of some of the case studies.

We believe that the data presented by Pavlopoulos [1] is equivocal and that the methodology adopted for the calculation of the rate of sea-level rise cannot withstand scrutinity. This discussion reports on our critical evaluation of data and reasoning.

2. Methodological approach: Calculation of the rate of relative sea-level rise

Pavlopoulos [1] assumes a continuous infilling of the lagoons or marshes in pace with the rising sea when considering sea-level data points from the sedimentary record. The continuous infilling is assumed on the basis of the presence of several peat beds in the infill of a lagoon, and hence, as an indication of a continuous relative sea-level (RSL) rise. To calculate the rate of RSL rise the author simply selects two data points on the sea-level graph or measures the thickness of the deposit between two dated horizons from the sedimentary record and calculates a rate of RSL rise for a certain period.

However, dividing the thickness of a certain vertical sediment succession by the time span between two dated horizons actually corresponds to the calculation of the sedimentation rate. Pavlopoulos [1] in fact equates the sedimentation rate with the rate of RSL rise. The sedimentation rate represents

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an average value for the dated section based on the assumption that during the corresponding time interval the sediments were deposited continuously at a constant rate and with the sediment source that remained unchanged. However, errors associated with the assumption of steady state of deposition within the measured section may be substantial. Fresh sediments have a high porosity which is later reduced under the load of younger sediments by compaction [4]. It is well known that most sediment successions have not accumulated continuously at a steady rate, but contain minor or major gaps. Deposits in lagoons or tidal flats are examples of discontinuously accumulating sediments [5]. Minor erosional events or wave and current reworking during storms are difficult to recognize. Sediments resulting from reworking and redeposition containing short episodes of erosion and sediment accumulation, can barely be detected [4]. Also peat is accumulating, however, at a different rate than the sedimentation rate. When the base of a peat bed has been selected as dated horizon, the rate of peat accumulation must be considered as well, which most of the time is not known. In order to determine the sedimentation rate, the capacity of the sediment-delivering system to accumulate a maximum of sediment per unit time must be known. This is particularly the case in a lagoon where the sediment supply can fill the lagoon as long as it can hold the total sediment input. As soon as the lagoon is filled, the subsequent sedimentation rate in the lagoon is controlled by its subsidence [4]. The fact that sedimentation rates may vary through time is not taken into account by Pavlopoulos [1]. Therefore the calculated rates of (inferred) RSL rise are highly unlikely to be real features.

With the assumption of a continuous infilling of the lagoons or marshes in pace with the rising sea, the various factors or processes affecting RSL rise are also ignored by Pavlopoulos [1]. However, the author acknowledges in his introduction that sea-level change is affected by eustatic, glacio-hydro-isostatic and tectonic processes. Nevertheless, the author explains the differences between his calculated rates and the modelled rates by probably an increase in the rate of tectonic uplift or subsiding movements for some of the case studies. For instance for the Marathon Plain the author compares a coastal peat at 3.50 m below present sea level dated to c. 4200 cal BP (3810 ± 110 BP) found at about 35 km northwest of the Marathon Plain with «a peat close to this age» occurring in the Marathon Plain, but at 1.60 m below sea level. On the basis of this comparison together with the modelled sea-level change, he concludes «an apparent subsidence at rates that are lower than the isostatic rate». Consequently, on the basis of an estimated discrepancy of about 1.50-2.00 m between the calculated and the modelled rise for the time interval 5500-1300 BP, the author concludes that the apparent subsidence suggests that the Marathon Plain «is undergoing tectonic uplift albeit at slower rates (cf. Lambeck [6])". According to the radiocarbon dates listed in Pavlopoulos *et al.* [7], the peat found in the Marathon Plain at 1.60 m below sea level is younger (3898-3701 cal BP; 3540 ± 70 BP). Besides, the middle of the peat bed was dated, a position that has no relation with sea level.

Another aspect concerning the calculation of the rate of RSL rise concerns the selection of sea-level points. For instance for the Delos-Mykonos and Palamari areas more than one altitude is indicated on the graph with a similar age. At Palamari the calculated rate varies between 1.03 and 1.13 mm/a for the last 6300 years. According to the graph, the index points lie at 7.0, 6.4 and 5.0 m below present sea level. The varying rate results from the use of the three different altitudes. At Delos-Mykonos three index points are indicated between 2000-2200 cal BP at the following depths below sea level: 3.40, 1.70 and 1.45 m. Nevertheless, the rate is set at 1.22 mm/a. The rate for the last 1000 years is calculated to 1.00 mm/a but three index points with a similar age are indicated: at 0.60, 1.00 and 2.10 m below sea level. The author neither indicates which point has been selected nor the argument for the particular selection.

3. Ages, altitude and material

With respect to the ages used for the calculation of the rate of RSL rise, Pavlopoulos [1] compares radiocarbon ages with calibrated ages or with the present day. The latter is for instance the case for the Vravron area where a peat horizon at 1.70 m below present sea level was dated to 3462 ± 105 BP. On the basis of the thickness of the sediment succession (1.70 m) until the present surface and the radiocarbon age (with moreover a large standard deviation), the author concludes that the rate of RSL rise was about 0.49 mm/a for the last 3462 years. For the same area, the author uses the dates of gastropods which gave evidence for a rate of RSL rise of 0.69 mm/a for the last 4709 years without any further information on the context of the gastropod. Besides, the use of gastropods (*Murex* sp. in this case according to Triantaphyllou *et al.* [8]) as sea-level index point is problematic because the relationship of a gastropod to the contemporaneous water level is not known. The same reasoning was applied for the area of Lafrouda where a piece of wood in marine deposits at 0.67 m below present sea level and dated to 2770 ± 30 BP was used to determine a minimum rate of RSL rise of 0.24 mm/a during the last 2770 years. Moreover, a piece of wood in marine sediments has no relation with the contemporary sea level, and besides, the marine sediments most probably experienced a certain degree of compaction. Hence, this material is useless as sea-level index point.

Altitudinal uncertainties were also found for the area of Palamari. The "sea-level graphical plotting" in Pavlopoulos [1] shows three dates around 6300 cal BP referring to Pavlopoulos *et al.* [9] in the figure caption. However, in the publication by Pavlopoulos *et al.* [10] showing the same figure, the altitude of the three dates shows a difference of 1 m when comparing the radiocarbon ages indicated on the core log with the radiocarbon ages listed in the table. It is not clear which depths are reliable, but the latter were used to calculate the rate of RSL rise for the last 6000 years.

With respect to the ages of the Marathon Plain, Pavlopoulos [1] made a remarkable exercise. He presents a series of five ages in years BP with a standard deviation from a paper discussing the Marathon Plain (Pavlopoulos *et al*. [7]). However, in the latter publication the authors present different radiocarbon ages together with their calibrated ages. The radiocarbon ages presented in Pavlopoulos [1] actually seem to be the result of a calculation of the average of the minimum and maximum of the calibrated ages, but presented with the standard deviation of the original radiocarbon dates. Pavlopoulos [1] writes "the main five peat horizons formed by the infilling of the Marathon lagoon [...] indicate the continuous relative sea level rise". These dates were used to calculate the rate of RSL rise. Three of the five dates were originally published in 1985 by Baeteman [11] for the purpose of a palaeogeographical reconstruction and cannot be used as sea-level indicator for several reasons. 1) Pavlopoulos *et al*. [7] changed the elevation of the cores and hence the sampling altitude published by Baeteman [11] because of the use of new topographical data. It is unclear how the authors could find the exact sampling location of the original cores after more than 25 years since fieldwork was carried out in a pre-GPS period. The original altitudes have been raised up to 1.65 m or lowered by 0.90 m, but it is also mentioned that the "corrected" altitudes still have a range of uncertainty of 20 cm. 2) The peat beds published by Baeteman [11] were recovered in a gouge hand auger and have been dated using the conventional radiocarbon method. Therefore, the sampling interval was 10 cm. Moreover, the middle and top of peat beds have been sampled and the ages have a standard deviation between 40 and 105 years. Age and altitude of such samples are no reliable sea-level data points (see e.g. Waller *et al*. [12]). 3) It is also mentioned in Baeteman [11] that the radiocarbon dates are problematic as the hard-water effect might have increased the ^{14}C ages by several thousand years. Because the Marathon Plain is surrounded by limestone mountains from which numerous freshwater springs originate, dissolved carbonate might have contaminated the radiocarbon ages. 4) All the dated peat beds are intercalated in highly compressible carbonate gyttja. The oldest peat bed moreover is overlain by a 6 m thick burden of lagoonal mud and fluvial sand resulting in consolidation of the deeper sediments. Because of the potential influence of compaction it is most likely that the peat beds are no longer at their original level (see e.g. Baeteman *et al*. [13]). Nevertheless, the sea-level graph presented by Pavlopoulos [1] that is based on nine index points contains four dates from Baeteman [11] with no relation to sea level.

4. The relation of intercalated peat beds to sea level

Pavlopoulos [1] considers radiocarbon-dated peat from "paralic" swamps or marshes as reliable sea-level data points. The author states that "the most favourable case is when the peat covers a marine sediment or a marsh sediment if its base corresponds to MHW (mean high water)". This favourable case, however, corresponds to an intercalated peat bed that should not be used as sea-level index point for several reasons. As mentioned above, intercalated peat beds are not at their original level because of compaction of the deposits underlying the peat beds. Pavlopoulos [1] is inconsistent in terms of using intercalated peat beds because the data that is used is not restricted to the base of the peat beds, but is an amalgam of radiocarbon dates of the top, the base and even the middle of peat beds. Although Pavlopoulos [1] states in the introduction that "a major problem when talking about past sea levels is identifying proper indicators and evaluating their precision", the author does not meet these prerequisites.

More importantly, the factors controlling the formation of intercalated peat beds in a marsh environment are not considered. Intercalated peat beds originate when the active sedimentation surface builds up high enough that it is permanently situated above the level of the highest astronomical tide. Then a freshwater marsh can form on which peat can start to accumulate on the condition that the sediment surface remains saturated [14]. However, the elevation of the sediment surface in not necessary in direct relation with sea level, but depends on the storage capacity of the marsh, the sediment availability and in particular on the distal or proximate position of the sediment source. It is well known that in the same area peat initiation can start at a different time even over short distances. Because intercalated peat beds have only an indirect relation to sea level as limiting date, it is essential to know the broader stratigraphic and palaeogeographic context to evaluate the indicative meaning of the dated sample and to ensure that the peat was formed in situ. Such information cannot be obtained on the basis of one or few cores which is the case in the paper by Pavlopoulos [1]. However, since Pavlopoulos [1] gives no stratigraphical context of the data used, the original publications have to be consulted to gain a better understanding for the evaluation of the data points. For instance for the area of Palamari, Pavlopoulos [1] refers to a paper by Pavlopoulos *et al*. [9] for the calculation of the rate of RSL rise. In another publication about the same area (Pavlopoulos *et al*. [10]), the information provided indicates that the three peat beds used to calculate the rate for the last 6300 years were encountered in only one core. Apart from the altitudinal confusion (see above), a careful interpretation of the sedimentary and dating evidence would have indicated that age, altitude and sediment context in that single core are problematic. The sediment thickness between the upper and lower peat bed is 2.20 m, but the peat beds have almost similar ages (-7.15 m: 6410-6190; -6.40 m: 6440-6020; -4.95 m: 6440-6270 cal BP). The two lower peat beds are found in clay, while the upper one, including freshwater shells, rests upon silty sand. It is stated that the environment in the period between c. 7500 and 6000 cal BP consisted of a shallow freshwater environment with some brackish marsh intervals with a tendency to oligohaline conditions. This environment must have had temporal-ephemeral connections with the sea. The questions arise how a two-meter thick clay could be deposited in this environment in such a very short time span, and how the position of the peat beds relates to sea level. A peat bed 20 cm deeper than the lower one was dated to 5920-5660 cal BP. This younger age is interpreted as age reversal due to bioturbation or contamination. It is most likely that the peat beds, which are very thin according to the core log, did not develop in situ and reworking must be considered. As stated above, sediment reworking and redeposition sometimes can barely be detected. A palaeogeographical context might provide further information in such a case.

Knowledge of the stratigraphical context in order to evaluate the relation of the dated sample with sea level is also missing for the data used in the area of Istron. According to the original publication by Theodorakopoulou *et al*. [15] four of the data used by Pavlopoulos [1] are from plant remains and "charred material" found in fluvial deposits.

Conclusion

Pavlopoulos [1] presents rates of RSL rise for six coastal areas in the Aegean Sea. The calculated rates are compared with the modelled rates of Lambeck [2] and Lambeck & Purcell [3]. Differences between the calculated and modelled rates are used to conclude subsidence or uplift of the studied areas. From our critical evaluation, it is clear that neither the methodology adopted nor the data used for the calculation of the rate of RSL rise can withstand scrutiny. Because of too many possible sources of age and altitudinal errors, and the lack of stratigraphical context and indicative meaning of the dated samples, the data presented here are not suitable sea-level index points. Therefore, the calculated high-precision rates of RSL rise cannot be considered as real features.

The author also fails to explain the differences for each region and between regions apart from a general statement such as descending long-term tectonic movements or tectonic uplift, altering the rate of RSL rise. If long-term tectonic movements are invoked, how to explain different rates of RSL rise for different periods in the same area. Because the author uses the sedimentation rate as rate of RSL rise, the major question arises how the rate of sea-level rise could be calculated without eliminating the effect of tectonic movement in the first place.

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