Holocene-emerged notches and tectonic uplift along the Jalisco coast, Southwest Mexico

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Abstract

This paper presents the preliminary results from a study of Holocene-emerged shorelines, marine notches, and their tectonic implications along the Jalisco coast. The Pacific coast of Jalisco, SW Mexico, is an active tectonic margin. This coast has been the site of two of the largest earthquakes to occur in Mexico this century: the 1932 (Mw 8.2) Jalisco earthquake and the 1995 (Mw 8.0) Colima earthquake. Measurement and preliminary radiocarbon dating of emergent paleoshorelines along the Jalisco coast provide the first constraints upon the timing for tectonic uplift. Along this coastline, uplifted Holocene marine notches and wave-cut platforms occur at elevations ranging from ca. 1 to 4.5 m amsl. In situ intertidal organisms dated with radiocarbon, the first ever reported for the Jalisco area, provide preliminary results that record tectonic uplift during at least the past 1300 years BP at an average rate of about 3 mm/year. We propose a model in which coseismic subsidence produced by offshore earthquakes is rapidly recovered during the postseismic and interseismic periods. The long-term period is characterized by slow tectonic uplift of the Jalisco coast. We found no evidence of coastal interseismic and long-term subsidence along the Jalisco coast.

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1. Introduction

The Jalisco coast, SW Mexico, has been the site of three of the largest earthquakes to occur in Mexico this century: the 1932 (Ms 8.1 and Ms 7.8) Jalisco earthquakes and the 9 October 1995 (Mw 8.0) Colima earthquake. The structure and the morphology of this coast have been influenced by the subduction of the Rivera Plate beneath the North America Plate and by crustal faulting within the Jalisco Block (Ramírez-Herrera and Urrutia-Fucugauchi, 1999; Ramírez-Herrera et al., 1999). Although there have been local studies of the tectonic deformation accompanying large earthquakes along this active plate margin (Cumming, 1933; Bodin and Klinger, 1986; Corona-Esquível et al., 1988; Hutton et al., 1997, 1998), an integrated approach to the study of emerged coastal features (ages and elevations) of this active margin has yet to be applied.

We identified in situ fossils of intertidal organisms and morphological indicators of relative sea-level changes along the Jalisco coast. Intertidal organisms
found in their growth position can be useful indicators of a rapid sea-level change. In situ fragile intertidal organisms, preserved above the supralittoral zone and above mean sea level, are possible only after a very rapid relative sea-level change (Pirazzoli, 1996). Because the distribution of many marine organisms is directly related to tide levels (or wave exposure), they are common sea-level indicators and, when preserved, may be used to identify former sea levels. Fossil intertidal organisms are very useful

Fig. 1. Tectonic setting of the Jalisco coast. Boundaries of the Rivera Plate: Rivera fracture zone (Fz), the East Pacific Rise (EPR), the Tamayo Fracture Zone, and the Middle America Trench (MAT). Rivera–Cocos Plate boundary: El Gordo graben (EGG) (Bandy, 1992). Symbols: Unfilled arrows show direction of plate motion, and numbers indicate convergence rate in centimeters per year. Insert shows area of study and site locations.
indications of former sea-level positions on the Jalisco coast.

We recognized a series of marine notches, wave-cut platforms, and remnants of marine terraces along the Jalisco coast of Mexico along about 153 km, from Barra de Navidad to Tomatlan that reflect relative sea-level changes (Fig. 1). Emerged marine shorelines are the depositional and erosional remains of abandoned shorelines (Lajoie, 1986). The number of emerged shorelines, their spacing, and their character are a function of tectonic movement and regional and global sea-level change (eustatic change). The best-preserved records of sea level do not come from stable coastlines but rather from coasts experiencing steady, long-term uplift. Few studies on Holocene eustatic and relative sea-level changes along the southwestern Pacific coasts of Mexico exist (Curray et al., 1969; Ortlieb, 1987). Moreover, no published studies are available of either emerged shorelines in this region or of previously reported radiocarbon dates for emerged coastal features in southern Mexico. This paper presents the preliminary results from a study of Holocene-emerged shorelines, marine notches, and their tectonic implications along the Jalisco coast. We present the first geomorphic study and preliminary radiocarbon data of emerged shorelines in this region. We discuss field-based results and the possible mechanisms for coastal emergence and propose a model for Holocene tectonic uplift of the Jalisco coast.

2. Setting of the Jalisco coast

2.1. Tectonics

The Jalisco coast is located along an active convergent margin where the Rivera oceanic plate subducts beneath the North American Plate along the Middle American trench (Fig. 1). The Rivera Plate, a young plate (sea floor age is 9 Ma (Klitgord and Mammerickx, 1982; Kostoglodov and Bandy, 1995)), moves to the N–NE with respect to the Rivera–North America Plate boundary, at rates of 2.0 and 3.3 cm/year, increasing from north to south (DeMets et al., 1994). Other studies suggest higher convergence rates up to 5.0 cm/year (Bandy, 1992; Kostoglodov and Bandy, 1995; Kostoglodov et al., 1997; Bandy et al., 1997, 1998). Recent studies show that the Rivera Plate subducts below the Jalisco Block of the North American Plate, with a shallow 10° dip angle down to about a depth of 20 km in the seismogenic zone; the dip gradually increases up to 46° at 65 km depth (Pardo and Suárez, 1993; Hurtado et al., 1997).

The Jalisco Block in SW Mexico is bounded inland on the NE by the Tepic–Zacoalco Rift (NW–SE) and on the SW by the Colima Rift (NE–SW) (Fig. 1). Rifting and volcanism are associated with movement of the Jalisco Block away from the North America Plate toward the NW (Luhr et al., 1985; Allan, 1986). The rate of movement of the Jalisco Block relative to North America may be very low (<5 mm/year; DeMets and Stein, 1990; Bandy and Pardo, 1994).

2.2. Morphology and sea-level history

2.2.1. Morphology

The Jalisco coast stretches along 180 km and subparallels the Middle American trench. The continental shelf here is relatively narrow, locally <1 km but reaching up to 2 km. The distance from the trench to the coast averages ~50 km, but increases to about 120 km near Bahia de Banderas (Fig. 1). The coastal landscape is characterized by cliffs and rocky promontories (mostly shaped on granite, rhyolite, and breccia), alternating with narrow beaches. Inland, sparse low plains with lagoons and estuaries, highly dissected hills and high mountains (up to ca. 2000 m) characterized the landscape. Some of these highly dissected hills are apparently remnants of emerged marine terraces that extend intermittently along the Jalisco coast. Although not yet surveyed with precision nor dated, these terrace remnants show consistent elevations ca. 40, 60, ~80, and 100 m amsl (topographic map estimates). Terrace remnants along this coast are highly dissected and weathered, exposing outcrops with a thick regolith layer on top of the terraces surfaces. Beach deposits were missing from the terrace surfaces, most probably washed away by streams and runoff. We speculate that the poor preservation of these terraces is related to climatic conditions (subtropical climate) and long time exposure, and that the apparent age of the terraces might be pre-Holocene (Ramírez-Herrera et al., 1998a,b). We suggest further study of these features that are very interesting but beyond the scope of this work.
Fig. 2. Historic seismicity and rupture zones along the Jalisco coast. Dates indicate main historical events and their magnitude. Shaded encircle areas show rupture zones for the 1932 and 1995 events (Pacheco et al., 1997).
2.2.2. Sea level history

Little is known about Holocene sea level along the southern Pacific coasts of Mexico. During the late Quaternary (stages 5a/c and 5e, 82/105 and 120 ka, respectively), two sea-level maxima have been described for NW Mexico; but evidence of only one transgression, which occurred after the sea level maximum (stage 5e), is distinguished in the Baja California Peninsula (Ortlieb, 1987). A study in the coast of Nayarit and Sinaloa (Curray et al., 1969), south of the Gulf of California, suggests the following chronology of events during the late Holocene. At ca. 18,000 years BP, sea level was at ca. −125 m. Between 18,000–7000 years BP, a rapid sea level rise took place to ca. −10 m. The middle Holocene (7000–3600 years BP) was characterized by slower rise of sea level to ca. −2 m. Between 4750 and 3600 years BP occurred the stabilization of shorelines near Nayarit and Sinaloa. Between 3600 and 1500 years BP, relative sea level may have been near present level, or could have risen rapidly to present level. By 1500 years BP, sea level reached its present level (Curray et al., 1969). Globally, sea level has been nearly stable during the past 6000 years. With most deglaciation complete by about 6 ka, subsequent sea-level changes are interpreted to be the consequence of seismotectonic effects, isostatic adjustments, and climatic changes (Pirazzoli, 1996).

2.3. Historic earthquakes and coastal movement

Large thrust earthquakes along the Mexican subduction zone occur on a shallow N–E (10–15°) dipping plate boundary because of sudden slip along the seismogenic zone between the Rivera and Cocos Plates and the overriding North America Plate (Singh et al., 1985). Along the Jalisco coast, three Ms>7.5 earthquakes have occurred during the past century: the 3 and 18 June 1932 Jalisco earthquakes (Ms 8.1 and 7.8, respectively) and the most recent 9 October 1995 Colima–Jalisco (Mw 8.0) earthquake (Fig. 2). Earthquakes of the nineteenth century were characterized by slower rise of sea level to ca. −2 m. Between 4750 and 3600 years BP, relative sea level may have been near present level, or could have risen rapidly to present level. By 1500 years BP, sea level reached its present level (Curray et al., 1969). Globally, sea level has been nearly stable during the past 6000 years. With most deglaciation complete by about 6 ka, subsequent sea-level changes are interpreted to be the consequence of seismotectonic effects, isostatic adjustments, and climatic changes (Pirazzoli, 1996). Historical data are insufficient to determine earthquake recurrence periods for this region (Nishenko and Singh, 1987). Singh et al. (1985) proposed an earthquake recurrence period of 77 years for the Jalisco coast based on historical earthquake records. Although large earthquakes occurred in the region in 1806 (M 7.5), 1818 (M 7.7), and 1900 (M 7.6, 7.1) (Singh et al., 1981), the rupture zones of these earthquakes have not been established (Pacheco et al., 1997). The study of past earthquakes, inferred from the geologic and geomorphic record, would improve our understanding on the time–space behavior of earthquakes along the Jalisco coast.

3. Holocene marine notches

On tectonically active coasts, marine notches are one of the most precise indicators of rates and patterns of uplift (Rust and Kershaw, 2000). On coasts with a moderate tidal range, the most common notch profiles have recumbent V-shaped or U-shaped morphologies. In sheltered sites, the depth of marine notches increase gradually above the notch floor to a most convex part of the notch. The retreat point or vertex, the most indented part of a notch, is located near mean sea level (Fig. 3). From that point, the width of the notch increases gradually upward and the notch floor to a more convex part of the notch. The retreat point or vertex, the most indented part of a notch, is located near mean sea level (Fig. 3). From that point, the depth decreases gradually upward and becomes negligible at the top of the notch near the highest tide level. In exposed sites, the elevation of marine notches above sea level increases because wave action regularly exceeds high-tide level in open and exposed coastlines (Pirazzoli, 1996).

Marine notches are best developed in the littoral zone where the intersections of rock, air, and sea are frequent and regular. Marine-notch development is mainly related to bioerosion, however, marine notches...
can be formed by abrasion and by differential erosion. Zones of rapid marine-notch development correlate well with zones of major eroding organisms. The maximum density of grazing organisms is near mean sea level. Rates of erosion of 0.2–5.0 mm/year have been reported in the literature, the most frequent values being 1.0–1.5 mm/year in the tropics (Fairbridge, 1968; Pirazzoli, 1996).

3.1. Field methods

We measured the relative elevations of marine notches above mean sea level between the Barra de Navidad and Cuitzmala sites with an Abney level and stadia above water levels, considering tide level at the time and date of observations. We estimated a measurement error of ca. ±20 cm. One of the problems in measuring elevations of marine notches is related to the wave run-up, particularly in exposed sites. In sheltered shores, such as Barra de Navidad, the effect of wave run-up is significantly reduced because this coast is protected from the open ocean winds. In order to effectively diminish the wave run-up effect when measuring notch elevations in exposed sites, we performed measurements at low tide and during the morning when winds were calm and the wave run-up effect decreases on this coast. Some notches located seaward were not accessible due to the wave action and elevations could only be estimated to the nearest level. Unfortunately, the nearest tide gauge is located 40 km south of the study area on a less-sheltered shore in the Manzanillo Bay, the data for which was available from the archives of the Institute of Geophysics at the National University of Mexico (UNAM). Calculated mean tide level at Manzanillo is 0.5 m, and 0.8 m at the Puerto Vallarta coast.

We considered the influence of El Niño Southern Oscillation (ENSO) on the sea level of the Pacific coast because one of our field seasons (1998) occurred during a strong El Niño event. We estimated the ENSO influence on sea level during the 1997–1998 field season using the image of the Pacific ocean taken by the TOPEX/Poseidon satellite that showed the sea surface along the SW Mexican coast 14–32 cm above normal. We used these corrections to determine mean sea level at the time and date of survey.
3.2. Marine notches along the Jalisco coast

We identified a suite of emerged notches along the Jalisco coast between Punta Farallon and Barra de Navidad (19°28′N, 105°04′W and 19°11′N, 104°40′W) (Fig. 1).

3.2.1. Barra de Navidad notch

A well-developed, slightly emerged notch cut into the base of granite cliffs is located in the inner shore of a lagoon protected from the open wave action by a bar near Barra de Navidad (Fig. 1). At Barra de Navidad, local tidal range is at ca. 0.5 m. The Barra de Navidad notch extends 250 m along an almost vertical cliff (4.6 m high). The retreat point of the emerged notch reaches an elevation between 0.6 and 0.9 m amsl (Table 1). The notch profile at Barra de Navidad shows a well-preserved floor. It exposes an abrasion platform cut into granite. Even during highest high tides, the notch and abrasion platform are still exposed above sea level (Fig. 3). On sheltered shores, the retreat point (the most indented part of a notch) is usually situated near mean sea level (Pirazzoli, 1996).

3.2.2. Cuitzmala notches

A series of notches cut into volcanic breccia (composed of porphyritic andesite in a lithic matrix) and andesitic lavas are exposed on an open shore near the mouth of the Cuitzmala River (Fig. 4). Winds in this area vary from SW to SE during the year. The shore here is moderately exposed to the NW, where waves regularly exceed high-tide level and may increase the elevation of the marine notches (Pirazzoli, 1996). Marine notches here are cut on near vertical cliff faces (6–8 m high), and their retreat points reach elevations ca. 4.5 to 4.7 m amsl (Fig. 4). We identified other indicators of emergent shorelines in this area, such as sea caves and a sea arch cut in volcanic bedrock at elevations ca. 4.5 m. Several breccia boulders (about 8 × 6 × 6 m) along the shore showed an indented surface at ca. 1.5 to 2.0 m amsl that is most probably a marine notch (Table 1).

3.2.3. El Tecuan notches

We recognized other notches along the Jalisco coast. At a highly exposed site at El Tecuan, a spectacular abrasion notch that is cut into breccia shows double erosional benches and honeycombs on the cliff profile. Although this notch reaches an elevation of ca. 3.0 to 3.5 m above mean high tide level, it is highly exposed to wave action; and local accounts suggest that the highest tides reach the notch and that breaking waves occasionally cover the erosional benches and abrasion platform (Table 1).

3.2.4. Benito Juárez notches

At Benito Juárez, emerged notches are cut into breccia at 1.0 m amsl. Tidal range at this locality is ca. 0.5 m, indicating that this notch has emerged. About 500 m seaward from the notch, several island stacks also show notches and abrasion platforms emerged above mean sea level (we were unable to measure the island notches due to strong wave action). Northwest of Benito Juárez, at the mouth of the Arroyo Seco River, an abrasion platform and notches are cut into andesites about 1 m amsl (Table 1).

<table>
<thead>
<tr>
<th>Location</th>
<th>Averaged elevations (m)</th>
<th>Elevation amsl (m)</th>
<th>Radiocarbon age</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Barra de Navidad notch</td>
<td>0.46 to 0.6b</td>
<td>0.6 to 0.9</td>
<td>Post 0 year BP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(ca. 1959 AD)d</td>
</tr>
<tr>
<td>2 Cuitzmala notch</td>
<td>4.5 to 4.7</td>
<td>4.5 to 4.7</td>
<td>1262 ± 51 years BPc</td>
</tr>
<tr>
<td>Cuitzmala sea caves</td>
<td>~ 4.5</td>
<td>~ 4.5</td>
<td>No datable material</td>
</tr>
<tr>
<td>Cuitzmala boulders (8x 6 × 6 m)</td>
<td>~ 1.5 to 2.0</td>
<td>1.5 to 2.0</td>
<td>No datable material</td>
</tr>
<tr>
<td>3 Tecuan notches</td>
<td>~ 3.0 to 3.5c</td>
<td>~ 3.0 to 3.5</td>
<td>No datable material</td>
</tr>
<tr>
<td>4 Benito Juarez and Arroyo Seco notches</td>
<td>0.8 to 1.0</td>
<td>0.8 to 1.0</td>
<td>No datable material</td>
</tr>
<tr>
<td>5 Punta Farallon notch</td>
<td>~ 4.0</td>
<td>~ 4.0</td>
<td>No datable material</td>
</tr>
</tbody>
</table>

a Elevation data corrected for tide level at time of measurement; Measurement error estimates ± 0.2 m. Mean tide range for locations near Manzanillo ca. ± 0.5 m, and ± 0.8 m for locations near to Puerto Vallarta.
b El Niño Correction (1998) + 0.14 to 0.32 m.
c AA-22193.
d 109% of modern (Beta-119880).
e Above mean high tide level. amsl = above mean sea level.
Fig. 4. Emerged tidal notches cut into volcanic bedrock and conglomerates near Cuitzmala. Tidal notches are on almost vertical cliff faces and their retreat points reach elevations ca. 4.5 m above mean sea level. Photographs show the ca. 4.5 m uplifted notch seawards (A), and the same notch extended inland (B). Tidal range is between 0.5 and 0.8 m. Symbols as in Fig. 3.
3.2.5. Punta Farallon notch

At Punta Farallon, a well-developed notch with a wave-cut platform at its base is cut into conglomerate along a 20-m-high cliff face. We also observed a modern notch at the foot of a paleowave-cut platform at ca. 1.0 m above mean tide level. The coast at Punta Farallon is very exposed, and the height of the emerged marine notch (ca. 4.0 m) probably differed from mean sea level at the time it was cut (Table 1). Unfortunately, the majority of these notches and wave-cut platforms are barren of organic material for radiocarbon dating. Advanced dating techniques, such as the use of cosmogenic isotope dating, should be applied here in order to determine exposure ages of these features.

3.3. Radiocarbon dating of Jalisco marine notches

Fossil intertidal barnacles, oyster shells, and red algae (Balanus) identified by Dr. A. García Cubas and Dr. M. Reguero, UNAM; and red algae identified by Dr. S. Tudhope from the University of Edinburgh) were collected at the base of the Barra de Navidad notch and inside the Cuitzmala notch at elevations corresponding to former low and mean tide level, respectively. All barnacles, oyster shells, and algae were clearly located above mean sea level at emerged notches (Fig. 5).

The AMS radiocarbon age for the red algae sample collected at Cuitzmala is 1262 ± 51 radiocarbon years BP (cal. AD 660–940) (AA-22193), suggesting that the emergence of the Cuitzmala coast occurred at about that time.

Shell samples from Barra de Navidad were analyzed for 14C activity using standard methods. The 13C/12C corrected age (Beta Analytic, Beta-119880) obtained from the oyster shells sample at Barra de Navidad is 109% of modern (Post 0 year BP, or ca. AD 1959). Because barnacles collected from the same site were encrusted on top of oyster shells, we assumed

Fig. 5. Elevations of the retreat points of the notches along the Jalisco coast and sea level. Elevation uncertainty limits are marked by vertical segments. Radiocarbon dates for fossil organisms found on Cuitzmala (C) are 1262 ± 51 years BP, Barra de Navidad (BN) 109% of modern (Post 0 year BP, or ca. AD 1959). Symbols: F = Punta Farallon, C = Cuitzmala, BJ = Benito Juarez, T = El Tecuan, BN = Barra de Navidad; masl = meters above sea level. Graphic indicates average regional: MSL = mean sea level, MHWL = mean high water level, MHHWL = mean highest high water level (for site location, see Fig. 1).
that the barnacles and shells were the same age. However, the vertical zonation of barnacles indicates that their living conditions can extend above the maximum tidal range, and in most cases indicate super-zero elevations. This helps explain the anomalous radiocarbon date at Barra de Navidad.

4. Mechanisms of coastal emergence

4.1. Holocene tectonic uplift

The Cuitzmala radiocarbon age and marine notch elevation indicate a relative sea-level fall on this segment of the Jalisco coast during the last 1300 years BP. The global history of relative sea-level change indicates that sea level has been at its present level since 6 ka (Pirazzoli, 1996). Along the northern coast of Jalisco, sea level was near or at present height by 3600–1500 years BP (Curray et al., 1969), and no major isostatic adjustments and climate changes have been reported for the area for that period of time. Two mechanisms might be involved in the emergence of the Jalisco marine notches intermittently exposed along 40 km of coast: (i) rapid uplift produced by large-magnitude, late-Holocene earthquakes generated on the active plate boundary, and/or (ii) long-term uplift of the coast produced by the permanent deformation of the overriding plate because of the subduction of the Rivera Plate (Fig. 2). We discuss these two mechanisms below.

First, rapid uplift movements might be coseismic because the preservation of in situ sublittoral and midlittoral shells, barnacles, and algae in the supralittoral zone would be enhanced by a very rapid, relative sea-level change (Pirazzoli, 1996). Intertidal organisms, red algae, were found in their growth position and well preserved on the Cuitzmala notch. The preservation of these organisms may be due to rapid uplift of the coast associated with shallow, large-magnitude earthquakes located close to the coast. Similar coastal features produced by coseismic uplifts have been observed in other parts of the world along active subducting plate margins: for example, New Zealand (Berryman et al., 1989; Ota et al., 1991), Japan (Kawana and Pirazzoli, 1991), and Alaska (Plafker and Rubin, 1967).

Alternatively, long-term deformation not directly associated with earthquakes might also be a mechanism for coastal uplift in Jalisco. Elastic strain deformation can be accumulated during the interseismic period causing upward flexing of much of the accretionary prism and adjacent local coastal areas. However, this strain would be released during the subsequent earthquake, producing abrupt coseismic submergence on coastal areas. This simple model of interseismic and coseismic deformation has been used to demonstrate the elastic behavior of the overriding lithospheric plate on the Cascadian subduction zone where the Juan de Fuca oceanic Plate underthrusts and where paleoseismic records report coseismic subsidence (Atwater, 1992).

Rapid uplift might partially explain coastal emergence evident by the Cuitzmala notches. Radiocarbon dating of the ca. 4.5-m elevated Cuitzmala marine notch indicates the time of uplift, inferred to be rapid because of the presence of well-preserved marine organisms found in their growth position. Uplift might have occurred during a large-magnitude earthquake at 1262 ± 51 years BP (cal. AD 660–940). Other emerged notches, exposed in the study region at different elevations above mean sea level (ca. 1, 1.5–2, and 4 m) might have a similar history of sudden uplifts associated with earthquakes. Unfortunately, most of these features were barren of datable material, and no ages could be used to determine uplift rates. The absence of intertidal organisms on these notches raises the question regarding whether a rapid or a slow uplift raised these features above mean sea level.

On the other hand, the elevation of the Cuitzmala notch at 4.5 m amsl could be explained by a large-magnitude shallow earthquake or a combination of a series of shallow earthquakes located near the coast and/or long-term tectonic uplift. None of these hypotheses can be proven at this point because historical records of earthquakes in this area do not go back far enough to prove or disprove these hypotheses.

The Barra de Navidad notch, elevated at ca. 0.6–0.9 m, shows an anomalous (109% of modern) radiocarbon age. According to this date, this shoreline could have emerged a few decades before or after AD 1959. This date could as well correspond to an
earthquake that occurred in the 19th century. The historical record indicates the occurrence of other larger earthquakes in the 19th century (1806, 1818, 1837, 1875, 1900), nevertheless, the effects of these earthquakes on the coast have not been documented. However, the vertical zonation of barnacles indicates that their living conditions can extend above the maximum tidal range. This might be a probable reason for the anomalous modern radiocarbon age of the Barra de Navidad raised notch.

The spatial-height distribution of the raised notches along the Jalisco coast illustrated in Fig. 5 suggests an anomalous non-uniform spatial arrangement that might be caused by differential uplift along the coast. This non-uniform distribution could be related with the presence of faults that make up the blocky structure of the Jalisco megablock (Lugo-Hubp and Ortiz-Perez, 1980; Ferrari and Rosas-Elguera, 2000; Ferrari et al., 2000).

4.2. Historic interseismic and coseismic observations

Observations of the historic earthquakes of 1932 and 1995 showed that coseismic subsidence was produced along the Jalisco coast (Cumming, 1933; Melbourne et al., 1997). After the 1932 earthquake, Cumming’s (1933) report indicates local coastal subsidence of about 40–75 cm near Manzanillo, south of Jalisco, produced by the 1932 earthquakes. The arrival of a tsunami was also reported by locals just after the earthquake (Cumming, 1933).

In October 1995, initial coseismic coastal subsidence (up to 20 cm at Chamela) was measured using geodetic-GPS and tide gauge data (Hutton et al., 1997). Measurements made barely 2 months after the earthquake demonstrate a period of rapid uplift, with some sites recovering almost the entire coseismic drop (Hutton et al., 1997). Thus, a detailed GPS survey before, during, and after the 1995 (Mw = 8) Colima earthquake showed postseismic motion ranging from 18% to 84% of the coseismic slip with postseismic displacements decaying rapidly (Hutton et al., 1998). GPS results indicate that almost 3 years after the earthquake, the coastal coseismic subsidence reported had been nearly completely recovered during the postseismic and interseismic periods (Hutton et al., 1997, 1998; O. Sanchez, UNAM, personal communication).

5. Discussion

Studies at other plate boundaries around the Pacific Rim showed that Holocene- and Pleistocene-emerged shorelines recorded both eustatic and coseismic relative sea-level changes (Plafker, 1969; Matsuda et al., 1978; Ota et al., 1991; Berryman, 1993). For example, the Papua New Guinea coastline, which has one of the most detailed records of emergent shorelines, shows that meter-scale uplifts represent great earthquakes (Ota and Chappell, 1996). Large coseismic uplifts can be identified from the geomorphic record; however, identifying less than 1-m uplifts from the geomorphic record is not possible because the effects of an instantaneous movement cannot be distinguish clearly from those events occurring over decades or centuries.

We believe that long-term slow uplift might also have contributed to the total net emergence of former Holocene shorelines on the Jalisco coast, although distinguishing the amount of coseismic uplift from that of the slow uplift produced during long-term periods is not possible. The mechanism that explains uplift produced during interseismic cycles and during the long-term period on the coastal area, as discussed above, can be related to the shortening of the accretionary prism and a flexural uplift of the overriding plate. Although the accretionary prism on this portion of the margin is relatively thin, then the deformation occurring on the overriding plate would be small also; the possibility of an increase of buoyancy of the subducting material might lead to an uplift of the plate margin in the long term (Buiter et al., 2001). Moreover, emerged shorelines clearly experienced overall uplift; and we found no evidence of a prolonged interseismic and of long-term subsidence.

Finally, although coseismic centimeter-scale coastal subsidence was reported for the 1932 and 1995 earthquakes (Cumming, 1933; Hutton et al., 1997, 1998; Kostoglodov et al., 1997), the rapid postseismic and interseismic recovery indicates a general trend to tectonic uplift during long-term periods. Apparently, interseismic and long-term uplift has been an important, if not the most important factor, in the emergence of the Jalisco coast. We propose a model for the Jalisco coast in which (based on geomorphic, historical, and GPS observations) the coast subsides during large earthquakes located offshore. This coseismic
subsidence is rapidly recovered during a short period of about 1–5 years. Then, during interseismic and long-term periods, the coast is uplifted slowly by upward flexing produced by the elastic deformation of the overriding plate. This amount of long-term uplift, although slow, does not seem to be completely lost during coseismic subsidence produced by subsequent earthquake events. The possibility of large-magnitude earthquakes producing tectonic uplift is not excluded from this model. If earthquakes are shallow and close to the coast, they are capable of producing coastal uplift. Large coseismic uplift has occurred in adjacent coastal segments of the subduction zone. The 1985 earthquake produced up to 1.10 m of coastal uplift in the adjacent Michoacan coastal segment (Bodin and Klinger, 1986). However, we found no further evidence of sudden uplift apart from in situ intertidal organisms present on the Cuitzmala notch and the history of coseismic uplifts that occurred on the adjacent coast of Michoacan. Therefore, at this point, coseismic uplift cannot be proven. However, while it is unfortunate that we have only two radiocarbon dates, these dates for the Cuitzmala and Barra de Navidad notches are consistent with their elevations, showing a younger age for the lower Barra de Navidad notch and an older age for the higher Cuitzmala paleoshoreline. The record of emerged coastal notches suggests a cumulative long-term slow uplift rate estimated at 3 mm/year.

We have raised questions and suggested possible explanations for Holocene uplift of the Jalisco coast in SW Mexico. However, further work should be performed on the absolute dating of emerged shorelines to determine uplift rates and perhaps establish earthquake recurrence intervals for the Jalisco coast. The lack of material suitable for radiocarbon dating on most of these notches warrants further work along with the introduction of other dating techniques on abraded landforms. Cosmogenic isotopes might prove to be a valuable tool in providing exposure ages for abrasion platforms and marine terraces (Hancock et al., 1999; Perg et al., 2001).

### 6. Conclusions

Intertidal notch elevations and their radiocarbon age, first ever reported for this sector of the Mexican active plate margin, show a relative sea-level “fall” in Jalisco during the late Holocene (at least during the last 1300 years BP). Emerged marine notches, ranging from 1 to 4.5 m in elevation, record coastal emergence since at least 1262 ± 51 years BP. We suggest that Holocene coastal uplift, registered by emerged marine notches, represents (i) slow tectonic uplift during the long-term period, and/or (ii) probably rapid tectonic uplift caused by great shallow earthquakes that might have occurred close to the Jalisco coast.

If the history of relative sea-level change in Jalisco is similar to histories on other northern Mexican coasts and globally, most of the relative sea-level fall that we measured would be caused by tectonic uplift of the Jalisco coast.

Although offshore earthquakes may produce local centimeter-scale coastal subsidence along the Jalisco coast, complete postseismic and interseismic recovery appears to follow (Hutton et al., 1997, 1998) leading to general coastal uplift. Slow long-term uplift is considered to be the most important factor to the total net vertical motion, uplift, along the Jalisco coast. We have found no evidence of coastal interseismic and long-term subsidence.

Judging by the morphologic evidence and the radiocarbon date of the 4.5-m elevation Holocene notches, we propose a Holocene long-term trend for tectonic uplift at estimated rates ~ 3 mm/year along the Jalisco coast. Further work on the precise dating of emerged notches and terraces is necessary to determine uplift rates in this area.

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