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Shore platform and cliff notch transitions along the La Paz Peninsula, southern Baja, Mexico

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ABSTRACT

Increasing exposure to wave action produces a northerly transition from high tidal notches to shore platforms in the andesitic lahar deposits of the La Paz Peninsula, southern Baja, Mexico. Twenty-four notches were surveyed and wear pins were cemented into the apex of each notch. Thirty-six transverse micro-erosion meter (TMEM) stations were installed on three surveyed platforms. Field measurements were made over a 2.5 year period. The wear pins suggested notch backwearing (horizontal erosion) is <2mm yr$^{-1.}$ The shore platforms were fairly narrow (a few tens of metres) and steeper (1°) than most platforms in similar microtidal environments, reflecting a weak wave environment and resistant rocks. Mean TMEM downwearing (vertical erosion) rates for each of the three platforms ranged from 0.14mm yr^{-1} to 0.42mm yr^{-1}. There was a good relationship between notch height (difference in elevation between the floor and the roof at the front of the notch) and exposure to wave action, but notch depth is time-dependent and the relationship with exposure was not statistically significant. Notch height was also related to the orientation and wave fetch of the site. Field evidence suggested that the notches were not produced by bioerosion or chemical weathering but by alternate wetting and drying or salt weathering from high tidal immersion and wave-generated splash and spray. Coastal morphology is fairly well adjusted to present sea level although notch occurrence in the upper portion of the high tidal zone suggests that there is slow tectonic uplift in this region.

KEYWORDS **Notches. Shore platforms. Erosion rates. Wave exposure. Weathering.**

INTRODUCTION

Once described as a neglected coastal element (Trenhaile 1980; Stephenson, 2000), a marked upsurge in interest over the last 10–20 years has produced a rapidly growing body of literature on shore platforms and other aspects of rocky coasts, including hard and soft rock cliffs and the occurrence, origin, and significance of associated boulder to megaclast deposits (Naylor *et al.*, 2010; Paris *et al.*, 2011; Trenhaile, 2011; Pérez-Alberti *et al.*, 2012; Stephenson *et al.*, 2013). Most investigations have been concerned with temperate regions, however, and there has been little work conducted in the last few decades in tropical and subtropical environments where wave and tidal regimes, climate-induced weathering processes and efficacy, and the role of bioerosional mechanisms are often quite different from those in cooler, wave-dominated regions (Dasgupta, 2011; Moses, 2013).

The effect of variable exposure to hurricanes and storm waves on coral reefs around and between tropical islands is well known (Stoddart, 1985; Scoffin, 1993), and there have been similar observations on the effect of exposure and wave intensity on rocky coasts (Trudgill, 1976; Focke, 1978; Woodroffe *et al.*, 1983). The terms “surf ledge” or “trottoir” have been used to describe a type of narrow shore platform, at or a little below mean sea level, that is characteristic of Mediterranean to tropical limestone coasts exposed to vigorous wave action. Surf ledges have been attributed to corrosional erosion in the spray zone and possible bio-protection of their wave-battered seaward edges above a subtidal notch (Dalongeville, 1977; Focke, 1978; Woodroffe *et al.*, 1983; Trenhaile, 1987). In the sheltered, low wave energy environments that are typical of much of the Tropics and Subtropics, surf ledges are replaced by deeply notched, often plunging, cliffs, although intertidal and high tidal notches and platforms do co-exist in some areas. Very low tidal ranges, which are characteristic of most tropical regions, also contribute to the formation of subhorizontal surf ledges and low, deep notches by concentrating marine processes within a narrow range of elevations (Newell, 1961; Butzer, 1962; Christiansen, 1963; Hodgkin, 1970).

Most research on notches and shore platforms in low latitudes has been conducted on calcareous rocks that are particularly susceptible to bioerosion, bioprotection, and to chemical or biochemical dissolution. This paper differs from most previous work in that it is concerned with a non-calcareous, microtidal, subtropical coast in a possibly active tectonic region. The main objective of this paper is to examine the effect of changing exposure to wave attack on notch and shore platform morphology and development along an indented peninsula.

THE STUDY AREA

The study area extended along the western and northern coast of the La Paz Peninsula in Baja California Sur, Mexico, in the Gulf of California (Sea of Cortes). The latitude is slightly above 24ºN, but although the area is technically subtropical, the climate, tidal range, and shelter from strong waves are typical of many places at lower latitudes (Fig. 1). The region is arid, most precipitation (averaging about 170mm a year), occurring in August and September with the arrival of tropical low pressure systems. Temperatures in summer are frequently higher than 30ºC, and in winter they are generally in the low 20ºC range. The tides are mixed semidiurnal with marked differences in the height of the two high tides and in the height of the two low tides each day and microtidal with a range of 0.5 to 1m.

Winds at La Paz are generally quite weak, ranging between 1.6 and 2.4m s^{-1} for mean monthly velocities and between 10.8 and 20.7m s^{-1} for mean monthly maximum velocities. During frequent, although brief, winter gales the wind can occasionally reach 30m s^{-1} and, on average, hurricanes with maximum wind speeds of 77m s^{-1} enter the Gulf at two year intervals. Hurricanes occur between late May and early November, and especially in September

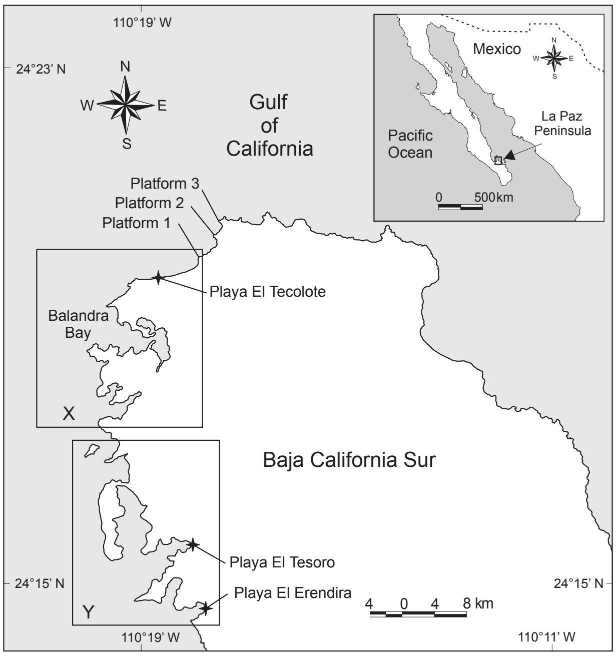

FIGURE 1. The study area along the western side of the La Paz Peninsula in southern Baja, Mexico. The inset maps X and Y refer to the notch location maps in Figures 6 and 7.

and October. Northwesterly winds are dominant in winter, whereas southerly to southeasterly winds are more common in summer (Roden 1964; Zaytsev *et al.*, 2010).

Historical wave data are absent for the southern Gulf of California. The waves are generally weak on the western side of the La Paz Peninsula, however, not only because of gentle winds but also because wave generation is inhibited by short fetches, which are only about 60km to the north, 40km to the northwest, 25km to the west, and 15km to the southwest. Fetches near the northern tip of the peninsula are up to 400km or more to the northwest and 200km to the east, and waves can also reach the area from the Pacific Ocean to the south. In each case, however, the study areas, especially in Balandra Bay and other deep embayments further south, can only be reached by waves that have been highly refracted and attenuated (Fig. 1).

The geological evolution of this region has been dominated by the interaction of lithospheric plates, principally subduction of the southern portion of the Farallon plate (Guadalupe plate) beneath the North American plate, and the volcanism that ensued (Mammerickx and Klitgord, 1982; Lonsdale, 1991; Bellon *et al.*, 2006). The widespread Comondú Formation dominates the geology of this region. The formation is composed of early to middle Miocene rhyolitic ash-flow tuffs with interbedded volcanic sandstones and conglomerates and, along the peninsula north from La Paz, andesitic lahars and lava flows (Hausback, 1984;

Aranda-Gomez and Perez-Venzor, 1988; Bellon *et al.*, 2006). The lahar deposits, which are up to 40m thick in some places, largely consist of dense, blocky flows of very resistant, grey to brown, poorly-sorted and poorly-stratified, sand-sized andesitic detritus, with angular clasts of up to 1m or more in diameter.

METHODS

The morphology of 24 notches was measured at 18 sites along the peninsula. Although periodic collapses were responsible for alongshore variations in notch depth within each site, other aspects of notch morphology were fairly uniform within each area. Notch measurements were made using a Leica DISTO D3 laser distance meter with an accuracy of ±1.5mm, and a range of up to 100m; this technique has been used for a similar purpose in Japan and on the Andaman Sea coast of Thailand (Kogure *et al.,* 2006; Kázmér and Taborosi, 2012). At each site, a measuring tape was extended, perpendicularly to the cliff, along the floor of the notch from the apex to the point at which the roof no longer covered the inside of the notch. Depending on the depth of the notch, the distance from the floor to the roof was measured every 5, 10, or 20cm to produce a cross-sectional profile. In addition, the angle of the floor of each notch and the height of the cliff on top of the notch (where applicable) were determined using an optical clinometer and the distance meter data. The gradient of the roof of the notch was calculated from the cross-sectional profiles (Fig. 2A). The distance of a notch site from the open sea, a measure of notch exposure, was measured along a line drawn down the main axis of each inlet or bay (Fig. 2B). A wear pin was installed at the apex of each of the 24 notches where backwearing (erosion in the horizontal plane) is at its maximum. These pins consisted of stainless steel bolts, 8mm in diameter and 65mm in length that were cemented into drill holes in the notch face, so that the top of each bolt was flush with the adjacent rock surface. Three shore platforms were surveyed along the exposed northwestern tip of the peninsula (Fig. 1), and 36 transverse micro-erosion meter (TMEM) stations were deployed on the platforms to determine rates of downwearing (erosion in the vertical plane), including four (stations 1, 2, 3, and 5) on the interior floor of notches behind platform 1 (Fig. 3). The wear pins and TMEM stations were installed in December 2008 and measurements were subsequently made in June 2011, providing a record of erosion over a 2.5 year period.

RESULTS

There was a transition northwards along the La Paz Peninsula from notches into shore platforms, corresponding to an increase in the exposure to wave action. The low notches furthest south were at the foot of cliffs that often had rubble extending a few metres seawards, whereas those further north were generally higher and fronted by shore platforms only a few metres in width (Fig. 4). Shore platform width increased northwards. The platforms were backed by cliffs with notches at the northwestern tip of the peninsula, but at the northern end of the peninsula the platforms were backed by rocky ramps sometimes covered in wind-blown sand (Fig. 5).

Notch profiles generally consisted of a linear or concave-upwards ramp at the base, and a more steeply sloping linear or concave-downwards roof. The deepest portion of the notches was between the neap and spring

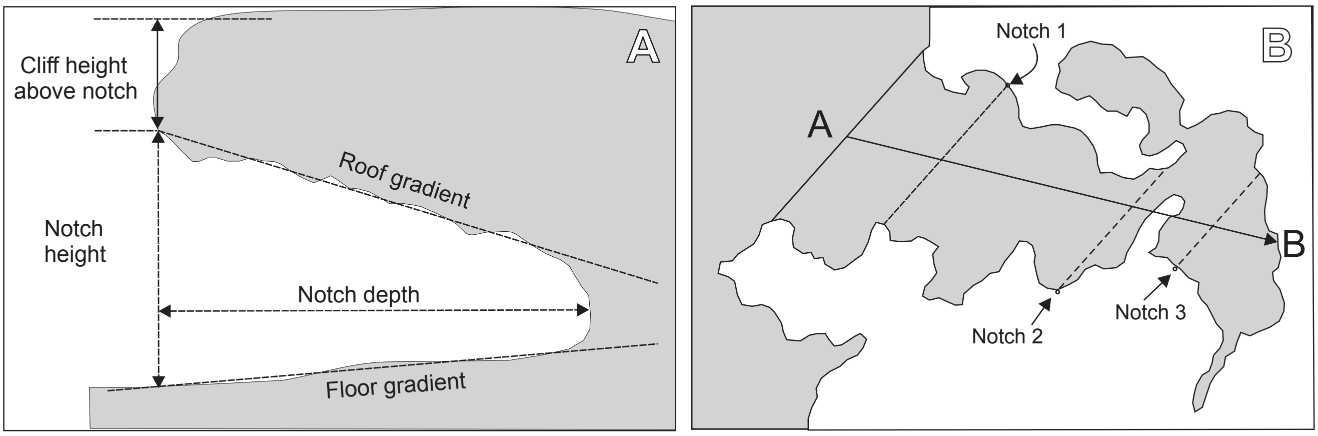

FIGURE 2. A) Notch morphological parameters. Notch floor and roof gradients were represented by estimated lines of best fit where the surfaces were irregular or non-uniform. B) Inlet distance measurements. A line was drawn across the mouth of each inlet and other lines (dashed), parallel to the line at the inlet mouth, were drawn to each notch. The distance from open water was then represented by the distance (from point A) of these secondary lines.

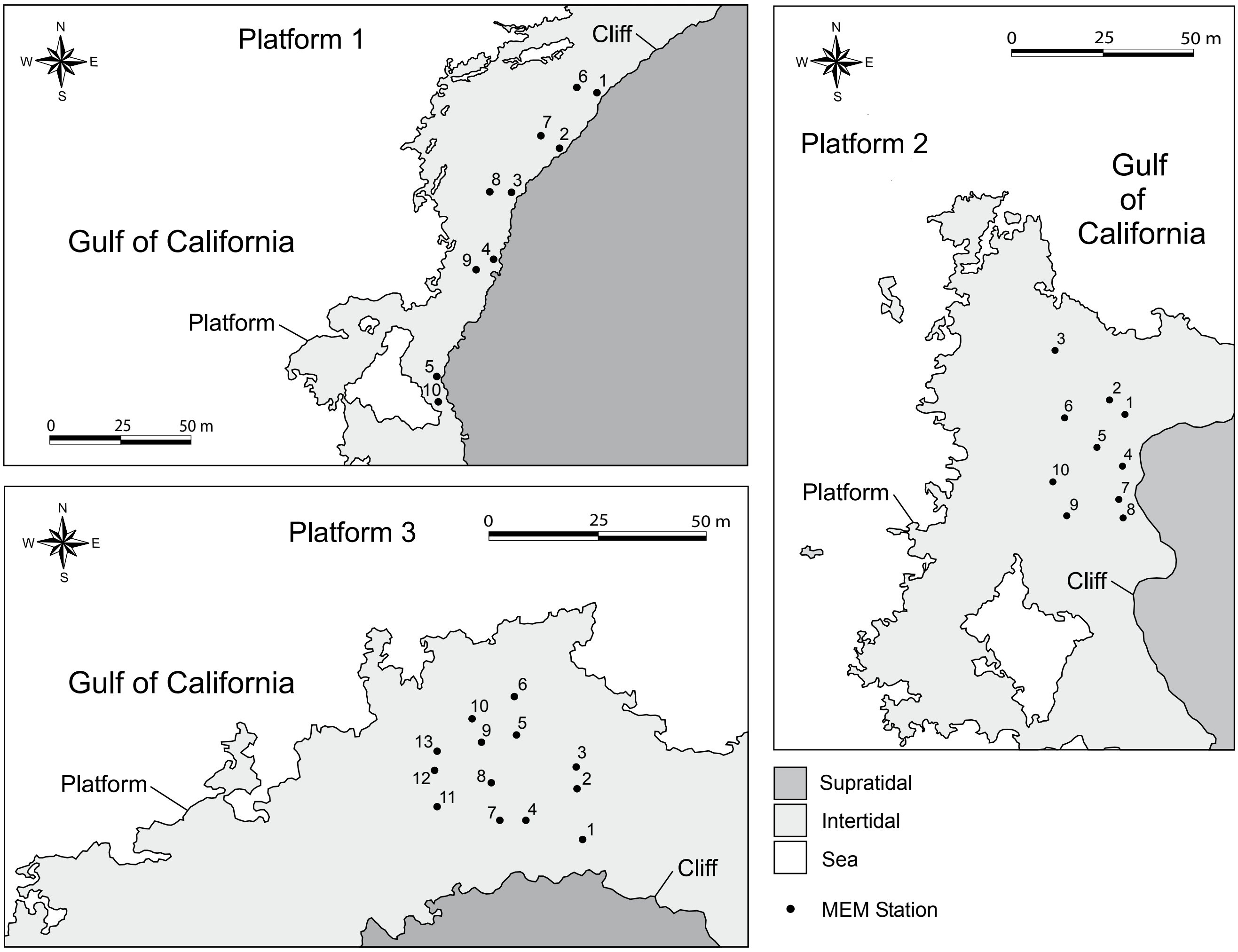

FIGURE 3. Shore platforms in the northwestern La Paz Peninsula (locations are shown in Fig. 1). Numbers refer to the location of the TMEM stations.

high tidal levels. The transition from floor to roof was generally quite abrupt, although there was a low linear or slightly concave backwall in some areas. The notches ranged in depth from <1m at site P to about 12m at site F, and in height (defined as the difference in elevation between the floor and the roof at the front of the notch) from 0.7m at site J to almost 9m at site B. The ratio of notch height to depth varied between 0.4 at site N to 2.7 at site H (Figs. 6 and 7). The gradients of the floors of the notches usually ranged between about 3º and 10º, and were generally much higher than the gradient of the platform surfaces that sometimes extended seawards in front of them. The roofs of the notches were often more irregular than the floors and usually much steeper, ranging in gradient between about 20º and 60º, although the roof was almost horizontal in sheltered notch site M. There was no correlation between the slope of notch roofs and the distance of the notch site from the open sea (distance up bays or inlets), or between the gradient of notch roofs and floors, but the relationship between the slope of the notch floor and the distance of the notch site from the open sea was significant and fairly strong (r^2=0.54; p=0.05).

Notch morphology varied along the coast and within each measurement site, although there was usually a characteristic morphology related to the exposure at each site. The notch at site L was particularly distinctive and well defined (Figs. 4C and 6). This notch, which is uniformly about 1m high and 0.5m deep, runs along both sides of a narrow, 360m long, southwesterly-trending bay. The bay is cut off from the sea by a spit or barrier across its mouth, and although tidal flows still access it through culverts, the bay is completely protected from waves. At the other extreme, at exposed site F, which faces a fetch of more than 50km to the west and northwest, there is a very large notch that is more than 6.5m in height and 12m in depth (Figs. 4E and 7).

There was a general tendency for notch morphology to change with decreasing exposure to wave attack along the axes of Balandra Bay and the Playa el Tesoro inlets (Figs. 6 and 7). The relationship between notch height and distance from the open coast was significant (r^2=0.55; p=0.05), but it was not significant for notch depth and distance. Most

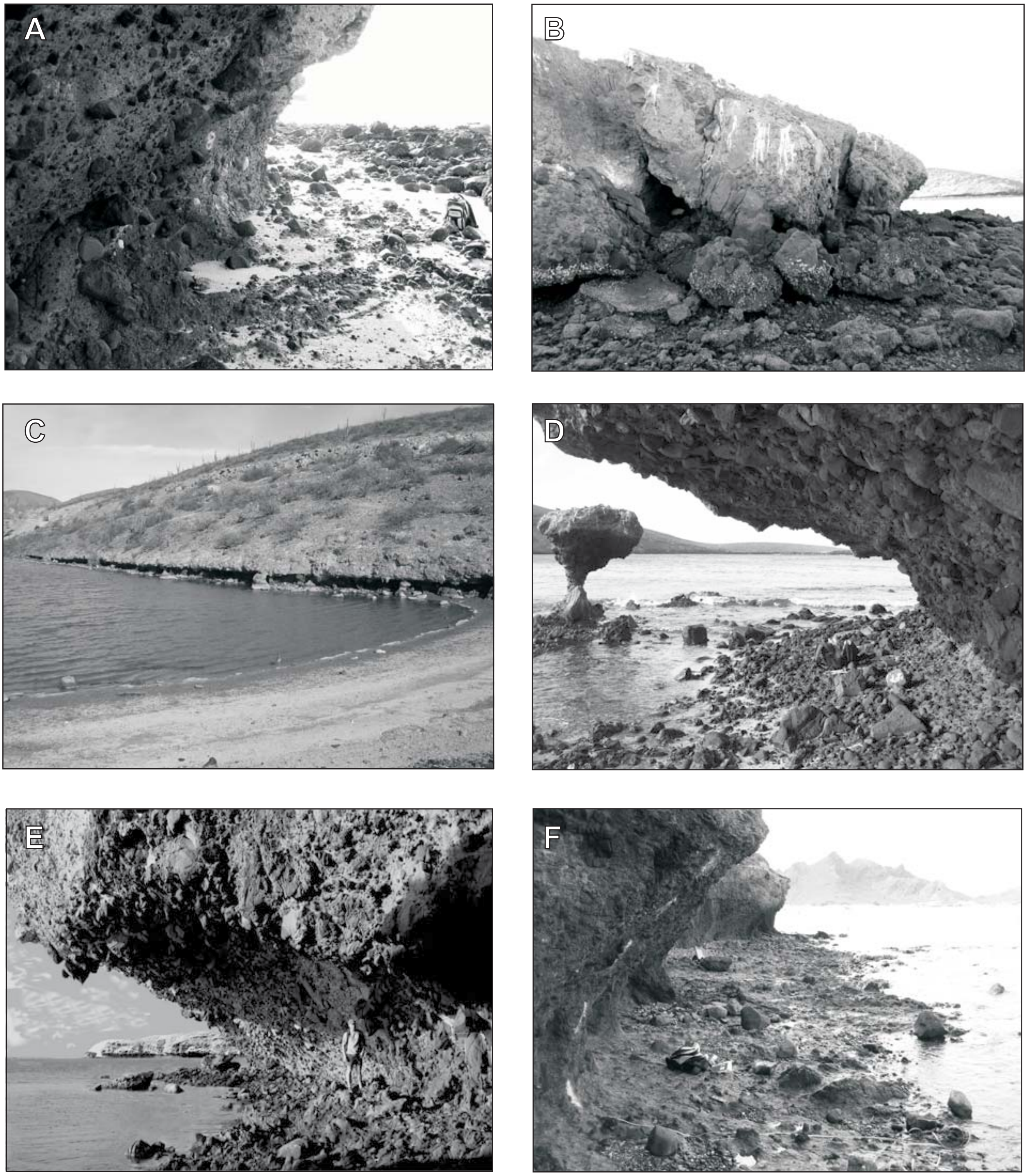

FIGURE 4. Examples of notches moving northwards. A) shallow notch at site H; B) collapsed notch at site O; C) Shallow and low notch around a very sheltered bay at site L; D) deep notch and small stack at site E near the mouth of Balandra Bay; E) high, deep notch at site F at the exposed mouth of Balandra Bay; F) low, shallow notch at exposed site A.

notches had a height to depth ratio between 0.5 and 1, although there were several higher values that, with the exception of site Q at the back of Balandra Bay, occurred at sites on or near the open ocean coast. There was no relationship between the height–depth ratio and distance from the open coast (Fig. 8).

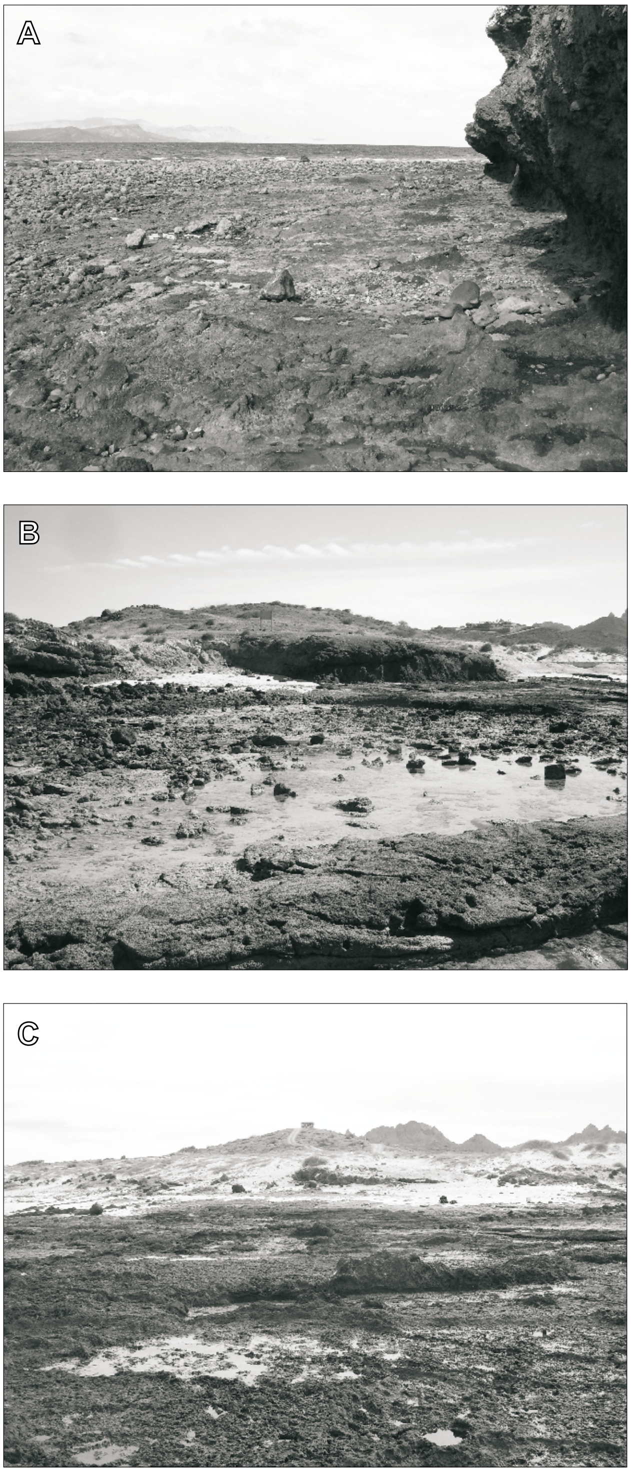

FIGURE 5. A) platform 1 (near notch site A), with a shallow notch at the cliff foot; B) platform 2 backed by a low cliff without a notch or a wind-blown sand- covered rocky ramp; and C) platform 3 with a ramp or dunes at the rear.

Despite some exceptions, plotting notch morphology against notch orientation and wave fetch revealed a tendency for the highest notches to face the longest wave fetches. Almost all the lowest notches occurred in areas where there were very small fetches. There was a similar tendency between notch depth and fetch, and consequently with orientation, although some moderately deep notches, such as at site N, faced very low fetches. There was little relationship between the ratio of notch height and depth and wave fetch or orientation (Fig. 8).

Shore platform surfaces are restricted to the floors of notches and they do not extend beyond the cliff face in the southern and central portions of the peninsula. Gradually, as one moves northwards, platform surfaces begin to extend up to several metres beyond the mouth of the notches and then, in the northwest, up to tens of metres seawards. Shore platforms ranged with increasing exposure from about 10 to 30m at platform site 1, where there was a notch at the foot of the cliff, to more than 50m at platform sites 2 and 3 where the notch was absent (Figs. 5 and 9). The cliff-platform junction at the foot of the cliff was close to the high tidal level. The platform profiles were essentially linear, although there were slight concave and convex slope elements in the upper portions of the intertidal zone. Platform gradients ranged from about 0.95 to 1.1°, and the platforms continued beneath the low tidal level without any abrupt terminus or low tide cliff.

The TMEM data suggested that the platforms experience surface downwearing at mean rates of 0.42mm yr^{-1} (median=0.26mm yr^{-1}, σ=0.46mm yr^{-1}) on platform 1, 0.14mm yr^{-1} (median 0.09mm yr^{-1}, σ=0.18 mm yr^{-1}) on platform 2, and 0.33mm yr^{-1} (median 0.21mm yr^{-1}, σ=0.48mm yr^{-1}) on platform 3 (Fig. 9). There was only one station (station 9 on platform 1) where the mean elevation of the surface had become slightly higher (surface swelling) than when the station was installed. Swelling was recorded at almost 14% of the individual measurement points, but despite maximum values of 0.20mm at two points, a median of only 0.05mm suggests that operator error was probably responsible for many of these occurrences. There was a significant correlation (r^2=0.15; p=0.05) between the mean annual downwearing rate at each station and the elevation of the station. Although only four TMEM stations at the rear of platform 1 were in the floor of notches, their mean downwearing rate of 0.67mm yr^{-1} was much higher than for the platform surfaces. No erosion was observed around the wear pins. Given the uneven surface of the rock, it should have been possible to observe backwearing of 4 to 5mm over the 2.5

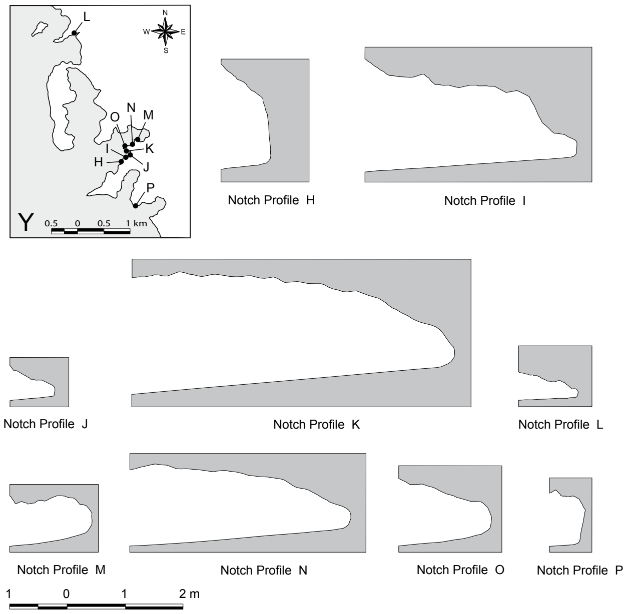

FIGURE 6. Sample notch profiles in the southern La Paz Peninsula (inset map location is shown in Figure 1). The horizontal and vertical scales are the same.

year study period. This suggests, as a rough estimate, that backwearing rates in the notches were within the range of 0 to about 2mm yr^{-1}.

DISCUSSION

There is a marked transition from notches to shore platforms on the La Paz Peninsula, and a related increase in erosion rates and a transition from notch to cliff to ramp profiles with increasing exposure has been reported in the reef limestones of Aldabra Atoll (Trudgill, 1976). Although more work needs to be conducted in tropical environments, and especially on non-calcareous substrates, the available evidence suggests that variations in coastal exposure may be even more critical in accounting for differences in coastal morphology in the low to moderate wave environments of tropical and subtropical regions than in the storm-wave-dominated environments of the mid-latitudes (Focke, 1978; Woodroffe *et al.*, 1983). The greater importance of wave exposure in tropical areas may reflect the frequent occurrence of fairly strong waves in even quite sheltered parts of the middle latitudes, and possibly the relationship in the Tropics between wave exposure and the efficacy of such influential mechanisms as wetting and drying, salt and chemical weathering, and bio-erosion and bio-protection.

Several workers have reported that notch height increases with exposure to the waves (Newell, 1961; Christiansen, 1963; Neumann, 1966; Hodgkin, 1970; Pirazzoli, 1986). Takenaga (1968) found that the height of the notch roof on the Ryukyu Islands corresponded to the upper limit of sea spray, and was therefore greatest on open coasts. There was a tendency for the highest notches on the La Paz Peninsula to face the longest wave fetches as well as a fairly strong inverse relationship between notch height and distance from the open coast, factors that were related to site exposure and the corresponding upward limit of sea spray. For example, the notch at profile L (Fig. 4C) is very low because it lies along the sides of a narrow, sheltered inlet where the waves are highly attenuated and there is little spray or splash. Conversely, the very high notch at site F (Fig. 4E) is at the wide, open mouth of Balandra Bay and is oriented almost perpendicularly to waves from the west and southwest, which throw splash and spray up to considerable elevations during storms. Notches along the La Paz Peninsula increase in depth until the growing weight of the overhang causes the roof to collapse. The maximum depth of the notches is controlled by collapse-induced thresholds which are, in turn, determined by the strength of the rock and by the height of the cliff. Cliff height is roughly uniform along this coast but the increase in notch height with increasing exposure reduces the amount of overburden and suggests that maximum notch depth might increase with the degree of exposure. Although there is a general tendency for notch depth to increase with exposure along the peninsula, however, the relationship is not statistically significant. There is also no strong relationship between notch depth and exposure on

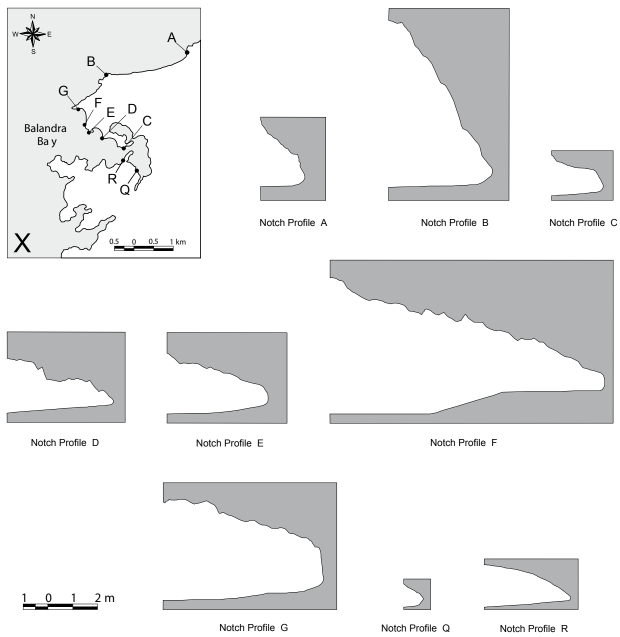

FIGURE 7. Sample notch profiles and locations in the northern La Paz Peninsula (inset map location is shown in Fig. 1). The horizontal and vertical scales are the same, but a smaller scale is used to accommodate the larger notches around Balandra Bay (site X) than around Playa El Tesoro (site Y) further south.

Barbados (Bird *et al.*, 1979), and whereas the relationship appears to be negative in some places (Newell, 1961; Takenaga, 1968; Vita-Finzi and Cornelius, 1973), this might be because notch collapse is less frequent in sheltered than in exposed areas. It has been proposed that notches have flat floors and steeply sloping roofs on exposed coasts and are essentially horizontal incisions with flat roofs on sheltered coasts (Verstappen, 1960; Russell, 1963). The notches on the La Paz Peninsula provide some support for this contention although the evidence is not conclusive, the highest roof gradients tending to be in the more exposed notches in the north (notches A, B, G, D, F, E) and the more gentle gradients in the more sheltered notches in the south (notches I, K, M, N, P) (Figs. 6 and 7).

Although platform gradients are generally subhorizontal to very gently sloping (0 to about 0.3º) in microtidal environments where they commonly terminate abruptly seawards in a low tide cliff, the platforms are steeper on the La Paz Peninsula and they lack an abrupt seaward terminus. In addition to tidal range, however, platform gradient also increases with the rate of erosion, as expressed by the resistance of the rocks in relation to the wave energy (Trenhaile, 1972, 1974, 1978, 2000; Kirk, 1977; Pérez-Alberti *et al.*, 2012). The narrowness of the platforms in the most exposed areas of the peninsula testifies to the hardness of the rocks and to the low wave energy environment in this region. Rates of platform downwearing (mean about 0.26mm yr^{-1}) are also much lower than the 2.04mm yr^{-1} that has been reported as the mean of published data, mainly for calcareous substrates, between latitudes of 20º and 30º, although similarly low rates have been reported from a surf ledge on the Cayman Islands and in some other areas (Trudgill, 1976; Spencer, 1981, 1985a,b; Woodroffe *et al.*, 1983; Viles and Trudgill, 1984; Moses, 2013). The combination of very hard rocks and fairly weak waves may therefore account for the fairly high, given the tidal range, platform gradients (about 1º) and the absence of surf ledges on the La Paz Peninsula. Conversely, the lack of surf ledges could reflect the type of rocks in this area and the negligible effect of bioerosional and bioprotectional organisms and of chemical or biochemical corrosion.

The shore platforms on the La Paz Peninsula develop through the formation and periodic collapse of notches at the cliff foot (Fig. 4B). In the southern part of the study area, the entire foreshore consists of the interior floors of notches, which implies that the notches have been developing very slowly and have not experienced any collapse since the sea reached its present level. As the degree of exposure increases to the north the progressive increase in platform width, which can be as much as twenty times notch depth, suggests that there have been many phases of notch formation and collapse (Fig. 5A). A few notches are fronted by sand or coarse debris and some of these have fairly smooth backwalls that imply that abrasion has been effective, although it is not an important mechanism along most of this coast. The notches are dry for long periods and there is a conspicuous lack of biological activity and consequently, in contrast to many tropical, calcareous coasts, of bioerosion, bioconstruction, and bioprotection. Therefore, the occurrence of notches in very sheltered locations in Balandra and other deep inlets, and their absence in the most exposed areas of the northern La Paz Peninsula indicate that they were probably produced by weathering rather than by wave erosion. The lack of any visible discolouration or other chemically induced changes in the rocks suggest that the most important mechanisms are salt weathering or wetting and drying; geochemical analyses and laboratory experiments, which will be described in a future paper, demonstrate that the dominant notch-forming mechanism in this region is salt weathering. Nevertheless, the relationship between the width of the rocky foreshore, the frequency of notch collapse, and site exposure implies that weathering is much faster in areas with stronger waves, presumably reflecting the effect of wave splash and spray on the cliff face, and possibly the mechanical removal of loosened blocks from the weathered matrix by mechanical wave erosion. This conclusion is supported by the relationship between notch height and the degree of exposure (Fig. 8), and consequently with the height reached by spray and splash during storms. The same processes probably have an important direct role in lowering the former notch floor as it is assimilated into the shore platform surface, as well as an indirect role in helping to free rock clasts from the andesitic matrix, thereby promoting wave quarrying.

Coastal morphology and tectonic uplift

The presence of marine notches and shore platforms, 1–4.5m above mean sea level, on the mainland Jalisco coast in southwestern Mexico (almost 700km southeast of La Paz) is indicative of tectonic uplift of about 3mm yr^{-1} over at least the last 1300 years (Ramírez-Herrera *et al.*, 2004). Uplift and westward tilting of the Comondú sequence in the La Paz region is the result of movement along the north-south trending Espiritu Santo fault, about 20km east of the La Paz Peninsula. The region is still tectonically active, as demonstrated by the occurrence of a 6.2 magnitude earthquake in late September 2012 that was centered about 75km north-northeast of La Paz. Terrace deposits near La Paz suggest that uplift since the last interglacial has occurred at rates of between 0.12 and 0.15mm yr^{-1}, a figure that is consistent with other terrace-based uplift rates on the eastern Baja California Peninsula, including those at Loreto, about 230km north of La Paz (Mayer and Vincent, 1999; DeDiego-Forbis *et al.*, 2004). Marine notches at Loreto also appear to be elevated above the modern high tidal level (Fig. 10A).

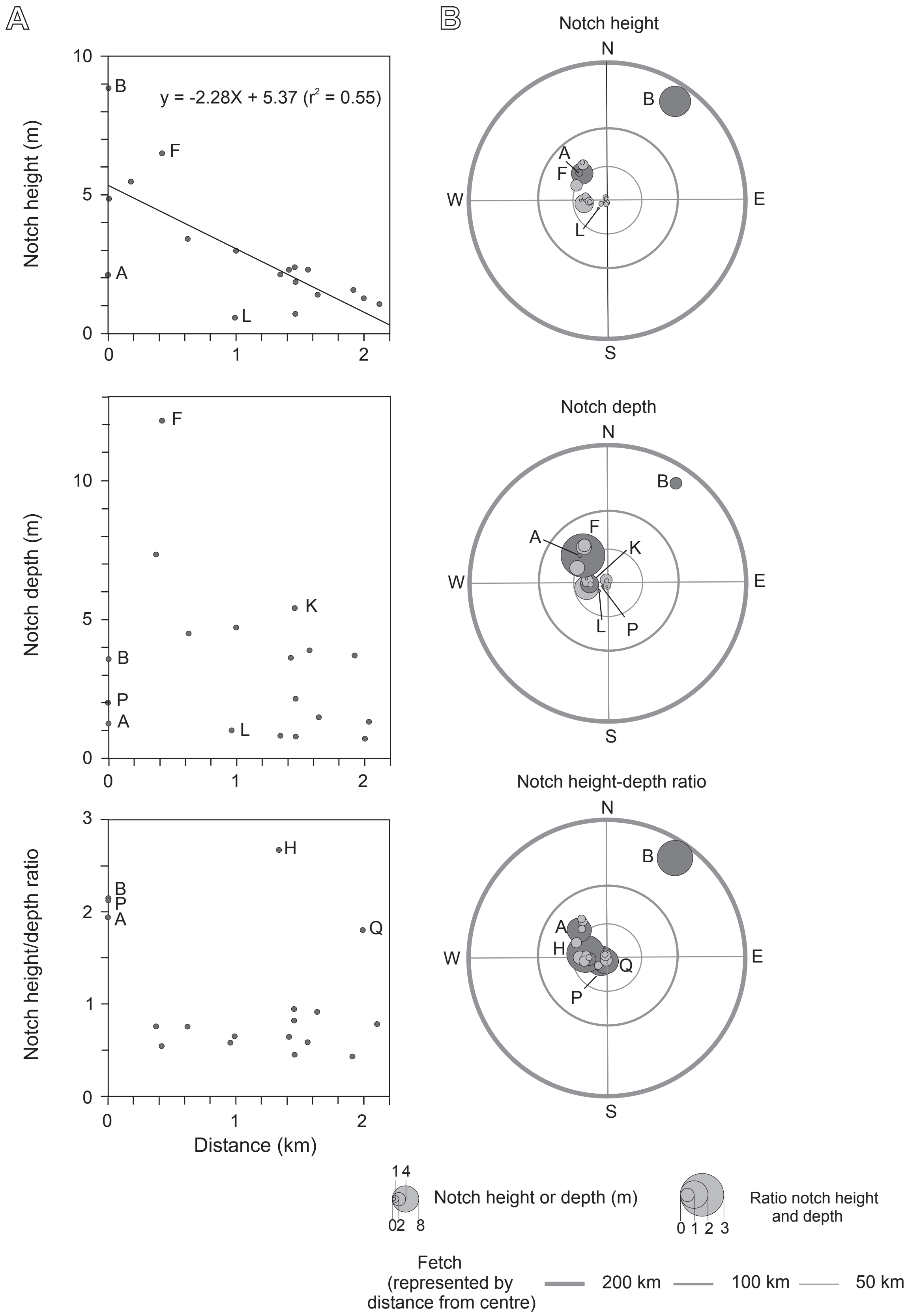

FIGURE 8. A) Relationships between mean notch height, depth, and height-depth ratio and distance from the open ocean coast. B) Relationships between mean notch height, depth, and height-depth ratio and site orientation and wave fetch. Notch morphological variables are scaled according to the diameter of the circles. Darker tones are used to highlight the circles representing the specific notches shown in A).

Estimated rates of uplift in the La Paz area are generally lower than rates of shore platform downwearing as measured with a TMEM in the field (mean 0.26mm yr^{-1}), and especially with the faster downwearing rates recorded on notch floors (0.67mm yr^{-1}) as they are integrated into the platform surface (Fig. 9, platform 1). Nevertheless, although the broad elements of the coastal morphology, including shore platforms, notches, and cliff-platform

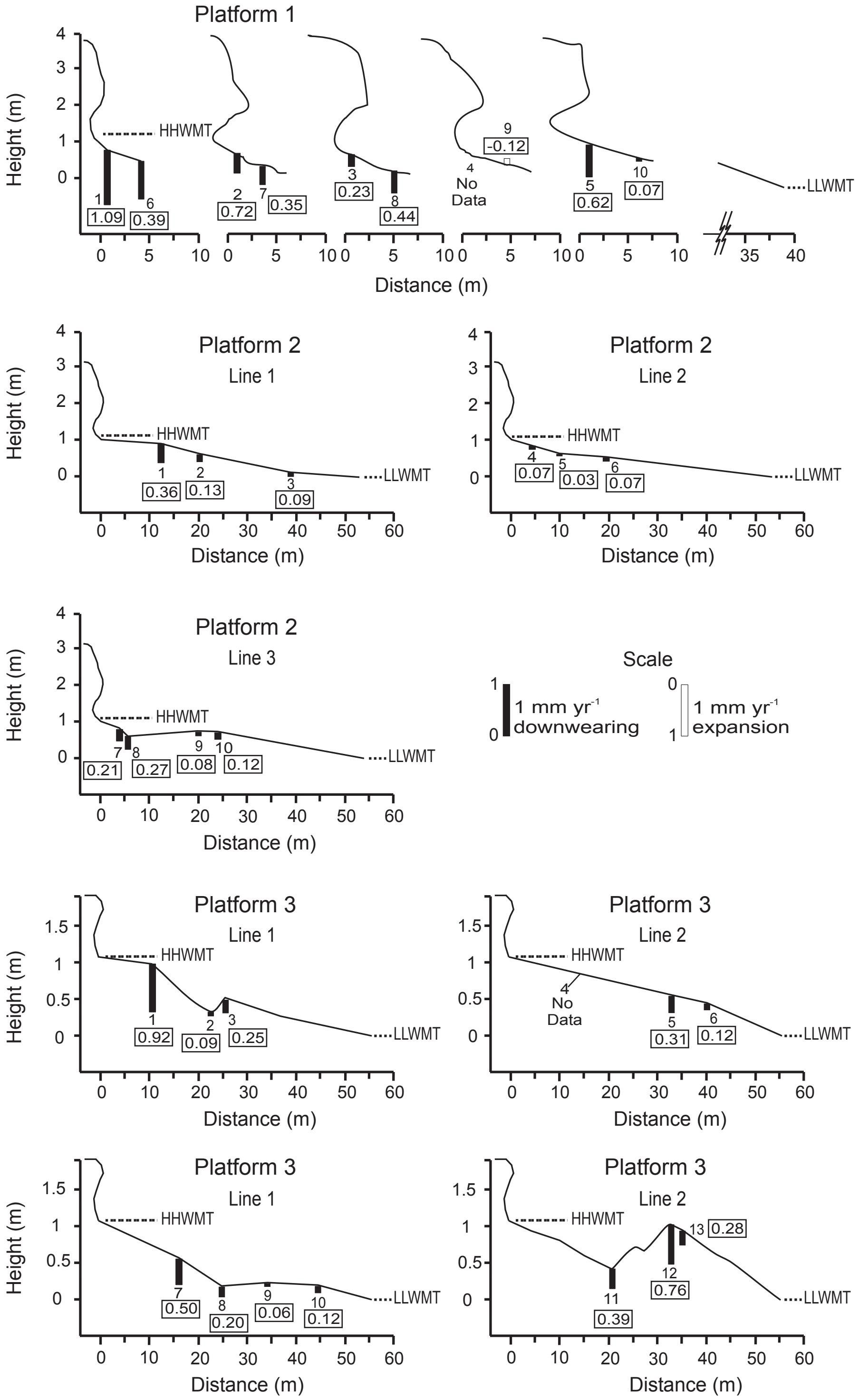

FIGURE 9. Surveyed platform profiles and surface downwearing rates (mm yr^{-1}) at TMEM stations (the only example of mean station swelling was at station 9 on platform 1). Downwearing rates are shown as histograms with the values in boxes below. Unboxed numbers by each histogram refer to the TMEM stations shown in Figure 3. HHWMT and LLWMT refer to high, high water mean tide and low, low water mean tide, respectively.

junctions, are generally concordant with the present level of the sea it is possible that they have not entirely adjusted to slow, tectonically induced, changes in relative sea level. In an experimental study using sandstones, basalts, and argillites from eastern Canada, Porter *et al.* (2010) found that the highest rates of surface downwearing in synthetic sea water and freshwater occurred at or below the lowest high tidal level (which is immersed once or twice every day, depending on the tidal regime). The notches on the La Paz Peninsula are nearer to the spring than to the neap tidal levels, including those in the most sheltered areas, which could therefore be indicative of slow uplift over the period of formation. Based on typical notch depths (1–2m) and rates of notch erosion (1–2mm yr^{-1}) in areas without strong wave action and with no evidence of previous collapse, the age of the notches might range from 500 to 2000 years in age. The rate of uplift required over this period to raise a notch about 15–25cm, which is the difference in elevation between the lower and upper high tidal zone in this low tidal range environment, is from 0.075 to 0.5mm yr^{-1}. These uplift rates are broadly consistent, given that they represent an extreme range of values, with the 0.12 to 0.15mm yr^{-1} figure that has been quoted for the eastern Baja California Peninsula.

There is an undated subhorizontal shore platform between platforms 1 and 2 (Fig. 10B). This 10 to 20m wide platform is riddled with potholes and with weathering and bioerosional pits and is obviously of some antiquity given the extent of the modern platform being cut into its base. The elevated platform is only about 1.5m above the present high tidal level and if it were of last interglacial age it would indicate that there has been little or no uplift, or even some subsidence, since its formation. The other possibility, given that this area is in Clark and Lingle's (1979) zone III, which experienced a rise in sea level to less than one metre above its present level several thousand years ago, is that the elevated platform is mid-Holocene in age. Although in the absence of any dating one can only speculate on its origin, it is interesting to note that the uplift of a platform formed a little below 1m above present sea level to its present elevation over several thousand years is broadly consistent with the slow rates of uplift that have been proposed previously for this region.

Notch formation and elevation

Notches develop at a variety of elevations in relation to mean sea level according to their mode of formation, which partly reflects the wave regime, tidal range, and rock type (Pirazzoli, 1986; Trenhaile, 1987; Kelletat, 2005; Moses, 2013; Pirazzoli and Evelpidou, 2013). This effect must be considered when using elevated notches to identify former relative sea levels, especially where the tidal range is significant relative to the difference in elevation between the notch and present sea level. Bioerosional and corrosional notches generally have the closest association with sea level. These types of notch, which are typically in calcareous substrates in tropical and subtropical regions, develop around mean sea level in sheltered locations and subtidally beneath bio-protected surf ledges in more exposed areas (Focke, 1978). Notches produced by wave quarrying or abrasion, and particularly by spray- or splash-induced weathering (salt or chemical weathering or wetting and drying) develop over a much greater geographical range and in a much greater variety of rock types. These notches are generally higher than calcareous notches in warm seas and, depending on the degree of exposure and the nature of the substratum, they can develop over a greater range of elevations. Notches produced by wave quarrying and abrasion occur in exposed areas at the foot of cliffs, often at the rear of shore platforms. The cliff-platform junctions and associated notches in these areas, which develop at the elevation of greatest erosion, are generally in the zone extending from the spring tidal level in more resistant rocks to the mean tidal level in less resistant rocks (Wright, 1970; Trenhaile, 1972). The experiments of Porter *et al.* (2010) suggested that wetting and drying and salt weathering produce notches in a variety of rocks in the lowest part of the high tidal zone. These weathering-produced notches occur at roughly similar elevations to wave cut notches and the two types of notch may therefore be difficult to distinguish. Abrasion notches are often along the sides of promontories and require the presence of suitable loose material, however, and wave-quarried notches are often irregular, structurally controlled, and laterally discontinuous. Furthermore, although waves play an important role in the formation of notches created by weathering on the La Paz Peninsula, this type of notch is quite rare in mid-latitude, temperate latitudes, possibly because of dominant mechanical wave erosion, generally high tidal ranges, and cool climates.

CONCLUSIONS

The main conclusions of this study are:

i) Exposure to wave action plays a dominant role in explaining the transition from various types of cliff notch to narrow shore platforms on the La Paz Peninsula.

ii) The notches in this area were probably produced by salt weathering or by alternate wetting and drying.

iii) The efficacy of the weathering processes responsible for notch formation is strongly dependent on the degree of exposure to wave action, which controls the frequency of immersion and the frequency and elevation attained by splash and spray.

FIGURE 10. A) Elevated notch and subhorizontal shore platform at Loreto (tidal range is generally <1m); B) The raised platform remnant in the north La Paz Peninsula. This platform is being replaced, though scarp recession, by a contemporary platform at a lower elevation.

iv) The shore platforms are narrow and steeper than most platforms in microtidal environments, reflecting a weak wave environment and resistant rocks.

v) The mean rate of shore platform downwearing is 0.26mm yr^{-1} and notch backwearing is less than about 2mm yr^{-1}.

vi) The coast along this peninsula is fairly well adjusted to the present level of the sea although the occurrence of notches in the upper high tidal zone supports other evidence for slow tectonic uplift in this region.

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