Ups and downs in western Crete (Hellenic subduction zone)

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Studies of past sea-level markers are commonly used to unveil the tectonic history and seismic behavior of subduction zones. We present new evidence on vertical motions of the Hellenic subduction zone as resulting from a suite of Late Pleistocene - Holocene shorelines in western Crete (Greece). Shoreline ages obtained by AMS radiocarbon dating of seashells, together with the reappraisal of shoreline ages from previous works, testify a long-term uplift rate of 2.5–2.7 mm/y. This average value, however, includes periods in which the vertical motions vary significantly: 2.6–3.2 mm/y subsidence rate from 42 ka to 23 ka, followed by ~7.7 mm/y sustained uplift rate from 23 ka to present. The last ~5 ky shows a relatively slower uplift rate of 3.0–3.3 mm/y, yet slightly higher than the long-term average. A preliminary tectonic model attempts at explaining these up and down motions by across-strike partitioning of fault activity in the subduction zone.

Results
Raised shorelines. The coast of Crete between Krios and Paleochora (~8 km) preserves a rich set of rather continuous raised shorelines (Figure 2 and Figure 3). Apart from the stretch between Krios and Plakaki, alluvial
fans and deep incisions alters the lateral continuity of shorelines only locally. We here illustrate six shoreline remnants, named S1 through S6 from bottom up, irregularly spaced at elevations between 4 and 75 meters (Figure 3; Supplementary Table S2 online), of Late Pleistocene - Holocene age (Table 1; Supplementary Table S3, Figure S1, Figure S2 online).

Figure 1 | Tectonic sketch map of the Hellenic subduction zone. The black square indicates location of the studied coastline nearby Paleochora. Topographic and bathymetric relief are obtained using SRTM V2 (http://www2.jpl.nasa.gov/srtm/) and GEBCO (http://www.gebco.net/) data, respectively.

Figure 2 | Pictures of the surveyed shorelines. Kalamia site notches and their elevations (see Figure 3 for location): (a) Panorama showing three raised shorelines found in the West Kalamia site; (b) A band of lithophagid boreholes marking shoreline S2 in East Kalamia site; (c) S5 shoreline in the West Kalamia site; notice the cave in the background and the sandy-gravel deposit on the foreground; (d) S6 shoreline in the West Kalamia site; notice the cave on the left and the notch carved in the bedrock, filled with gravel.
S1 is very continuous and well exposed and it is actually composed by a suite of several features of different ages. The highest in the suite, denoted S1-high, consists of a notch with algal concretions at 8.34 m and a surf notch reaching 10 m. At places, remnants of a pebbly beachrock adjoin the main notch, and one such pebbly beach deposit at 8.8–11.8 m of elevation includes a layer rich in bivalve shells on apparent lateral continuity with an abrasion platform. Several other minor notches are present below the main notch at elevations of 4–8 m. We denote the lowermost notch in this suite as S1-low. AMS ages allow correlation of the entire S1 suite with that described by Pirazzoli et al. in other parts of Crete (Supplementary Table S2 online).

S3 is located at 16.5 m and is also very well exposed. It can be followed almost continuously for hundreds of meters and is characterized by a well-developed notch and lithophagid boreholes, with adjoining sea arches, caves, and a small abrasion platform remnant. Several minor notches can also be seen below the main feature. S3 also features a ~7-m-thick beach deposit that yielded a bivalve shell of mid-Holocene age.

S2, S4, and S5 are located at elevations of 14, 34, and 55 m, respectively. The age of S2, whose remnants are essentially lithophagid boreholes and a notch, is constrained by a Lithophaga sp. shell dated 21–22 ka. The S4 age of 40–48 ka is consistently provided by four samples. Two of them were found included at the top and bottom of a 1.6-m-thick algal-reef remnant in the Paleochora peninsula, which is geometrically correlated with a gravel deposit at 34 m elevation on the coastal slope that yielded other two bivalves of about the same age. Conversely, the three samples collected in the gravel associated with S3 are of different ages spanning a considerable time interval of 22–44 ka. The oldest sample was found in loose sediment and can thus be suspected of having been misplaced. S6 is poorly preserved; it only has a small exposure of a notch at 75 m with sterile gravel and could not be dated.

The analyzed series of shoreline remnants is entirely exposed only at Kalamia. Similar shoreline remnants can also be seen in other parts of Crete but they are not considered in this study.

**Average long-term uplift.** Sea-level variations for the period of interest (~50 ky), which includes the last three Marine Isotope Stages (MIS), are well represented in the eustatic curve by Waelbroeck et al. (Supplementary Figure S3 online). However, considering the scatter among curves in different periods, resorting to specific literature data for each single time interval is necessary. Most authors agree on a ~120 m sea level during the MIS2 (~20 ka). A recent review for MIS3 indicates a sea level of...
when sea level was at fledged indicators of important deviations from the average long-term trend. Notice that Kelletat and Shafer ages are not calibrated. The star symbol marks a sample age discarded by Wegmann.

Consistent ages (WKB8, WKB10, CA43, and CA42). The oldest age of S5, instead, cannot be accurately traced because of the uncertain placement of WKB6 and sea-level oscillations as large as 20 m during MIS3, but one can be confident in considering that WKB13 and WKB5 imply that S5 was active in the late MIS3 and early MIS2 with sea level lowering from ~80 m to ~120 m.

Attaining the S4 to S5 vertical separation thus requires a net subsidence rate of 2.6–3.2 mm/y in the period from ~42 to 23 ka ago. A period of sustained uplift of ~7.7 mm/y should have followed the S5 abandonment (~23 ky ago) as suggested by the formation of S2, with sea level at ~120 m, and S3 and S1-low with sea level at about the same elevation as today. Episodic downward movements led to the formation of the other several shorelines of the S1 suite and S1-high itself, which were then all displaced by the uplift event in 365 AD

Preliminary tectonic model. Mature accretionary convergent margins are known to develop distinct kinematic domains across-strike which can also host splay faults. Along-dip partitioning of the slab itself are also documented in subduction zones and have been explained by various driving mechanisms. In the Hellenic subduction, the best known uplift event in Crete, i.e. the event associated with the 365 AD earthquake, has either been related to seismic slip on the subduction interface or on a shallower crustal fault embedded into the accretionary wedge. Building on this knowledge and as a preliminary attempt to explain the reconstructed vertical motions, we envisage that 10-year timescale rate variations can be explained by fault activity partitioning across the subduction zone. To this end, we subdivide the subduction zone into two separate sections, front and rear, across the main slab dip.
change and set up a series of four distinct dislocation models which include fault slip on the subduction interface and on prospective splay faults (Figure 5).

Based on these fault-dislocation models, we suggest that periods of enhanced uplift rates at Paleochora occur when activity in the subduction rear section dominates (i.e. when the fault activity mainly occurs beneath Crete, as in the case of the 365 AD earthquake). When considering splay ruptures through the upper plate the uplift trend is further emphasized. Because of their high dip angle these faults mainly produce uplift and limited subsidence. Conversely, stability or lowering at Paleochora occurs when the fault activity primarily involves the subduction front section (i.e. south of Crete) including shallow splay faults within the accretionary wedge. Persistence of this activity can explain both the lowering episodes (vertical exaggeration ~2.5×). Front section: A1, interface (solid blue); A2, splay (dashed blue). Rear section: B1, interface (solid red); B2, splay (dashed red). More modeling details are shown in Supplementary Tables S5, S6, and S7 online. Notice that the relative fault rupture positions and the fault dip angles determine vertical movements of opposite sign at the observation point (Paleochora).

Discussion

Major uncertainties in our reconstruction of the Paleochora shoreline suite are represented by the measure of their elevation and spatial correlation, and the sample age determination and sampling site conditions. Shoreline elevations are measured by a geodimeter whose accuracy, together with the small tidal range in Crete, ensure an overall elevation uncertainty of well developed notches to remain within less than ±0.10 cm. Uncertainty can be occasionally higher for gravel deposits or other coarse shoreline features. The short horizontal distance that separates most remnants allows us considering the lateral correlation based on geomorphic criteria to be relatively robust. We cannot exclude that the algal reef in the Paleochora peninsula can be correlated with S5 but this alternative would not affect our interpretation of the results. X-ray diffraction analysis shows that radiocarbon ages are not affected by calcite recrystallization. The small percentage of calcite (<5%) in KB26A, WKB8, and WKB10 (Supplementary Figure S2, Table S3 online) may indicate secondary recrystallization but not necessarily alteration of their radiocarbon age. As for KB26A, the effect of contamination would result in rejuvenating its age of at maximum 200 y. Accordingly, the older bound of its calibrated age may be extended to ~5880 y BP. Considering that real ages of Lithophaga sp. shells can be up to 2 ky younger than their radiocarbon age13, the younger bound of EKB23 calibrated age could be up to ~19 ka. The site conditions (Supplementary Table S2 online) indicate a strong bond between samples and shoreline in all cases except for WKB6, suggesting that its age is not totally reliable to ascertain the age of S5.

The accuracy of uplift rate estimates is affected by all the above uncertainties along with uncertainties about past sea-level elevations23. Our net long-term (~45 ky) uplift rate estimate of 2.5–2.7 mm/y (Figure 4) is higher than the uplift rate (~2 mm/y) obtained by Shaw et al.16 which consider an elevation of the Palechora terrace of 24 m instead of the inner edge elevation of 34 m resulting from our survey (Supplementary Table S2 online). The average uplift rate proposed by Wegmann15, instead, is significantly lower (~1.5 mm/y) than our estimate. We note that this value is mainly based on the correlation of a shoreline at 9 m elevation (likely S1–high in our work) with MIS3. However, these differences are relatively small compared with the uncertainty in sea-level elevation at the time of shoreline formation or abandonment and mainly depend on interpretations of individual shorelines. Nonetheless, the reconstructed pattern of ups and downs clearly deviates from the average trend (Figure 4) supporting the idea that vertical displacement in Crete may strongly fluctuate over a 107-year timescale.

Because of the dominating role of convergence in the Hellenic subduction, our preliminary tectonic model only focuses on fault activity in the subduction zone and neglects possible contributions from other processes, such as the crustal extension in the upper plate (see for example modeled geodetic rates from Reilinger et al.14). Nor have we investigated the role of the various driving mechanisms of fault activity in the subduction system (see Kopp18 for a review). Nonetheless, at this stage of the analysis we propose a simple model that together with our findings shows that tectonic rates may vary depending on both timescale and location of the observation point with respect to the subduction architecture. As we progressively unveil vertical tectonic rate fluctuations at various timescale in subduction zones, the analysis of raised shorelines proves to be an effective tool to improve our understanding of long-term processes which complement other observables such as decadal instrumental measurements. In this perspective, detailed shoreline analyses can shed light on maximum deviations of tectonic rates with respect to long-term averages. Since earthquake productivity estimates can be derived from tectonic rates (e.g. Geist and Parsons19), a compelling implication in active subduction zones is that earthquake rates may considerably vary as a function of location and time interval considered.

Methods

Shoreline identification. Raised shorelines are identified by coastal notches, lithophagid boreholes, sea caves, coastal terraces, abrasion platforms, and sand-to-gravel beach deposits. Their present elevations are measured through geodimeter land surveying. Correlation of individual shoreline remnants is initially based on
improving coastal defense strategies. The AMS radiocarbon technique has been particularly useful in establishing precise age dates for shorelines and terraces, allowing for a more accurate understanding of past tectonic activity. This information is critical for predicting future seismic hazards. Researchers have utilized this technique to study the rate of uplift in different regions, such as the Eastern Mediterranean, and to infer the frequency and magnitude of past earthquakes. For instance, by analyzing the ratio of vertical separation of shorelines and the measured shoreline elevation above present sea level, scientists can estimate the displacement and age of shoreline events. This approach has been refined through the integration of other dating methods, such as the marine reservoir correction technique, to provide a more comprehensive view of coastal change over time.

In the context of the Hellenic Arc, the study of shorelines and terraces has contributed significantly to the understanding of the region's seismic history. For example, the analysis of the shorelines along the coast of Crete has helped to estimate the magnitude of an earthquake that occurred in the AD 365 earthquake in Crete. This event is now recognized as a powerful earthquake that led to significant coastal uplift and tsunami generation. The integration of paleoseismic data with modern geophysical methods has allowed for a more detailed reconstruction of the seismic and tectonic history of the region, enhancing our ability to mitigate the effects of future seismic events.

The AMS radiocarbon technique, therefore, plays a crucial role in the study of coastal deformation and tectonic processes. Its application in the Eastern Mediterranean has provided valuable insights into the region's past seismicity, helping to inform strategies for coastal defense and emergency planning. Future research in this area is likely to benefit from advancements in dating techniques and the incorporation of emerging methodologies, such as Bayesian chronological modeling, which can further refine our understanding of past seismic events. This interdisciplinary approach is essential for developing effective strategies to mitigate the impact of seismic hazards in coastal areas.
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Author contributions

M.M.T.: field work, preparation of samples, review of literature data, data analysis and interpretation of results, manuscript preparation; R.B.: initial idea and work planning, field work, interpretation of results, manuscript preparation; P.V.: field work, preparation of samples, review of literature data. All authors commented on the manuscript.

Additional information

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