Quaternary shorelines along the northeastern Gulf of California; Geochronological data and neotectonic implications

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ABSTRACT

A general reconnaissance of the remnants of Pleistocene high sea-level stands was conducted along the Sonora coast, between the Rio Colorado delta and the Guaymas area, to determine the neotectonic comportment of the mainland margin of the Gulf of California plate boundary.

The generally low relief of this coastal region and the extensive cover of the late Quaternary eolian sands (in the northern gulf) and alluvium (in the eastern gulf) somewhat limit the study of Pleistocene shorelines, but coastal deposits corresponding to several episodes of high sea level are preserved at low elevations all along the coastline. The morphostratigraphic interpretations and lateral correlations of these deposits support the conclusion that, unlike the Baja California peninsula and coastal California, the northeastern Gulf of California remained vertically stable, at least during the late Quaternary. Pleistocene vertical motions have been insignificant on the edge of the North American plate, except in the Rio Colorado delta area and along the Cerro Prieto fault zone, which links the San Andreas fault system and the northeastern Gulf of California.

This chapter emphasizes the problems of correlation and age determination of the terrace remnants and particularly those met in the identification of the last interglacial maximum (isotopic substage 5e, about 125,000 yr ago). Uranium-series, radiocarbon, and amino-acid stereochemistry data from fossil pelecypod shells provide useful geochronologic information, but in some cases proved to be inaccurate (large spread of Th/U ages from a single locality), or unreliable (radiocarbon), because of contamination and diagenetic alteration.

The Holocene coastal deposits are generally well developed along the Sonoran shores; several lines of evidence indicate that the sea level nearly reached its present position about 4,000 yr ago.

MARINE TERRACES, QUATERNARY CLIMATOSTRATIGRAPHY, AND RECENT VERTICAL MOTIONS

A marine terrace is a coastal landform resulting from littoral erosion produced when sea level remains long enough at a given position relative to the land. In the “stable” and slowly uplifted regions, emerged marine terraces generally correspond to the highest sea stands coeval with the Quaternary warmest episodes (global glacial minima).

It is now widely accepted that the Quaternary was characterized by glacial/interglacial climatic cycles, identified in the deep-sea-core oxygen-isotope records. The $^{18}$O isotopic variations measured in foraminifers of deep oceanic cores register the basis of the Quaternary chronostratigraphy (Shackleton and Opdyke, 1973, 1976). The episodes of eustatic high sea-level stands,
and thus of marine terrace formation, are correlatable with the main interglacial stages (IS), as defined in the oceanic isotopic curves: IS 5, 7, 9, 11, etc. During these interglaciations, which occurred, respectively, at ~125 ka (125,000 yr ago), ~200 ka, ~320 ka, etc., the sea level was close (within a few meters) to the present mean sea level (MSL).

On rapidly uplifted coastal areas of the world, three marine terraces were formed during the last interglacial period (IS 5) by high sea-level stands identified as substages 5c, 5a, and 5e, and radiometrically dated as ~125, ~105, and ~85 ka (Broecker and others, 1968; Bloom and others, 1974; Chappell, 1974; Aharon, 1983; Chappell and Shackleton, 1986). In so called “stable” areas and in coastal regions that suffered slow uplift motions in the late Quaternary (less than 100 mm/10^3 yr), only the earliest substage IS 5e marine terrace is present, which means that the last time the sea level reached a eustatically higher position than present was at 125 ka. Worldwide comparisons of last-interglacial marine-terrace elevations (involving reconstructions of uplift rates) led to the consideration that the IS 5e eustatic high sea-level stand reached a +6-m elevation above the present datum.

In this chapter, the following divisions of the Quaternary were adopted: early Pleistocene (1.8 to 0.7 Ma), middle Pleistocene (0.7 to 0.15 Ma), late Pleistocene (150 to 10 ka), Holocene (10 ka to present). The term “late Quaternary” is here meant to include the late Pleistocene and Holocene.

VERTICAL MOTIONS ALONG THE PACIFIC/NORTH AMERICAN PLATE BOUNDARY

Along the Pacific coast of the United States and northwestern Mexico, the marine terrace coeval with the IS 5e high sea-level stand is generally well preserved and identified through faunal analyses, radiometric dating, and aminostratigraphic measurements (Wehmlller and others, 1977; Kennedy and others, 1982; Kern, 1977; Ortlieb, 1984c, 1987, 1990). In this wide region, only one recent marine terrace is locally identified below the IS 5e; according to one or the other of the models of sea-level fluctuations (Bloom and others, 1974; Stearns, 1976; Aharon, 1983; Chappell and Shackleton, 1986), this terrace may be correlated with the IS 5c high sea-level stand.

Marine-terrace studies in coastal California provided estimates of middle and late Quaternary uplift rates, which generally range between 100 and 300 mm/10^3 yr (Palmer, 1967; Bradley and Griggs, 1976; Lajoie and others, 1979; McLaughlin and others, 1983).

The distribution of Pleistocene marine terraces around Baja California peninsula indicates that, since Pliocene time, the mean regional uplift rate has been of the order of 100 mm/10^3 yr, but that it has much diminished in the last few hundred thousand years in most of the area (Ortlieb, 1978, 1979, 1980, 1982b, 1984b, 1987, 1990). There are only three coastal areas that experienced recent vertical motions with rates above 100 mm/10^3 yr: east-central (Santa Rosalia), west-central (Vizcaino peninsula), and northwestern Baja California (Punta Banda). In these tectonically active areas, the IS 5e shoreline is preserved at more than +15 m, and an IS 5c (?) high sea-level stand is registered well above the present MSL (Ortlieb, 1982a, 1984a, 1984c, 1987).

Marine terraces along the eastern Gulf of California have not been studied as late as the last decade; the generally accepted idea, based on limited work in the northernmost Gulf of California (Ives, 1951, 1959, 1964; Merriam, 1965), was that the margin of the North American continent also registered strong uplift motions, particularly during the late Quaternary (Richards, 1973).

PREVIOUS STUDIES ON THE QUATERNARY COASTAL DEPOSITS IN SONORA

One of the first mentions of emerged Quaternary marine deposits on the east coast of the Gulf of California concerned the finding of marine fossils on the Sonora side of the Infiermillo Straits (McGee and Johnson, 1896; Fig. 1). Later, some brief descriptions of Pleistocene marine terraces on several islands of the eastern Gulf of California were given by Beal (1948) and Anderson (1950).

Ives, the first author to publish several papers (1951, 1959, 1964) on Quaternary shorelines, worked along the northern coast of the Gulf of California, in the vicinity of Puerto Peñasco. He supposedly identified several Pleistocene shorelines, and inferred that the area had undergone recent uplift. In contrast, Hertlein and Emerson (1956) described a relatively low-lying (+7 m maximum elevation), late Pleistocene shoreline in the same area, which would indicate that the area had not suffered vertical motions in the late Quaternary.

On the Sonoran side of the Rio Colorado delta, Merriam (1965) observed uplifted marine sediments that he supposed were fairly recent, and that thus would have documented strong Holocene uplift motions associated with the “San Jacinto” fault activity. This fault, later renamed Cerro Prieto fault, lies along the eastern side of the Rio Colorado delta and is the principal structural link between the San Andreas and Gulf of California systems (Elders and others, 1972; Fuis and others, 1982).

At a short distance from the Baja California/Sonora state boundary, Pleistocene marine deposits of the southwestern Rio Colorado delta area were studied by Thompson (1968), Walker and Thompson (1968), Ortlieb and Malpica (1978), and Ortlieb (1982b, 1987); these workers concluded that a late Pleistocene (most probably the IS 5c) shoreline is preserved at +7 to +10 m and that it shows little vertical deformation. Holocene deltalic sediments have been investigated by Gorsline (1967), Meckel (1975), and Thompsoon (1968); a few radiocarbon dates indicate that sea level reached its present position at least 3,000 yr ago (Thompson, 1968). It should be noted that, immediately north of the Mexico/U.S. border, the Salton trough has had a long history of marine, lagoonal, and lacustrine flooding since the end of the Miocene (Blake, 1854; Tarbet, 1941; Dibblee, 1954; Arnal, 1961; Thomas, 1963; Stanley, 1962; Van den Kamp, 1973; Waters, 1983; Johnson and others, 1983). During the late Quater-
nary, the episodic flooding of the Salton basin (~85 m deep at its lowest point) by northerly diversions of the Rio Colorado, has been controlled by the building up of the deltaic fan and by the neotectonic comportment of this actively faulted area (Gilmore and Castle, 1983; Gilmore, 1985, 1986; Sharp, 1982, 1986).

Marine-terrace studies along the eastern coast of the Gulf of California prior to 1975 have been very limited. The reconnaissance geologic map covering the central Sonoran coast and Tiburon Island by Gastil and Krummenacher (1974, 1977) shows a few localities of Quaternary marine deposits, which were not specifically studied.

In the last decade, detailed studies on Quaternary littoral sediments along the Sonoran coast were carried out by a Franco-Mexican group within the framework of a general reconnaissance of Quaternary marine terraces in the Gulf of California region (Geocortez program, between ORSTOM and the Instituto de Geología, Universidad Nacional Autónoma de México). This multidisciplinary work included several unpublished theses (Chavez, 1975; Celis-Gutierrez, 1975, 1979; Luna-Guerin, 1981; Gonzalez-Gonzalez, 1982), as well as published reports (Malpica and others, 1978; Ortlieb and Malpica, 1978; Coletta and Ortlieb, 1979, 1981; Bernat and others, 1980; Celis-Gutierrez, 1980; Gastil and Ortlieb, 1981), and has been updated by more recent geochemical and geochronological analyses (Ortlieb and Triclot, 1984; Ortlieb, 1987, 1990). This chapter presents a more complete panorama of the distribution of the Quaternary marine remnants, synthesizing the available information on recent vertical motions along the Sonoran coast.

Figure 1. Tectonic setting of the Sonoran coast, northeastern Gulf of California, on the edge of the North American plate. The order of magnitude of middle and late Quaternary mean uplift rates, deduced from marine-terrace studies along southwestern California and Baja California, is indicated. Map locations for this chapter are indicated by circled numbers, which refer to Figures 2, 4, 6, 8, and 10.
THE NORTHERNMOST GULF OF CALIFORNIA AND THE RIO COLORADO DELTA

Pleistocene deltaic deposits. The mouth of the Rio Colorado delta is bordered on its eastern margin by a dissected plateau called Mesa de Sonora (Fig. 2), which is essentially formed by fluvio-deltaic sediments and covered by active desert sands. The relief of the Mesa de Sonora results from an uplift motion linked to the Cerro Prieto fault activity (Colletta and Ortlieb, 1979, 1981, 1984). The substrate of the plateau had been assigned several ages: undifferentiated Tertiary (Kniffen, 1932), Pliocene (Beal, 1948), and Quaternary (Merriam, 1965). It is now well established that the sediments overlying the 1- to 3-km-thick Pleistocene deltaic sequence, revealed by recent drilling in the northernmost Gulf of California region (Eberly and Stanley, 1978; Trinidad-Reyes and Rueda-Gaxiola, 1982; Viñas-Gómez, 1982, 1984), are of middle to late Quaternary age (Ortlieb, 1987).

The coastal cliffs of the Mesa de Sonora cut fluvial continental sediments between Golfo de Santa Clara and Punta Gorda, and nearshore and marine deltaic sediments between Punta Gorda and the western shores of Bahia Adair (Fig. 2). The last-
The younger sequence includes a great variety of interfingering deltaic units capped by a coquina (Figs. 3a, b, c). The deltaic units, composed of sands, sandy silts, and silty sands, correspond to fluvial, estuarine, tidal flats, shoreface, and shallow sublittoral environments. The marine coquina is formed by slightly rounded shells of *Chione cortezii* and *Chione gnidia*, and laterally grades to fossiliferous sublittoral sandy units containing a more varied fauna (predominantly *Trachycardium panamense*, *Chione californiensis*, *Polinices reclusianus*, *Anomia adamas*). The coquina is generally covered by a thin sheet of oxidized sandy silts (including reworked material), and by eolian sands of late Quaternary age. This unit, which is relatively resistant to erosion and which has a wide lateral extent, is interpreted to register the maximum of a transgressive event. It is assigned an IS 5e age, on the triple basis of its morphostratigraphic position (highest elevated and most recent marine remnant of the area), of a uranium-series date on *Chione* shell of 129 ± 13 ka (LU 981, Table 1), and of three mentioned coastal deposits may be correlated with two, and possibly three, episodes of high sea level: a younger sequence largely cropping out in the recent sea cliffs of the southeasternmost Mesa de Sonora and along the western shores of Bahia Adair, and a few isolated remnants of older Pleistocene transgression.

### Table 1. Radiometric $^{232}Th/^{238}U$ Data from Pleistocene Pelecypod Shells Collected Along the Sonoran Coast

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Genus†</th>
<th>Calcite§</th>
<th>Lab. Number**</th>
<th>$^{238}U$ (ppm)$^\dagger$</th>
<th>$^{234}U/^{238}U$ (activity)$^\ddagger$</th>
<th>$^{230}Th/^{232}Th$ (activity)$^\mathsection$</th>
<th>$^{234}U/^{232}Th$ (activity)</th>
<th>$^{230}Th/^{232}Th$ (ka)††</th>
<th>Individual Mean</th>
<th>Morphostratigraphic age (ka)$^{\mathparagraph}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LU 221</td>
<td>Chi</td>
<td>0</td>
<td>UCT 36</td>
<td>0.524 ± 0.012</td>
<td>1.226 ± 0.034</td>
<td>142.823 ± 30.298</td>
<td>199.455 ± 42.705</td>
<td>129 ± 13</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>LQ 202</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NICC 45</td>
<td>1.00 ± 0.03</td>
<td>1.21 ± 0.08</td>
<td></td>
<td></td>
<td>42 ± 8</td>
<td>125</td>
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</tr>
<tr>
<td>LP 58</td>
<td>Dos</td>
<td>3</td>
<td>NIMB a</td>
<td>1.55 ± 0.04</td>
<td>1.16 ± 0.10</td>
<td></td>
<td></td>
<td>118 ± 17</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>LQ 181</td>
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<td>17</td>
<td>NIMB b</td>
<td>0.89 ± 0.02</td>
<td>1.38 ± 0.100</td>
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<td></td>
<td>160 ± 25</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>LP 49</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NIMB c</td>
<td>0.60 ± 0.02</td>
<td>1.26 ± 0.06</td>
<td></td>
<td></td>
<td>93 ± 13</td>
<td>125</td>
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</tr>
<tr>
<td>LP 134 a</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NIMB 37</td>
<td>0.88 ± 0.02</td>
<td>1.22 ± 0.08</td>
<td></td>
<td></td>
<td>83 ± 12</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>LP 134 b</td>
<td>Dos</td>
<td>0</td>
<td>NIMB 38</td>
<td>0.27 ± 0.010</td>
<td>1.24 ± 0.08</td>
<td></td>
<td></td>
<td>102 ± 14</td>
<td>98.5 ± 18</td>
<td></td>
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<tr>
<td>LP 134 c</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NICC 39</td>
<td>0.99 ± 0.020</td>
<td>1.31 ± 0.10</td>
<td>30.80 ± 17.59</td>
<td>49.43 ± 15.10</td>
<td>95 ± 18</td>
<td>125</td>
<td></td>
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<tr>
<td>LP 134 d</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NICC 39</td>
<td>0.30 ± 0.020</td>
<td>1.25 ± 0.120</td>
<td>88.06 ± 16.020</td>
<td>95.89 ± 32.82</td>
<td>96 ± 14</td>
<td>125</td>
<td></td>
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<tr>
<td>LP 134 e</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NIMB 41a</td>
<td>0.43 ± 0.010</td>
<td>1.14 ± 0.08</td>
<td>48.62 ± 5.800</td>
<td>71.4 ± 12.5</td>
<td>120 ± 18</td>
<td>108.0 ± 15</td>
<td></td>
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<tr>
<td>LP 134 f</td>
<td>Dos</td>
<td>0</td>
<td>NIMB 41b</td>
<td>0.55 ± 0.02</td>
<td>1.18 ± 0.08</td>
<td>115.30 ± 42.50</td>
<td>253.14 ± 114.64</td>
<td>64 ± 10</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>LP 134 g</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NIMB 41c</td>
<td>0.57 ± 0.02</td>
<td>1.23 ± 0.08</td>
<td>74.90 ± 32.800</td>
<td>252.08 ± 120.19</td>
<td>85 ± 10</td>
<td>64.5 ± 10</td>
<td></td>
</tr>
<tr>
<td>LP 134 h</td>
<td>Dos</td>
<td>0</td>
<td>NIMB 41d</td>
<td>0.92 ± 0.02</td>
<td>1.15 ± 0.08</td>
<td></td>
<td></td>
<td>80 ± 12</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>LP 134 i</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NIMB 41e</td>
<td>1.02 ± 0.03</td>
<td>1.17 ± 0.10</td>
<td>80.70 ± 15.000</td>
<td>&gt;100</td>
<td>84 ± 12</td>
<td>85 ± 13</td>
<td></td>
</tr>
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<td>Dos</td>
<td>0</td>
<td>NIMB 42</td>
<td>0.48 ± 0.010</td>
<td>1.21 ± 0.10</td>
<td>31.09 ± 7.800</td>
<td>57.37 ± 17.96</td>
<td>83 ± 13</td>
<td>82 ± 11</td>
<td></td>
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<tr>
<td>LQ 149 a</td>
<td>Dos</td>
<td>&lt;3</td>
<td>NIMB d</td>
<td>0.46 ± 0.010</td>
<td>1.26 ± 0.10</td>
<td></td>
<td></td>
<td>84 ± 12</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>LQ 149 b</td>
<td>Dos</td>
<td>&lt;3</td>
<td>NIMB e</td>
<td>0.46 ± 0.010</td>
<td>1.18 ± 0.08</td>
<td></td>
<td></td>
<td>100 ± 14</td>
<td>125</td>
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</tr>
<tr>
<td>LP 1075a</td>
<td>Dos</td>
<td>0</td>
<td>UQT 42</td>
<td>1.147 ± 0.029</td>
<td>1.229 ± 0.031</td>
<td></td>
<td></td>
<td>66.6 ± 5</td>
<td>125</td>
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</tr>
<tr>
<td>LQ 141</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NIMB f</td>
<td>0.71 ± 0.02</td>
<td>1.21 ± 0.08</td>
<td></td>
<td></td>
<td>86 ± 12</td>
<td>125</td>
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<tr>
<td>LQ 175</td>
<td>Dos</td>
<td>&lt;1</td>
<td>NIMB g</td>
<td>0.92 ± 0.02</td>
<td>1.26 ± 0.08</td>
<td></td>
<td></td>
<td>83 ± 12</td>
<td>125</td>
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<tr>
<td>LP 28</td>
<td>Dos</td>
<td>&lt;3</td>
<td>NIMB h</td>
<td>2.66 ± 0.070</td>
<td>1.25 ± 0.04</td>
<td></td>
<td></td>
<td>22.8 ± 3</td>
<td>20.9 ± 3</td>
<td>125</td>
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<td>Dos</td>
<td>1</td>
<td>NIMB i</td>
<td>1.53 ± 0.4</td>
<td>1.28 ± 0.08</td>
<td></td>
<td></td>
<td>19 ± 2.5</td>
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</tbody>
</table>

*See location of the samples in the maps of Figures 2, 4, 6, and 10, and in the sections shown in Figures 3, 5, 7, and 9. The Th/U geochronological results are poorly reliable, and generally provide only minimum ages (see text).
†Dos = Dosinia ponderosa; Chi = Chione sp.
‡Calcite/(aragonite + calcite) x 100.
§Lab. Number = Lab. Géotop (UQAM, Montreal); NICC = Lab. Géochronol., Univ. Nice (C. Gausse); NIMB = Idem (M. Bernat).
$^\dagger$Low (<0.5 ppm), or high (>2 ppm), uranium content.
$^\ddagger$Activity >1.30.
$^\mathsection$Activity <1 percent.
††Calculated error corresponding to ± 1σ.
$^{\mathparagraph}$See discussion in text.
of out of four aminostratigraphic analyses (LS 647, LS 649, and LS 660, Table 2).

Between Punta Gorda and Bahia Adair, the younger deltaic and marine sequence unconformably overlies one or two series of marine sediments (Figs. 3b, c). The older units are distinguished from the IS 5e deposits by the stronger cementation of the sediments and by the fact that the invertebrate skeletal remains are much more altered than are the fossils of the younger unit. In the older unit(s), the remaining fossils are those that were originally composed of low-magnesium calcite, like Encope sp. (echinoderms), Anomia sp., Ostrea palmula, and Pecten sp. (pelecypods); the originally aragonitic mollusk shells (like Chione sp., Trachycardium sp., etc.) are found mostly in casts, many of which are now filled with sparry calcite. Petrographic studies clearly indicate that the older sediments suffered a long diagenetic history, involving several cycles of calcite dissolution/precipitation and neomorphic transformations, while the late Pleistocene sediments show only one main cycle of partial dissolution of bioclasts and intergranular cementation (Ortlieb, 1987).

The older sediments, which generally crop out underneath (or at least morphostratigraphically below) the late Pleistocene sequence, are interpreted to be coeval with one of the latest middle Pleistocene high sea-level stands (IS 7 and/or 9 7). It has not been determined whether distinct outcrops of pre–late Pleistocene marine and nearshore units correspond to a single, or to several episode(s) of high sea level. From the present position of these sediments, and by extrapolating the uplift evidenced in the late Quaternary, it is inferred that during the last interglaciation(s) of the middle Pleistocene, sea level reached an elevation close to its present position.

The Chione coquina, and all previous nearshore sediments, are totally lacking in the sea cliffs from Punta Gorda northwestward. The thick fluvio-deltaic sands, which crop out in the cliff along the shore from Punta Gorda to the Rio Colorado mouth, are stratigraphically older than the late Pleistocene marine-deltaic sequence, and thus are assigned a late middle Pleistocene age. North of Golfo de Santa Clara, these relatively old fluvio-deltaic sediments are locally eroded and overlain by a narrow fluvial channel deposit that has been tentatively correlated with the late Pleistocene marine-deltaic sequence (Colletta and Ortlieb, 1981, 1984). The stratigraphic and geographic distribution of late Quaternary sediments (Ortlieb, 1987) suggests that during the last high sea-level stand (IS 5e) the Rio Colorado delta was forked, with another arm running southeastward from Yuma to the area of Salina Grande (Fig. 2).

Tectonic deformation. The Chione coquina, which is considered an index bed and is believed to have been originally horizontal (interbedded unit), shows that the southeastern part of the Mesa de Sonora underwent recent vertical motion. This unit crops out at a maximum elevation of +23 m at Punta Gorda, then slopes down toward the east, and is observed at +12 to +10 m between Punta Gorda and Bahia Adair. The altimetric position of the Chione coquina thus depicts both a local relative upwarding of more than 10 m at Punta Gorda and a wider regional uplift, which only amounts to a few meters (with respect to an assumed “eustatic” +6-m position of the sea during IS 5e).

At the top of the sea cliff at Punta Gorda, the Chione coquina is the only unit that is not displaced by the Punta Gorda fault. This WNW-ESE–oriented fault is the southeasternmost feature associated with the Cerro Prieto fault system, along the Mesa de Sonora (see location in Fig. 11; Colletta and Ortlieb, 1984). As a major structural feature, this fault system has probably been active during the entire Quaternary, and possibly since the Pliocene. From the deformation evident on the southwestern edge of the Mesa de Sonora, it is deduced that a major faulting event, accompanied by a strong uplift (or more than 100 m), occurred at the end of the middle Pleistocene. The uplift may be the result of a transpressive folding, like the one described at present on Durmid Hill along the Banning–Mission Creek (San Andreas) fault (Hudnut and others, 1985; Maloney, 1986). During the late Quaternary, the focus of the main faulting activity apparently migrated toward the southwest, along the present-day coastline, and the uplift continued, probably at a lesser rate than at the end of the middle Pleistocene. The vertical motion experienced since 125 ka by the southeastern rim of the Mesa de Sonora, rapidly decreased from a maximum (mean) rate of 200 mm/10^3 yr (at Punta Gorda) to a low rate of less than 30 mm/10^3 yr.

THE NORTHEASTERN EXTREMITY OF THE GULF OF CALIFORNIA

Pleistocene nearshore deposits. The coastal area and a large part of the hinterland of the northeastern extremity of the Gulf of California are mantled with thick dunes and eolian sand sheets, which were deposited during the major part of the Quaternary. This wide sand cover hampers the recognition of emerged remnants of high sea-level stands. Actually, the only well-identified Pleistocene marine deposits crop out along the present coastline. These partially cemented fossiliferous sands and gravels, which reach a maximum elevation of +7 to +8 m, have been described in the northeasternmost Bahia Adair (Ortlieb, 1987), in the Punta Pelicano–Puerto Peñasco area (Hertlein and Emerson, 1956; Ortlieb and Malpica, 1978; Malpica and others, 1978; Ortlieb, 1987), and in Bahia San Jorge (Estero San Jorge, Isla San Jorge near the railroad station at Almejas; Beal, 1948; Ortlieb, 1987; Fig. 2); no Pleistocene marine deposits were observed in southeastern Bahia San Jorge or along the Rio Concepcion delta (Fig. 2).

The outcrops from the Puerto Peñasco area provided 14C ages of 35,200 and 43,000 B.P. on mollusk shells (Inman, in Sandusky, 1969), which are not considered reliable, and did not yield Th/U dates. Nevertheless, morphostratigraphic, petrographic, and paleontologic criteria support a chronologic correlation of these marine sediments with the last interglacial maximum (IS 5e).

In the vicinity of Puerto Peñasco, Ives (1951, 1959, 1964, 1971) reported possible remains of several distinct shorelines: at a
### TABLE 2. AMINOSTRATIGRAPHIC DATA, AND COMPARISON WITH OTHER GEOCHRONOLOGICAL RESULTS OBTAINED ON PELECYPOD SHELLS FROM EMERGED PLEISTOCENE COASTAL DEPOSITS OF SONORA*

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Genus†</th>
<th>Morphostratigraphic Age (IS)§</th>
<th>Radiometric Age (ka)**</th>
<th>Aminostratigraphic Age</th>
<th>Racemized State‡</th>
<th>Aminostratigraphic Interpretation (IS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP 28</td>
<td>Dos</td>
<td>5e</td>
<td>32(0)/21(+)</td>
<td>0.90(*)</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LS 642 a</td>
<td>Chi</td>
<td>5e? (or 5c)</td>
<td>33.5(0)</td>
<td>0.81</td>
<td>R</td>
<td>5e or 5c?</td>
</tr>
<tr>
<td>LS 681 a</td>
<td>Chi</td>
<td>5e? (or 5c)</td>
<td>31(0)</td>
<td>1.06</td>
<td>R</td>
<td>5e or 5c?</td>
</tr>
<tr>
<td>LT 700 i</td>
<td>Pro</td>
<td></td>
<td></td>
<td>0.662</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LT 700 o</td>
<td>Chi</td>
<td>5e? (or 5c)</td>
<td>31–33(0)</td>
<td>0.71</td>
<td>5e or 5c?</td>
<td></td>
</tr>
<tr>
<td>LQ 202</td>
<td>Dos</td>
<td>5e</td>
<td>42(+)</td>
<td>0.86(+)</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LP 49 Dp</td>
<td>Dos</td>
<td>5e</td>
<td>93(+)</td>
<td>1.09(*)</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LP 49 d</td>
<td>Chi</td>
<td></td>
<td></td>
<td>0.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP 49 d</td>
<td>Chi</td>
<td></td>
<td></td>
<td>0.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP 58 Dp</td>
<td>Dos</td>
<td>5e</td>
<td>118(+)</td>
<td>0.89(*)</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LP 63</td>
<td>Chi</td>
<td></td>
<td></td>
<td>0.86(*)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP 134 Dp</td>
<td>Dos</td>
<td>5e</td>
<td>82(+)</td>
<td>0.88(*)</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LP 134 a</td>
<td>Dos</td>
<td>5e</td>
<td>84(+)</td>
<td>1.33</td>
<td>R</td>
<td>5e or 5c?</td>
</tr>
<tr>
<td>LP 134 a</td>
<td>Chi</td>
<td></td>
<td></td>
<td>1.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP 134 d</td>
<td>Chi</td>
<td></td>
<td></td>
<td>0.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LQ 141 a</td>
<td>Chi</td>
<td>5e</td>
<td>86(+)</td>
<td>1.11</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LQ 141 Dp</td>
<td>Dos</td>
<td>5e</td>
<td>1.05(+)</td>
<td>5e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LQ 149 a</td>
<td>Dos</td>
<td>5e</td>
<td>84(+)</td>
<td>0.91(*)</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LQ 149 b</td>
<td>Dos</td>
<td>5e</td>
<td>86(+)</td>
<td>0.95(+)</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LQ 181 Dp</td>
<td>Dos</td>
<td>5e</td>
<td>180(+)</td>
<td>0.96(+)</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LQ 181 a</td>
<td>Dos</td>
<td></td>
<td></td>
<td>1.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LQ 175 Dp</td>
<td>Dos</td>
<td>5e</td>
<td>83(+)</td>
<td>0.89(*)</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LQ 175 a</td>
<td>Chi</td>
<td>5e</td>
<td>83(+)</td>
<td>0.89</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LQ 175 d</td>
<td>Dos</td>
<td></td>
<td></td>
<td>1.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LQ 175 Dp</td>
<td>Chi</td>
<td></td>
<td></td>
<td>0.86</td>
<td>5e</td>
<td></td>
</tr>
<tr>
<td>LQ 159 c</td>
<td>Dos</td>
<td>5e</td>
<td></td>
<td>0.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS 847</td>
<td>Chi</td>
<td>5e</td>
<td>129(+)</td>
<td>0.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS 849</td>
<td>Chi</td>
<td>5e</td>
<td>129(+)</td>
<td>0.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS 560</td>
<td>Chi</td>
<td>5e</td>
<td>1.13</td>
<td>5e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LT 755</td>
<td>Chi</td>
<td></td>
<td></td>
<td>1.18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*See location of the samples in Figures 2 to 10. The accuracy of the aminostratigraphic interpretation is limited by high late Quaternary temperatures in the Gulf of California, but it may be considered that localities that contain at least one unracemic sample are not older than early late Pleistocene (IS 5e, Ortlieb, 1987).
†Dos = Dosinia ponderosa; Chi = Chione sp.
‡See discussion in text; IS = Isotopic stage.
**α = apparent Th/U age (see Table 1); δ = apparent 14C age (see Table 3).
†Analyses by G. Miller (INSTAAR, University of Colorado), except for (α) by R. Mitterer (University of Texas).
§SR = racemic samples.
Quaternary shorelines, northeastern Gulf of California

few meters above MSL, at +23 m (“Chione cancellata shoreline”); at +35 m; and at +60 to 90 m (“Turritella shoreline”). Later studies in the area (Hertlein and Emerson, 1956; J. F. Schreiber, Jr., personal communication, 1977; Ortlieb and Nalpica, 1978) established that the only well-preserved coastal remnants are those related to the \(-7\) high sea-level stand (Figs. 3d, f), and that the more elevated “shorelines” were either misinterpreted eolian sands or artificial accumulations of marine shells (by prehistoric Indians or by animals) (Ortlieb, 1987). In one locality in northeasternmost Bahia Adair (Fig. 2), not mentioned by Ives, two Quaternary marine deposits can be distinguished at maximum elevations of +7 and +13 m (Figs. 3d, e). The strong alteration of the sediments and poor exposure conditions hindered a definitive chronostratigraphic interpretation of these deposits; the lowest-lying unit shows many sedimentologic and faunal similarities with the Chione coquina of southwesternmost Bahia Adair and, on this basis, is tentatively assigned an IS 5e age.

Thus, in the northeasternmost Gulf of California, the remnants of a late Pleistocene transgression indicate a +6- to +7-m sea-level maximum, while middle Pleistocene emerged marine sediments have been preserved in only one locality (northeastern Bahia Adair) at as much as +13 m.

**Beachrock and Holocene coastal deposits.** Wide beachrock units crop out in the intertidal and upper sublittoral zones, between Bahia Adair and Bahia San Jorge (particularly at Playa Hermosa and Playa de Oro, respectively west and east of Puerto Peñasco), and were interpreted to be of possible Holocene age (Sandusky, 1969; Jones, 1975; Rose, 1975). Petrographic studies show that this extensive beachrock unit is primarily of late Pleistocene age (Ortlieb, 1987); evidence of dissolution by meteoric and vadose water of the aragonitic bioclasts and of the primary cement indicate that the unit was originally formed in the intertidal zone and subsequently emerged during a relatively long period. Recent typical beachrock cementation is now in process in the intertidal zone and affects Holocene sands and submerged outcrops of the IS 5e sandstone and beachrock (Fig. 3f). The succession of dissolution and cementation phases evidenced by petrographic analyses are diagnostic to distinguish between presently submerged Pleistocene and Holocene nearshore sediments.

In the northern Gulf of California, the high tidal range (about 4 m), the seasonally elevated temperature (above 30°C) and the abundance of sands and biogenic carbonates in the coastal area have been favorable conditions for beachrock formation during both the last (IS 5e) and the present interglacial periods.

A Holocene coastal sequence, including consolidated fossiliferous beach sands, lagoonal silty clays, and marsh peat beds, crops out below the high-tide level at Campo Santo Tomas, 30 km north of Rio Concepcion mouth (Fig. 2). This sequence pre-dates the formation of the Holocene dune ridge that rims the coastline all along the Rio Concepcion delta (Fig. 3g). Two \(^{14}C\) ages of 4,000 \pm 170 and 5,570 \pm 270 B.P. were obtained on shell and peat samples (LT 933 and LT 936, Table 3). A stratigraphic study of these deposits suggests that Holocene sea level reached its present position about 5,000 yr ago; the regressive part of the sequence is more probably due to a progradation of the shoreline rather than to a fall of the sea level in mid-Holocene time.

This model of Holocene sea-level evolution, according to which the sea would have been close to its present position for several thousand years, is supported by many observations along the northern Gulf of California, and especially in the southwestern Rio Colorado delta (Thompson, 1968), Bahia Adair, and Bahia San Jorge (Ortlieb, 1987).

**THE CENTRAL SONORAN COAST**

Between Puerto Lobos and Guaymas (Fig. 4), the eastern coast of the Gulf of California is characterized by an alternation of large bays, protected by hilly headlands and steep rocky stretches, where the coastline cuts the N-S-oriented ranges. Three typical coastal landscapes may be distinguished in central Sonora: rocky cliffs, sandy beaches backed by eolian dunes, and piedmont sequences (bajadas) cut in vertical cliffs by the Holocene sea. Pleistocene high sea-level stands are registered as abraded littoral platforms or as sequences of nearshore sediments capped by late Quaternary eolianites or thick bajada deposits. The erosional features register the position of former sea-level maxima better than the depositional sequences do.

**Puerto Lobos area**

The coastal cliffs of Bahia Lobos, south of Puerto Lobos, contain remains of two Pleistocene marine sequences (Fig. 4). The younger marine unit crops out on the abraded littoral platform, which constitutes the peninsula of Puerto Lobos (Fig. 5a), in the low sea cliffs located immediately east of Puerto Lobos village (Fig. 5b), and in the southeastern Bahia de Lobos (Campo Julio) (Figs. 5d, e). These beach deposits, which reach a maximum elevation of +7 m, are characterized by a weak cementation and a well-preserved fauna. They are overlain by a few-meter-thick, poorly consolidated alluvium. A Dosinia ponderosa shell from the marine unit (LQ 202; 1 km east of Puerto Lobos) provided a Th/U age of 42 \pm 8 ka (Bernat and others, 1980; Table 1) and an aminostratigraphic result that suggests an IS 5e age (Table 2). Because of their morphostratigraphic position (below a late Quaternary continental sequence) and petrographic characteristics (similar to that of early late Pleistocene sediments of the northernmost gulf), these beach deposits are interpreted to be coeval with the IS 5e.

The older marine sequence crops out in the middle part of Bahia Lobos, at the base of the vertical sea cliffs, under 10 to 30 m of consolidated alluvium (Fig. 5c). The nearshore sediments, which include marine conglomerate and fossiliferous sandstones, as well as tidal-flat silts and estuarine gravels, are more indurated and altered than the younger marine unit. In these sediments, the aragonitic bioclasts have been dissolved and/or replaced by sparry calcite; the only preserved fossil shells are oysters (Ostrea californica cf. osunai, O. columbiensis, O. corteziensis) and cir-
ripeds (*Tetraclita squamosa*). This composite nearshore sequence is seen from below sea level up to a maximum elevation of +12 m. Its age has not been determined, but is most probably middle Pleistocene.

**Puerto Libertad area**

The surroundings of Puerto Libertad (Fig. 4) contain the most numerous, and highest-elevated Quaternary marine remnants that have been identified along the Sonoran coast. The youngest Pleistocene marine deposits crop out extensively to the north and south of Punta Bola, the headland that limits Bahia Libertad to the north (Fig. 4). They typically consist of poorly consolidated fossiliferous sands and gravels that overlie littoral platforms cut in substrates of various lithologies. These coastal marine sediments, in turn, are mantled by alluvium and/or several-meter-thick eolianites, especially at Playa Santa Maria (Fig. 5f), Playa Lobitos (Figs. 5h, i), and southeastern Bahia Libertad (Figs. 5j, k, l). The sea-level maximum coeval with these deposits reached an elevation of about +6 m. The faunal content of the unit, which is particularly fossiliferous northwest of the Puerto Libertad village, has been described by Stump (1975), Celis-Gutierrez (1979, 1980), Celis-Gutierrez and Malpica-Cruz (1981), and Ortlieb (1987).

A *Dosina ponderosa* shell, collected 1 km west of Puerto Libertad (LP 58), yielded a Th/U age of 118 ± 17 ka (Table 1). The same *Dosina ponderosa* specimen and a *Chione* sp. shell (LP...)

<table>
<thead>
<tr>
<th>Locality</th>
<th>Sample Number</th>
<th>Species</th>
<th>Calculated 14C Age (uncorrected)</th>
<th>δ13C/PM</th>
<th>δ18O/PM</th>
<th>Analysis Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estero Las Lisas LS 662</td>
<td><em>Chione</em> sp.</td>
<td>21,000 ± 1,600</td>
<td>+1.14</td>
<td>-1.14</td>
<td>University Paris Sud UPS 2435</td>
<td></td>
</tr>
<tr>
<td>Bahia San Jorge LT 726</td>
<td><em>Chione</em> sp.</td>
<td>26,500 ± 200</td>
<td>+1.13</td>
<td>-1.20</td>
<td>University Paris Sud UPS 3779</td>
<td></td>
</tr>
<tr>
<td>Santo Tomás LT 933</td>
<td>Various mollusks</td>
<td>4,000 ± 170</td>
<td>-4.65</td>
<td>-1.50</td>
<td>University Paris Sud UPS 2442</td>
<td></td>
</tr>
<tr>
<td>LT 936</td>
<td>Peat</td>
<td>5,570 ± 270</td>
<td></td>
<td></td>
<td>University Paris Sud UPS 2465</td>
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</tr>
<tr>
<td>Rio San Ignacio Estuary HGR 1</td>
<td><em>Lyropecten</em> sp.</td>
<td>29,550 ± 1,115</td>
<td></td>
<td></td>
<td>Results from H. G. Richards, 1973</td>
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</tr>
<tr>
<td>HGR 2</td>
<td><em>Muricanthus</em> sp.</td>
<td>26,770 ± 525</td>
<td></td>
<td></td>
<td>University Paris VI</td>
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</tr>
<tr>
<td>HGR 3</td>
<td><em>Anomia peruviana</em></td>
<td>≥42,000</td>
<td></td>
<td></td>
<td>University Paris VI</td>
<td></td>
</tr>
<tr>
<td>HGR 4</td>
<td><em>(Chione sp.,?)</em></td>
<td>26,770 ± 525</td>
<td></td>
<td></td>
<td>University Paris VI</td>
<td></td>
</tr>
<tr>
<td>NPM</td>
<td><em>Chione</em> fluctifraga</td>
<td>20,150 ± 230</td>
<td></td>
<td></td>
<td>University Paris VI</td>
<td></td>
</tr>
<tr>
<td>LTf 1</td>
<td><em>Chione</em> fluctifraga</td>
<td>27,900 ± 1,000</td>
<td></td>
<td></td>
<td>University Paris VI</td>
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<tr>
<td>LTf 3</td>
<td><em>Chione</em> fluctifraga</td>
<td>29,500 ± 950</td>
<td></td>
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<tr>
<td>LR 642</td>
<td><em>Chione</em> fluctifraga</td>
<td>33,500 ± 2,945</td>
<td>-2,140</td>
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<tr>
<td>LS 666a</td>
<td><em>Chione</em> fluctifraga</td>
<td>35,300 ± 2,500</td>
<td>-1,900</td>
<td></td>
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<tr>
<td>Tezopopa Region LS 666b</td>
<td><em>Chione</em> fluctifraga</td>
<td>32,520 ± 1,725</td>
<td>-1,420</td>
<td>+0.61</td>
<td>Queens College (N.Y.) QC 556/2</td>
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<tr>
<td>LS 669</td>
<td><em>Chione</em> undata</td>
<td>30,580 ± 1,200</td>
<td>+0.88</td>
<td>-1.63</td>
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<tr>
<td>LS 680</td>
<td><em>Chione</em> fluctifraga</td>
<td>33,800 ± 1,500</td>
<td>+0.48</td>
<td>-1.41</td>
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<td>LS 681a</td>
<td><em>Chione</em> fluctifraga</td>
<td>31,200 ± 850</td>
<td>+0.95</td>
<td>-1.09</td>
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<td>LT 681b</td>
<td><em>Chione</em> fluctifraga</td>
<td>24,150 ± 150</td>
<td>+0.61</td>
<td>-1.44</td>
<td>University Paris Sud UPS 2578</td>
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<tr>
<td>LT 700a</td>
<td><em>Ostrea</em> palmula</td>
<td>33,000 ± 1,500</td>
<td>+1.06</td>
<td>-1.22</td>
<td>University Paris VI</td>
<td></td>
</tr>
<tr>
<td>LT 700b</td>
<td><em>Trachycardium panamense</em></td>
<td>31,530 ± 1,500</td>
<td>+1.06</td>
<td>-0.79</td>
<td>University Paris VI</td>
<td></td>
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</tbody>
</table>

*Beside the results from Santo Tomas, which correspond to mid-Holocene samples (LT 933 and LT 936), all the apparent 14C ages are interpreted to be minimum ages; emerged pelecypod shells, which provided dates in the range 20,000 to 35,000 B.P., are most probably of early late Pleistocene (IS 5) age. The measured activity is attributed to contaminations by modern organic matter (1 to 3 percent).*
Quaternary shorelines, northeastern Gulf of California

Figure 4. Puerto Lobos–Punta Cuevas region: distribution and height of Pleistocene shorelines. 1. Quaternary alluvium and colluvial sands. 2. Pre-Quaternary units (geologic contours simplified from Gastil and Krummenacher, 1974). 3. Location of the sections of Quaternary coastal deposits shown in Figure 5 (a to m, upper half), and in Figure 7 (a to d, bottom). 4. Maximum elevation (meters above present MSL) of the early late Pleistocene (IS 5e) shoreline. 5. Elevation of middle Pleistocene shorelines (meters above present MSL).
ternary coastal dunes overlying the graphic analyses could be established with the middle Pleistocene. The +23-m marine bench of Playa Santa Maria is the highest-marine remnants of Bahia Libertad. Nevertheless, the geometric high-tide level; this small remnant of an old unit, with recrystalized bioclasts, is tentatively correlated with the oldest middle Pleistocene. Thus, two middle(? Pleistocene transgressions have been registered in southeastern Bahia Libertad, before the deposition of the IS 5e sediments. The maximum sea level coeval with the oldest marine unit was probably at more than +10 m, while the reconstructed paleo-sea level responsible for the intermediate fluvi-marine unit probably reached a lower elevation, between +5 and +10 m.

In the embayment of Playa Lobitos, north of Puerto Libertad (Fig. 4), the main outcrops of Quaternary coastal deposits are those left by the late Pleistocene highest sea-level (IS 5e) episode, which point to a +6-m sea level (Figs. 5i, j). In the center of the bay, a single outcrop of cemented gravel may be observed below high-tide level; this small remnant of an old unit, with recrystallized bioclasts, is tentatively correlated with the oldest middle Pleistocene sublittoral sequence described in southeastern Bahia Libertad.

At Playa Santa Maria (named Playa Santa Margarita by Gastil and Krummenacher, 1974; Fig. 4), coastal deposits, which have many similarities with those described at Playa Lobitos and Bahia Libertad and which reach the same +5 to +6-m elevation, are also assigned an IS 5e age (Fig. 5f). Three other littoral platforms, veneered with marine pebbles, are preserved at elevations of +10 to +12, +15, and +23 m (Fig. 5g). These remains of Pleistocene high-sea-level stands are devoid of any fossil material and therefore could not be dated; as the shore platforms do not support consolidated sediments, no correlation based on petrographic analyses could be established with the middle Pleistocene marine remnants of Bahia Libertad. Nevertheless, the geometric relations existing between these marine benches and the late Quaternary coastal dunes overlying the IS 5e marine unit indicate that the former must have been carved out before the late Pleistocene. The +23-m marine bench of Playa Santa Maria is the highest-elevated Pleistocene shoreline known in the eastern Gulf of California.

South of Punta Cirio, along the Sierra Bacha coast, a low-lying marine terrace, correlatable with the IS 5e sea-level maximum, is relatively well preserved. A conspicuous marine bench, which reaches a maximum +5-m elevation and supports associated nearshore deposits, is visible north and south of the Punta Cuevas fishermen camp. A Th/U age of 180 ± 25 ka, obtained on a Dosinia ponderosa shell from Punta Cuevas (LQ 181, Table 1), is not significant because 17 percent of the original aragonite has recrystallized to calcite. Aminostratigraphic data from the same shell and another one from the same locality (LQ 181, Table 2) rule out the possibility that this marine terrace is older than IS 5e (or that the shells had been reworked from a pre–late Pleistocene deposit). In the same bay of Punta Cuevas, there are some faint morphologic indications of an older (middle Pleistocene) shoreline several hundred meters inland from the coastline and under a relatively thick unit of late Quaternary alluvium (Ortlieb, 1987).

**Topopa area**

**Morphostratigraphy of Pleistocene nearshore units.** The coastal region extending from the southern extremity of Sierra Bacha to the northern end of the Canal del Infiernillo (Figs. 4 and 6) contains two sequences of Pleistocene marine sediments. The two sequences are observed in stratigraphic order at the

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**Figure 5. Sections of Quaternary coastal deposits in the Puerto Lobos (a to e)–Puerto Libertad (f to m) region (see locations in Fig. 4). Section a: 1. Marine platform cut in Mesozoic volcanic substrate. 2. Late Quaternary terrestrial sediments. Section b: 1. Consolidated alluvium (middle Pleistocene). 2. Early late Pleistocene nearshore sequence (LQ 202). 3. Unconsolidated bajada sediments (late Quaternary). Section c: 1. Cemented alluvium (middle Pleistocene). 2. Middle Pleistocene nearshore sequence. 3. Consolidated bajada sediments (late middle Pleistocene) (see b1). Section d: 1. Tidalites and bioclastic littoral sands (middle Pleistocene). 2. Late Pleistocene nearshore sequence. 3. See b3. Section e: 1. See c1. 2. See d2. 3. See d3. Section f: 1. Marine platform cut in Mesozoic substrate. 2. Early late Pleistocene nearshore sequence. 3. Late Quaternary sand dune. Section g: 1. Mesozoic substrate. 2. Littoral platforms veneered with marine pebbles, at +10 to +12 m and +15 m (middle Pleistocene). 3. Highest observed marine platform (+23 m), covered with poorly cemented gravels (middle Pleistocene). 3. See f3. Section h: 1. Consolidated conglomerate including shell fragments (middle Pleistocene). 2. Early late Pleistocene nearshore sequence. 3. Late Pleistocene laggonal fine sands and alluvium. 4. Late Quaternary sand dune. Section i: 1. Granodioritic substrate. 2. Late Pleistocene nearshore sequence. 3. Late Quaternary slope deposits and alluvium. 4. See h4. Section j: 1. Early late Pleistocene nearshore sequence, ending with a Tagelus californianus–Chione californiensis coquina. 2. Late Quaternary sand dune. Section k: 1. Wave-abraded Miocene volcanoclastic substrate. 2. Early late Pleistocene nearshore sequence (LP 58 and LP 63). 3. Late Quaternary alluvial cover. Section l: 1. Fossiliferous sublittoral sand, rich in echinoids and oysters, locally covered by unconformable bioherms (middle Pleistocene). 2. Early late Pleistocene upper-beach deposits. 3. Late Quaternary sand dunes. Section m: 1. Mesozoic granitic substrate. 2. Middle Pleistocene nearshore sequence. 3. See i3.
Figure 6. The Tepopa region: main morphological units, and locations of the sections of Quaternary coastal deposits shown in Figure 7 (d to h) and geochronological samples of Tables 1, 2, and 3.
Quaternary shorelines, northeastern Gulf of California

Figure 7. Sections of Quaternary coastal deposits in the Rio San Ignacio delta, Tepopa region (see location in Figs. 4 [a to d] and 6 [d to i]. Section a: 1. Mesozoic granodioritic substrate. 2. Early late Pleistocene nearshore sequence. 3. Late Quaternary bajada deposits. Section b: 1. Fossiliferous cemented gravels and sandstones (middle Pleistocene). 2. Bioherm of Ostrea fisheri (middle Pleistocene?). 3. Early late Pleistocene nearshore sequence (LP 49). 4. See a3. Section c: 1. See a1. 2. Consolidated alluvium (latest[?] middle Pleistocene). 3. See b3. 4. See b4. Section d: 1. Poorly consolidated and very fossiliferous conglomerate (early late Pleistocene). 2. Upper-beach deposits (early late Pleistocene). 3. Late Pleistocene eolianite. 4. Holocene sand dune. Section e: 1. Early late Pleistocene beach deposits (LT 700). 2. Late Pleistocene lagoonal sediments. 3. Late Quaternary alluvium. 4. Late Quaternary eolian sands. Section f: 1. Mesozoic substrate. 2. Early late Pleistocene nearshore sequence. 3. Late Quaternary slope deposits. Section g: 1. See f1. 2. Early late Pleistocene nearshore sequence, including thick units of boulders (LP 134). 3. See f3. Section h: 1. Fossiliferous early late Pleistocene nearshore sequence. 2. Early late Pleistocene shingle ridge deposits. 3. Late Quaternary alluvium cover. Section i: 1. Latest middle Pleistocene alluvium. 2. Early late Pleistocene nearshore and lagoonal sequence. 3. Late Quaternary bajada deposits. 4. Late Quaternary eolian sands. 5. Playa reworked sediments (Holocene).

southwestern end of Sierra Bacha (S. Tordilla), 4 km north of the mouth of Rio San Ignacio (Figs. 7a, b, c). The older sequence crops out at the base of the coastal cliff, up to an elevation of +5 to +10(?) m, and mainly consists of well-cemented gravels and sandstones, which include pectens (*Pecten vogdesi*, *Argopecten circularis*), oysters (*Ostrea cortesiensis*), and molds of other mollusk shells (*Trachycardium* sp., *Codakia distinguenda*, *Glycymeris* sp.). This several-meter-thick unit is locally covered by an unconformable bioherm of *Ostrea fisheri* and *Encope grandis*, which postdates it (distinct interglacial high sea-level stand, or separate high sea-level episode during the same interglaciation?).

Stratigraphically above all these deposits (Figs. 7b, c), or directly above a marine bench carved out in the granodioritic substrate (Fig. 7a), lies a younger marine unit formed by poorly consolidated beach sands and gravels. The sea level coeval with this deposit may be reconstructed at about +6 m above MSL. *Dosinia ponderosa* shells, collected in this marine unit (LP 49), yielded an apparent Th/U age of 93 ± 13 ka (Table 1) and two aminostratigraphical results compatible with an IS 5e age (Table 2).

The youngest marine unit is covered by several meters of unconsolidated bajada deposits that accumulated during the late Quaternary. The older marine sequence (Figs. 7b, c), which is also locally overlain by bajada deposits (twice as thick and a little more cemented than the late Quaternary alluvium), is interpreted to be of latest[?] middle Pleistocene age.

Around the headland of Punta Tepopa (Fig. 6), the IS 5e high-sea-level stand reached a maximum elevation of about +6 m, evidenced by almost continuous coastal deposits. During this early late Pleistocene high sea-level stand, the steep, rocky coastline was actively eroded by wave action and was bordered by narrow cobble beaches. Southeast of Cerro Tepopa, this late
Pleistocene nearshore conglomerate grades to more fossiliferous and finer sediments that were deposited in a protected environment.

Combined morphostratigraphic, sedimentologic, and paleontologic studies in the Tepopa region (Lecolle and Ortlieb, 1978; Lecolle, 1980; Ortlieb, 1981, 1984a, 1987; Luna-Guerin, 1981; González-González, 1982; González and others, 1984) indicate that all the marine sediments cropping out between the southwesternmost Sierra Bacha and Punta Tepopa are most probably penecontemporaneous with the last interglacial high stand(s) of sea level (IS 5). These deposits correspond to various nearshore paleoenvironments and include: fluvi-marine conglomerates at the Rio San Ignacio mouth, open-shore fossiliferous sandstones in Bahía Tepopa, lagoonal and shallow-bar fine sands in the center of the Tepopa bolson ("Playa Tepopa" of various authors), and shingle and cobble beach ridges to the southeast of Cerro Tepopa (Fig. 6).

A paleogeographic reconstruction of the Tepopa area suggests that at the beginning of the last interglaciation (IS 5e) the Cerro Tepopa was an island, which later became attached to the mainland by a tombolo that grew southward from the area of El Desemboque village (Fig. 6). After the building-up of this land bridge and the encroachment of coastal dunes, the "Playa Tepopa" area constituted a protected embayment that rapidly filled with fine-grained and fossiliferous (Chione californiensis, C. fluitifraga, Rhynocoryne humbleti, Cerithium stercusmuscarum, Cerithidea mazatlanica) sediments. Subsequently, sea level dropped, and the paleoembayment of Tepopa was covered with various types of eolian dunes: the sand source was provided by the nearby exposed infralittoral area. During the glacial period (encompassing IS 4, 3, and 2), the foot of the bajadas flanking the Sierra Seri and the Cerro Tepopa prograded toward the center of the bolson and totally buried the former shorelines. In the Holocene, the post-glacial sea invaded the southern part of the bolson and formed the El Sargento lagoon, which was promptly bordered by a thick mangrove (Sherwin, 1971; Fig. 6). In the last few thousand years and up to the present, the "Playa Tepopa" lows (altitude +4 m) have been periodically inundated by runoff waters.

In such reconstitution of the late Quaternary paleogeographic evolution, which takes into account all the available data from all the outcrops of marine and nearshore sediments in the Tepopa area, and from a series of auger perforations (maximum depth from the surface: 6 m) in the "Playa Tepopa" zone (Lecolle, 1980; Ortlieb, 1984a, 1987), it could not be unequivocally determined whether the early late Pleistocene high sea-level stand was a single one (IS 5e), or if the IS 5e was followed by another high stand (IS 5c?) that would have left its deposits above present MSL.

Geochronological analyses of mollusks from this region were of limited help in unravelling this uncertainty, and illustrated the limits of reliability of the chronological methods.

**Geochronological problems and neotectonic implications.** A series of six Dosinia ponderosa shells was collected in situ (with their articulated valves) in a single locality, 3 km west of Campo Dólar (Figs. 6 and 7g), and submitted for U-series analyses (LP 134, Table 1). The results, including repeated measurements on the same individuals, show a wide range of apparent ages (64 to 120 ka); such a scatter of results necessarily reflects an anomaly, since the conditions of occurrence of the fossils leave no doubt that the sampled shells lived at the same time (within a few centuries?) and none appear to have been reworked.

It is known that, unlike corals which are at equilibrium with sea water, mollusk shell carbonates incorporate most of their uranium after their death (Broecker, 1963). This particular characteristic, which for many authors (Kaufman and others, 1971; Ku, 1976; and others) discredited mollusks as suitable material for U-series geochronology, explains that "molluscan" calculated ages are generally younger than "coral" ages and should be taken as minimum ages (Veeh and Valentine, 1967; Stearns, 1980). For the same reason it may be considered that in a series of dates from a collection of coexisting mollusk shells, the oldest apparent ages have more probability of being close to the true age than the statistical mean value. The set of data from the Campo Dólar locality, which is most probably 125,000 yr old, brings another confirmation of such interpretation.

Another geochronological problem met in the Tepopa area deals with a series of radiocarbon ages that suggest the main nearshore units cropping out above MSL are about 30,000 yr old.

After a preliminary 14C dating of four shells by the late H. G. Richards (1973), a dozen additional radiocarbon dates were obtained on shells of the El Desemboque–Tepopa area (Table 3). The 16 dated shells were sampled in several places and various paleogeographic units: at the Rio San Ignacio mouth (three samples from a deltaic unit), 5 km south of El Desemboque (two samples from an intertidal unit on the former tombolo), and in the "Playa Tepopa" lows (11 samples from laguno-marine beds) (Fig. 6). The apparent 14C ages of 15 of these samples range from 20,150 to 35,300 B.P. (most of the ages between 27,000 and 33,000 B.P.), while one last sample (from Richards, 1973) is apparently >42,000 B.P. (Table 3). Such a series of relatively consistent radiometric ages (except for the two extreme values of ~20 ka and >42 ka) suggests that the three main outcrops of nearshore sediments from the Tepopa–El Desemboque area are coeval with an ~30-ka episode of high sea level (last warm interstadial IS 3).

The significance of 14C-dated 30-ka emergent shorelines in regions of the world that have not been notably uplifted has been much debated in the last three decades (see discussion by Morner, 1971; Thom, 1973; Giresse and Davies, 1980); in many cases (particularly in areas where the well-identified IS 5e shoreline is preserved at a low elevation above present MSL), it has been concluded that the radiocarbon age determination was inaccurate, and that the 30-ka age calculations probably resulted from small contamination by modern carbon.

Aminostratigraphic measurements on some coexisting shells (Chione sp. and Protothaca sp.) from the radiocarbon-dated "Playa Tepopa" beds and the Bahía Tepopa locality (Table 2) do
not support an age much younger than 125 ka. As only one sample (LT 7000; *Chione* sp.) provided a relatively low α/Fe ratio, the aminostratigraphic data are inconclusive as to whether these deposits are strictly coeval (IS 5e; 125 ka) with, or slightly younger (IS 5e?; ~105 ka?) than, the Punta Teopopa–Campo Dólar samples.

In conclusion, the morphostratigraphic evidence that the Teopopa area was only submerged once in the late Quaternary and that this high sea level almost certainly corresponds to the IS 5e are considered more reliable than most apparent ages (obtained by one method or the other). The idea that the Teopopa beds may be accurately dated by the radiocarbon method is rejected, and it is interpreted that the apparently consistent radiocarbon ages result from a generalized contamination by 1 or 2 percent modern carbon. Such contamination was probably facilitated by the previous nature of the sandy sediments and endogenic character of the area.

It has been emphasized that the Th/U-dated shells from the Campo Dólar locality should be considered coeval with the IS 5e, in spite of the spread of individual geochronologic results. The aminostratigraphic results seem to confirm the IS 5e age assignment to two localities, although one sample may be interpreted as possibly younger (IS 5e?) than the IS 5e episode.

The proposed chronostratigraphic interpretation implies that no recent vertical displacements have been recorded in the area. Actually, the NW-SE faults (Gastil and Krummenacher, 1974) that controlled the typical Basin-and-Range morphology of the region do not seem to have been active during the late Quaternary.

**Canal del Infiernillo and Bahía Kunkaak**

On the sides of the Canal del Infiernillo, between Tiburon Island and the continent, late Quaternary marine sediments have been widely covered by an overwhelming accumulation of colluvium derived from the Sierra Seri (mainland side) and Sierra Kunkaak (on Tiburon Island) (Fig. 8). Furthermore, Holocene constructional coastal features (sand spits, marginal lagoons, and mangroves; see Sherwin, 1971; Lancin, 1979, 1985) contributed to restrict the exposures of the Pleistocene marine deposits. Thus, Pleistocene nearshore sediments, which are comparable with the last glaciation, are observed in only four localities: Palo Fierro (Fig. 9b), Punta Tormenta (Fig. 9c), Punta Santa Rosa, and 2 km north of Punta Chueca (Fig. 9j). In the first three localities, fossiliferous conglomerates, deposited in intertidal and uppermost sublittoral zones, point to a maximum sea-level stand at ~+5-m elevation. The sequence located between Punta Chueca and Punta Onah (Fig. 9j) is different from the deposits of the other outcrops: the top of the marine beds reaches a maximum +9-m elevation, and the base of the sequence is made of infralittoral fossiliferous sands. The latter unit contains micro- and macrofauna that suggest that the coeval sea level was more than 10(?) m above the mentioned bed (Celis-Gutiérrez, 1975, 1979; Stump, 1981). A *Dosinia ponderosa* shell (LU 1075e, Table 1) from this infralittoral unit yielded a Th/U age of 67 ± 5 ka. The fact that this sequence crops out in the only cliffed coastal segment of the Infiernillo Straits supports the hypothesis that this locality registered a limited fault-controlled uplift motion.

Without accepting at face value the single Th/U apparent age of the LU 1075 sample, it is conceivable that the sequence could be younger than the IS 5e episode, and that it was uplifted more than a few meters in the second half of the late Quaternary. Recent vertical deformation observed between Punta Chueca and Punta Onah has a limited lateral extent, although it should be noted that the prolongation of the same fault trace (Gastil and Krummenacher, 1974) crosses the Teopopa area. This fault activity is interpreted to result from a small structural reaccommodation at the margin between the Basin and Range province and the Gulf of California system (Ottlieb and others, 1989).

In the Palo Fierro locality (Fig. 9c), two *Dosinia ponderosa* shells submitted for Th/U dating gave apparent ages of 84 ± 12 and 100 ± 14 ka (Table 1), which are interpreted as minimum ages. Aminostratigraphic data (Table 2) support assignment of this locality to the IS 5e.

In Bahía Kunkaak, the remnants of a late Pleistocene high sea-level stand consist of gravelly sandstones deposited on wave-cut benches (maximum elevation +6 m) and in low-lying nearshore sequences that upgrade into alluvial and colluvial deposits (Fig. 9k). The reconstructed high sea-level stand is interpreted to be of IS 5e age, on the basis of the low degree of alteration of the sediments and the fauna (when the deposits are located above the Holocene high-tide level) and because of the assignment of the few-meter-thick bajada unit to the last glacial cycle. No evidence of older Pleistocene high sea-level stands has been found in the area; any emerged middle Pleistocene marine terrace would be deeply buried under the thick alluvium, inland from the present coastline, and/or would have been eroded by the early late Pleistocene transgression.

**Isla Tiburon**

Tiburon Island registers the IS 5 high sea-level stand relatively well, at least along the rocky stretches of the coast (Fig. 8). At its northern end, wave-cut benches covered with nearshore sediments and slope deposits clearly indicate that the sea level reached a ~+6-m elevation (Punta Ast Hoe Ben Oh Galp, Fig. 9a, southwestern Agua Dulce, Tecomate). Similar features were observed along the southeastern coast (embayments of El Perro, Fig. 9d, and La Cruz, Fig. 9g) and the southwestern part of the island (Punta Sauzal, Fig. 9b, Bahía Blanca, Bahía Vaporeta). Two *Dosinia ponderosa* shells collected at Ensenada El Perro (LQ 141) and Ensenada La Cruz (LQ 175) provided Th/U ages of 86 ± 12 and 83 ± 12 ka, respectively (Table 1); aminostratigraphic results on the same individuals and other shells (Table 2) favor an IS 5e age. Like in the above mentioned Palo Fierro locality (northeastern coast of the island), it is interpreted that the radiometric dates should be taken as minimum ages, and that all these deposits are more probably coeval with the early late Pleistocene (IS 5e) high sea-level stand.
Figure 8. Tiburon Island and the Infiernillo Straits: location of the sections of Quaternary coastal deposits (a to k) shown in Figure 9. Simplified geology from Gastil and Krummenacher (1974).
1. Quaternary marine terraces, according to Gastil and Krummenacher (1974). 2. Quaternary alluvium. 3. Pre-Quaternary units. 4. Observed and inferred faults. 5. Location of the sections of Quaternary coastal deposits shown in Figure 9 (a to k). 6. Maximum elevation (meters above present MSL) of the early Late Pleistocene (IS 5e) shoreline. 7. Elevation of middle Pleistocene shorelines (meters above present MSL).
It should be added that the southern coast of Tiburon Island shows numerous evidences of post-Miocene faulting activity ("La Cruz fault" system of Gastil and Krummenacher, 1974, 1977: "Southern Tiburon fault" of Sanchez and others, 1985). If some of these faults had been recently active (Ortlieb and others, 1989), they do not appear to have induced important vertical offsets, at least during the late Quaternary, since the IS 5e shoreline is identified in several localities at its common elevation of +5 to +6 m (very close to its assumed "eustatic" position).

A few middle Pleistocene marine deposits are preserved in the southwesternmost and southeasternmost parts of Tiburon Island. At Ensenada La Cruz (Fig. 9e), indurated and poorly fossiliferous silts, unconformably overlain by IS 5e sediments, which are probably the localities previously studied by Anderson (1950) and Durham (1950), suggest that during their deposition the sea level was at least 10 m above the present datum.

In Bahia Blanca (Fig. 9i), a marine platform covered by a thick unit of consolidated eolianite is interpreted as probably pre-Late Pleistocene. In northern Bahia Vaporetta, elevated (middle and early?) Pleistocene marine terraces have been mentioned by Gastil and Krummenacher (1974, 1977) but have not yet been specifically studied. It would not be surprising if this region of Tiburon Island, which is thought to show exposures of the earliest Miocene marine rocks of the whole Gulf of California (Smith and others, 1985), would still be experiencing slow uplift.

**Bahia Kino–Guaymas area**

The Bahia Kino–Laguna La Cruz area (Fig. 10) is dominated by late Quaternary (mostly Holocene) sediments; late Pleistocene marine sediments have only been observed around Cerro San Nicolas. Littoral embankments on the northern and western exposed coasts of this headland show that late Quaternary nearshore beds reach a maximum +5-m elevation, and that they are covered with several meters of eolianites and alluvium (Fig. 9i). Various morphostratigraphic arguments suggest that these deposits are of early late Pleistocene age (IS 5e), even if one of these localities (Punta Kino) yielded discordant radiocarbon logic data: coexisting shells provided a relatively young Th/U age (20.9 ± 3 ka, mean of two measurements on the same individual of Dosinia ponderosa, Table 1), an older 14C age (32,500 ± 1,500 B.P., Table 3), and an alle/Ile ratio that supports an IS 5e age (Table 2). On one hand, the high content of 238U measured in the LP 28 sample reveals an anomalous intake of uranium, which invalidates the Th/U geochronological determination; on the other hand, the radiocarbon age, which is close to the theoretical range limit, is not reliable either.

The wide coastal plain that spreads between Cerro San Nicolas and Tastiota ("Costa de Hermosillo", or "Llanos de San Juan Bautista," Fig. 8) is formed by late Quaternary alluvial and fluvi-deltaic fine sediments from the paleo-Rios Sonora and La Pozo; its shore is lined with an uninterrupted dune ridge that has been built in the second half of the Holocene. Preliminary stratigraphic and sedimentologic studies in the coastal lagoons of the area (La Cruz, El Cardonal, Tastiota) suggest that the postglacial sea level practically reached its present position about 5,000 yr ago (Nichols, 1965).

Remnants of late Pleistocene high sea-level stands reappear as narrow abraded terraces along the rocky coastline south of Tastiota (Fig. 9m). These benches, which have generally been stripped of nearshore sediments (except near Tastiota), are observed in several places at about +5 m along the coast of Sierra Algodones southward to San Carlos (Fig. 10).

The hilly Guaymas area differs from the other rocky coastal regions of Sonora by the fact that its steep cliffs and scree do not present any wave-cut remnants above the Holocene shoreline. The harbor of Guaymas, located in a faulted Miocene caldera, has been recognized as a typical, recently submerged, drowned area (Anderson, 1950). The nearby Empalme lagoon probably constitutes another evidence of such recent local submergence. This late Quaternary subsidence, apparently related to some unusual microseismic activity (G. Ness, personal communication, 1986) and to local gravimetric anomalies (Harrison and Mathur, 1964), is interpreted as a possible consequence of the termination of a transform fault of the gulf system, close to the Guaymas basin "spreading center" (Moore, 1973; Bischoff and Heney, 1974).

**THE SOUTHWESTERN GULF OF CALIFORNIA**

South of Guaymas, the coast of southern Sonora and Sinaloa (Fig. 1) is largely dominated by Holocene progradational features (coastal dunes, lagoonal complexes, deltaic sediments, alluvial plains, etc.) and by the hydrologic regime of several permanent rivers coming from the Sierra Madre Occidental; these conditions are particularly unfavorable for the study of Pleistocene shorelines (and explain why this region has not been more studied). The rarity of emerged remnants of Pleistocene high sea levels in the southwestern Gulf of California seems to be due to poor conditions of exposure rather than to a regional subsidence. In a few localities, such as Mazatlán (Gutiérrez-Estrada and Castro del Río, 1984) or northwestern Nayarit (Curry and others, 1969), late or middle Pleistocene marine sediments have been observed near present MSL.

In this part of the Gulf coast, between Mazatlán and San Blas, controversial ideas have been published concerning the late Quaternary vertical movements in relation to postglacial sea-level-rise evidences. Curry and others (1969) elaborated a local model of relative sea-level rise, according to which the coastal area could be considered stable, and in which sea level would have slowly risen in the last few thousand years (—10 m at around 7,000 B.P., and —2 m at around 3,600 B.P.). More recently, new stratigraphic and paleosol evidence led Connolly (1984) and Sirkin (1984) to suggest that this region registers an alternation of submersions and emersions (with amplitudes of relative vertical motions reaching several tens of meters) in the last 15,000 yr. The latter interpretation seems to be based on unreliable and insufficient data, which led to inaccurate reconstructions of successive sea-level positions.
MARINE SEDIMENTS Do CROP OUT ABOVE MSL), IT MAY BE DUE EITHER EMERGED FEATURES ALONG A COASTAL REGION (WHERE LATE PLEISTOCENE SHORELINES ARE KNOWN TO USUALLY PROVIDE MINIMUM AGES). THE SERIES OF 11 MEASUREMENTS MADE ON SIX SHELLS FROM A SINGLE LOCALITY (CAMPO DÓLAR, LP 134, TABLE 1) ILLUSTRATES THAT THE TRUE AGE IS MOST PROBABLY THE OLDEST APPARENT AGE, AND THAT THE SCATTER OF NUMERICAL AGES MAY REACH AS WIDE AS 60,000 YR. THE FACT THAT COEXISTING SHELLS FROM A GIVEN LOCALITY SHOW THE SAME SCATTER OF APPARENT AGES OF THE WHOLE SET OF (RADIOCHEMICALLY RELIABLE) DATA FROM THE NORTHEASTERN COAST OF THE GULF OF CALIFORNIA SUPPORTS THE INTERPRETATION THAT THE INDIVIDUAL RADIOMETRIC RESULTS SHOULD NOT BE TAKEN AT FACE VALUE, AND, ON THE CONTRARY, ALL THE ANALYZED SHELLS MAY WELL BE COEVAL WITH THE SINGLE IS 5e HIGH SEA-LEVEL STAND.

AS A COROLLARY, IT MAY BE ADDED THAT THE U-SERIES GEOCHRONOLOGICAL METHOD APPLIED TO MOLLUSK SHELLS IS KNOWN TO USUALLY PROVIDE MINIMUM AGES. THE SERIES OF 11 MEASUREMENTS MADE ON SIX SHELLS FROM A SINGLE LOCALITY (CAMPO DÓLAR, LP 134, TABLE 1) ILLUSTRATES THAT THE TRUE AGE IS MOST PROBABLY THE OLDEST APPARENT AGE, AND THAT THE SCATTER OF NUMERICAL AGES MAY REACH AS WIDE AS 60,000 YR. THE FACT THAT COEXISTING SHELLS FROM A GIVEN LOCALITY SHOW THE SAME SCATTER OF APPARENT AGES OF THE WHOLE SET OF (RADIOCHEMICALLY RELIABLE) DATA FROM THE NORTHEASTERN COAST OF THE GULF OF CALIFORNIA SUPPORTS THE INTERPRETATION THAT THE INDIVIDUAL RADIOMETRIC RESULTS SHOULD NOT BE TAKEN AT FACE VALUE, AND, ON THE CONTRARY, ALL THE ANALYZED SHELLS MAY WELL BE COEVAL WITH THE SINGLE IS 5e HIGH SEA-LEVEL STAND.

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Quaternary shorelines, northeastern Gulf of California
Figure 10. Bahía Kino-Guaymas region: distribution and height of the early late Pleistocene shoreline.
1. Pre-Quaternary units. 2. Quaternary alluvium and eolian sands. 3. Location of the sections of Quaternary coastal deposits (k to m) shown in Figure 9. 4. Maximum elevation (meters above MSL) of the early late Pleistocene (IS 5e) shoreline.
IS 5e shoreline is observed, or can be reconstructed, at a nearly constant elevation of $\geqslant +6$ (± 1) m between Bahia Adair and Guaymas (Fig. 11). Assuming that this $\sim +6$-m elevation is very close to its original "eustatic" position, it may be inferred that during the late Quaternary (i.e., the last 125,000 yr), vertical deformations have been practically nonexistent, or of less than 1 to 2 m (mean uplift rates of 8 to 16 mm/10^3 yr).

The eastern bank of the Rio Colorado mouth is the only area that underwent important vertical displacements (maximum rate of 170 mm/10^3 yr). This displacement is interpreted to be the result of transpressive folding directly related to the Cerro Prieto fault activity. The uplifted area is limited to the southwestern edge of the Mesa de Sonora. On the southwestern extremity of the Rio Colorado delta and in northern Bahia Adair, the IS 5e shoreline is very close to its "eustatic" position.

Another kind of recent deformation, of much more limited amplitude (a few meters?) than along the Mesa de Sonora, has been described in the Canal del Infiernillo, and corresponds to a late Quaternary reactivation of one of the numerous, NW-SE–oriented, late Cenozoic faults that control the structure of the Sonoran coast.

In conclusion, vertical displacements along the northeastern coast of the Gulf of California appear to have been very limited during the entire Quaternary, and particularly in the late Quaternary. The only segment of the coast that had important vertical deformations associated with strike-slip along the Cerro Prieto fault is located on the eastern side of the Rio Colorado delta (Fig. 11).

A comparison of the neotectonic comportment of both sides of the Gulf of California (Ortlieb, 1990) shows that since the Pliocene the Sonoran coast has been significantly less uplifted than the peninsula of Baja California.

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