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

Luc Ortlieb*
Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM), 213 rue La Fayette, 75010 Paris, France

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 northernmost 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,

*Present address: Misión ORSTOM en el Perú, Apartado 18-1209, Lima 18, Peru.

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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 5e, 5c, and 5a, 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 (Wehmiller 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 Rosalía), 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 Infiernillo 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 5e) shoreline is preserved at +7 to +10 m and that it shows little vertical deformation. Holocene deltaic sediments have been investigated by Gorsline (1967), Meckel (1975), and Thompson (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-

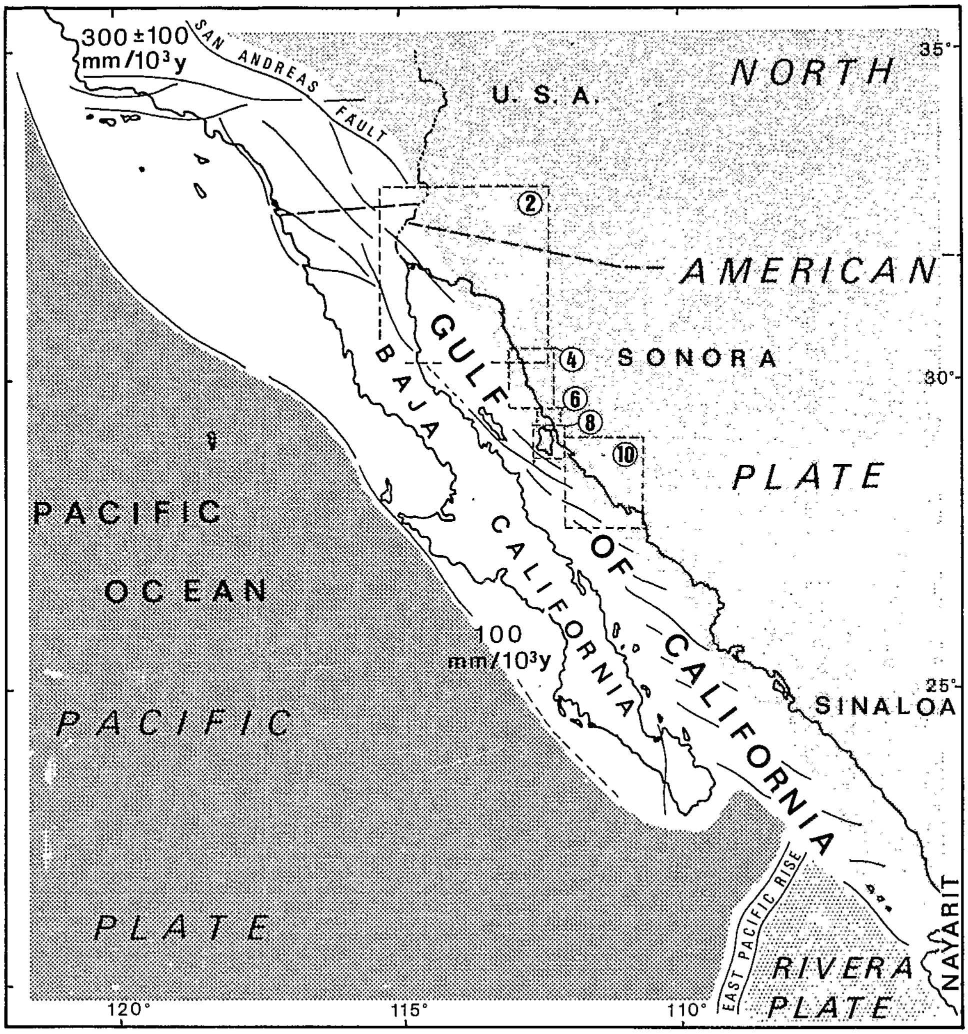


Figure 1. Tectonic setting of the Sonoran coast, northeastern Gulf of California, on the edge of the North American plate. The order of magnitude of middle and late Quaternary mean uplift rates, deduced from marine-terrace studies along southwestern California and Baja California, is indicated. Map locations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

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.

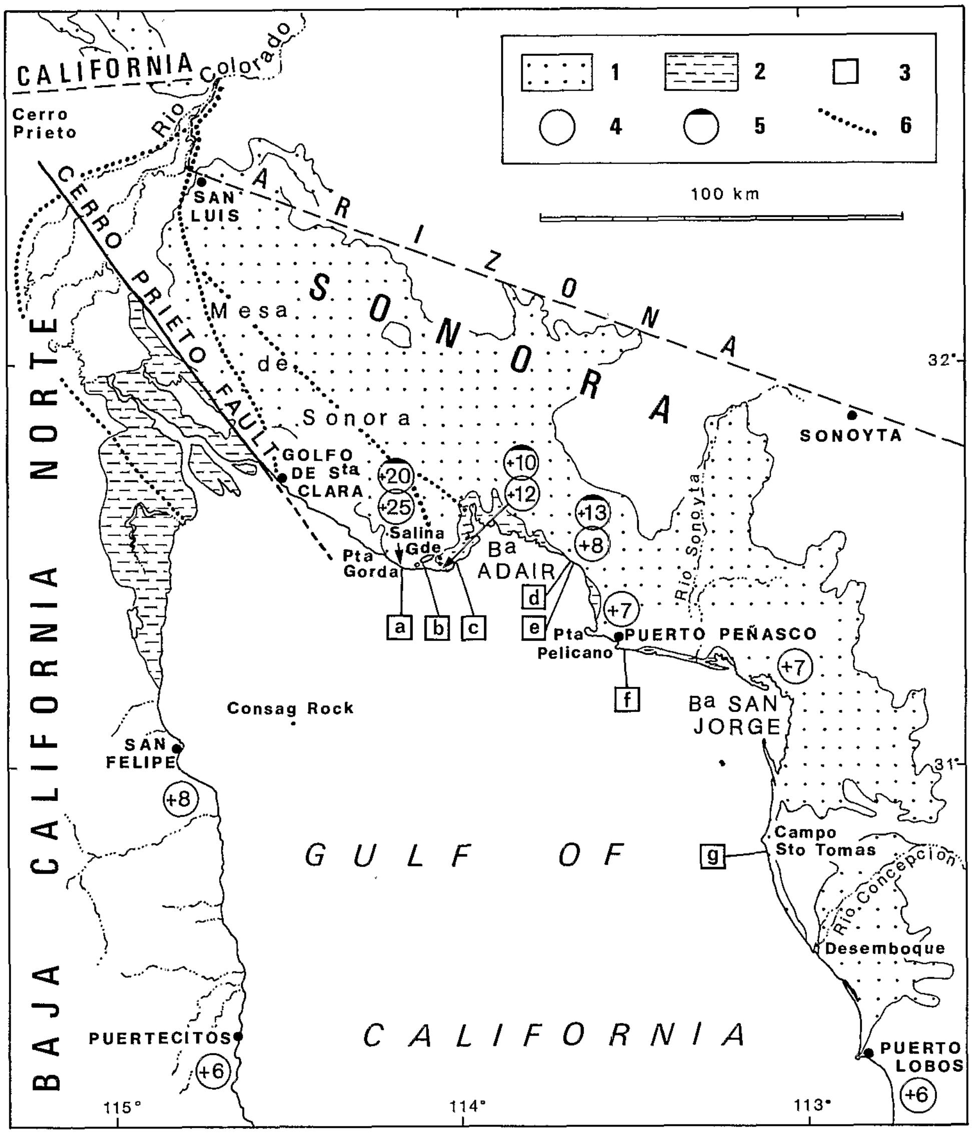


Figure 2. The northernmost Gulf of California: distribution and height of Pleistocene shorelines. 1. Late Quaternary eolian sands. 2. Lagoonal and deltaic areas. 3. Location of the sections of Quaternary coastal deposits (a to g) shown in Figure 3. 4. Maximum elevation (in meters above present MSL) of the early late Pleistocene (IS 5e) shoreline. 5. Elevation of middle Pleistocene shorelines (meters above present MSL). 6. Former courses of the Rio Colorado estuaries during the IS 5e maximum sea-level stand.

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-

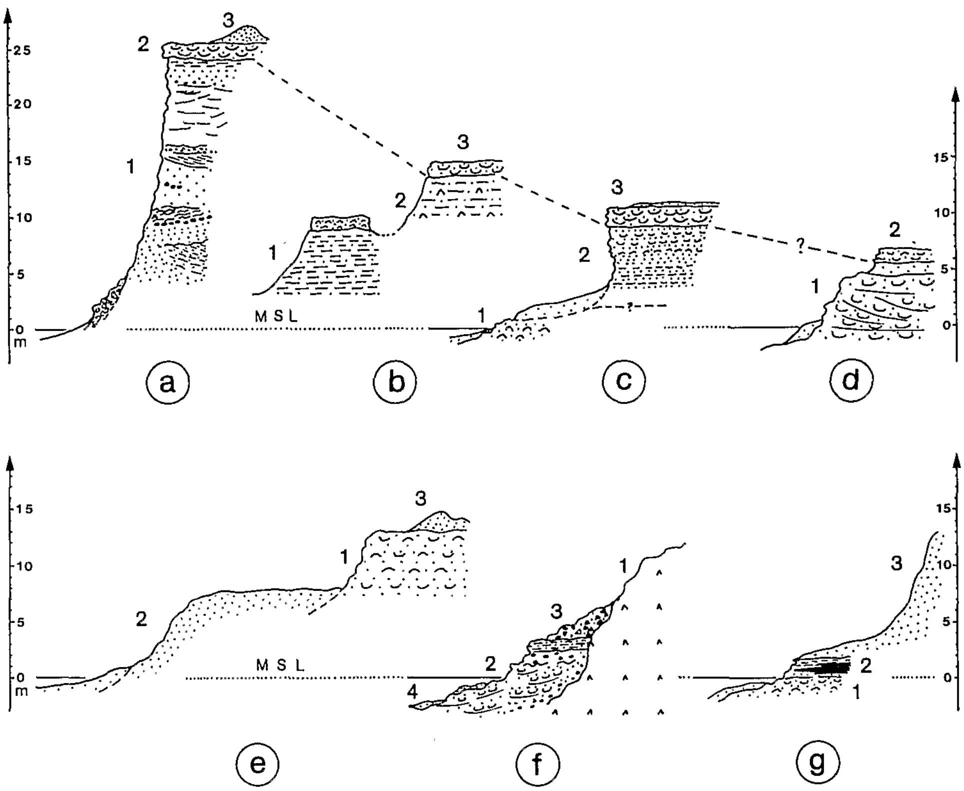


Figure 3. Sections of Quaternary coastal deposits along the northern Gulf of California (see location in Fig. 2). Section a: 1. Composite sequence of fluvio-deltaic deposits (earliest late Pleistocene, or latest middle Pleistocene?). 2. Early late Pleistocene *Chione* coquina bed. 3. Holocene sand dunes, and late Quaternary terrestrial reddish silts. Section b: 1. Lagoonal silty sands capped with a fossiliferous calcarenite layer (middle Pleistocene?). 2. Silty and clayey sands, with abundant gypsum crystals (latest middle Pleistocene, or earliest late Pleistocene). 3. Early late Pleistocene *Chione* coquina bed. Section c: 1. Sublittoral calcarenitic sandstone, rich in *Encope* sp. shells (middle Pleistocene). 2. Series of intertidal sandy and silty layers, including weathered shell fragments (late middle Pleistocene?). 3. Early late Pleistocene *Chione* coquina bed (LU 981) covered with late Quaternary eolian sands and terrestrial silts. Section d: 1. Calcarenitic sandstones rich in *Chione californiensis* shells (middle Pleistocene). 2. Fossiliferous bioclastic sands with *Chione cortezi* and *C. californiensis* (late Pleistocene). Section e: 1. Calcarenitic sandstones with weathered shells (middle Pleistocene?). 2. Lower terrace covered with eolian sands (late Pleistocene?). 3. Holocene sand dunes. Section f: 1. Volcanic substratum. 2. Early late Pleistocene beachrock, capped with fossiliferous sands and organic-matter-rich sediments. 3. Cemented scree deposits (late Quaternary). 4. Holocene beachrock forming atop the unit (2). Section g: 1. Cemented sands including *Chione fluctifraga* and *C. cortezi* (LT 933) (mid-Holocene). 2. Fine sands and clayey silts with peat layers (LT 936), plant remains, and lagoonal fauna capped with alluvial clays (mid-Holocene). 3. Sandy coastal ridge (second half of the Holocene).

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.

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 cortezi* and *Chione gnidia,* and laterally grades to fossiliferous sublittoral sandy units containing a more varied fauna (predominantly *Trachycardium panamense, Chione californiensis, Polinices recluzianus, 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

TABLE 1. RADIOMETRIC $^{230}Th/^{234}U$ DATA FROM PLEISTOCENE PELECYPOD SHELLS COLLECTED ALONG THE SONORAN COAST*

Sample Number	Genus†	Calcite§ %	Lab Number**	^{238}U (ppm)‡	$^{234}U/^{238}U$ (activity)§§	$^{230}Th/^{232}Th$ (activity)***	$^{234}U/^{232}Th$ (activity)	Measured Age: $^{230}Th/^{234}U$ (ka) †††	Measured Age: Individual Mean	Morphostratigraphic age (ka)§§§
LU 981	Chi	o	UQT 36	0.524 ± 0.012	1.226 ± 0.034	142.823 ± 30.298	199.455 ± 42.705	129 ± 13		125
LQ 202	Dos	<1	NICC 45	1.00 ± 0.03	1.21 ± 0.08			42 ± 8		125
LP 58	Dos	3	NIMB a	1.35 ± 0.04	1.16 ± 0.10			118 ± 17		125
LQ 181	Dos	17	NIMB b	0.89 ± 0.02	1.38 ± 0.10◊			180 ± 25		125
LP 49	Dos	<1	NIMB c	0.60 ± 0.02	1.26 ± 0.06			93 ± 13		125
LP 134 a	Dos	<1	NIMB 37	0.85 ± 0.02	1.22 ± 0.08			83 ± 12		
LP 134 b	Dos	0	NIMB 38	0.27 ± 0.01◊	1.24 ± 0.08			102 ± 14		
LP 134 b			NICC 38	0.32 ± 0.020◊	1.14 ± 0.10	31.80 ± 7.500◊	49.43 ± 15.10	95 ± 18	98.5 ± 18	
LP 134 c	Dos	<1	NICC 39	0.38 ± 0.020◊	1.39 ± 0.120◊	58.06 ± 16.020◊	95.898 ± 32.82	96 ± 14		
LP 134 c			NIMB 39	0.43 ± 0.010◊	1.14 ± 0.08	48.60 ± 5.500◊	71.4 ± 12.5	120 ± 16	108.0 ± 16	125?
LP 134 d	Dos	1	NICC 40a	0.55 ± 0.02	1.16 ± 0.05	115.30 ± 42.50	253.14 ± 114.64	64 ± 10		
LP 134 d			NICC 40b	0.57 ± 0.02	1.23 ± 0.08	74.50 ± 32.300◊	252.06 ± 120.10	65 ± 10	64.5 ± 10	(or
LP 134 e	Dos	<1	NIMB 41a	0.92 ± 0.02	1.15 ± 0.08			88 ± 12		
LP 134 e			NIMB 41b	1.02 ± 0.03	1.17 ± 0.10	80.70 ± 15.000◊	>100	84 ± 12	85 ± 13	105)
LP 134 e			NICC 41	0.96 ± 0.02	1.17 ± 0.08	31.00 ± 7.800◊	57.37 ± 17.96	83 ± 13		
LP 134 f	Dos	0	NIMB 42	0.48 ± 0.010◊	1.21 ± 0.10	5.8 ± 0.050◊	10.8 ± 1.1	82 ± 11		
LQ 149 a	Dos	<3	NIMB d	0.40 ± 0.010◊	1.26 ± 0.10			84 ± 12		125
LQ 149 b	Dos	<3	NIMB e	0.46 ± 0.010◊	1.18 ± 0.08			100 ± 14		
LP 1075e	Dos	0	UQT 42	1.147 ± 0.029	1.229 ± 0.031			66.6 ± 5		125?
LQ 141	Dos	<1	NIMB f	0.71 ± 0.02	1.21 ± 0.08			86 ± 12		125
LQ 175	Dos	<1	NIMB g	0.92 ± 0.02	1.26 ± 0.08			83 ± 12		125
LP 28	Dos	<3	NIMB h	2.66 ± 0.070◊	1.25 ± 0.04			22.8 ± 3		
LP 28			NIMB i	1.53 ± 0.4	1.28 ± 0.08			19 ± 2.5	20.9 ± 3	125

*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.

**UQT = Lab. Géotop (UQAM. Montréal); NICC = Lab. Géochronol., Univ. Nice (C. Causse); NIMB = idem (M. Bernat).

‡ ◊ = low (<0.5 ppm), or high (>2 ppm), uranium content.

§§ ◊ = Activity >1.30.

*** ◊ = ^{232}Th content <1 percent.

†††Calculated error corresponding to ± 1σ.

§§§See discussion in text.

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 ?). 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 (intertidal 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 upwarping 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 locus 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 Pelícano–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 ^{14}C 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*

Sample Number	Genus†	Morphostratigraphic Age (IS)§	Radiometric Apparent Age (ka)**	alle/Ile Ratios‡	Racemized State§§	Aminostratigraphic Interpretation (IS)
LP 28	Dos	5e	32(◊)/21(¤)	0.90(•)		5e
LS 642 a	Chi	5e? (or 5c)	33.5(◊)	0.81		5e
LS 681 a	Chi		31(◊)	1.06	R	
LT 700 i	Pro			0.862		
LT 700 o	Chi	5e? (or 5c)	31–33(◊)	0.71		5e or 5c?
LT 700 o				0.69		
LQ 202	Dos	5e	42(¤)	0.86(•)		5e
LP 49 Dp	Dos			1.09(•)		
LP 49 d	Dos	5e	93(¤)	0.82		5e
LP 49 d				0.81		
LP 58 Dp	Dos	5e	118(¤)	0.89(•)		5e
LP 63	Chi			0.86(•)		
LP 134Dp	Dos			0.88(•)		
LP 134 a	Dos	5e	82(¤)/100(¤)	1.33	R	5e
LP 134 a				1.24	R	
LP 134 d	Chi			0.84		
LQ 141 a	Chi	5e	86(¤)	1.11	R	5e
LQ 141 Dp	Dos			1.05(•)		
LQ 149 a	Dos	5e	84(¤)/100(¤)	0.91(•)		5e
LQ 149 b	Dos			0.96(•)		
LQ 181 Dp	Dos	5e	(180)(¤)	0.98(•)		5e
LQ 181 a	Dos			1.12		
LQ 175 Dp	Dos			0.89(•)		
LQ 175 a	Chi	5e	83(¤)	0.89		5e
LQ 175 d	Dos			1.20		
LQ 159 c	Dos	5e	....	0.95		5e
LS 647	Chi			0.86		
LS 649	Chi	5e	129(¤)	0.77		5e
LS 660	Chi			0.93		
LT 755	Chi			1.18	R	

*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.
**¤ = apparent Th/U age (see Table 1); ◊ = apparent ^{14}C age (see Table 3).
‡Analyses by G. Miller (INSTAAR, University of Colorado), except for (•) by R. Mitterer (University of Texas).
§§R = racemic samples.

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-m (IS 5e) 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 ± 170 and 5,570 ± 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 ± 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 cirripeds (*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 3. RADIOCARBON DATA FROM LATE QUATERNARY COASTAL DEPOSITS ALONG THE SONORAN COAST*

Locality	Sample Number	Species	Calculated ^{14}C Age (uncorrected)	$\delta^{13}C/_{PDB}$	$\delta^{18}O/_{PDB}$	Analysis Laboratory
Estero Las Lisas	LS 662	*Chione* sp.	21,000 ± 1,600	+1.14	-1.14	University Paris Sud UPS 2435
Bahia San Jorge	LT 726	*Chione* sp.	26,500 ± 200	+1.13	-1.20	University Paris Sud UPS 3779
Santo Tomás	LT 933	Various mollusks	4,000 ± 170	-4.65	-1.50	University Paris Sud UPS 2442
	LT 936	Peat	5,570 ± 270			University Paris Sud UPS 2465
Rio San Ignacio Estuary	HGR 1	*Lyropecten* sp.	29,550 ± 1,115			
	HGR 2	*Muricanthus* sp.	26,770 ± 525			Results from
	HGR 3	*Anomia peruviana*	≥42,000			H. G. Richards, 1973
Tepopa Region	HGR 4	(*Chione* sp. ?)	26,770 ± 525			
	NPM	*Chione fluctifraga*	20,150 ± 230			University Paris VI
	LTF 1	*Chione fluctifraga*	27,900 ± 1,000			University Paris VI
	LTF 3	*Chione fluctifraga*	28,500 ± 950			University Paris VI
	LR 642	*Chione fluctifraga*	33,500 + 2,945 - 2,140			Queens College (N.Y.) QC 472
	LS 666a	*Chione fluctifraga*	35,300 + 2,500 - 1,900			Queens College (N.Y.) QC 556
	LS 666b	*Chione fluctifraga*	32,520 + 1,725 - 1,420	+0.61		Queens College (N.Y.) QC 556/2
	LS 669	*Chione undatella*	30,580 ± 1,200	+0.88	-1.63	University Paris VI
	LS 680	*Chione fluctifraga*	33,800 ± 1,500	+0.48	-1.41	University Paris VI
	LS 681a	*Chione fluctifraga*	31,200 ± 850	+0.95	-1.09	University Paris VI
	LT 681b	*Chione fluctifraga*	24,150 ± 150	+0.61	-1.44	University Paris Sud UPS 2578
	LT 700a	*Ostrea palmula*	33,000 ± 1,500	+1.06	-1.22	University Paris VI
	LT 700b	*Trachycardium panamense*	31,530 ± 1,500	+1.06	-0.79	University Paris VI
Punta Kino	LP 28Dp	*Dosinia ponderosa*	32,500 ± 1,500			University Paris Sud

*Beside the results from Santo Tomas, which correspond to mid-Holocene samples (LT 933 and LT 936), all the apparent ^{14}C 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).

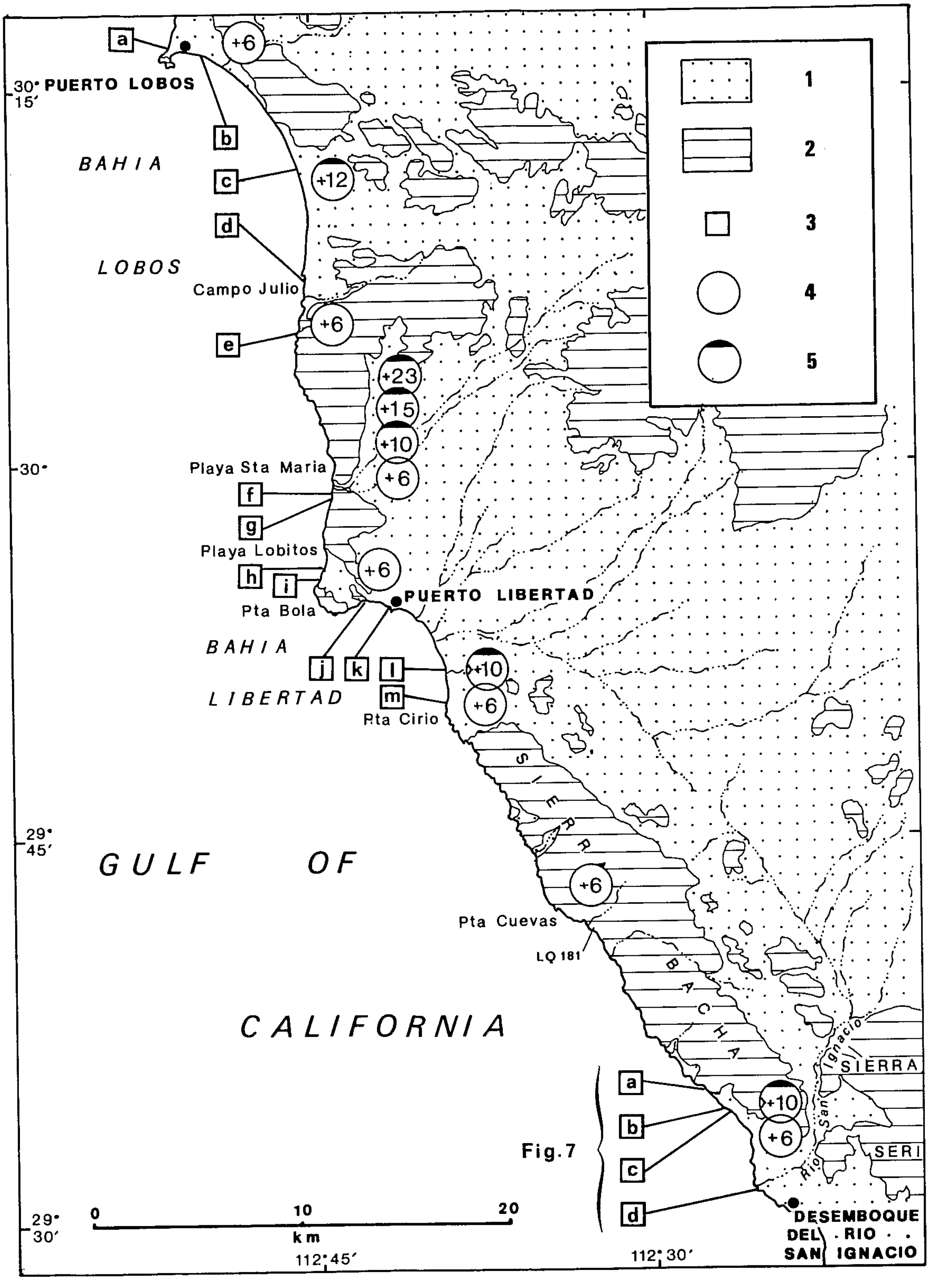


Figure 4. Puerto Lobos–Punta Cuevas region: distribution and height of Pleistocene shorelines. 1. Quaternary alluvium and eolian sands. 2. Pre-Quaternary units (geologic contours simplified from Gastil and Krummenacher, 1974). 3. Location of the sections of Quaternary coastal deposits shown in Figure 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).

63) gave aminostratigraphic data (Table 2) that further confirm the IS 5e age previously inferred solely on a morphostratigraphic basis (Malpica and others, 1978; Ortlieb and Malpica, 1978; Ortlieb, 1980).

Along southeastern Bahia Libertad, marine and fluvial sediments have been preserved below the early late Pleistocene marine unit and the more recent eolianite (Figs. 5l, m). These sediments are mainly infralittoral coarse sandstones with abundant echinoids (*Encope micropora, E. grandis*), oysters shells (*Ostrea fisheri, O. columbiensis*), and badly altered shells, or molds of aragonitic mollusks (*Dosinia ponderosa, Oliva sp., Strombus* sp., *Polinices* sp., *Cypraea* sp.); the matrix is well cemented with calcite and shows evidence of a complex diagenetic history. This marine unit has been abraded, at an elevation of a few meters above present MSL, during two successive episodes of high sea-level stands. Before the last interglacial maximum, identified by the most recent unconsolidated coastal sediments, another transgression left a few remnants that consist of a condensed fluvio-marine sequence capped by a layer of very thick oysters (*Ostrea fisheri* and *O. corteziensis*) (Fig. 5l).

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 fluvio-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. 5h, i). 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.

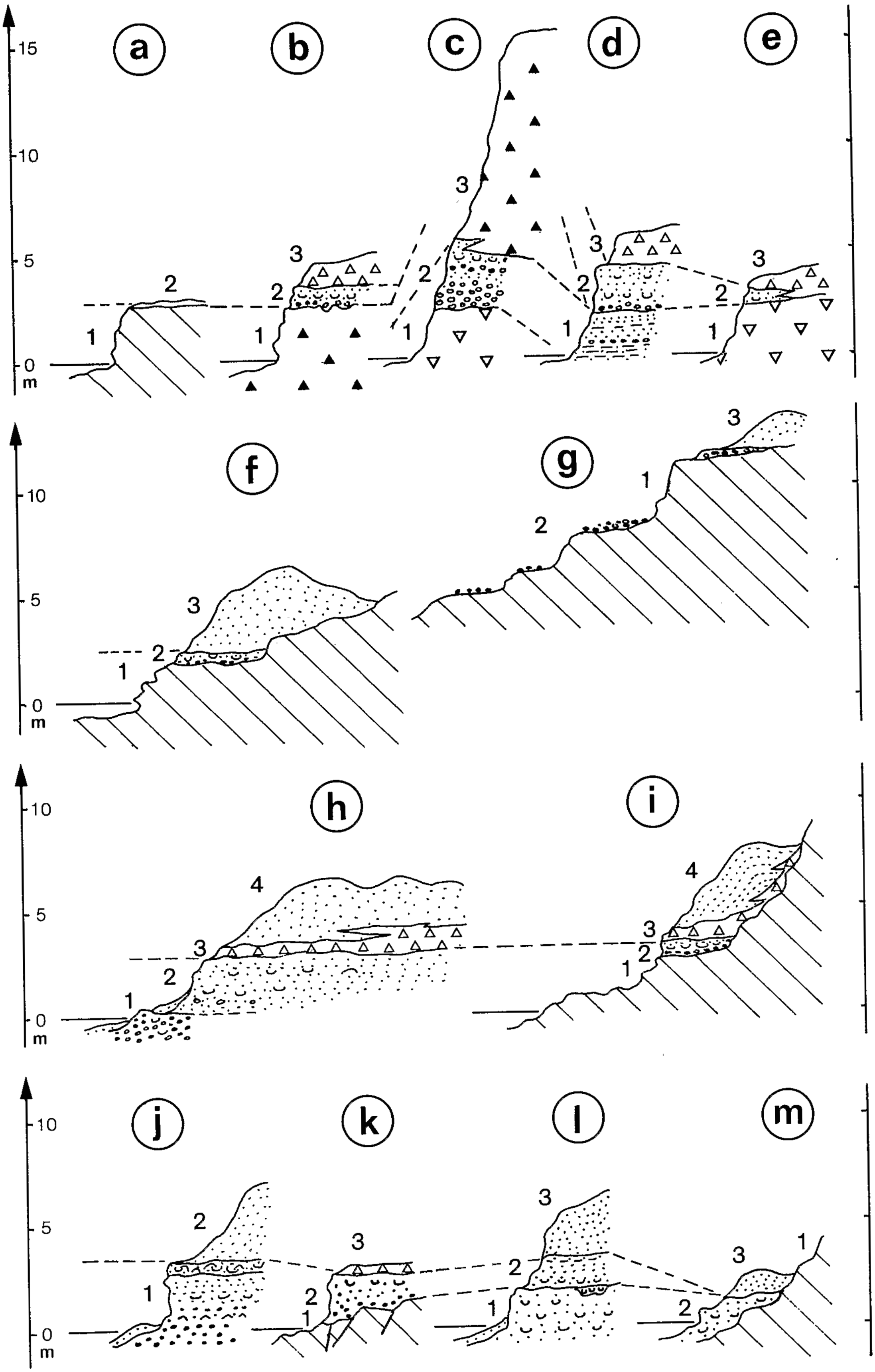
South of Punta Cirio, along the Sierra Bacha coast, a low-lying marine terrace, correlatable with the IS 5e sea-level maximum, is relatively well preserved. A conspicuous marine bench, which reaches a maximum +5-m elevation and supports associated nearshore deposits, is visible north and south of the 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).

Tepopa 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

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 (latest 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 (latest 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 lagoonal fine sands and alluvium. 4. Late Quaternary sand dune. Section i: 1. Granodioritic substrate. 2. Early 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 13.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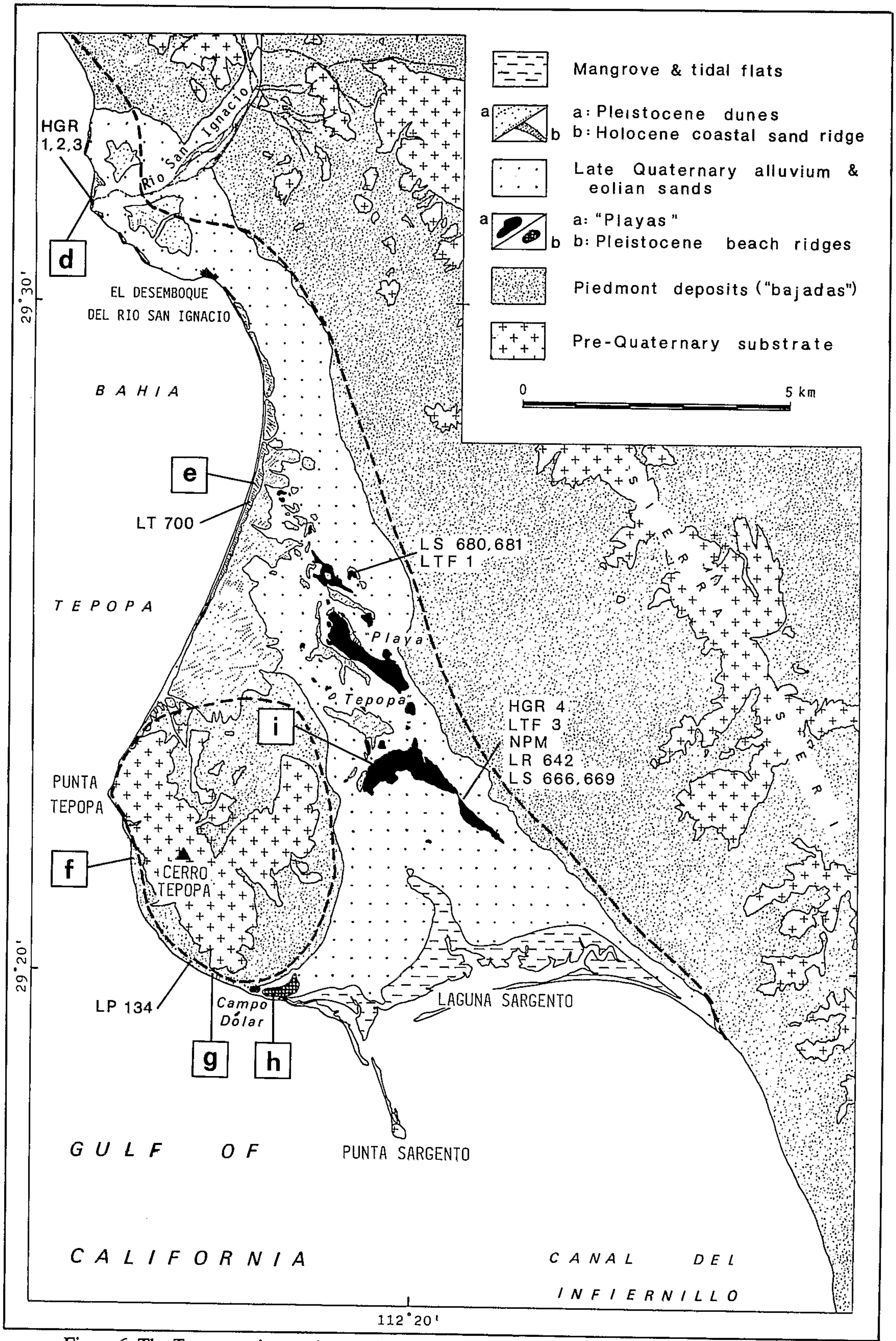


Figure 6. The Tepopa region: main morphological units, and locations of the sections of Quaternary coastal deposits shown in Figure 7 (d to h) and geochronological samples of Tables 1, 2, and 3.

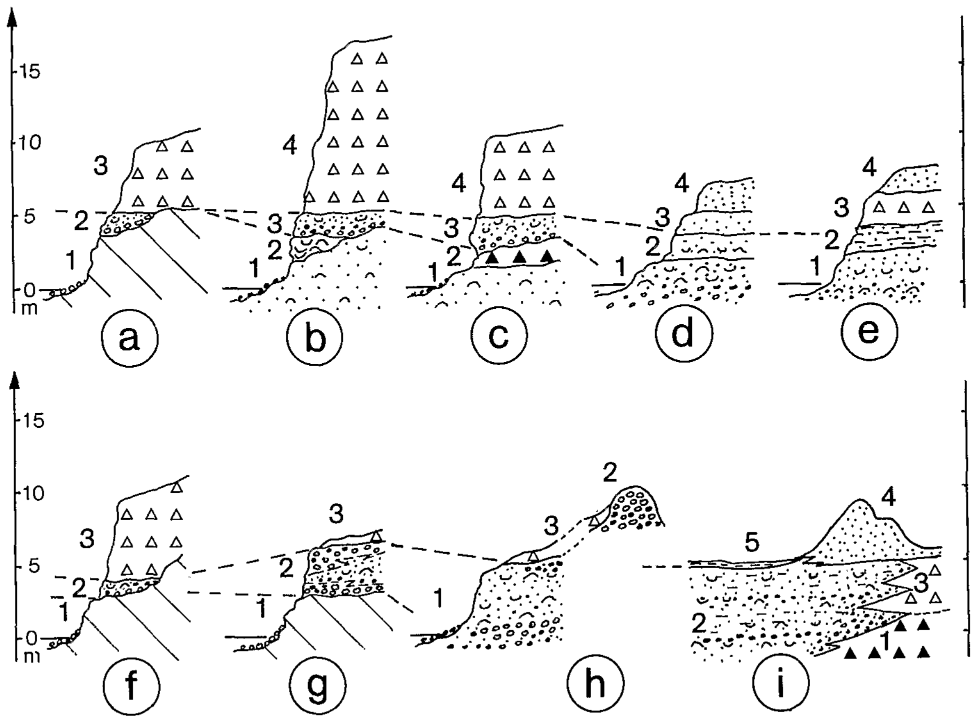


Figure 7. Sections of Quaternary coastal deposits in the Rio San Ignacio delta, Tepopa region (see location in Figs. 4 [a to d] and 6 [d to i]. Section a: 1. Mesozoic granodioritic substrate. 2. Early late Pleistocene nearshore sequence. 3. Late Quaternary bajada deposits. Section b: 1. Fossiliferous 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 corteziensis*), 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: fluvio-marine conglomerates at the Rio San Ignacio mouth, open-shore fossiliferous sandstones in Bahia 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 infilled with fine-grained and fossiliferous (*Chione californiensis, C. fluctifraga, Rhynocoryne humboldti, Cerithium stercusmuscarum, Certhidea 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 depth (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 ^{14}C 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 ^{14}C 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 ^{14}C-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 Bahia Tepopa locality (Table 2) do not support an age much younger than 125 ka. As only one sample (LT 700o; *Chione* sp.) provided a relatively low aIle/Ile ratio, the aminostratigraphic data are inconclusive as to whether these deposits are strictly coeval (IS 5e; 125 ka) with, or slightly younger (IS 5c?; ~105 ka?) than, the Punta Tepopa–Campo Dólar samples.

In conclusion, the morphostratigraphic evidence that the Tepopa 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 Tepopa 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 pervious nature of the sandy sediments and endoreic 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 5c?) 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 Bahia 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 correlatable with the last interglaciation, 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 Tepopa 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 (Ortlieb 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 Bahia 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. 9h, Bahia Blanca, Bahia 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.

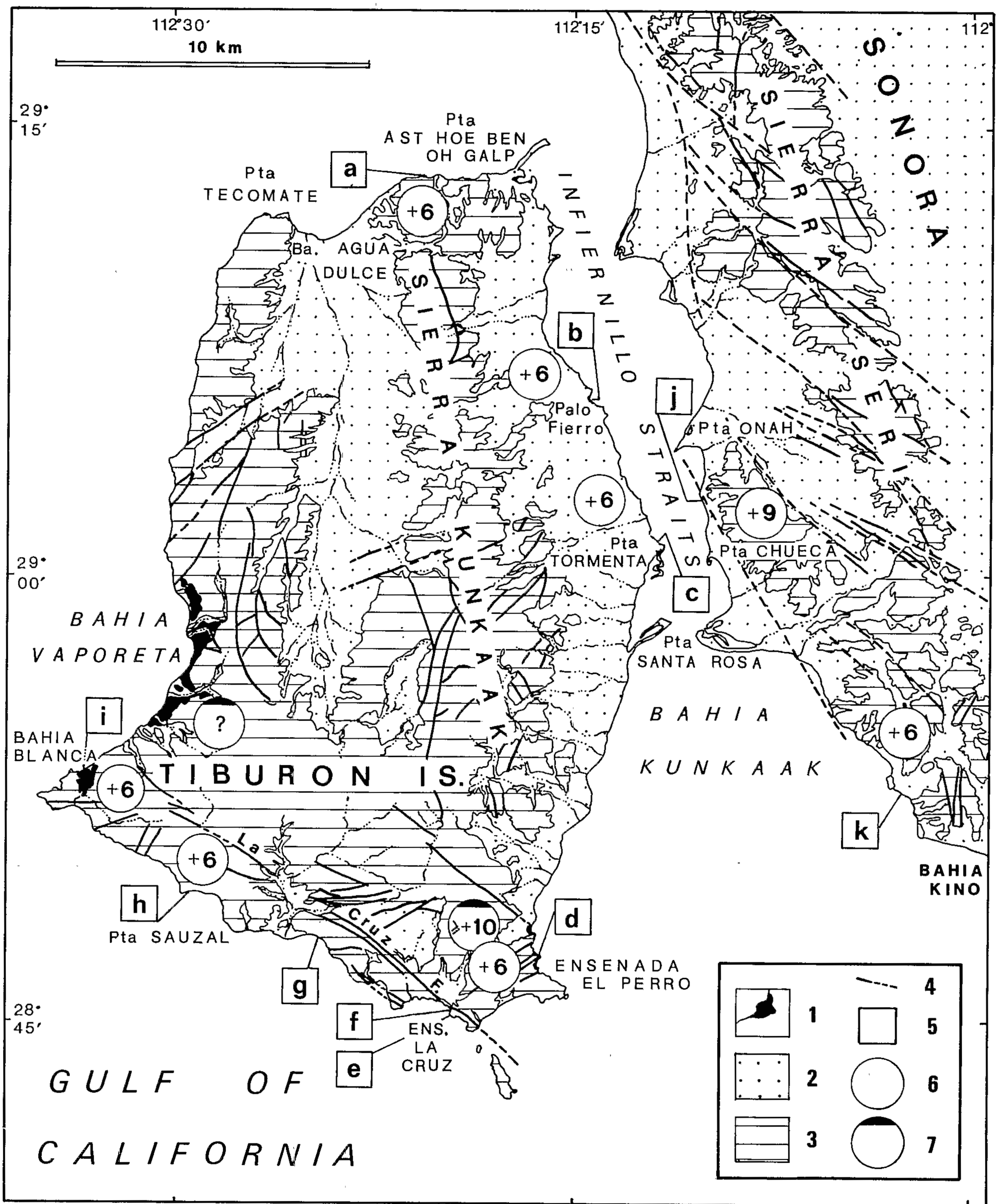


Figure 8. Tiburon Island and the Infiernillo Straits: location of the sections of Quaternary coastal deposits (a to k) shown in Figure 9. Simplified geology from Gastil and Krummenacher (1974). 1. Quaternary marine terraces, according to Gastil and Krummenacher (1974). 2. Quaternary alluvium. 3. Pre-Quaternary 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 Vaporeta, 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 latest 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. 9l). 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 radiochronologic 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 ^{14}C age ($32{,}500 \pm 1{,}500$ B.P., Table 3), and an alle/Ile ratio that supports an IS 5e age (Table 2). On one hand, the high content of ^{238}U measured in the LP 28 sample reveals an anomalous intake of uranium, which invalidates the Th/U geochronologic 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 fluvio-deltaic fine sediments from the paleo-Rios Sonora and La Poza; 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 screes 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 Henyey, 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 (Curray 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 Blás, controversial ideas have been published concerning the late Quaternary vertical movements in relation to postglacial sea-level-rise evidences. Curray 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 Connally (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.

GEOCHRONOLOGY OF THE PLEISTOCENE SHORELINES AND NEOTECTONIC IMPLICATIONS

Late Pleistocene shorelines

Along the Sonoran coast, the identification of the IS 5e shoreline is primarily based on morphostratigraphic evidence and lateral correlation. As found in numerous coastal regions of the world, the last Pleistocene transgression, during which the sea appears to have stood several meters above the present level, may be correlated with the last interglaciation maximum (IS 5e). The fact that in Sonora all the marine deposits that predate the most recent Pleistocene coastal sequence are significantly more altered, indicates that the latter sequence cannot be correlated with a late, last interglacial, high sea-level stand (IS 5a or 5c), and thus suggests that it corresponds to the IS 5e. Besides, the assignment of the well-preserved and most recent (Pleistocene) deposits to the IS 5e is supported, to some extent, by aminostratigraphic and radiometric data.

Measurements of aIle/Ile ratios of *Chione* and *Dosinia* shells of distinct Quaternary ages, collected in the Gulf of California (Ortlieb, 1982a, 1984c, 1987), established that the late Quaternary temperatures have been so high that only late Pleistocene fossils yield ratios below racemic equilibrium. In other words, unracemized *Dosinia* and *Chione* shells may be assigned a younger age than middle Pleistocene. It should be noted that this does not preclude the possibility that the late Pleistocene fossils be racemized because of local (warmer) diagenetic conditions. Aminostratigraphic analyses performed on Sonoran material (Table 2) thus proved useful to separate late Pleistocene from middle Pleistocene samples.

The Th/U dating 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.

As a corollary, it may be added that the U-series geochronological method applied to mollusks would not be an efficient means to distinguish IS 5e from 5c (or 5a) samples. The only places where the neotectonic setting would have made possible the emersion of IS 5c (or 5a) deposits are the Mesa de Sonora and Tepopa areas.

Middle Pleistocene shorelines

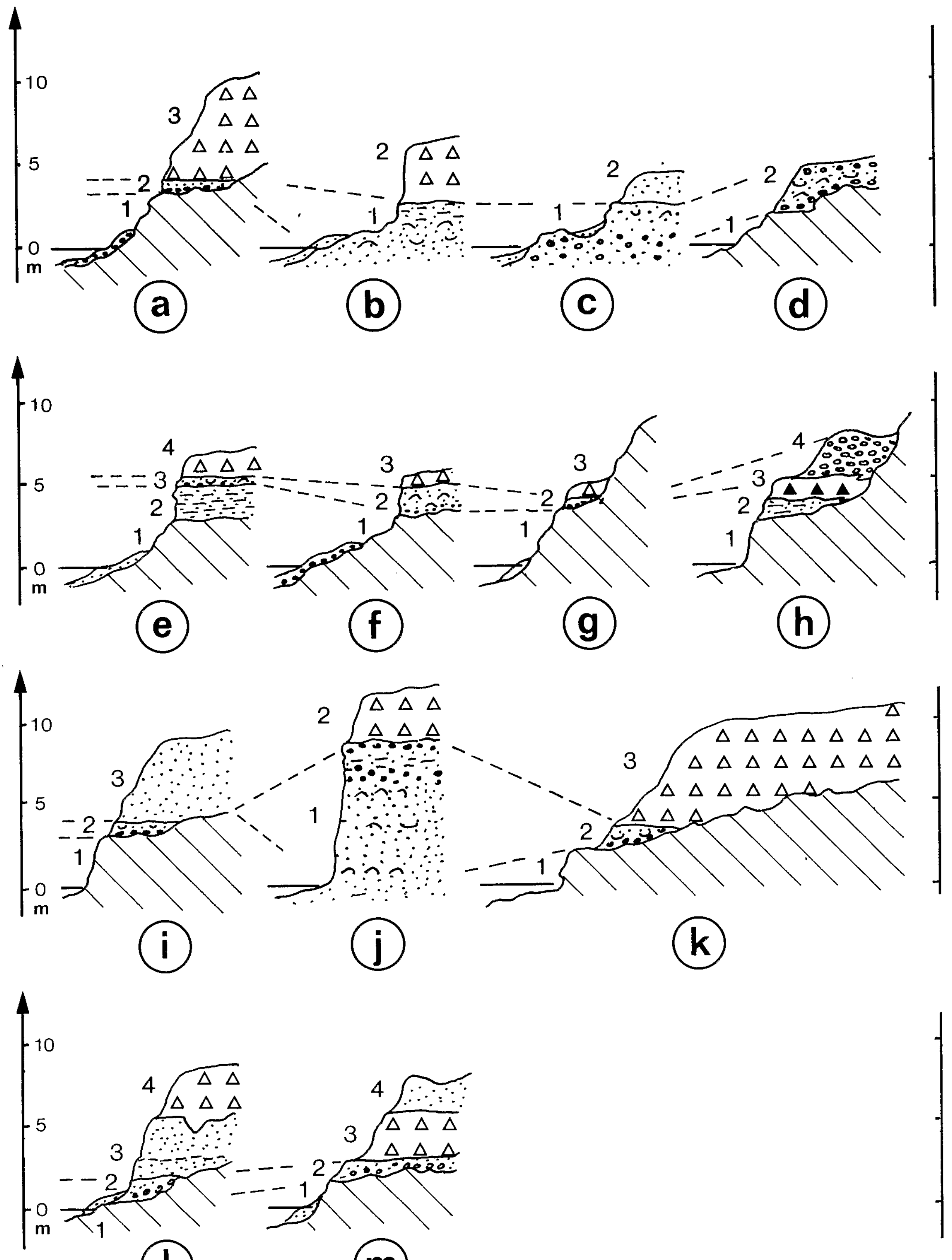
When middle Pleistocene shorelines are not preserved as emerged features along a coastal region (where late Pleistocene marine sediments do crop out above MSL), it may be due either to the fact that the coast is subsident or the erosion has destroyed (or sedimentation has hidden) the middle Pleistocene interglacial shorelines. In Sonora, several outcrops of pre–late Pleistocene marine sediments have been observed from the northernmost gulf southward to Tiburon Island (and possibly to the southeasternmost gulf).

In most cases, the middle Pleistocene deposits crop out below the late Pleistocene units, thus at a very low elevation; reconstructions of paleo–sea level based on paleobathymetric interpretations indicate that the corresponding high sea-level stands were at elevations of the order of +10 to +20 m. The locality of Playa Santa Maria, where the highest elevated shoreline reaches +23 m, may have been uplifted by a few meters at the end of the middle Pleistocene and before the late Quaternary. The scarce middle Pleistocene remains are taken as indications that the eastern coast of the Gulf of California, as a whole, has not been subsiding in the last few hundred thousand years. If, during the middle Pleistocene interglaciations, sea level reached a position close to the present MSL, it is inferred that some uplift may have occurred in several places (if not all the Sonoran coastline) prior to the late Pleistocene.

Neotectonic conclusions

In spite of the poorly preserved condition of early and middle Pleistocene shorelines, the vertical distribution of Quaternary marine deposits indicates that the recent vertical displacements have been of limited amplitude along most of the eastern coast of the Gulf of California. In this chapter, it has been stressed that the

Figure 9. Sections of Quaternary coastal deposits around Tiburon Island (a to i) and in the Infiernillo Straits–Bahia Kino–Tastiota area (j to m). See locations on Figure 8 (a to k) and Figure 10 (k to m). Section a: 1. Mesozoic granitic substrate. 2. Early late Pleistocene nearshore sequence (LQ 159). 3. Late Quaternary slope deposits. Section b: 1. Early late Pleistocene very fossiliferous sublittoral sands (LQ 149). 2. Late Quaternary bajada deposits. Section c: 1. Early late Pleistocene nearshore sequence. 2. Late Quaternary sand dune. Section d: 1. Tertiary volcanic substrate. 2. Early late Pleistocene nearshore sequence (LQ 141). Section e: 1. See d1. 2. Poorly fossiliferous, lagoonal, fine-grained sandstone (middle Pleistocene). 3. Early late Pleistocene nearshore sequence. 4. Late Quaternary alluvium. Section f: 1. See d1. 2. Early Pleistocene fossiliferous nearshore sequence (LQ 175). 3. See e4. Section g: 1. See d1. 2. Early late Pleistocene condensed nearshore sequence. 3. Late Quaternary slope deposits. Section h: 1. See d1. 2. Lagoonal siltstones and sandstones (middle Pleistocene). 3. Middle Quaternary slope deposits. 4. Early late Pleistocene shingle ridge. Section i: 1. See d1. 2. Middle(?) Pleistocene nearshore sequence. 3. Consolidated eolianite (middle Pleistocene?). Section j: 1. Early late Pleistocene fossiliferous sublittoral and nearshore sequence (LU 1075). 2. Late Quaternary slope deposits. Section k: 1. Mesozoic granitic substrate. 2. Early late Pleistocene nearshore sequence. 3. Thick late Quaternary bajada sequence. Section 1: 1. Mesozoic granitic substrate. 2. Early late Pleistocene nearshore sequence (LP 28). 3. Late Pleistocene eolianites. 4. Late Quaternary alluvium. Section m: 1. Miocene volcanoclastic substrate. 2. Early late Pleistocene nearshore sequence. 3. Late Pleistocene alluvium. 4. Late Quaternary eolian sands.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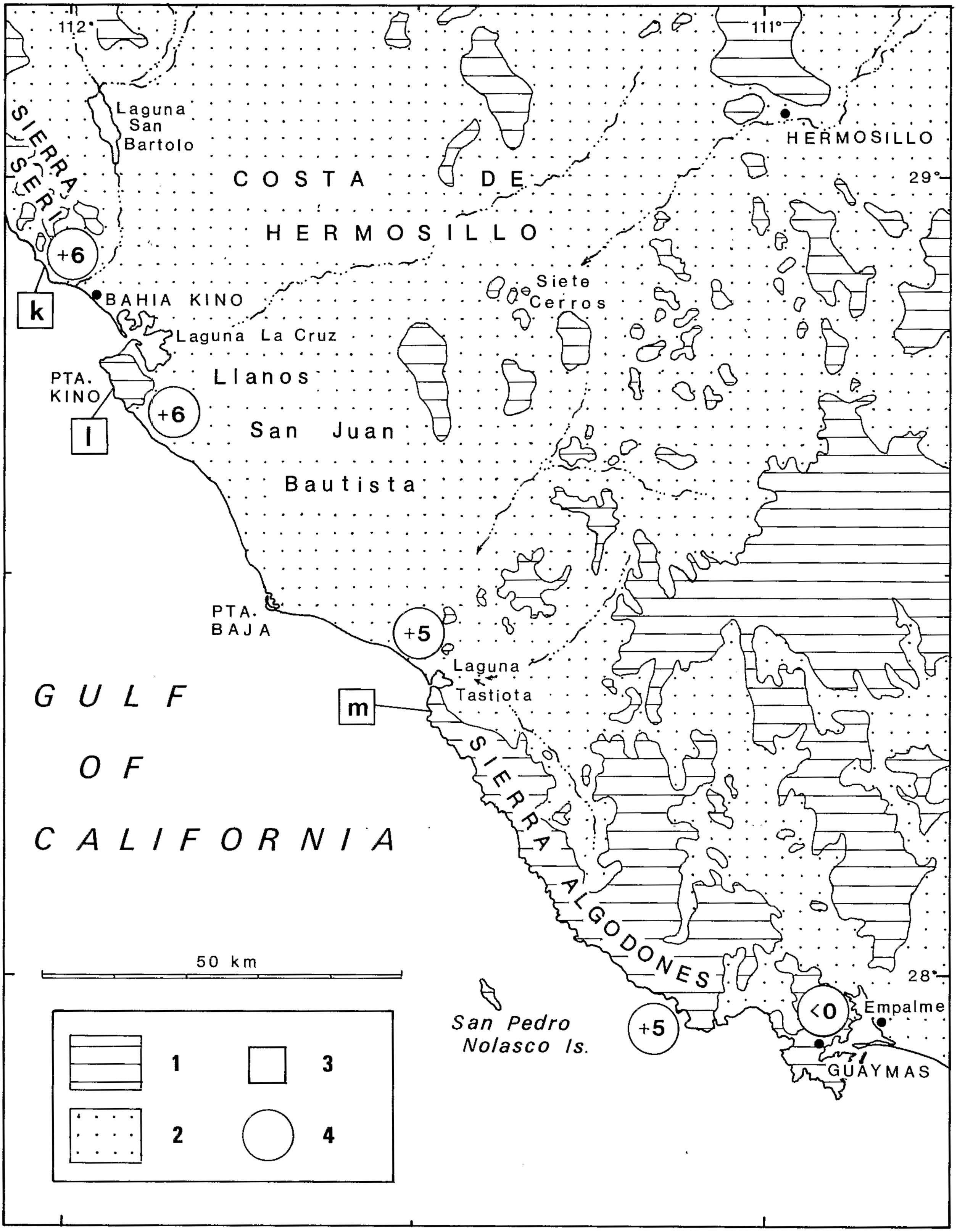

Figure 10. Bahía Kino–Guaymas region: distribution and height of the early late Pleistocene shoreline. 1. Pre-Quaternary units. 2. Quaternary alluvium and eolian sands. 3. Location of the sections of Quaternary coastal deposits (k to m) shown in Figure 9. 4. Maximum elevation (meters above MSL) of the early late Pleistocene (IS 5e) shoreline.

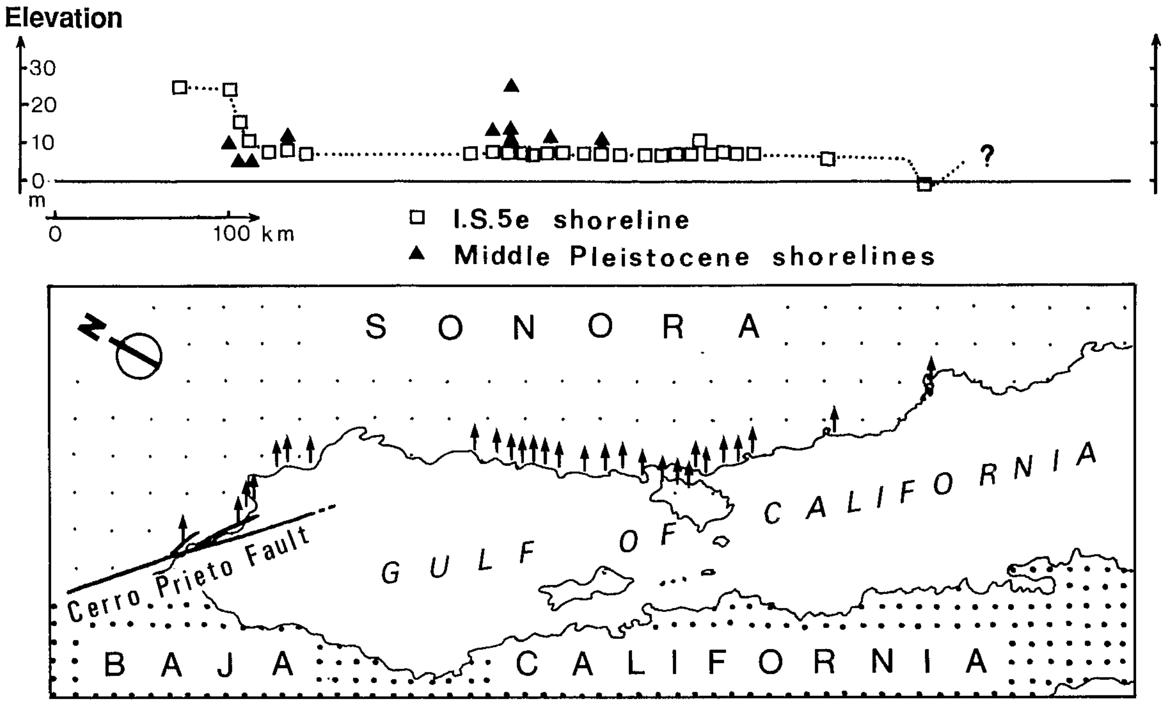

Figure 11. Height distribution of late (IS 5e) and middle Pleistocene shorelines along the Sonoran coast. The even elevation of the IS 5e shoreline along most of this coastal segment indicates that the northeastern Gulf of California did not register vertical motion in the late Quaternary.

IS 5e shoreline is observed, or can be reconstructed, at a nearly constant elevation of $\geqslant$+6 ($\pm$ 1) m between Bahia Adair and Guaymas (Fig. 11). Assuming that this ~+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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REFERENCES CITED

Aharon, P., 1983, 140,000 yr isotope climatic record from raised coral reefs in New Guinea: Nature, v. 304, p. 720–723.

Anderson, C. A., 1950, 1940 E. W. SCRIPPS cruise to the Gulf of California; Part 1, Geology of the islands and neighboring land areas: Geological Society of America Memoir 43, 53 p.

Arnal, R. E., 1961, Limnology, sedimentation, and micro-organisms of the Salton Sea, California: Geological Society of America Bulletin, v. 72, p. 427–478.

Beal, C. H., 1948, Reconnaissance of the geology and oil possibilities of Baja California, Mexico: Geological Society of America Memoir 31, 138 p.

Bernat, M., Gaven, C., and Ortlieb, L., 1980, Datation de dépôts littoraux du dernier interglaciaire (Sangamon) sur la côte orientale du Golfe de Californie, Mexique: Société Géologique de France, Bulletin, ser. 7, t. 22, no. 2, p. 219–224.

Bischoff, J. L., and Henyey, T. L., 1974, Tectonics elements of the central part of the Gulf of California: Geological Society of America Bulletin, v. 85, p. 1893–1904.

Blake, W. P., 1854, Ancient lake in the Colorado desert: American Journal of Science, v. 17, p. 435–438.

Bloom, A. L., Broecker, W. S., Chappell, J.M.A., Matthews, R. K., and Mesolella, K. J., 1974, Quaternary sea level fluctuations on a tectonic coast; New $^{230}Th/^{234}U$ dates from the Huon Peninsula, New Guinea: Quaternary Research, v. 4, p. 185–205.

Bradley, W. C., and Griggs, G. B., 1976, Form genesis and deformation of central California wavecut platforms: Geological Society of America Bulletin, v. 87, p. 22–40.

Broecker, W. S., 1963, A preliminary evaluation of U-series disequilibrium as a tool for absolute age measurements of marine carbonates: Journal of Geophysical Research, v. 68, p. 2817–2834.

Broecker, W. S., Thurber, D. L., Goddard, J., Ku, T. L., Matthews, R. K., Mesolella, K. J., 1968, Milankovitch hypothesis supported by precise dating of coral reefs and deep-sea sediments: Science, v. 159, p. 297–300.

Celis-Gutiérrez, S., 1975, Estudio microfaunístico y paleoecológico de una sección estratigráfica, entre Punta Onah y Punta Tormenta, Sonora, México [Profession thesis in biology]: Mexico, Facultad de Ciencias, Universidad Nacional Autónoma de México, 47 p.

—— , 1979, Les foraminifères quaternaires des anciennes lignes de rivage de la côte de Sonora et de Basse Californie, Mexique [Speciality doctoral thesis]: Paris, Université P. et M. Curie, 110 p.

—— , 1980, Estudio microfauníistico de una sección del Pleistoceno superior en la región de Puerto Libertad, Sonora: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 4, p. 76–81.

Celis-Gutierrez, S., and Malpica-Cruz, V., 1981, Interpretación paleoambiental y diagenética de sedimentos marinos del Pleistoceno tardío al noroeste de Puerto Libertad, Sonora, México: Geological Society of America Abstracts with Programs, v. 12, p. 48–49.

Chappell, J. M. A., 1974, Geology of coral terraces, Huon Peninsula, New Guinea; A study of Quaternary tectonic movements and sea level changes: Geological Society of America Bulletin, v. 85, p. 553–570.

Chappell, J. M. A., and Shackleton, N. J., 1986, Oxygen isotopes and sea level: Nature, v. 324, p. 137–140.

Chavez, E., 1975, Fauna de invertebrados de Bahía Kino, Sonora [Professional thesis in biology]: México, Facultad de Ciencias, Universidad Nacional Autónoma de México, 52 p.

Colletta, B., and Ortlieb, L., 1979, Neotectonic evolution of the northernmost coastal area of the Gulf of California, Mexico: Geological Society of America Abstracts with Programs, v. 11, p. 403–404.

—— , 1981, La actividad tectónica cuaternaria en le extremidad meridional del sistema de San Andrés, *in* Memoria del Simposio sobre asentamientos humanos en la Falla de San Andrés, Tijuana, 1979: México, Secretaría de Asentamientos Humanos y Obras públicas, p. 79–90.

—— , 1984, Deformations of middle and late Pleistocene deltaic deposits at the mouth of the Rio Colorado, northwestern Gulf of California, *in* Malpica-Cruz, V., Celis-Gutiérrez, S., Guerrero-García, J., and Ortlieb, L., eds., Neotectonics and sea level variations in the Gulf of California area; A symposium, Hermosillo, México, Universidad Nacional Autónoma de México, Instituto de Geología, p. 31–53.

Connally, G. G., 1984, Soil stratigraphy and inferred tectonic history of the West Mexican Coastal Plain, *in* Malpica-Cruz, V., Celis-Gutiérrez, S., Guerrero-García, J., and Ortlieb, L., eds., Neotectonics and sea level variations in the Gulf of California area; A symposium, Hermosillo: Mexico, Universidad Nacional Autónoma de México, Instituto de Geología, p. 55–73.

Curray, J. R., and Emmel, F. J., and Crampton, P. J., 1969, Holocene history of a strand plain lagoonal coast, Nayarit, Mexico, *in* Lagunas costeras, un simposio, México, 1967: Mexico, Universidad Nacional Autónoma de México, p. 63–100.

Dibblee, T. W., 1954, Geology of the Imperial Valley region, California, *in* Jahns, R., ed., Geology of Southern California: California Division of Mines Geology Bulletin, v. 170, p. 21–28.

Durham, J. W., 1950, 1940 E.W. SCRIPPS cruise to the Gulf of California: Part 2, Megascopic paleontology and marine stratigraphy: Geological Society of America Memoir 20, 68 p.

Eberly, L. D., and Stanley, T. B., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geological Society of America Bulletin, v. 89, p. 921–940.

Elders, W. A., Rex, R. W., Meidav, T., Robinson, P. T., and Biehler, S., 1972, Crustal spreading in Southern California: Science, v. 178, p. 15–24.

Fuis, G. F., Mooney, W. D., Healy, J. H., Lutter, W. J., and McMechan, G. A., 1982, Crustal structure of the Imperial Valley region, *in* The Imperial Valley, California, earthquake of October 15, 1979: U.S. Geological Survey Professional Paper 1247, p. 25–49.

Gastil, R. G., and Krummenacher, D., 1974, Reconnaissance geologic map of coastal Sonora between Puerto Lobos and Bahia Kino: Geological Society of America Map and Charts Series MC-16, scale 1:150,000.

—— , 1977, Reconnaissance geology of coastal Sonora between Puerto Lobos and Bahia Kino: Geological Society of America Bulletin, v. 88, p. 189–198.

Gastil, R. G., and Ortlieb, L., 1981, Geology of coastal Sonora between Puerto Lobos and Bahia Kino, roadlog for a field trip, *in* Ortlieb, L., and Roldan, J., eds., Geology of northwestern Sonora and southern Arizona, fieldguides and papers: Hermosillo, Universidad Nacional Autónoma de México, Instituto de Geología, p. 52–72.

Gilmore, T. D., 1985, Episodic regional uplift in southeastern California preceding major historic earthquakes in the Imperial Valley (abs.): EOS Transactions of the American Geophysical Union, v. 66, p. 856.

—— , 1986, Historic vertical displacements in the Salton trough and adjacent parts of southeastern California: U.S. Geological Survey Open-File Report 86-380, 177 p.

Gilmore, T. D., and Castle, R. O., 1983, Tectonic preservation of the divide between Salton basin and the Gulf of California: Geology, v. 11, p. 474–477.

Giresse, P., and Davies, O., 1980, High sea levels during the last glaciation; One of the most puzzling problems of sea levels studies: Quaternaria, v. 22, p. 211–236.

González-González, R. M., 1982, Comparación sedimentológica y faunistica (*Mollusca, Gastropoda*) de diferentes paleoambientes costeros del Pleistoceno superior de la región Tepopa, Sonora [Professional thesis in biology]: México, Facultad de Ciencias, Universidad Nacional Autónoma de México, 174 p.

Gonzalez-Gonzalez, R. M., Luna-Guerin, B., and Ortlieb, L., 1984, Análisis faunístico (*Bivalvia* and *Gastropoda*) de depósitos litorales del Pleistoceno tardío en diversas localidades del área de Tepopa, Sonora, *in* Malpica-Cruz, V., Celis-Gutiérrez, S., Guerrero-García, J., and Ortlieb, L., eds., Neotectonic and sea level variations in the Gulf of California area; A symposium, Hermosillo: Mexico, Universidad Nacional Autónoma de México, Instituto de Geología, p. 125–137.

Gorsline, D. S., 1967, Sedimentologic studies of the Colorado delta: University of Southern California, Report USC-Geol. 67-1, submitted to Geogr. Branch, Office of Naval Research, 89 p.

Gutiérrez-Estrada, M., and Castro del Río, A., 1984, Terrazas marinas pleistocénicas en el área de Mazatlán, Sinaloa, México, *in* Abstracts Symposium on Neotectonics and Sea Level Variations in the Gulf of California Area, Hermosillo: México, Universidad Nacional Autónoma de México, Instituto de Geología, Abstracts, p. 27.

Harrison, J. C., and Mathur, S. P., 1964, Gravity anomalies in the Gulf of California, *in* van Andel, H., and Shor, G. G., eds., Marine geology of the Gulf of California: American Association of Petroleum Geologists Memoir 3, p. 76–89.

Hertlein, L. G., and Emerson, W. K., 1956, Marine Pleistocene invertebrates from near Puerto Peñasco, Sonora, Mexico: San Diego Society of Natural History Transactions, v. 12, p. 154–176.

Hudnut, K., Beavan, J., and Bilham, R., 1985, Salton sea level data; Active transpression on the southern San Andreas fault [abs.]: EOS Transactions of the American Geophysical Union, v. 66, p. 383.

Ives, R. L., 1951, High sea levels of the Sonora shores: American Journal of Science, v. 249, p. 215–223.

——, 1959, Shell dunes of the Sonoran shore: American Journal of Science, v. 257, p. 449–457.

——, 1964, The Pinacate region, Sonora, Mexico: California Academy of Science Occasional Papers 47, 43 p.

——, 1971, An archeological sterile area in northern Sonora: Kiva, v. 36, p. 1–10.

Johnson, N. M., and 5 others, 1983, Rates of late Cenozoic tectonism in the Vallecito–Fish Creek basin, western Imperial Valley, California: Geology, v. 11, p. 664–667.

Jones, P. L., 1975, Petrology and petrography of beachrock (Pleistocene?), Sonora coast, northern Gulf of California [M.S. thesis]: Tucson, University of Arizona, 47 p.

Kaufman, A., Broecker, W. S., Ku, T. L., and Thurber, D. L., 1971, The status of U-series methods of mollusks dating: Geochimica et Cosmochimica Acta, v. 35, p. 1155–1183.

Kennedy, G. L., Lajoie, K. R., and Wehmiller, J. F., 1982, Aminostratigraphy and faunal correlations of late Quaternary marine terraces, Pacific coast, U.S.A.: Nature, v. 299, p. 545–547.

Kern, J. P., 1977, Origin and history of Upper Pleistocene marine terraces, San Diego: Geological Society of America Bulletin, v. 88, p. 1553–1566.

Kniffen, F. B., 1932, The natural landscape of the Colorado delta: University of California Publications in Geography, v. 5, p. 149–244.

Ku, T. L., 1976, The Uranium-series methods of age determination: Annual Review of Earth and Planetary Sciences, v. 4, p. 347–379.

Lajoie, K. R., and 7 others, 1979, Quaternary shorelines and crustal deformations, San Diego to Santa Barbara, California, *in* Abbott, P. L., ed., Geological excursions in Southern California: San Diego, California, San Diego State University, p. 3–15.

Lancin, M., 1979, Géomorphologie des littoraux du Canal de l'Infiernillo et du Canal Ballenas-Salsipuedes, Golfe de Californie, Mexique [Speciality doctoral thesis]: Paris, Université Paris I, 184 p.

——, 1985, Geomorfología y génesis de las flechas litorales del Canal del Infiernillo, Estado de Sonora: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 6, p. 52–72.

Lecolle, J., 1980, Morphologie, formation et aspects sédimentologiques de la Lagune Tepoca (Sonora), Mexique: Cahiers ORSTOM, sér. Géologie, v. XI–2, p. 205–224.

Lecolle, J., and Ortlieb, L., 1978, Etude préliminaire de l'évolution paléogéographique au Quaternaire supérieur de la Laguna Tepoca, Golfe de Californie, Mexique: *in* Abstracts 10th International Congress of Sedimentology, Jerusalem, Abstracts, v. 1, p. 272–273.

Luna-Guerin, B., 1981, Comparación sedimentológica y faunística (phylum *Mollusca,* clase *Pelecypoda*) en diferentes paleoambientes costeros del Pleistoceno Superior en la región de Tepopa, Sonora [Thesis manuscript]: 202 p.

Maloney, N. J., 1986, Late Holocene uplift of Bat Cave buttes, Salton trough, California: Geological Society of America Abstracts with Programs, v. 18, p. 114.

Malpica, V., Ortlieb, L., and Castro del Rio, A., 1978, Transgresiones cuaternarias de la costa de Sonora: Mexico: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 2, p. 90–97.

McGee, W. J., and Johnson, W. D., 1896, Seriland: National Geographic Magazine, v. 8, p. 125–133.

McLaughlin, R. J., Lajoie, K. R., Sorg, D. H., Morrinson, S. D., and Wolf, J. A., 1983, Tectonic uplift of a middle Wisconsin marine platform near Mendocino triple junction, California: Geology, v. 11, p. 35–39.

Meckel, L. D., 1975, Holocene sand bodies in the Colorado delta area, northern Gulf of California, *in* Broussard, M. L., ed., Deltas, models for exploration: Houston Geological Society, p. 239–265.

Merriam, R. H., 1965, San Jacinto fault in northwestern Sonora, Mexico: Geological Society of America Bulletin, v. 76, p. 1051–1054.

Moore, D. G., 1973, Plate-edge deformation and crustal growth, Gulf of California structural province: Geological Society of America Bulletin, v. 84, p. 1883–1905.

Mörner, N. A., 1971, The position of the ocean sea level during the interstadial at about 30,000 BP; A discussion from a climatic-glaciologic point of view: Canadian Journal of Earth Sciences, v. 8, p. 132–143.

Nichols, M. M., 1965, Composition and environment of recent transitional sediments on the Sonoran coast, Mexico [Ph.D. thesis]: Los Angeles, University of California, 401 p.

Ortlieb, L., 1978, Relative vertical movements along the Gulf of California, Mexico, during the late Quaternary: Geological Society of America Abstracts with Programs, v. 10, p. 466.

——, 1979, Terrasses marines dans le nord-ouest mexicain, étude au long d'une transversale entre la côte Pacifique et le Sonora en passant par la péninsule de Basse California, *in* Suguio, K., Fairchild, T. R., Martin, L., and Flexor, J. M., eds., Proceedings, International Symposium on coastal evolution in the Quaternary, Sao Paulo: Instituto Astronomico e Geofisico, Universidade de São Paulo, p. 453–474.

——, 1980, Neotectonics from marine terraces along the Gulf of California, *in* Mörner, N.-A., ed., Earth rheology, isostasy, and eustasy: New York, John Wiley and Sons, p. 479–504.

——, 1981, Recent investigations on Quaternary geology of the coast of central Sonora, Mexico, *in* Ortlieb, L., and Roldan, J., eds., Geology of northwestern Sonora and southern Arizona, Fieldguides and Papers: Hermosillo, Universidad Nacional Autónoma de México, Instituto de Geología, p. 137–149.

——, 1982a, Geochronology of Pleistocene marine terraces in the Gulf of California region, northwestern Mexico, *in* Abstracts, 11th International Union for Quaternary Research Congress, Moscow, v. 2, p. 229.

——, 1982b, La ligne de rivage du dernier interglaciaire autour de la péninsule de Basse Californie (Mexique); Reconnaissance générale et implications néotectoniques: Cahiers ORSTOM, sér. Géologie, v. 12, p. 103–115.

——, 1984a, Fieldtrip Guidebook prepared for the Symposium on Neotectonics and Sea Level Variations in the Gulf of California Area: Mexico, Universidad Nacional Autónoma de México, Instituto de Geología, 152 p.

——, 1984b, Pleistocene high stands of sea level and vertical movements in the Gulf of California area, *in* Abstracts Symposium on Neotectonics and Sea Level Variations in the Gulf of California Area, Hermosillo: Mexico, Universidad Nacional Autónoma de México, Instituto de Geología, p. 131–132.

——, 1984c, Radiometric and aminoacid dating of late Pleistocene fossils in the Gulf of California area, Mexico; Available results and problems of interpretation, *in* Abstracts Symposium on Neotectonics and Sea Level Variations in the Gulf of California Area, Hermosillo: Mexico, Universidad Nacional Autónoma de México, Instituto de Geología, p. 133–134.

——, 1987, Néotectonique et variations du niveau marin au Quaternaire dans la région du Golfe de Californie, Mexique [Doct. Sc. thesis]: Marseilles, Université Aix-Marseille II, 2 volumes, 779 p. + 442 p. [Published *in* Etudes et Thèses ORSTOM, Paris, 2 vol., 779 p. + 257 + 4 microforms].

——, 1990, Quaternary vertical movements along the coasts of Baja California and Sonora, *in* Dauphin, J. P., and Simoneit, B.R.T., eds., The Gulf and Peninsular Province of the Californias: Tulsa, American Association of Petroleum Geologists Memoir 47.

Ortlieb, L., and Malpica-Cruz, V., 1978, Reconnaissance des depôts pléistocènes marins autour du Golfe de Californie, Mexique: Cahiers ORSTOM, sér. Géologie, v. 10, p. 177–190.

Ortlieb, L., and Triclot, M. P., 1984, Etude préliminaire sur la structure et la composition géochimique de test de *Dosinia ponderosa* (Gray, 1838) actuels et fossiles du Golfe de Californie, Mexique, *in* Malpica-Cruz, V., Celis-Gutiérrez, S., Guerrero-García, J., and Ortlieb, L., eds., Neotectonics and Sea Level Variations in the Gulf of California Area; A symposium, Hermosillo: Mexico, Universidad Nacional Autónoma de México, Instituto de Geología, p. 269–294.

Ortlieb, L., and 5 others, 1989, Geodetic and tectonic analyses along an active plate boundary; The central Gulf of California: Tectonics, v. 8, p. 429–441.

Palmer, L. A., 1967, Marine terraces of California, Oregon, and Washington [Ph.D. thesis]: Los Angeles, University of California, 379 p.

Richards, H. G., 1973, A Quaternary elevated beach along the Gulf of California in Sonora, Mexico, *in* Abstracts, 9th International Union for Quaternary Research Congress: Christchurch, New Zealand, p. 306.

Rose, M. W., 1975, Sedimentology of Estero La Cholla, northwest coast of Sonora, Mexico [M.S. thesis]: Tucson, University of Arizona, 99 p.

Sanchez, O., Ness, G. E., Couch, R. W., and Dauphin, J. P., 1985, Present-day faulting and major structural blocks of the northern Gulf of California [abs.]: EOS Transactions of the American Geophysical Union, v. 66, p. 844.

Sandusky, C. L., 1969, Sedimentology of Estereo Marúa, Sonora, Mexico [M.S. thesis]: Tucson, University of Arizona, 84 p.

Shackleton, N. J., and Opdyke, N. D., 1973, Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28–238; Oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year time scale: Quaternary Research, v. 3, p. 39–55.

——, 1976, Oxygen isotope and paleomagnetic stratigraphy of Pacific core V28–239; Late Pliocene to latest Pleistocene, *in* Cline, R. M., and Hays, J. D., eds., Investigation of late Quaternary paleoceanography and paleoclimatology: Geological Society of America Memoir 145, p. 449–464.

Sharp, R. V., 1982, Tectonic setting of the Imperial Valley region, *in* The Imperial Valley, California, earthquake of October 1979: U.S. Geological Survey Professional Paper 1254, p. 5–14.

——, 1986, Holocene sedimentation in the Imperial Valley, California: Geological Society of America Abstracts with Programs, v. 18, p. 183.

Sherwin, R. W., 1971, Coastal landforms and vegetation associations of the Straits of Infiernillo region, Sonora, Mexico [M.S. thesis]: Tucson, University of Arizona, 78 p.

Sirkin, L., 1984, Late Pleistocene stratigraphy and environments of the West Mexican Coastal Plain, *in* Malpica-Cruz, V., Celis-Gutiérrez, S., Guerrero-García, J., and Ortlieb, L., eds., Neotectonics and Sea Level Variations in the Gulf of California Area; A Symposium, Hermosillo: Mexico, Universidad Autónoma de México, Instituto de Geología, p. 309–318.

Smith, J. T., and 6 others, 1985, Fossil and K-Ar age constraints on upper middle Miocene conglomerate, SW Isla Tiburon: Geological Society of America Abstracts with Programs, v. 17, p. 409.

Stanley, G. M., 1962, Deformation of Pleistocene Lake Cahuilla shoreline, Salton basin, California: Geological Society of America Special Paper 87, p. 165.

Stearns, C. E., 1976, Estimates of the position of sea level between 140,000 and 75,000 years ago: Quaternary Research, v. 6, p. 445–449.

——, 1980, A molluscan revival?; Actes du Colloque Niveaux marine et tectonique quaternaires dans l'aire méditerranéenne: Paris, Centre National de la Recherche Scientifique and Université Paris I, p. 15–26.

Stump, T. E., 1975, Pleistocene molluscan paleoecology and community structure of the Puerto Libertad region, Sonora, Mexico: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 17, p. 177–226.

——, 1981, Some Pleistocene facies and faunas of coastal Sonora and Tiburon Island, Mexico, *in* Ortlieb, L., and Roldan, J., eds., Geology of northwestern Sonora and southern Arizona Fieldguides and Papers: Hermosillo, Universidad Nacional Autónoma de México, Instituto de Geología, p. 125–131.

Tarbet, L. A., 1941, Imperial Valley, California, *in* Possible future petroleum provinces of North America: American Association of Petroleum Geologists Bulletin, v. 35, p. 260–263.

Thom, B. G., 1973, The dilemna of high sea levels during the last glaciation: Progress in Geography, v. 5, p. 170–246.

Thomas, R. G., 1963, The late Pleistocene 150-foot fresh water beach line of Salton Sea area: California Academy of Science Bulletin, part 1, p. 62, p. 9–17.

Thompson, R. W., 1968, Tidal flat sedimentation on the Colorado River delta: Geological Society of America Memoir 107, 133 p.

Trinidad-Reyes, R., and Rueda-Gaxiola, J., 1982, La historia sedimentaria y climática de la secuencia cortada por el pozo Extremeño 301 en el delta del Colorado, *in* Abstracts 6th Convención Geológica Mexicana, Mexico: Sociedad Geológica Mexicana, p. 109–110.

Van den Kamp, P. C., 1973, Holocene continental sedimentation in the Salton basin, California; A reconnaissance: Geological Society of America Bulletin, v. 84, p. 827–848.

Veeh, H. H., and Valentine, J. W., 1967, Radiometric ages of Pleistocene fossils from Cayucos, California: Geological Society of America Bulletin, v. 78, p. 545–550.

Viñas-Gomez, F., 1982, Estudio bioestratigráfico basado en nanoplanctón calcáreo de sedimentos calcáreos en el Mar de Cortez: *in* Abstracts 6th Convención Geológica Mexicana, Mexico: Sociedad Geológica Mexicana, p. 33.

——, 1984, Calcareous nannoplankton in the well Extremeño 301, *in* Abstracts Symposium on Neotectonics and Sea Level Variations in the Gulf of California Area, Hermosillo: Mexico, Universidad Nacional Autónoma de México, Instituto de Geología, p. 151.

Walker, T. R., and Thompson, R. W., 1968, Late Quaternary geology of the San Felipe area, Baja California, Mexico: Journal of Geology, v. 76, p. 479–485.

Waters, M. R., 1983, Late Holocene lacustrine chronology and archeology of ancient Lake Cahuilla, California: Quaternary Research, v. 19, p. 373–387.

Wehmiller, J. F., and 8 others, 1977, Correlation and chronology of Pacific coast marine terrace deposits of continental United States by fossil amino-stereochemistry; Technique evaluation, relative ages, kinetic model ages, and geologic implications: U.S. Geological Survey Open-File Report 77–680, 191 p.

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