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Late Pleistocene (Last Interglacial) terrace deposits, Bahia Coyote, Baja California Sur, México

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Abstract

Late Pleistocene age terrace deposits are exposed in the narrow cliffed coastal plain of Bahia Coyote, Baja California Sur, resting unconformably on the lagoonal-shallow water volcaniclastics of the early Miocene Cerro Colorado Member of the El Cien Formation. The terrace is dissected by widely spaced arroyos and partically covered by alluvial fans in the inner and central areas. The marine deposits vary in thickness from 0.5 to 10 m and were laid down in pre-existing erosional channels and depressions in the Pleistocene landscape. The sequence begins with a cobble conglomerate with oyster shells, overlain by poorly bedded molluscan-rich bioclastic sands and coral rubble, beds of massive *Porites* in growth position and coral-rhodolith sands and marls. Beach sands and gravels and coastal dunes cap the sequence.

Samples of *Porites panamensis* selected for U/Th dating are well-preserved aragonite (>95%). Preliminary results yield U/Th ages of 109–209 ka but the corals have initial δ^{234}U values in excess of modern seawater values. This indicates open-system behavior and uncertainty associated with the ages. A corrected age for the top of the massive *Porites* unit suggests that the corals grew during the last interglacial, marine isotope stage (MIS) 5e sea level high stand.

Assuming global sea level during MIS 5e was ca. 4–5 m above present-day sea level (McCulloch and Esat, 2000) and the growth position of the corals was 1–5 m below sea level, the terraces have been uplifted between 12 and 25 m (12–15 cm/kyr). This is consistent with other terrace-based uplift rates for the central Baja California peninsula, north of the La Paz fault.
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1. Introduction

Along the emergent coastline of the Baja California peninsula and immediate offshore islands, Quaternary terraces are common geomorphic features. Marine terraces and terrace deposits, particularly those attributed to the last interglacial sea level high stand at marine isotope stage (MIS) 5e, are widespread between Santa Rosalia and Cabo Pulma, near the tip of the peninsula and have been important in describing the last interglacial cycle in the Gulf of California and deciphering the neotectonics of the peninsula (Ashby et al., 1987; Ortlieb, 1987, 1991; Sirkin et al., 1990; Libby and Johnson, 1997; Johnson and Ledesma-Vasquez, 1999; Ledesma-Vazquez and Johnson, 2001; Nava-Sanchez et al., 2001; Muhs et al., 1994, 2002a; Mayer et al., 2002).

Typical Pleistocene terraces in Baja California are wave-cut benches or small platforms cut into the bedrock, covered by a thin layer of sand and gravel with broken and weathered mollusk shells, coral and algal fragments and other invertebrate remains. Most are small remnants of more extensive deposits, buried beneath non-marine alluvial gravels and now exposed in limited outcrops along arroyos or in sea cliffs. Such deposts formed on open, exposed, high-energy portions of the coast.

In contrast, there are a few sites on the Baja California peninsula where the terrace sequences were deposited in shallow, protected embayments and the original near-shore depositional environments and associated fossil biotas have been well preserved. In part, these unusual deposits are due to the higher stand in eustatic sea level during the last interglacial (Bard

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et al., 1990; Chen et al., 1991; McCulloch and Esat, 2000) and the subsequent abandonment of coastal features. One such site is at Bahia San Antonio, near Bahia Concepcion, where a late Pleistocene rocky shoreline, including an exposed outer shore, sheltered inner shore and protected cove with patches of *Porites* corals can be identified, complete with evidence for a vertical zonation in the shore-line biotas (Johnson and Ledesma-Vasquez, 1999). At San Telmo, the extensive coral deposits and associated facies are described in a reconnaissance study by Squires (1959).

Another exceptional occurrence of emergent late Pleistocene marine deposits is located in an embayment on the western margin of Bahia de La Paz. This small embayment, referred to locally as Bahia Coyote, extends from Punta Coyote to near a fish camp at El Saladito, a distance of nearly 37 km. Here a marine transgressive–regressive sequence that includes basal conglomerates, gravels, fossil-bearing sands, rhodolith–molluscan marls, corals, and beach sands and gravels cover dissected older wave-cut platforms. Small coastal dunes cap the sequence. Late Pleistocene–Holocene alluvial gravels obscure the original inland extent of the deposits but rocky shoreline boulders and inner-shore sands have been mapped at least 3 km from the present coastline.

We present here a preliminary report of research in progress on the late Pleistocene deposits at Bahia Coyote which is aimed at (1) documenting the stratigraphic relations of the various litho- and biofacies, in particular the original depositional context of the massive *Porites* beds, (2) describing the diverse invertebrate biota and its paleoecology and (3) determining the age and implications of the deposits for the neotectonic history of the Bahia de La Paz region.

2. General setting

Bahia Coyote is an open embayment located about 70 km north of La Paz. It is the modern expression of a larger ancient embayment that occupied portions of the coastal plain located between the main rift escarpment and the present-day coast of the Gulf of California. In the study area the plain is 1–4 km wide with low, along shore sea cliffs cut by wave action. Alluvial fans dissected by arroyos draining from the eastern side of the escarpment form the inner edge of the plain, and in places bury it. To the north and south, the study area is bounded by large arroyos that terminate at the coast in small fan-deltas. The larger fan-delta to the north forms Punta Coyote (Fig. 1). Ridges or spurs carved from the nearly flat-lying Cerro Colorado Member of the Isidro Formation (hereafter simply referred to as the Cerro Colorado) and capped by fanglomerates and alluvial

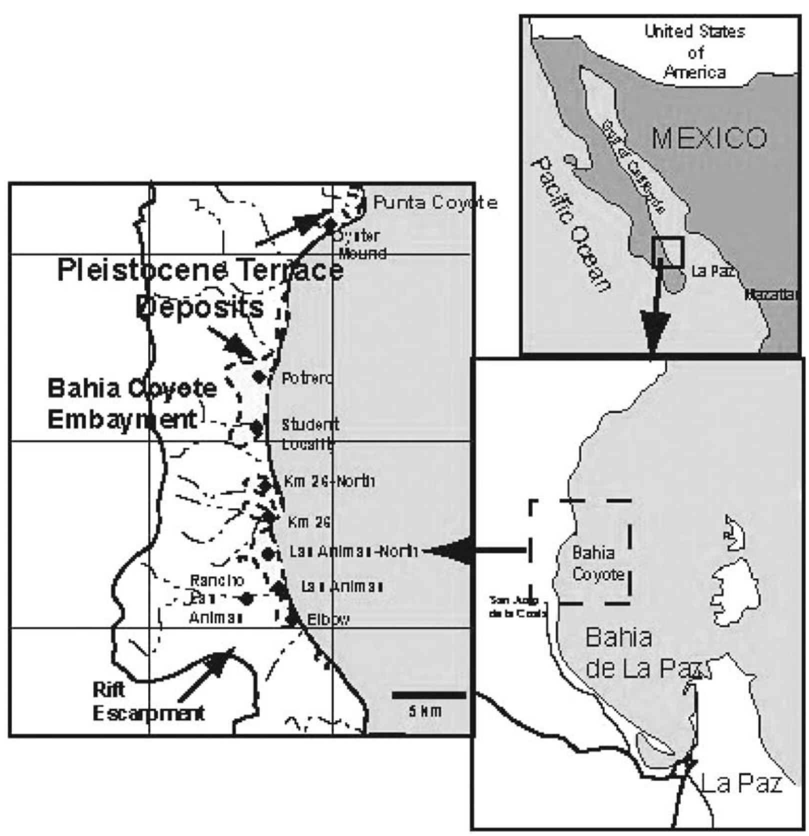

Fig. 1. Location map of Bahia Coyote and the late Pleistocene terrace deposits.

gravel and boulders of Miocene volcanics and reworked Cerro Colorado Member, extend from the escarpment onto and across the plain. Three of these ridges continue to the coast and cut the ancient embayment into several smaller embayments. Near the coast, in the center of the study area, the Pleistocene land surface was beveled by wave erosion to form an extensive wave-cut platform. During sea level low stands (probably MIS 2 and 3) this marine terrace was dissected into separate segments or blocks by the development of the modern arroyos. Today the terrace segments are isolated, roughly elongate blocks (in plan view) from about 0.7 km to more than 3 km in length and stand 15–20 m above the surrounding arroyo floor. They are distributed over a distance of about 25 km. At the coast small coastal dunes cover the terraces. Within the wave-cut platforms are old channels and depressions that formed on the landscape prior to the marine transgression. Terrace deposits fill these channels and depressions and cover the beveled terrace surface.

With a few exceptions, the Pleistocene deposits rest unconformably upon the underlying shallow-water to lagoonal Cerro Colorado Member, a distinctive flat-lying volcaniclastic unit of early Miocene age (Smith, 1991; Gidde, 1992). Typically, the unit is interbedded dark green sandstone, gravely sandstone, siltstone and shale with a few interbeds of pink-colored pyroclastic mudstone. Its dark green color is in sharp contrast to the overlying terrace deposits. At a few locations exposed in the sea cliff, erosion has removed the Cerro Colorado deposits over structural flexures or faulted blocks and the Pleistocene deposits rest on sandstones and shales of the older San Gregorio Formation (late Oligocene–early Miocene).

3. Terrace deposits and biota

The several terrace segments located between Rancho Las Animas and the kilometer post km 26 and between the Student Locality and Potrero preserve the most complete and thickest marine sequences (Figs. 2 and 3). These emergent deposits, including the beach sands and gravels, vary from several centimeters to nearly 10 m thick. The following brief discussion of stratigraphy, lithofacies and fossil biotas is based in large part on the exposures in these two areas (Fig. 3a–c). In the more northern and southern areas, the same lithofacies and fossil assemblages are recognized but the sequences are either less well exposed, thinner or less complete (DeDiego-Forbis, 2003).

3.1. Basal conglomerate and storm beds (Fig. 4)

The marine sequence begins with a sandy conglomerate of rounded to angular pebbles, cobbles and

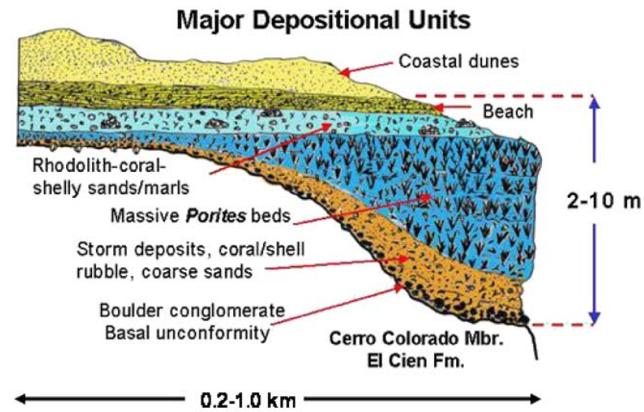

Fig. 2. Schematic diagram of the major depositional facies and their stratigraphy in the Bahia Coyote terrace deposits.

boulders of Miocene volcanics and reworked Cerro Colorado (El Cien Formation) and fossil fragments in a coarse-grained sand matrix. The unit varies in thickness and extent. It is thin (<20 cm thick) with pebbles and small cobbles where it rests directly upon the eroded terrace surface (Cerro Colorado) and thickens to several meters in channels and depressions. Small oyster shells are commonly cemented to the rounded cobbles and boulders suggesting they were derived from the rocky shoreline. In depressions, the basal beds are ungraded with matrix-supported larger clasts suggesting large storm deposits. Storm deposits are also common within the overlying units composed of a few cobbles and boulders suspended in bioclastic rubble of displaced molluscs, echinoid spines, broken corals and algal debris.

3.2. Oyster beds and mounds

Oyster shells and shell fragments representing a number of different species are ubiquitous throughout the Pleistocene sequence. In several facies cemented oyster shells form mounds varying from less than a meter to many tens of meters in size. In the protected lee of the Coyote fan-delta, at the locality referred to as the Oyster Mound, 0.5–1.5 m thick beds of *Ostrea palmula* occur with abundant *Nassarius tiarula, Oliva spicata, Isogonomon chemnizianus* and small *P. panamensis* in a matrix of rhodolith–bioclastic sand. The species found at the locality suggest a lagoon/bay environment 10–20 m deep. In other localities, such as at Las Animas-North, oyster beds are interbedded or form small mounds in the bioclastic sands on top of the terrace.

3.3. Small porites and pocillopora beds (Fig. 5)

Two different coral species, a small *Pocillopora* sp. and small branching forms of *P. panamensis* form distinct coral-dominated facies. Small forms of

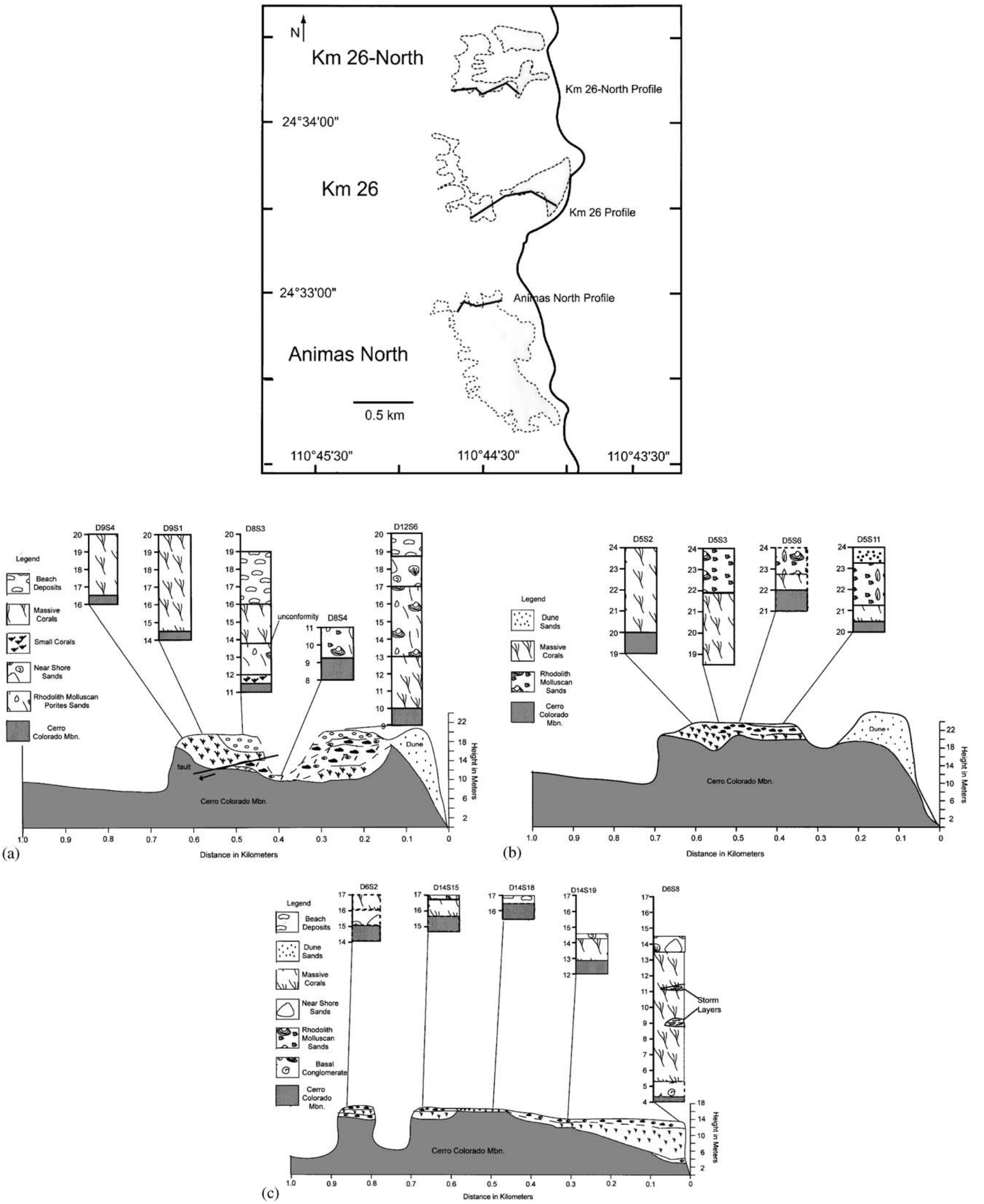

Fig. 3. Location map of terrace profiles across segments of the Bahia Coyote Terrace. (a) Profile of the terrace at Dune locality, illustrating the distribution and thickness of the main facies. Profile drawn roughly perpendicular to the coastline. Elevations in meters; distances in km. (b) Profile of the terrace at Las Animas-North locality, illustrating the distribution and thickness of the main facies. Profile drawn roughly perpendicular to the coastline. Elevations in meters; distances in km. (c) Profile of the terrace at Km 26-South locality, illustrating the distribution and thickness of the main facies. Profile drawn roughly perpendicular to the coastline. Elevations in meters; distances in km.

Fig. 4. Small arroyo cutting the terrace segment at Las Animas-North with a view of the basal conglomerate resting on the eroded Cerro Colorado Member, El Cien Formation, overlain by sands and storm deposits and massive *Porites* beds. Large, columnar forms of *Porites panamensis* are typical of the lower part of the "massive *Porites* beds" which is thickest where it fills channels and depressions.

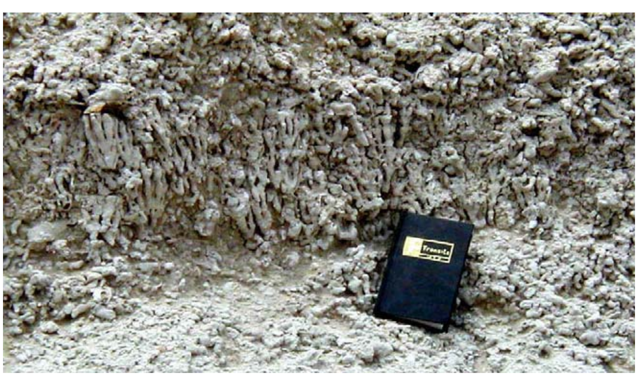

Fig. 5. Beds of small, branching forms of *Porites panamensis* ("*pencil*"-*Porites*) are widely distributed on the terrace surface. The coral heads typically range from 10 to 25 cm in height and form beds 0.5–2 m thick. Example from the Road Cut Locality, near Potrero.

branching *Porites* (which we referred to as "pencil-*Porites*") with branches 0.5–2 cm in diameter and heads 10–20 cm high, form beds up to 25 cm thick with abundant molluscs, including *Chione* sp., *Chama* sp., *Spondylus princeps, Plicatula inezana* and *Turritella* sp. (Fig. 5). Typically thin, discontinuous layers of coral rubble and sand separate pencil-*Porites* beds from corals in growth position. This facies is best developed on the terrace platform in the central portion of the study area.

Thin beds of small lobed corallites of *Pocillopora* about the width of a finger and no more than 10–12 cm in lengths are found within the rhodolith–molluscan marls and sands. These beds include abundant *Petalconchus* sp., *Trigonocardia biangulita,* and *Chione* sp. These are the only occurrences of *Pocillopora* in the Pleistocene deposits although this genus forms most of the coral patches/reefs living in the Gulf of California today (Brusca, 1980; Glynn et al., 1983).

3.4. Massive porities beds (Figs. 4, 6 and 7)

A distinctive feature of the terrace deposits are beds of densely packed, bouquet-shaped coral heads of *P. panamanensis* in growth position enclosed in an uncemented matrix of bioclastic sand, algal debris and abundant molluscan shells (Figs. 6 and 7) that we referred to as the "massive *Porites* beds". In growth position the coral heads are typically 20–50 cm and range to over 160 cm long in the lowest part of the unit (Fig. 6). The coral heads are arranged in poorly defined beds, typically 1–3 m thick, separated by thin layers of sand or coral rubble. In the ancient channels and depressions, the massive *Porites* beds attain a thickness

Fig. 6. Thick beds of densely packed, large, bouquet-shaped coral heads of *Porites panamensis* form the unit referred to as the "massive-*Porites* beds". Individual coral heads are typically 25–50 cm in length and range up to 170 cm. Note the platy morphology developed on the outside of the large *Porites* corals in the channels and depressions and interpreted as a response to stronger wave and/or current action.

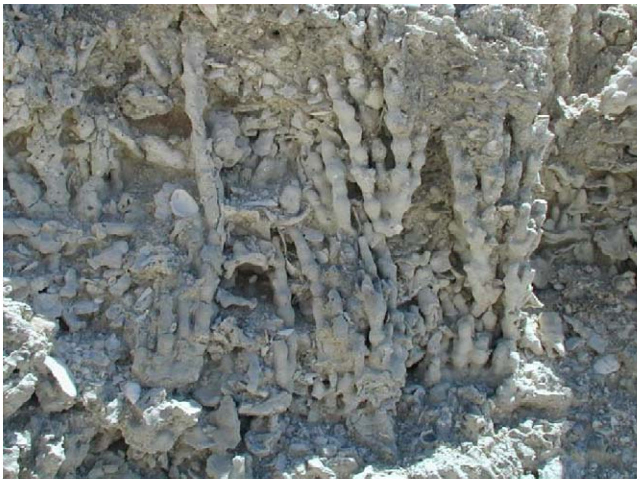

Fig. 7. Corals in the "massive-*Porites* beds" form an uncemented, open-framework structure filled with rhodolith bioclastic sand and shell fragments.

Fig. 8. Close-up of rhodolith–molluscan–*Porites* bioclastic sand. Most rhodolith specimens are nobly, suggesting wave action rolled them on the seafloor (Foster et al., 1997). *Porites* specimens are small, branching forms typically less than 1 cm in diameter. Sand size particles are algal debris, shell fragments and volcanic materials.

up to 8 m and rest directly on coarse bioclastic sand, oyster debris and sparse cobbles. Small irregular beds of toppled and broken coral heads occur in places and suggest storm deposits.

In life the corals formed large patches on the sea floor, mainly concentrated in the central part of the ancient embayment where they first colonized pre-existing channels and depressions in the ancient topography and spread to the terraced surface of the Cerro Colorado with the rise in sea level. While the coral colonies may have modified wave patterns, they do no appear to have been reefs in the classic sense. The corals forming open-framework structures (Fig. 7) are not cemented and unlikely to have been wave-breaking features, although the platy morphology of large specimens at the base of the unit (Fig. 6) suggests wave action or strong currents.

There is no direct counterpart to the massive *Porites* beds in the modern Gulf of California. *Pocillopora* dominates lager patch reefs in the southern Gulf and *Porites* is a minor element although widespread in intertidal to subtidal environments (Squires, 1959; Glynn et al., 1983; Brusca, 1980).

3.5. Rhodolith–molluscan–porites sands and coquinas (Fig. 8)

Light gray-buff coarse- to medium-grained shelly sands or marly sands containing abundant small *Porites*, rhodoliths, isolated oyster mounds and a diverse molluscan assemblage cover the terraces and massive *Porites* beds. Gastropods are common, including *Acmaea* sp., *Aarchotectonic nobilis*, *Collisella strongiana*, *N. tiarula*, *Oliva* sp. and *Terebra* sp. together with the bivalve genera *Chione* sp., *Lucina cancellaria* and *Megapitaria* sp. Rhodoliths are either nobby ("lumpy" of Foster et al., 1997) or branching. The unit varies laterally in thickness, ranging from 0.25 to 3 m, and is preserved in discontinuous patches. In the terrace deposits near the present coast, the sands grade upwards into a coquina with pebbles.

3.6. Near shore sands

Exposed in a few places inland, beneath the alluvial gravels and resting on the terraces of eroded Cerro Colorado to the south are sands that were deposited at the edge of the ancient embayment. The sands are uncemented, medium- to fine-grained with nobby rhodoliths, sand dollars (*Encope*), common bivalves (*Trigoniocardia biangulita, Anadara mulicosta, Cardita affnis*, *Codakia* sp., *Megapitaria* sp., *Plicatula inezana*) small oysters and burrows. Reworked fragments of small *Porites* are common. The deposits found at the inner edge of embayment, nearest the rocky shoreline, are light colored and quartz-rich whereas the sands to the south are dark-colored and rich in volcanic-derived grains. The enclosed fossil assemblages are similar, however.

3.7. Beach deposits

Much of the inner terrace margin is covered by alluvial fans that have buried the shoreline. Near the heads of some arroyos, however, can be found the inner edge of the embayment in deposits of cobbles and boulders with cemented oyster shells and shell fragments which formed the rocky shoreline and cemented coquinas. This facies has the aspects of a beach rock and probably marks the low tidal portion of the ancient shoreline.

Nearer to the present coast, dark-colored rounded pebbly conglomerates with abundant shell fragments cap the terrace deposits. Fossils include mostly broken clams (*Chione* sp., *A. multicosta*, *T. biangulita*). These deposits are lenticular and cross-bedded.

4. Uranium-series ages of the massive Porites beds

To determine the age and duration of the Bahia Coyote sequence and its relationship to the last interglacial stage (MIS 5), specimens of the coral *P. panamensis* were selected for U-series TIMS analysis. Large, bouquet-shaped coral heads of *Porites* in growth position were collected intact from the top, middle and base of the massive *Porites* unit and smaller, pencil-size specimens from the thin *Porites* unit resting on the terrace surface. We report here results from the localities at Las Animas-North, Km 26-north and Km 26-beach (Fig. 1). The stratigraphic position of the U-series samples is shown diagrammatically in Fig. 9.

Selected pieces from within individual coral heads were cut into centimeter-size pieces, removing the outer surface, cleaned mechanically, crushed to millimeter-size pieces, again cleaned, washed in deionized water and X-rayed for aragonite content. Based on X-ray diffraction of powdered samples the corals are 95–97% aragonite.

Coral fragments examined by scanning electron microscopy (SEM) reveal no evidence of crystal overgrowth or recrystallization (Fig. 10) to calcite but did reveal a thin (1–3 μm thick) coating of silica in some skeletal material (Fig. 11). The veneer is irregularly distributed within an individual coral head and is most prevalent in the large bouquet-shaped *Porites* found in the channels. It has not been found in the small, pencil-size *Porites* from beds resting directly on the terrace surface.

In a few locations the massive *Porites* beds, the sediment matrix and contained molluscan fossils are stained a green color by material remobilized from the underlying Cerro Colorado. The corals are typically weathered, coated with a dark-colored patina and poorly preserved. These sites are in the immediate vicinity of small normal faults. We suspect the green-stain is the mineral celadonite which gives the

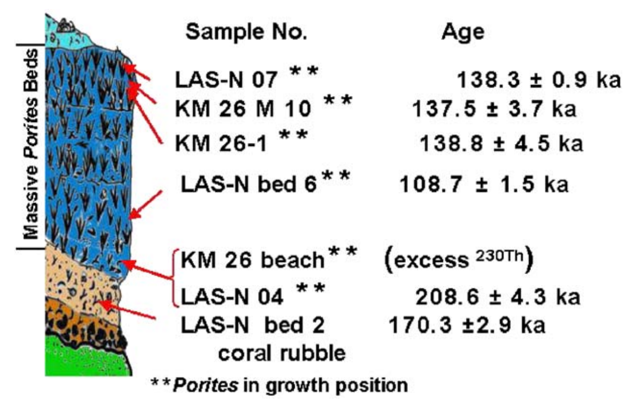

Fig. 9. Schematic diagram of the stratigraphic position of the *Porites* samples dated by U-series.

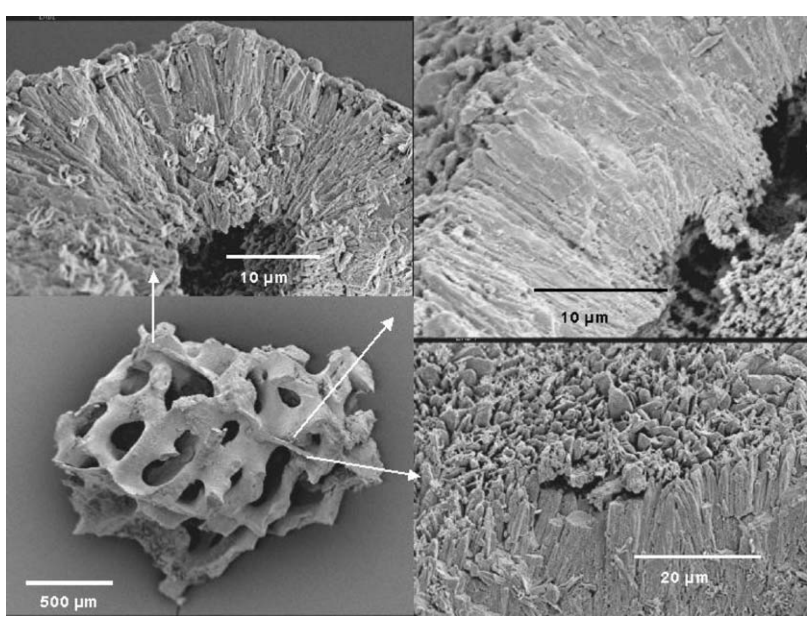

Fig. 10. Scanning-electron micrographs of fragments of *Porites panamensis* selected for U-series analysis. Lower left, fragment of corallite (LAS-N 07); bar equals 500 μm. Fractured edges of corallites (LAS-N 07, Km 26-M10 and Km 26-1) showing no evidence of either recrystallization or crystal overgrowths.

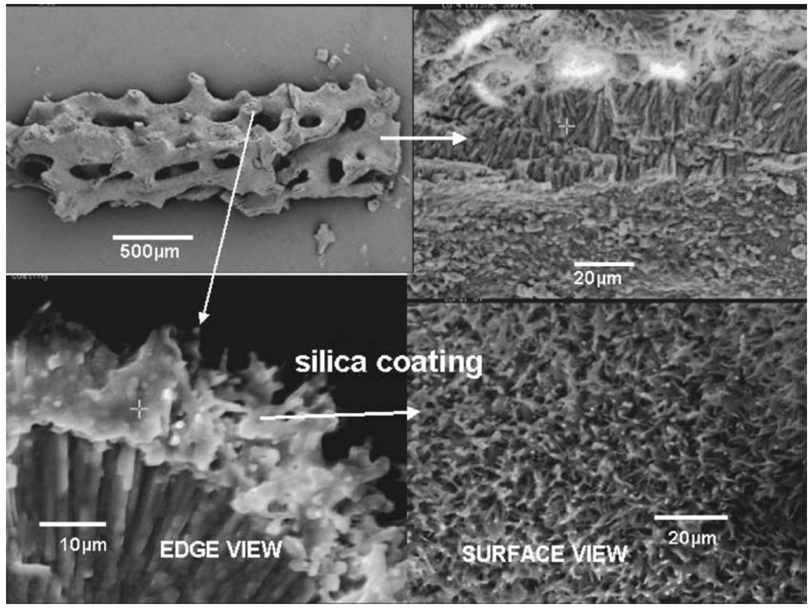

Fig. 11. Silica overgrowths on the surface of corallite (LAS-N 04) from near the base of the massive *Porites* bed, Las Aminas-North. Upper left, corallite specimen; upper right, view of typical surface. Lower left, edge view (bar equals 10 µm) of silica coating, lower right the surface texture of the silica coating. See Fig. 9 for the stratigraphic position of the samples.

Table 1
Isotopic values and U-series ages of coral samples from the massive *Porites* beds

Sample	^{238}U (ppm)	^{232}Th (ppb)	^{230}Th (pg/g)	δ^{234}U today	U/Th age (ky)[a]	U/Th age (ky)[b]	δ^{234}U initial
Km 26 m10	4.354 ± 0.004	191.4 ± 2.4	60.4 ± 0.2	143.1 ± 0.9	137.5 ± 3.7	140.1 ± 1.3	211.1 ± 2.6
Km 26-1	2.658 ± 0.002	137.4 ± 1.4	36.4 ± 0.1	121.7 ± 0.8	138.8 ± 4.5	141.9 ± 1.6	180.2 ± 2.6
LAS-N 04	4.17 ± 0.005	177.8 ± 1.7	80.3 ± 0.4	172.5 ± 1.0	208.6 ± 4.3	210.6 ± 3.4	311.0 ± 4.3
LAS-N 07	3.416 ± 0.003	136.1 ± 0.06	46.7 ± 0.1	136.4 ± 1.2	138.3 ± 0.9	138.6 ± 0.8	201.7 ± 1.8
LAS-N bed 2	4.681 ± 0.005	140.9 ± 1.5	69.9 ± 0.2	122.0 ± 1.0	170.3 ± 2.9	172.1 ± 1.7	195 ± 2.3
LAS-N bed 6	6.027 ± 0.008	100.2 ± 0.09	71.8 ± 0.2	127.3 ± 1.0	108.7 ± 1.5	109.7 ± 0.7	173.1 ± 1.6
Km 26-beach	2.663 ± 0.002	177.8 ± 2.0	81.2 ± 0.3	142.2 ± 1.0	Excess ^{230}Th		

See Fig. 9 for stratigraphic position of the coral samples.
[a] Assumes initial $^{230/232}$Th = 0.000015.
[b] Assumes initial $^{230/232}$Th = 0.0000044.

underlying Cerro Colorado its distinctive green color (Gidde, 1992). How it was remobilized into the Pleistocene terrace deposits is unclear and the subject of research in progress. Silica-coated *Porites* specimens appear to be more common in the vicinity of the green-stained deposits. Based on field observations, the affected sites may be ancient hydrothermal vents that were located along the faults. Such vents are known in the modern Gulf, for example in the intertidal zone at Bahia de Los Planes and recently described in Bahia Concepcion (Forrest et al., 2002).

Analytical methods and procedures, isotopic ratios and U-series systematics for the age determinations are modifications of those reported previously in Musgrove et al. (2001). In this paper, we report the uranium and thorium isotopic composition and concentrations and ^{230}Th/^{234}U ages (Table 1).

The reliability of U-series ages is usually based on four criteria: (1) little or no evidence of recrystallization to calcite, (2) U concentration similar to those in living corals of the same genus, (3) low concentrations of ^{232}Th and high ^{230}Th/^{232}Th values and (4) a calculated initial δ^{234}U value similar to those of modern seawater (Chen et al., 1991; Gallup, et al., 1994; Muhs et al., 2002a). While there are no obvious indications of recrystallization, we note that all of the coral samples analyzed have (1) initial δ^{234}U values in excess of those for modern seawater, and (2) higher U concentrations compared to *Porites* reported in the literature (Chen et al., 1991). Uranium concentrations in Bahia Coyote corals average 4.074 ppm and two samples exceed 6.0 ppm compared to values of 2–3 ppm for most open ocean *Porites* (Chen et al., 1986). Initial δ^{234}U activity values are higher-than-acceptable (Gallup et al., 1994; Muhs et al., 2002a) and indicate open-system behavior and uncertainty associated with the ages.

Samples from the top of the massive *Porites* unit yielded a tight cluster of apparent ages, ranging from 137.5 to 138.8 ka. These corals have initial $^{234}U/^{238}U$ ratio values of 1.1802–1.2111 suggesting a bias toward older ages (Gallup et al., 1994; Muhs et al., 2002a). While it is not possible to determine precise ages, using the approach of Gallup et al. (l994) and assuming the corals have been closed-systems since they were buried, the true ages of the corals at the top of the *Porites* unit may be closer to 128–130 ka. Ages for samples from the base of *Porites* unit are older but have even higher $\delta^{234}U$ values. Additional age control is required to define the age of the basal beds and the duration of the sequence.

The U-series TIMS ages from Bahia Coyote terrace deposits are similar in precision and broadly overlap U-series ages reported for other late Pleistocene terrace deposits on the eastern Baja California peninsula (Ashby et al., 1987; Sirkin et al., 1990; Szabo et al., 1991; Muhs et al., 1994, 2002a; Halfar, 1999). Ages from these deposits cluster between ca. 120 and 145 ka. In all cases the corals have initial $\delta^{234}U$ values higher than modern seawater. Muhs et al. (2002a) found that reanalysis of *Porites* and *Pocillopora* specimens from Cabo Pulma (Muhs et al., 1994) using U-series TIMS analysis did not solve the problem and that the corals still yielded older ages by perhaps 4000–5000 years. Despite the lack of precision, the U-series ages suggest that they all represent the same eustatic sea level event and most likely correlated with the last interglacial high stand period, MIS 5e. Recently, Mayer et al. (2002) suggested that the terraces formed at 5a and 5c may also be present in the Loreto area.

5. Late pleistocene MIS 5e sea level

On the rifted and uplifted coastline of Baja California, marine terraces correlate to the high stands of sea level and permit an evaluation of post-depositional tectonic motion. Ancient sea level position is commonly determined by measuring the terrace shoreline angles. However, the nature of the terraces in Bahia Coyote generally do not permit this calculation, so we have used the elevation of the wave-cut platform and/or the top of the massive *Porites* unit as indicators of Pleistocene sea level.

Muhs et al. (2002a, b) discuss models (based on Bradley and Griggs, 1976 and Edwards et al., 1987) of the timing of marine-terrace formation as a function of sea level high stands during an interglacial period. For high energy, erosional coastlines like Baja California, the model suggests that the early stages of a sea level high stand may be dominated by terrace cutting and fossils deposited on the terrace surface represent late stages, left behind just before sea level regression. They also note the complication of reef type. ‘‘Keep-up’’ reefs are rapidly growing fringing and barrier reefs dominated by *Acropora* communities that can accommodate rising sea level, whereas ‘‘catch-up’’ reefs are slower growing types whose development may be delayed until sea level has stabilized in the late stages of sea level rise (Muhs et al., 2002b). Patch reefs are referred to as ‘‘catch-up’’ types (Neumann and MacIntyre, 1985). The massive *Porites* beds of Bahia Coyote are uncemented open-framework structures that do not easily fit classic reef terminology but are closest to ‘‘patch reefs’’. The coral colonies are built upon cobbles and reworked Cerro Colorado that forms the basal conglomeratic unit. Oysters and molluscan fragments indicate that these deposits are marine and represent the early stages of sea level rise and terrace cutting, as predicted by the model. The *Porites* communities and the platform deposits point to development late in the last interglacial sea level high stand, near its maximum height.

The determination of sea level during the last interglacial high stand is complicated and the results often controversial (Muhs and Szabo, 1994; Stirling et al., 1995, 1998). Early estimates suggested +9 m above present sea level (Shackleton, 1987) based on the deep ocean isotopic record, but high precision U-series TIMS dates and coral reef data from tectonically stable areas generally suggest lower estimates of the height of the last interglacial sea level high stand. Based on coral reefs from the western Australian margin, McCulloch and Esat (2000) calculate maximum sea level high stand during MIS 5e at ca. +4–5 m. Most previous studies of terrace-based uplift rates in Baja California have used +6 m as the elevation of the last interglacial high stand (Ashby et al., 1987; Ortlieb, 1991; Johnson and Ledesma-Vazquez, 1999; Ledesma-Vazquez and Johnson, 2001). We have adopted the conservative value of +4 m for sea level during MIS 5e and no correction for crustal rebound has been applied (Table 2).

6. Tectonic implications of the Bahia Coyote terrace deposits

Three terrace features have been used as indicators of late Pleistocene sea level: the beveled surface of the main terrace, the top of the massive *Porites* bed (*Porites* coral-heads in growth position), and the highest position of the rocky shoreline. All of these features were formed within a few meters of sea level and their present elevation provides a basis for estimating the amount of post-depositional tectonic uplift in the area. The top of the massive *Porites* unit is nearly always at the same level as the wave-cut platform. The *Porites* beds were beveled during falling sea level and subsequently covered by the regressive rhodolith–molluscan–*Porites*

Table 2
Elevation and uplift rates of Late Pleistocene terraces along the eastern margin of the Baja California peninsula

Location	Mulege/San Nicolas	El Bajo/San Telmo	Bahia Coyote	El Coyote	Punta Colorado	Cabo Pulmo	San Jose Del Cabo
Terrace elevation	+12–13 coral rubble	+8–9 reefs	+13–25 reefs	+7–10 coral rubble	+5 sand	+6 coral rubble	+6–8 sand
^{230}Th/^{234}U age (ka)	124±6	(1 2 5)	138±1	123±6	(1 2 5)	120±1	(1 2 5)
	144±7		137±4	135±6		127±1	
			139±4	140±6		139±1	
				146±9		140±4	
Rate of uplift (cm/ka) (L1 = +4 m)	6–7	(~4)	9–19	3–5	(<1)	<1	(<1)

Terraces believed to be correlative with MIS 5e but undated are shown as (125 ka). Data from many sources, including Ashby et al. (1987), Muhs et al. (1994, 2002a); Ledesma-Vazquez and Johnson (2001), Ortlieb (1987, 1991), Halfar (1999), Sirkin et al. (1990) and Szabo et al. (1990).

sands and beach deposits that cover both the terrace and corals.

The topographically highest rocky shoreline deposits at the innermost edge of the ancient embayment and in the vicinity of Punta Coyote fan-delta are located at +18–22 m above present sea level. The elevation of the terrace surface and/or massive *Porites* bed over much of the central part of the study area is +13 to +16 m, whereas the terrace block at Las Animas-North is at +20–25 m. To the north, near the Student Locality, the top of the massive *Porites* bed is ca. 16 m. Terraces to the south, outside the study area have been measured at 26 m (Nava-Sanchez, per. commun. 2002). In the center of the ancient embayment the surface of the terrace platform tilts gently towards the coast.

Living coral communities in the shallow bays surrounding the Gulf of California live at water depths of 1–10 m but are most prevalent in depths of <5 m (Squires, 1959; Brusca, 1980; Glynn et al., 1983). We have assumed a paleodepth of −3 m for the top of the massive *Porites* at the time of last interglacial sea level high stand, recognizing that this is a conservative value considering the relief of the channels in which they grew, the fact that they were eroded during falling sea level and the distance of the deposits from the ancient shoreline at maximum sea level height.

Based on elevations of the terrace surface and top of the massive *Porites* beds, assuming the corals grew at −3 m and that the last interglacial high stand sea level was +4 m, the terraces have been uplifted a minimum of 12–20 m. Assuming an age of 128 ka for the top of the *Porites* bed, the Bahia Coyote terraces have been uplifted at an average rate of ca. 8–15 cm/ka (0.08–0.15 m/ka) since the Late Pleistocene (Fig. 12).

Uplift in the Bahia Coyote area is comparable to other assumed MIS 5e terraces in the region of the Baja Peninsula between Santa Rosalia and the La Paz Peninsula. Mayer et al. (2002) report a 125 ka terrace

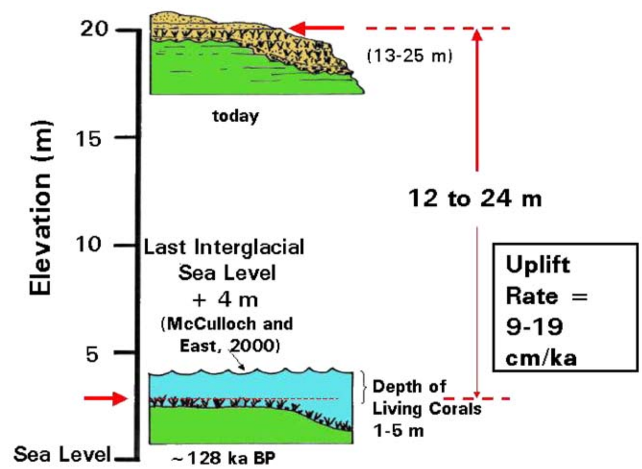

Fig. 12. Schematic diagram of modern terrace elevation compared to Late Pleistocene sea level, assuming that the massive *Porites* beds grew at a depth of about 3 m below sea level. Adjusting for a +4 m MIS 5e sea level, the Bahia Coyote terrace has been uplifted 12–24 m.

on the east side of Isla Carmen, at ca. +25 m and at El Bajo at +16 m, in the Loreto area. In the Bahia Concepcion-San Nicolas area (Ashby et al., 1987; Ortlieb, 1991; Ledesma-Vazquez and Johnson, 2001), the marine terraces are typically +12 to +13 m, at San Telmo +9 m (Squires, 1959) and the at Tecalode-El Coyote +7 to +10 m (Sirkin et al., 1990; Szabo et al., 1990). These values are in the range of the regional elevation of ca.10 m for MIS 5e terraces along the west coast of Baja California (Ortlieb, 1991, Fig. 14). South of the La Paz Fault the terraces are generally lower, +5 to +8 m (Muhs et al., 1992, 1994) and after correction for MIS 5e sea level high stand, indicate little or no tectonic uplift. Overall, the terrace data suggest that the Baja California peninsula, except for local tectonics has experienced only modest uplift in the past ca. 125 ka, a conclusion reached earlier by Ortlieb (1991).

7. Summary

The late Pleistocene terrace deposits at Bahia Coyote preserve a depositional cycle resulting from sea level rise and fall during the last interglacial. Basal beds of cobbles, reworked Cerro Colorado sandstones and oysters signal the onset of sea level rise and early terrace cutting as the Pleistocene embayment expanded across a landscape of arroyos and low ridges. As the sea level still stand developed, large, columnar *Porites* colonies which grew in thick patches spread across the central part of the embayment, filling broad channels and depressions of the flooded arroyos. In the absence of cementing algae, these patches formed open-framework structures and while they may have modified wave and tidal patterns, they were not solid reef-structures in the classic sense. U-series TIMS ages suggest the massive coral patches were well established by the early stages of MIS 5e and persisted through the high stand. The duration of the massive coral beds is unknown, but given the thickness and extend of the corals and the evidence for multiple periods of interruption and recolonization, we suspect the corals persisted through the entire interglacial sea level high stand and that the regressive rhodolith–molluscan–*Porites* marls and sands which contain small, pencil-size branching *Porites* and oyster mounds developed with the sea level fall following MIS 5. Subsequent sea level low stands produced several cycles of fanglomerates that covered much of the marine deposits.

The emergent marine terraces are now elevated +12 to +25 m above present-day sea level. Adjusting for a MIS 5e high stand sea level of +4 m (McCulloch and Esat, 2000) and probable depth of the corals when alive, the ancient embayment has been uplifted a minimum of ca. 15–20 m, although there is evidence for small differential displacement along several of the NE–SW normal faults which cut the terraces. The magnitude of the uplift of the Bahia Coyote terraces is comparable to the uplift of MIS 5e terraces along the eastern margin of the Baja California peninsula and in general agreement with the observations of Ortlieb (1991) for the entire peninsula.

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