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Holocene Coastal Notches in the Mediterranean Region: Indicators of Palaeoseismic clustering?

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Abstract

Marine tidal notches are developed by bioerosion in the intertidal zones of rocky coasts, but a combination of sea-level change and crustal movements can result in them being raised above or submerged below the water line. For that reason, the present-day elevation of these former shorelines relative to mean sea level has long been used to quantify relative coastal uplift and subsidence in tectonically active areas, assuming that the sea-level (eustatic) change component is known. Along the microtidal Mediterranean littoral, it is generally assumed that notches develop during relative stillstands of sea level, when tectonic and eustatic trends are in unison, and that discrete notch levels record abrupt shoreline changes caused by local seismic displacements. Recently, however, a climatic model for notch formation has been proposed, in which stable periods of Holocene climate favour enhanced erosion; in this competing model, the rate of sea-level rise is lower than the tectonic uplift rate and individual notches are not specific seismic indicators. Because marine notches are widely used as geomorphic markers of tectonic, and in some cases palaeoseismic, movements, a reappraisal of the geological significance of these strandlines is warranted. In this paper, we explore the two conflicting notch models using a database of Eastern Mediterranean palaeoshorelines. Although we conclude that the spatial and temporal distribution of the notches supports a dominantly tectonic control on notch genesis as a result of earthquake clustering, we highlight how the diachronous timing of notch development tempers their value as tectonic markers.

Keywords: Bioerosion; marine notch; neotectonics; Mediterranean; paleoseismology; climate.

1. Introduction

For many decades, the Mediterranean's rocky coastline has been used to derive information about tectonic movements (Pirazzoli 1991). In this microtidal setting, bioerosion and bioconstruction can lead to the development of distinct ecological and morphological features that define the modern shoreline (Fig. 1). When equivalent older features are found raised or lowered relative to the present-day water line, coastal uplift or subsidence, respectively, can be inferred (Stewart and Morhange, 2009). Because these relict features originated at sea level, and assuming the general history of sea-level change can be constrained, such 'palaeoshorelines' can be used to quantify relative coastal uplift and subsidence in tectonically active areas. Tidal notches, i.e., physical indentations into a steep, hard substrate at sea level, have been an especially important measure of coastal tectonism around the Mediterranean basin, helping to establish Holocene relative land movement histories in southern Italy and Sicily (e.g., Firth et al., 1996; Pirazzoli et al., 1997; Stewart et al., 1997; Rust and Kershaw, 2000; Antonioli et al., 2006; Scicchitano et al., 2011), Greece (e.g., Pirazzoli and Thommeret, 1977; Pirazzoli et al., 1981, 1982, 1989, 1994a, 1994b, 1999, 2004; Stiros et al., 1992, 2000; Stewart and Vita-Finzi, 1996; Soter 1998; Kershaw and Gui, 2001; Shaw et al., 2008; Evelpidou et al., 2012a; b; 2013; Vacchi et al., 2012), Turkey (Pirazzoli et al., 1991), Syria (Sanlaville et al., 1997) and Lebanon (Morhange et al., 2006).

The utility of notches as tectonic indicators comes from the assumption that they form in the tidal zone when the trend and rate of sea-level change matches that of land-elevation change. When a coastline is uplifting at the same rate at which sea level is rising, or is subsiding at the same rate at which sea level is falling, a temporary sea-level stillstand prevails. The sustained action of bioerosional processes develops a distinct shoreline, in many cases etching out a prominent strandline – a tidal notch. Bioencrustations of coralline algae and other organisms may additionally act to develop a ledge on the lower edge of the notch but this is not always present. At other times when the two are not in union - when sea-level rise or fall is outpacing land movements, or when the opposite is the case – there is insufficient time to sculpt a discernible shoreline. Once a shoreline is cut, it needs to be quickly removed from the tidal zone for its form and biota to be faithfully preserved – slow emergence will expose it to gradual destruction in the supralittoral wave zone. Consequently, well-preserved coastal notches, especially those with fragile inter-tidal fauna intact, are assumed to have been lifted beyond the reach of waves by seismic uplift events. A classic example of this is the prominent strandline developed up to 9 metres above sea level around the rocky headlands of western Crete, and attributed an abrupt coseismic emergence accompanying a huge ($M_w > 8$) earthquake on the 21st of July, 365 A.D (Pirazzoli, 1986a; Shaw et al., 2008). Such very large magnitude earthquakes are not typical of the eastern Mediterranean littoral, however, and along many stretches of coast it is less clear whether apparent notches reflect occasional, discrete seismic events or the cumulative, prolonged effect of multiple seismic cycles in which individual notch levels cannot be attributed to specific earthquakes (e.g., Stewart and Vita Finzi, 1996).

Figure 1. Photographs of marine notches from the Mediterranean. A). 'Mushroom rock' with well-developed marine notch just above present day sea-level, Perachora Peninsular, Greece; B). A suite of five marine notches exposed at Mylokopi on the Perachora Peninsular, Greece; C). Example of a well-developed roof notch at 2 m

above mean sea-level from the Milazzo Peninsula, Northern Sicily; D). By contrast a poorly developed notch at ~4.5 m above mean sea level (indicated with arrow) lacking a floor from Toarmina, Eastern Sicily.

Recently, this simple tectonic interpretation of notches has been questioned. One well developed suite of notches in the footwall of an active normal fault in the Gulf of Corinth, Greece, has also been linked to Holocene climate change (Cooper et al., 2007) opening the discussion of whether notches may have multiple causes. Cooper et al. (2007) reappraised the timing and formation of a suite of coastal notches etched into the limestone cliffs of the Gulf of Corinth's Perachora Peninsula. They noted that individual earthquakes along the fault are too small to raise a notch clear of the associated swash zone as coseismic uplift is often an order of magnitude too low and too many earthquakes have occurred in the Holocene to correlate with the four observed notch intervals, leading the authors to '*discount any direct correlation between notches and individual seismic events*' (Cooper et al., 2007: p. 4). However, since the Holocene uplift rate indicated by the notches was similar to the Quaternary slip-rate on the fault, it did suggest that over longer timescales notches do faithfully record tectonic motion.

Specifically, Cooper et al. (2007) propose that during periods of relative climatic stability, increased biological productivity could be expected to produce higher rates of bioerosion, and consequently accelerate notch formation on uplifting coastlines. Moreover, during these stable climatic conditions the rate of sea-level rise could be expected to be slower, keeping pace with tectonic movements along these uplifting shores and favouring longer notch development. In contrast, during the intervening low-productivity phases of rapid climate change (RCC) bioerosion rates wane, allowing the eroded notches to emerge with continuing coastal uplift. Consequently, Cooper et al. (2007) regard the preservation of notches as relict features of regional climate stability superimposed on tectonic uplift, neatly explaining the disparity between the elevation of notches and the amount of potential coseismic uplift.

This intriguing reinterpretation of coastal notches, which if applicable elsewhere, means these features cannot be used as simple measures of palaeoseismic activity. Instead, it could be expected that around the circum-Mediterranean region, Holocene notch sequences might record a mainly climatic rather than tectonic signal. In particular, since the five periods of climate stability (Mayewski et al., 2004) that separate rapid climate change events are regional, even hemispheric, phenomena, we might expect the quintet of notch levels to be a consistent Holocene feature on emerging rocky coasts throughout the Mediterranean realm.

In order to differentiate between these contrasting models of palaeoseismic or climatic origin for tidal notches, we examine how climatic and tectonic factors can be discriminated in Mediterranean notch records. First, we consider the conceptual framework for notch formation in the region, using simple models to explore the effects of likely contrasting relative sea-level trajectories. In particular, we use it to appraise what the morphological effects would be of likely tectonic and climatic influences. Second, we compile a comprehensive dataset of Mediterranean palaeoshoreline data (supplementary data) to define age and height relationships and test correlations with periods of inferred climate stability. We show that although the climatic origin for notch formation is unlikely, the tectonic interpretation of notches is by no means straightforward and while some tidal notches do represent unique coseismic uplift events, most represent more complex histories likely the result of earthquake clustering.

2. Notch formation

In his seminal work on marine notch formation, Pirazzoli (1986a, 1986b) showed how various trajectories of relative sea-level change, under different erosion rates, tidal ranges and cliff slopes, would give rise to contrasting notch morphologies. Trajectories of relative sea-level change are the combination of eustatic, glacio-hydro-isostatic, and tectonic factors, each of which vary over time and space (Lambeck et al., 2004).

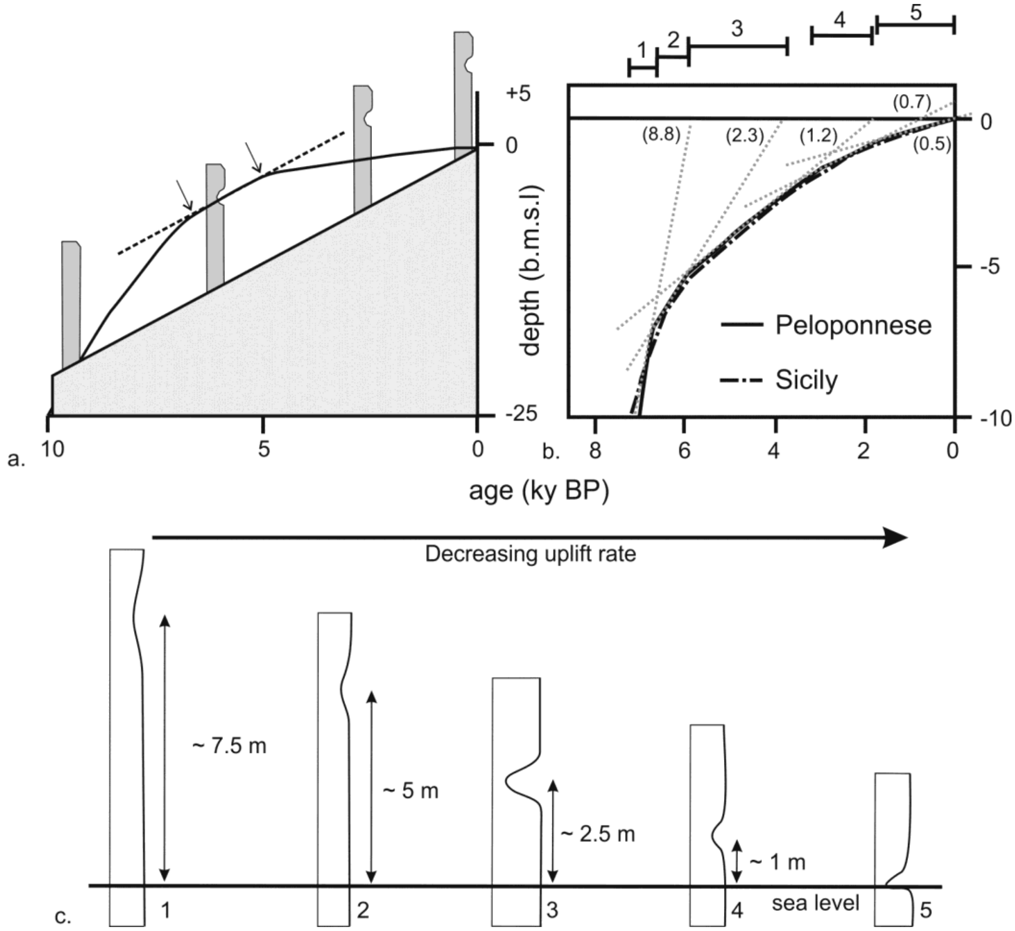

Figure 2. Schematic diagrams illustrating how the interplay of tectonics and sea level can result in notch formation; a) Simplified Mediterranean sea-level curve (black solid line) and constant uplift of shoreline (grey) with a schematic cliff showing development of a notch when uplift rate = sea-level rise as indicated by the dashed black line. Notch formation takes place in the period indicated by the two arrows; b) two sea-level curves for the Mediterranean region (black) with tangential uplift rates shown in light grey (dashed), numbers in brackets indicate uplift rate in mm/yr for each straight line. Above the graph are the periods of notch formation for each uplift rate where period 1 correlates to the highest uplift decreasing in turn so that period 5 indicates the lowest uplift rate; c) theoretical notch height and form development for the 5 uplift rates shown in b.

Under global eustatic effects, and in the absence of vertical tectonic motions, all Mediterranean coastlines should have experienced rapidly rising sea levels from 16,000 to 8,000 years BP, followed by a slower rise from around 6,000 years BP to present day levels (Pirazzoli, 1991). Despite being dominated by this eustatic signal, local Mediterranean sea-level histories are modulated by glacio-hydro-isostatic (i.e. the response of the sea surface and the crust to changing volumes and patterns of ice loading) recovery following loading by the northern European ice sheets. Since the Last Glacial Maximum (c.20,000 years ago), the Mediterranean region has been broadly but modestly subsiding due to 'collapse' of the formerly upwarped southern foreland of the ice sheet, and there is no empirical evidence for short-term fluctuations in sea level during this period (Lambeck et al., 2004). However, by far the most variable and uncertain component of the relative sea-level trajectory is the tectonic signal. Tectonically active sectors of the Mediterranean are partitioned by a network of active faults and their relative movements induce complex coastline changes. This block faulting can result in adjacent coasts experiencing contrasting histories of sea-level change dependent on the rates of fault motion and location on the hangingwall or footwall of active normal and reverse faults.

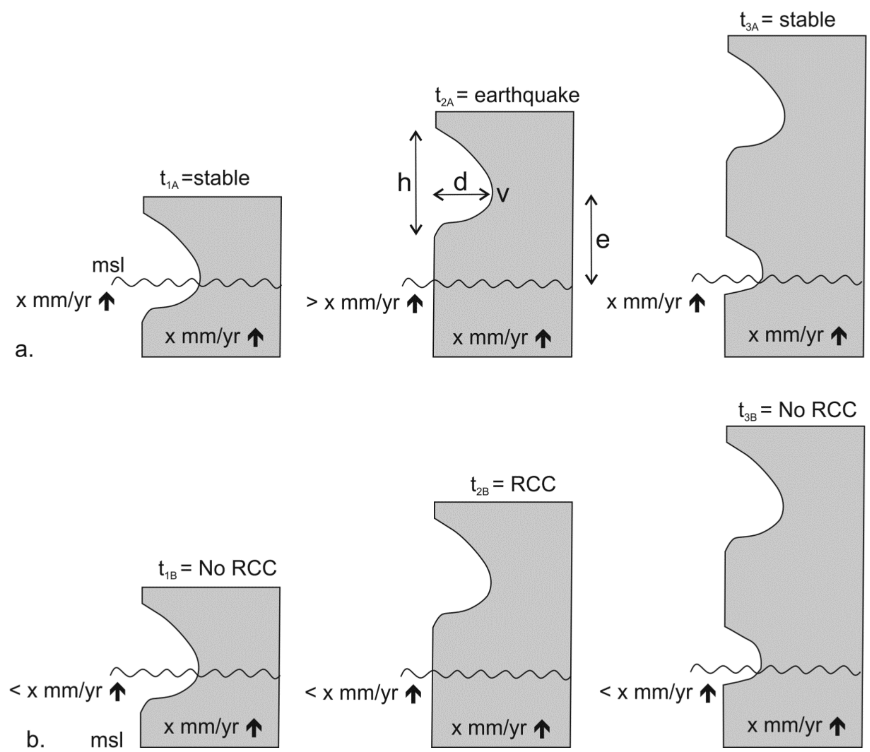

Figure 3. Schematic illustrations comparing the two models for notch development. In a) the tectonic model is shown, the coastline uplifts at the same rate as sea-level rises resulting in a still stand at time 1 (t1A) and the development of a notch. At time 2 (t2A) an earthquake results in the coseismic uplift of the notch formed at t1A by elevation , e, above the swash zone preserving the feature. h = notch height, d = notch depth, v = notch vertex. At time 3 (t3A) the uplift rates are once again equal and a new notch develops. Also shown are key notch parameters discussed in the text; h = height, d = depth and e = elevation of the notch. By contrast in b) illustrating the climatic model for notch formation the coastline uplifts more rapidly than sea level rises (modified from Cooper et al., 2007). At time 1 (t1B), there is no RCC providing ideal conditions for bioerosion and notch development. By time 2 (t2B) the notch formed during t1B has been uplifted out of the water and the climate is now unstable so no notch is carved. At time 3 (t3B) a new period of climatic stability allows organisms to create a new notch at sea level below the t1B notch and the t2B cliff.

Thus, although modulated somewhat by differential glacio-isostatic rebound, the first-order sea-level history of the Mediterranean Sea is one of a rapid rise in early Holocene times switching in the mid Holocene to a very minor rise over subsequent millennia (Lambeck et al. 2004). Under this simple sea-level construction, we can derive basic conceptual 'rules' for how variation in tectonics and also erosion rate might modify notch morphology. To do this, we use a basic model of sea level and tectonics formulated by Soter (1998) and simplified here. The model envisages a sea cliff uplifting at rate, *r*, defining a reference frame that is moving with respect to the absolute frame of reference (i.e., eustatic sea level). If a tidal notch is eroded (or another palaeoshoreline indicator formed) along the cliff face at the contemporaneous sea level, at any time, *t*, the elevation above sea level of the tidal notch (ζ_b) is:

$$\zeta_b = -rt$$

where *t* is positive in the past.

For a tidal notch to form when sea level is constantly rising the cliff must be uplifting at the same rate as sea level is rising (Fig. 2a); in other words, there is a relative sea-level stillstand. The longer the duration of the stillstand, the more deeply cut and prominent the notch. Estimates of intertidal erosion rates are generally in the range of 0.3-1 $mmyr^{-1}$ (Pirazzoli, 1986b; Laborel et al., 1999), so a notch 20 cm deep could take only ~ 200 - 700 years to form. Whereas the height of the notch (i.e., the distance from the base to the top of the tidal notch) corresponds to the local midlittoral zone, ~ 20-30 cm in the Mediterranean (Evelpidou et al., 2012a). In the Mediterranean region, where sea level has been rising slowly for the last 6,000 years, for a late Holocene notch to be uplifted beyond the effect of coastal erosion and preserved without further modification, the gross tectonic uplift must outpace sea-level rise, and be abrupt enough to prevent total erosion of that notch by wave action after formation. Slow emergence or subsidence can lead to the modification of the notch (i.e., increase in the height of the notch) but unless further relative sea-level change occurs over time this process would eventually result in the erosion of the cliff back to the depth of the vertex. Using these assumptions, and subject to the sea level trajectory outlined above, the age, elevation and degree of development of sea-level markers for the region can be predicted under differing rates of uplift (Fig. 2 b; c).

2.1. Conceptual models of notch formation – tectonics

The simplest model is of a shoreline uplifting at a constant rate. In this scenario, tidal notch formation is promoted when that uplift rate is in tandem with rate of eustatic rise - in other words, when the slope of the sea-level curve is parallel with that of the rate of uplift. We illustrate that with sea-level curves for southern Greece and Sicily (Fig. 2b), broadly comparable with other sectors of the Mediterranean, to which a series of theoretical constant uplift rates (shown in grey) have been fitted tangentially to the curve. From this, we see that that the longest period of hypothetical tidal notch formation possible would be for a region uplifting at ~ 1.2 $mmyr^{-1}$, which gives a relative stillstand occurring from ~4000 – 6000 yrs BP (Fig. 2). Shorelines uplifting at rates progressively higher than 1.2 $mmyr^{-1}$ would have typically successively smaller time intervals in which to form a notch resulting in ill-defined notches (Fig. 2c). Few parts of the Mediterranean realm are uplifting at such rates, making such older 'cryptic' notches unlikely. For coastlines uplifting at < 1.2 $mmyr^{-1}$, the principal notch would typically be younger than 4000 yrs BP (Fig. 2b). These moderately emerging shores would have longer to form tidal notches as the rate of sea-level rise slowed 6000 years ago. For those slowly emerging shores, uplifting at rates of 0.5 $mmyr^{-1}$ or less, a modern marine notch might be expected because sea level would have been relatively constant for the last two millennia (Fig. 2b).

Stable coastlines (i.e., those not experiencing tectonic movements) will have been progressively drowned by rising sea levels and a down-warping seaboard since the LGM (c. 20 kyrs BP). With net stability an erosional notch might to be evident at, or just below, present-day sea level and could extend below the water line due to the slight increase in sea level during recent millennia (Evelpidou et al., 2012c).

For those Mediterranean coastlines that have been continually subsiding over Holocene times, erosional features should be absent as these shores would have experienced a transgression too fast to permit notches to develop. For notches to develop on subsiding coasts eustatic sea-level fall would also be required to generate the necessary stillstand, there is no evidence that this is the case. So for a coast undergoing constant subsidence tidal notches should not be present.

Such simple scenarios envisage uniform monotonic coastal uplift or submergence, but what about when differential or episodic vertical motions take place? In areas exhibiting varying uplift, it is possible to generate a series of notches if the changes in uplift rate produce relative stillstands for periods of several hundred years. Multiple stillstands could occur if Holocene uplift rate of a coastline decreased over time, though in geodynamic terms this does not seem to be a particularly likely scenario. More likely would be a coastline affected by periodic uplift and/or subsidence as a result of moderate to large earthquakes (M>6), which are common in the Mediterranean region (Vannucci et al., 2004). In this scenario, multi-centennial interseismic periods of tectonic quiescence associated with the build-up of tectonic strain could produce relative stillstands long enough for notches develop, followed by abrupt seismic movement that raises or lowers the notch above the wave zone (Fig. 3a). For a notch to form the background uplift rate of the coastline would need to be low enough to match slow eustatic rise, otherwise even moderately rising sea levels would result in a transgression and inhibit notch formation. A set of notches developed in this way could be taken as evidence of a modest background regional uplift rate onto which local, fault-related uplift events are superimposed.

In this case, the rate of uplift (U) calculated from the age of the notch at the highest elevation would be the sum of the regional (U_R) and local (U_L) uplift rates:

$$U = U_R + U_L$$

Thus, $$U_L = U - U_R$$

It follows that, if a regional uplift rate is known, it should be possible to extract the rate of ‘local’ fault motion from the net uplift rate derived from palaeo-sea level indicators.

From these simple notch scenarios envisaged under different tectonic conditions (but with the common assumption of a constant uplift rate) the following testable hypotheses can be formulated: (1) the highest elevation tidal notch along most emerging coastlines will date to ~ 6000 years BP; (2) a single tidal notch feature will be present at, or just below, modern mean sea level where uplift is very slow or absent; (3) tidal notches should not develop on constantly subsiding coasts, (4) multiple notches will only occur in areas of slow regional uplift with superimposed local rapid uplift (or subsidence) events.

2.2. Conceptual models of notch formation – climate change

The climate of the Holocene has been shown to be extremely variable, oscillating between stable climates and periods of Rapid Climate Change (RCC) (Mayewski et al., 2004). Cooper et al. (2007) proposed that raised notches in the Gulf of Corinth, central Greece - long regarded as solely tectonic uplift markers - might have additional climatic influence. In this model enhanced erosion during stable climatic periods promotes tidal notch development. During subsequent RCC episodes, notch formation would be inhibited. In this climatic model sea-level rise is envisaged to be *lower* than tectonic uplift, resulting in the newly-formed notch being raised above mean sea level during RCC episodes. Later, when the climate stabilises, a fresh phase of notch formation recommences back at sea level cutting a continual notch until conditions become unsuitable once more (Fig. 3b).

A model where climate is the main control on notch formation results in three testable hypotheses. First, notches ought to date only to periods of climatic stability (not to RCC episodes). Second, because this model also acknowledges prior to 6000 years ago sea levels were rising too rapidly for notches to form, the highest (and oldest) notches are likely to date to around 6000 years or younger. Thirdly, since notch development is effectively decoupled from the sense of land movement, climatically-enhanced notches can equally form on subsiding coasts, and should mirror the sequence on an equivalent uplifting coast. Finally, it should also be noted that the magnitude of Holocene tectonic uplift is still recorded by the elevation of the highest notch in this scenario but that the vertical separation between notches does not correlate with the timing of coseismic events.

3. Analysis of a Mediterranean shoreline database

In order to interrogate the timing and nature of Mediterranean marine notch formation, a database of raised shorelines was compiled from published data from around the region (Fig. 4; Supplemental Data). We emphasize that this is *not* a complete dataset of every observed tidal notch ever recorded in the scientific literature. The palaeo-shoreline inventory includes only sea-level index points that have identifiable locations (preferably GPS coordinates, but also detailed location maps in the journal article), corresponding age data (conventional radiocarbon data), and are described as discrete identifiable erosional levels; therefore, only those that have reliable dates clearly associated with the tidal notch are included allowing us to robustly test the conceptual models of notch formation. We also only include the original source of the data as many results have been used multiple times by successive authors.

The result is a database of 240 dated samples derived from 26 separate studies that were undertaken at sites across the Eastern Mediterranean. In addition to raised tidal notches, various other geomorphological features (e.g., trottoirs, rock platforms), sedimentary deposits (beachrock accumulations) and archaeological artefacts (e.g., fish ponds, building foundations) have been reported, dated and used in tectonic analyses of this kind (e.g. Stewart and Morhange, 2009). In many cases, however, the vertical control and relationship to sea level for many of these features are unclear and consequently, they have also been excluded from our analysis.

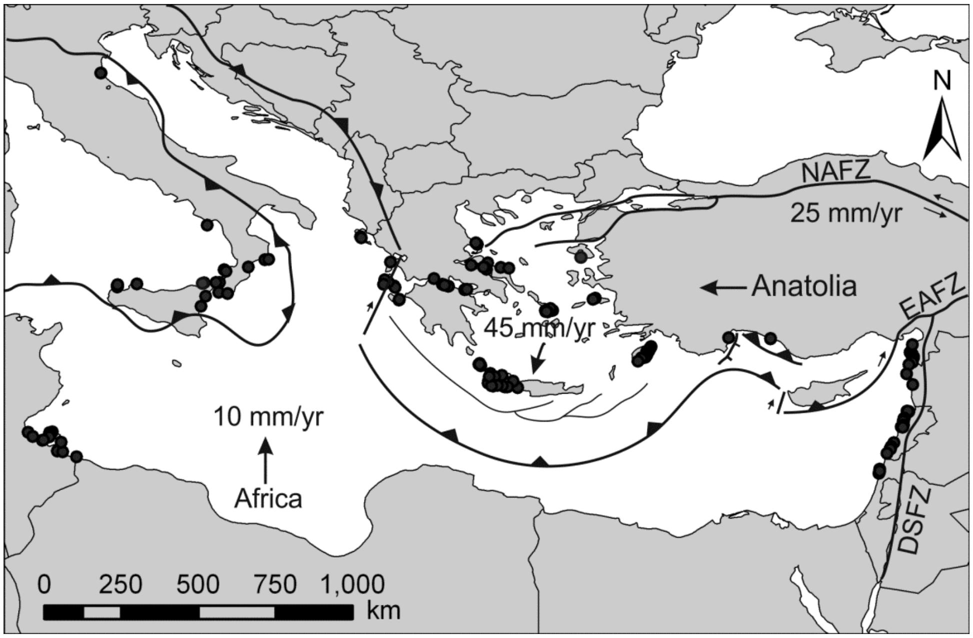

Figure 4. Map of the Eastern Mediterranean showing location of Holocene raised shorelines (supplementary data) used to compile Figure 5. Plate margins and vectors from Papazachos et al., (1998, 2006).

Another potential inconsistency in the dataset is that, due to the samples having been collected and dated over several decades, contrasting carbon-14 calibrations have been applied in the original studies (Stuvier et al., 1986, 1998; Stuvier and Reimer, 1986; 1993; Stuvier and Braziunas, 1993). In order to permit direct comparison of the data, Calib 5.0 (Stuvier and Reimer, 2006) was used in this study to recalculate the calibrated age of the samples from the conventional radiocarbon date, using a common reservoir age of ΔR = 58 +/- 74 years [the Mediterranean average reservoir age derived by Reimer and McCormac (2002)]. In other words the ages reported here may differ from those presented in earlier studies.

The resulting 'screened' dataset is plotted as a histogram (Fig. 5a) and shows that the majority of the sea-level index points date to 1000–2000 yrs BP; a smaller peak dates from ~ 500 years ago to the present day. There is a modest spread of notches with dates of ~ 2000 years up to 6000-6500 yrs

BP, but at only three localities are notches that date to > 6500 yrs BP. When the height of these older notches is considered (Fig. 5b) they are all found to be > 4 m in elevation; by contrast notches older than 4000 yrs BP but younger than 6000 yrs BP are all above 1 m in elevation. The youngest notches (<4000 yrs BP) exhibit a range of elevations but generally correspond to two populations; a low-elevation set and a higher elevation set (Fig. 5b).

4. A Test of Competing Models

In this section, we use the results of the database analysis to test the conceptual hypotheses set out earlier. Our first contention was that both the tectonic and climatic models for notch formation predict the oldest (and therefore highest) notches to date to around 6000 yrs BP. The notch database supports this view - when only the oldest date obtained from each area is plotted the majority of the notches fall within the 5000 – 6500 years BP age range (Fig. 5c), with only three samples older than 6.5 kyrs.

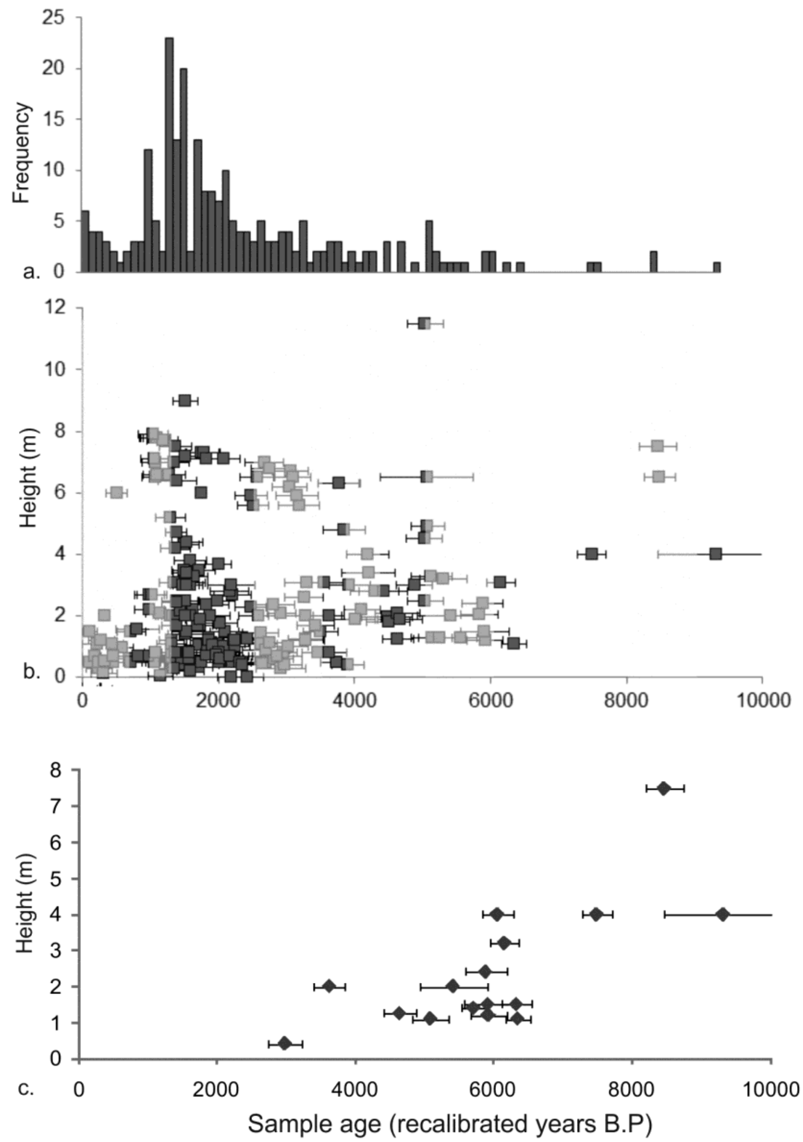

Figure 5. a) Histogram showing frequency of samples against age from notches around the Eastern Mediterranean in 100 year groups; b) Graph of calibrated radiocarbon age with horizontal error bars indicating the 2σ (95%) confidence interval against height of all notch data for the Eastern Mediterranean region. Grey bars on both graphs indicate the periods of proposed Holocene rapid climate change (RCC); c) Graph showing only the date for the highest erosional feature at each location, note how the majority cluster around 6000 yrs BP.

The spread of notch age data also allows the competing 'tectonic' versus 'climatic' models to be discriminated. If climate is the dominant control on notch formation, the timing of notches will concentrate in periods of climatic stability (no RCC), whereas if tectonic uplift is the dominant control, notches will have an even spread of ages determined by local tectonic and seismic histories. As Figure

5b shows, there is no direct correlation between stable climatic periods and notch occurrence; numerous notches appear to also date to periods of RCC. Although error ranges associated with shoreline ages produce some overlap with the boundaries between periods of RCC and climate stability, the bulk of the notch age ranges fall within both climatic phases.

Our meta-analysis is strongly at odds with the hypothesis that a primary control on the formation of marine notches in the Mediterranean is fluctuating Holocene climate. Moreover, there are other obvious difficulties with this notion. One is that there have been five periods of stable climate (no RCC) in the last 10 kyrs (Mayewski et al., 2004), so the climatic model would predict the formation of a quintet of notches at any one place. In fact, few places along the Mediterranean coast show five notch levels. Along the islands of the Hellenic arc there are far more: on Crete, nine to ten well preserved superimposed shorelines can be observed (Pirazzoli et al., 1981; 1982) and on Rhodes eight are present (Pirazzoli et al., 1982; 1989). In contrast, on the inner gulfs of the Aegean Sea, typically only one or two notch levels are developed. Another objection noted by Pirazzoli and Evelpidou (2013) is that tidal notches often have limited lateral continuity that does not seem to fit with the idea of climate stability forming notches. These disparities with that expected from regional climatic influences strongly suggest that enhanced erosion is not a key controlling factor for notch formation.

5. Problems and Promises

Although the 'climate model' appears inadequate in explaining the development of Mediterranean notches, there are clearly some difficulties with the competing 'tectonic model'. One issue lies with submerged notches, which appear inconsistent with our simple scenario of tectonic uplift and yet which are evident along subsiding stretches of the north Mediterranean littoral (e.g., Benac et al., 2004; Antonioli et al., 2007). Under conditions of steadily rising sea levels, a subsiding coast will not experience a relative stillstand, and consequently ought not to develop a prominent notch. Clearly, the presence of drowned notches requires more intricate tectonic histories. Some might be explained if a coastline had uplifted in the past, allowing a notch to form during a relative stillstand, only for tectonic activity to cease or to switch to subsidence thereby resulting in the transgression and submergence of the notch. This scenario would be consistent with the tectonic setting of the Adriatic coast where submerged notches have been described (e.g., Benac et al., 2004). The point is that it relies on more involved complex tectonic movements.

Another problem is the objection raised by Cooper et al., (2007) that reported marine notches in the Mediterranean are too few in number and too large to record individual earthquakes. Mediterranean seismicity is dominated by moderate to large (M 6-7) earthquakes, events which result in only a few centimetres or decimetres of surface displacement along the causative fault (and substantially less along nearby coastlines). This is especially the case in the region's extensional provinces, where coseismic slip on normal faults is partitioned between footwall uplift and hangingwall subsidence. Recent observations after the M_w 6.3 earthquake at L'Aquila (Central Italy) showed only 35 cm of ground deformation partitioned between 25 cm of hanging-wall subsidence and 10 cm footwall uplift, a ratio ~ 1:3 (Papanikolaou et al., 2010). Armijo et al. (1996) modelling the Corinth Rift determined ratios of uplift to subsidence of 1:3.5 to 1:2.7, while McNeill et al., (2005) found ratios between1:1.2 and 1:2.2 for the same region. These are similar ratios of hanging-wall subsidence to footwall uplift that have been documented elsewhere (e.g., Teton Range 1:2; Byrd et al., 1994). This implies that even when normal faults rupture with 1 m of surface displacement only ~30 cm of uplift could be expected in the area of maximum displacement. These studies clearly show that generating metre-scale coseismic coastal uplift would require an unfeasible amount of slip on a fault.

In other tectonic settings such metre-scale coastal movements are more expected. Along the Mediterranean's compressional (subduction) plate boundaries, large (M8) to giant (M9) 'megathrust' earthquakes can produce uplift of many metres. Both recent (e.g., Kefalonia (Ionian) earthquake in 1953; Pirazzoli et al., 1994a) and well constrained historical (e.g. AD 365 earthquake, Crete) earthquakes show that elevated notch levels can be confidently ascribed to individual seismic events. These far larger earthquakes, especially when located on faults close to the coast, clearly have the ability to substantially uplift shorelines. For that reason, these lower frequency events probably account for some of the decimetre intervals between multiple notches on coastlines. Yet overall, the bulk of the background seismicity experienced by an emerging coastline will be dominated by smaller, incremental motions. In other words, the majority of Mediterranean notches express a cumulative record of multiple coseimic events not simply a few 'big ones'.

An alternative to the prevailing tectonic model that assumes an elevated notch to be the result of a single coseismic event is the likelihood that it may instead be the product of uplift accompanying an earthquake cluster - multiple events closely spaced in time and space. Palaeoseismic and instrumental records convincingly show that in many regions earthquakes occur in clusters of ruptures along several nearby faults separated by long periods of quiescence as a result of phase locking (Scholz, 2010; Cowie et al., 2012). Modern examples of coupled seismic sequences include the 1981 Corinth Rift M_w 6.7, 6.4 and 6.2 sequence (Jackson et al., 1982) and the 2009 L'Aquilia M_w 6.3, 5.4, 5.5 events (Papanikolaou et al., 2010) and larger and more destructive seismic episodes have been inferred in the past (Pirazzoli, 1986a; Pirazzoli et al., 1996). The emerging tendency for earthquake faulting to be strongly clustered in time and space offers a potentially important new perspective on how coastal notches may reflect palaeoseismicity.

In the Eastern Mediterranean, the effect of earthquake clustering may be recognised through differences in notch height. As the tidal range is generally 20-30 cm, we would expect a notch forming during a seismically quiet period to have a similar height to the tidal range (the exposure of individual coasts to storms will also affect this height). Therefore, narrow notches may represent quiescent periods of earthquake cycles and notches of increasing height may represent periods of small earthquakes that cumulatively move the coastline by small increments but over sustained periods (Fig. 6). A similar enlarging of the notch could also be formed by a sustained increase in the rate of eustatic sea-level rise but there is no evidence for this rise from late Holocene sea-level curves; however, as Evelpidou et al. (2012c) note, recent eustatic sea-level rise is too rapid for continued notch development in the mid-littoral zone of many regions. Importantly, the depth of the notch will be determined by the duration of the relative stillstand (as well as coastal lithology). In consequence, a qualitative impression of the seismic history of a coastline may be ascertained but correlating specific notches to individual earthquakes is problematic, and is arguably a spurious exercise in most cases.

Given that most notches are likely to represent composite features representing multiple earthquakes rather than single events, perhaps the most promising use of notches is as regional indicators of Holocene tectonic motions. With the exception of a few outliers, the notion that an initial phase of notch development in the Mediterranean during the period 5000 – 6500 years BP is supported by the database (Fig. 4c), with the majority of the older notches clustering around this time. Those that do not conform appear to fit a very particular tectonic setting. Thus the highest and oldest notches are located along the central coast of the Gulf of Corinth, which is one of the Mediterranean region's most active fault zones, and for some an incipient plate boundary structure (Armijo et al., 1996). It is entirely possibly that atypically high uplift rates along this seismogenic structure are the reason why this region experienced a relative stillstand with rising sea levels far earlier than elsewhere. By contrast, most higher notches coincide with the mid-Holocene slowdown and stabilisation in the rate of sea-level rise ~ 6000 yrs ago, when eustatic rates reduced from as much as 7.5 – 9.5 mmyr^{-1} to < 1.0 mmyr^{-1} (Siddall et al., 2003; Bassett et al., 2005; Rohling et al., 2009). The dramatic eustatic deceleration at this time ensures that along many tectonically uplifting coasts, land emergence and sea-level rise were synchronous and so notch development could take place. Thus along many coasts the oldest notch could be used as a reference marker for late Holocene uplift rates, in a similar manner to the way post-glacial fault scarps are used as reference markers for fault-slip rate in the Mediterranean region (Giraudi, 1995; Tucker et al., 2011).

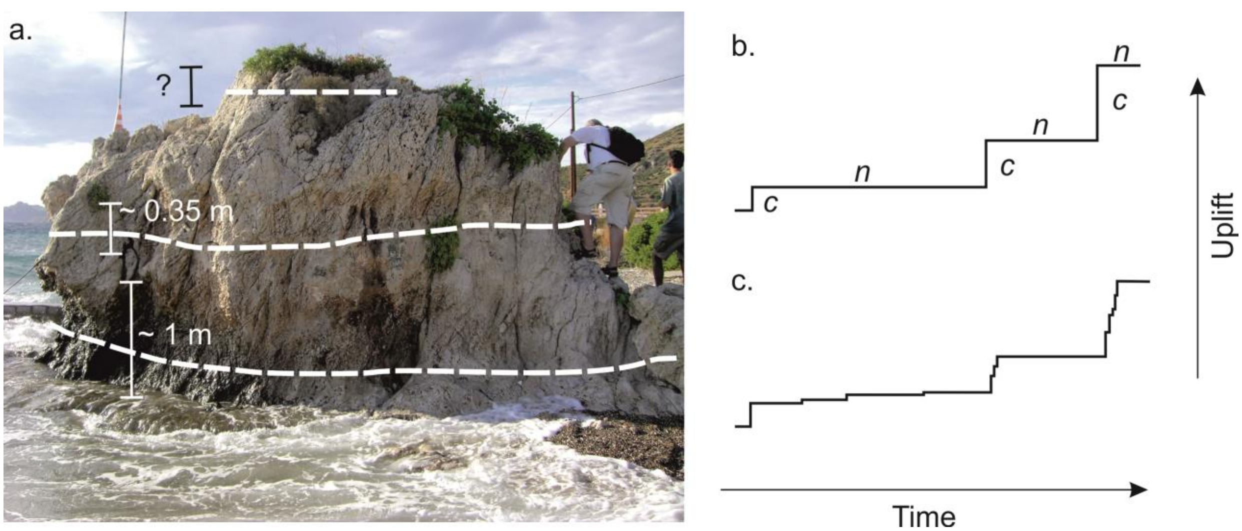

Figure 6. a) Holocene palaeoshorelines from the Perachora Peninsular studied by Cooper et al. (2007) and Roberts et al. (2009). Dashed lines show approximate positions of former sea level with the upper notch with Lithophaga at ~3 m absl dating to ~ 6000 yrs BP, the middle notch at ~ 2 m absl dates to ~ 2000 yrs BP and the lowest elevation notch at ~ 0.2 m absl was uplifted during the 1981 earthquake (Pirazzoli et al., 1994b; Roberts et al., 2009). The middle notch is ~ 0.35 m in height, while the lower notch is ~ 1 m in height suggesting that the lower notch may represent the cumulative effect of many small earthquakes over a long period of time. The central notch has height near that of the tidal range suggesting stable relative sea level during formation. Traditionally, three significant coseismic events, c, would be used to explain the separation between the distinct notch, n, levels (scenario shown in b), such as the 1981 event. In the new model, notch uplift is the result of

earthquake clustering resulting in short term higher uplift rates raising the notches above sea level. Periods of earthquake activity are followed by periods of relative stability but where small events can act to increase the height of the notch above that expected due tidal or eustatic effects (shown in c).

As well as being useful regional reference markers, notches offer potential for determining local fault motions. Cooper et al. (2007) and Roberts et al. (2009) present notch data measured along the strike on the footwall of an active fault on the Perachora Peninsula (Greece), which shows a systematic change in notch elevation from a minimum at the fault tip to a maximum in the centre of the fault. This elevation pattern clearly matches the pattern of footwall uplift exhibited by the fault along strike and, therefore can be used to determine short-term uplift rates on faults. To our knowledge these studies are the only ones to systematically document along-strike variations in notches, but this approach could be usefully applied elsewhere where coastlines emerge on the shoulders of active bounding faults.

Where faults cross coastlines, notches can also usefully document post-notch deformation and motion of the fault, if the notch has been offset vertically. For example, Pirazzoli et al. (1989) documented ‘crustal block movements’ affecting the coast of Rhodes identified due to variations in the height of marine notches. However, the authors focussed on the sea-level history inferred for the different blocks and did not consider how these records could be used to resolve the underlying faulting behaviour. Offset shorelines have been documented from few other locations (i.e., Hatay; Pirazzoli et al., 1991) but it is likely that their occurrence is more widespread and could be used to determine local fault histories.

6. Conclusions

Over the last 40 years, marine notches round the coasts of the Eastern Mediterranean have been recorded and dated. That impressive dataset has been used in this study to test two current conflicting models for the formation of these palaeoshoreline markers. The long-standing model attributes notch formation to stable tectonic periods, punctuated by coseismic events that uplifted the erosional features above sea level. This ‘tectonic model’ requires that regional uplift rates match rates of sea-level rise. The new alternative model advocates climate as the dominant control, suggesting that notches form during stable climatic periods; subsequent periods of unstable or rapid climate change causes erosion rates to decrease, thereby inhibiting notch formation. This 'climatic model' requires uplift rates to be greater than the rate of sea-level rise allowing the notches to be uplifted during times of unstable climate.

The database compiled in this study demonstrates that notch ages span the duration of the Holocene and show no clustering in periods of stable or unstable climate. This finding favours the tectonic model for notch emergence. However, quite how we use tidal notches for tectonic studies is open to question. Although they can be used as regional markers to measure the amount of net coastal movement since the abrupt mid-Holocene sea-level slowdown, the recognition that the exact timing of notch inception varies with local uplift rate means that they constitute a somewhat regionally variable and diachronous marker. Furthermore, documented individual coseismic offsets on normal faults are at least an order of magnitude smaller than that often proposed to raise notches suggesting that earthquake clustering is a more likely mechanism of tidal notch uplift. Instead, their utility may be more as local indicators of differential fault displacements and the relative palaeoseismic expression of coastal-bounding faults.

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