Quaternary Vertical Movements Along the Coasts of Baja California and Sonora

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ABSTRACT

A regional survey of emerged Pleistocene marine terraces, with emphasis on chronostratigraphic data, permits documentation of recent deformation in coastal areas adjacent to the plate boundary of northwestern Mexico.

During the last million years, the eastern coast of the Gulf of California, on the North American plate, remained vertically "stable," whereas the Baja California peninsula was subjected to a slow and fairly continuous uplift. As a whole, the peninsular block has been uplifted at a mean rate of approximately 100 mm/10^3y in the past million years. However, uplift rates seem to have decreased, at least locally, based on the relative stability of the late Pleistocene terrace (ca. 125,000 years BP) in several areas of the northeastern, southern, and west central parts of the peninsula.

During the late Quaternary, the most deformed and uplifted areas were located close to the main fracture zones—in northwesternmost Baja California (between the Agua Blanca and Rose Canyon-San Miguel fault systems), in the westernmost Vizcaíno region (along the Bahía Tortugas fault, related to the Tosco-Abreojos fault system), and in the Colorado delta region (along the Cerro Prieto fault system). Strong uplift and warping motions also occurred in the Santa Rosalía area, but these are controlled by volcano-tectonic events related to the La Reforma Plio-Quaternary caldera.

The Baja California peninsula behaved as one large crustal block, in near-isostatic equilibrium, and was much less deformed than the California coast. This block has not been tilted westward since the Pliocene. This study supports the concepts that the peninsula is not completely attached to the Pacific plate, and that there is some plate motion along the western continental margin of Baja California.

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INTRODUCTION

Previous Investigations

Since the first mention of emerged Pleistocene shorelines in Baja California (Gabb, 1868; Lindgren, 1888; Emmons and Merrill, 1894) and in Sonora (McGee and Johnson, 1896), it has been known that the coastal areas of northwestern Mexico (Figure 1) have been somewhat uplifted in recent times. One of the most common ideas encountered in the literature on the tectonic history of the Gulf of California region is that strong vertical motions had occurred during the late Cenozoic, notably during the Quaternary.

This concept stemmed from a series of papers covering various areas of Baja California, in which Böse (1907), Wittich (1909, 1911, 1912, 1915, 1920), and Böse and Wittich (1913) described what they interpreted to be remnants of a regional transgression followed by a minimum 1000-m emergence in post-Pliocene time. Later, this interpretation was largely accepted, notably by Beal (1948) in the first important published work dedicated to the geology of the Baja California peninsula. In fact, Wittich, Böse, and Beal had been misled by the presence of modern shells brought to elevated camp sites by Indians. These misinterpretations were avoided by a few authors (such as Hertlein and Emerson, 1956), but the idea that the peninsula had been greatly submerged, and subsequently emerged, has lingered on for many years (see Eardley, 1951; McFall, 1968).

Just before the development of the plate tectonics model, Rusnak and Fisher (1964) conceived that the peninsula was a "continental marginal block resting in an area of regional uplift and tension" and that the vertical motions had induced gravitational sliding of Baja California crustal blocks.

After the general recognition that the North American/Pacific plate boundary in the Gulf of California as a series of en echelon transform faults, it has been inferred that the ongoing opening of the Gulf was accompanied by vertical motions and active block faulting of the peninsula (Fife, 1968, 1974; Moore and Buffington, 1968; Normark and Curray, 1968; Orme, 1972; Minch and James, 1974; Minch, 1975). Some authors even extended this concept to assume major recent tectonic activity in the southeastern gulf coast area (Connally, 1984; Connally and Sullivan, 1984).

Another concept commonly found in the literature is that the peninsula is a block recently tilted toward the Pacific Ocean and that the eastern coast had been strongly uplifted relative to the Pacific coast (Lindgren, 1888; Beal, 1948; Rusnak and Fisher, 1964).

Previous work on Pleistocene marine terrace deposits in northwestern Mexico has been performed by two kinds of scientists—paleontologists, who have been mainly concerned with the faunal content of late Cenozoic marine and littoral units; and geologists/geomorphologists, who were more specifically interested in the spatial distribution of Quaternary shorelines and in their neotectonic implications. The first group gathered information on a large number of outcrops of Pleistocene (and Pliocene) marine deposits, but naturally paid more attention to the more recent, better-preserved, and more fossiliferous localities (Hertlein, 1934, 1957; Durham, 1950; Emerson, 1956, 1980; Valentine, 1957, 1980; Emerson and Hertlein, 1964; Valentine and Rowland, 1969; Dowlen and Minch, 1973). The second category of workers generally surveyed marine terraces in relatively restricted areas, sometimes within regional mapping projects (Anderson, 1950; Ives, 1951, 1959, 1964; Hammond, 1954; Orme, 1971, 1972, 1974; Gastil et al., 1975; Woods, 1978, 1980). As a direct consequence of the fragmentary and local character of most of these studies, no clear regional picture of Quaternary vertical motions around the Gulf of California and in Baja California was obtained.

Between 1975 and 1981, within the framework of a cooperative French-Mexican project, ORSTOM-UNAM (Instituto de Geologia), a general reconnaissance of the Quaternary shorelines and a study of the recent deformations was carried out in northwestern Mexico, specifically along the entire coastline between Guaymas (Sonora) and Ensenada (Baja California Norte). The main results of this research, which included many geochronological and geochemical analyses oriented toward a better chronostratigraphic control on Quaternary marine deposits, are gathered in the author's French "thèse d'Etat" dissertation (Ortlieb, 1987). This paper presents some of the main conclusions of that work.

METHODOLOGY

Quaternary Variations in Sea Level

Regional correlation of remnants of Pleistocene shorelines constitutes one of the most useful and satisfactory ways to document vertical deformations of coastal areas. Relative recent vertical motions—such as local or regional uplift, warping, and block faulting—are evidenced through deleveling surveys of the ancient shorelines. Furthermore, when "absolute" geochronological data are available, and provided that assumptions can be made about the paleosea level height (paleogeoid position), it becomes possible to evaluate the net absolute vertical motion experienced at any given area during the elapsed time.

In the present state of knowledge of Quaternary sea level variations, it is reasonably well established that during the larger part of the early Pleistocene, climatic variations and induced sea level fluctuations were characterized by lower amplitudes and higher frequencies than during the second half of the Quaternary (Shackleton and Opdyke, 1973, 1976; Chappell, 1981; Williams et al., 1981; Prell, 1982). For the last 0.9 to 1.0 m.y. (that is, since the present regime of climatic variations began), sea level has been fluctuating with a major periodicity of 90,000/100,000 years. During each interglacial peak, the sea level was close to its present position, and during glacial maxima, it was more than 100 m below present mean sea level (MSL). This simplified model is complicated by the occurrence of interstadial events, during both glacial and interglacial episodes, which produced intermediate seastands.

The last interglacial is characterized by a highest seastand at about 125 ka (kilo annum = 1000 years before Present), followed by two slightly less elevated sea level maxima at about 105 and 85 ka (Broecker et al., 1968; Matthews, 1973; Bloom et al., 1974; Chappell, 1974; Shackleton and Chappell, 1985). The highest level reached was several (? 6) meters above the present datum and most probably higher than former interglacial high seastands. This high interglacial position of sea level is directly related to a well-documented warmer climate (Shackleton, 1969; Chappell, 1974; Kennedy, 1982; CLIMAP Project Members, 1984).

For most authors, the chronostratigraphic scale of the Quaternary marine units is based on oxygen-isotope curves of the V28-238 and V28-239 deep-sea cores (Shackleton and Opdyke, 1973, 1976). In the present paper, the interglacial stages corresponding to the highest sea level episodes are referred to by their odd numbers in the V28-238 isotopic curve. These "Isotopic Stages" are I.S. 5 (~130-80 ka),

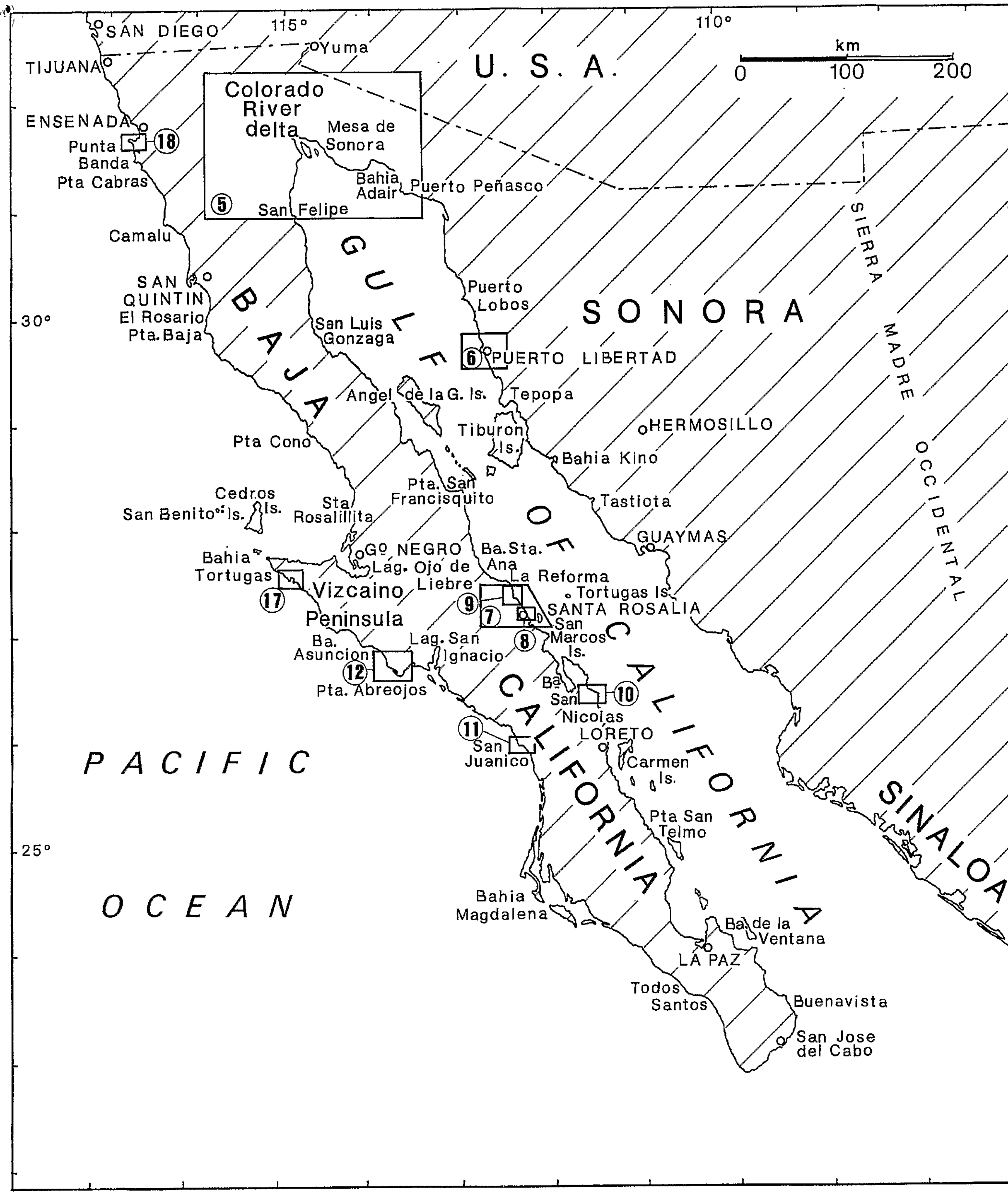


Figure 1—Index map of the area studied around the Gulf of California and the Baja California peninsula, showing main localities mentioned in the text and locations of the detailed maps (circled numbers correspond to figure numbers).

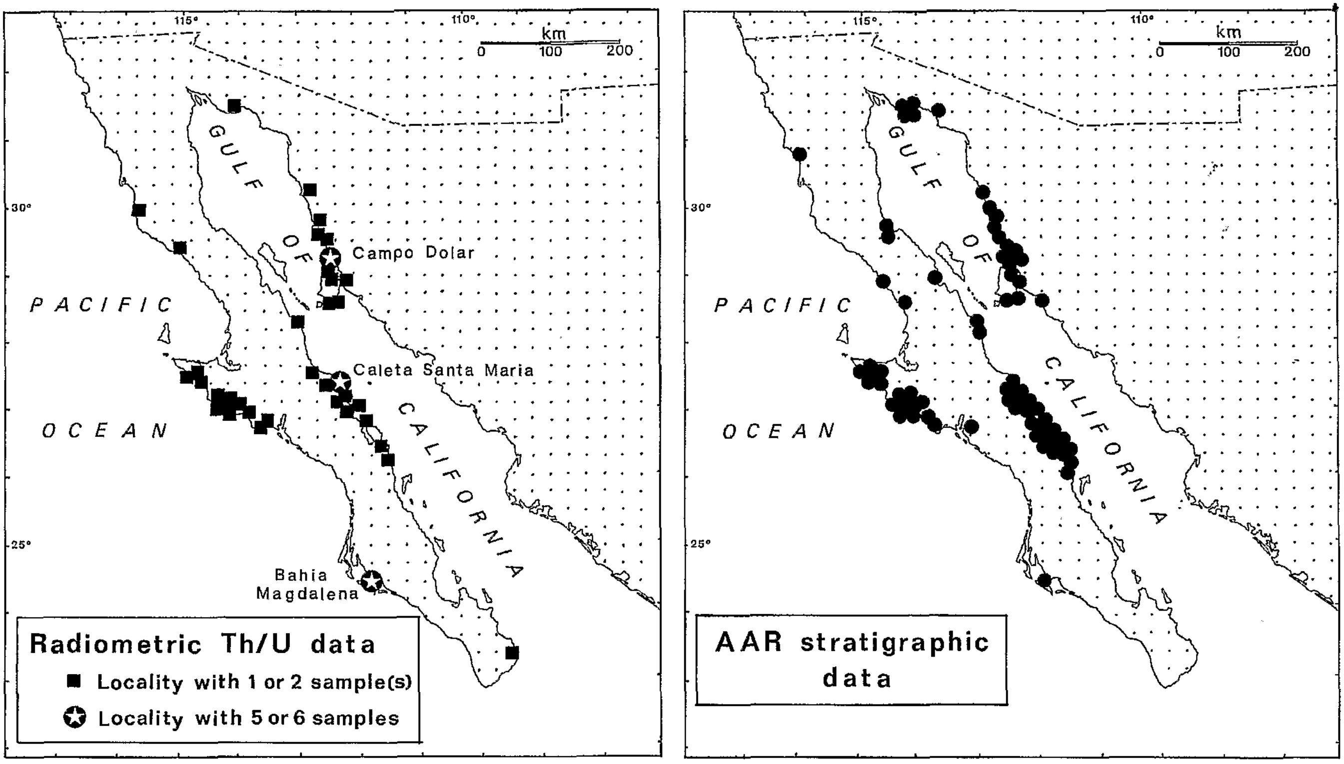


Figure 2—Geochronological data on late and late middle Pleistocene marine shells from Baja California and the east coast of the Gulf of California: Localities yielding radiometric Th/U data and amino acid racemization (AAR) stratigraphic data.

I.S. 7 (~240-200 ka), I.S. 9 (~320 ka), etc. The subdivisions of the Quaternary period adopted here are as follows: early Pleistocene (1.8-0.7 Ma), middle Pleistocene (0.7-0.13 Ma), late Pleistocene (150-10 ka), and Holocene (10-0 ka). The term "late Quaternary" is meant to encompass both the late Pleistocene and the Holocene.

In general, one may thus assume that coastal regions showing a last interglacial (I.S. 5e) shoreline a few meters above present MSL, and with no highly elevated middle Pleistocene terraces, have not been subjected to recent vertical motions. Conversely, a "staircase" arrangement of marine terraces, with several interglacial marine platforms lying significantly higher than +10 m, may be taken as evidence for uplift motions during the last few hundred thousand years.

Geochronology

Dating Pleistocene shorelines is the second main challenge in the analysis of recent vertical movements in coastal areas. For the last 150,000 years (the late Quaternary), radiometric methods generally provide acceptable results; mollusk shells and corals associated with the littoral deposits are dated through the classical 14C and uranium-series methods.

Another recently developed method, based on the racemization of amino acids, yields relative chronological information which may be converted to "absolute" ages if kinetic models can be established for the given area and if some assumptions are made on the evolution of the Quaternary ground temperatures. In the Gulf of California area, however, the arid climate seriously interferes with the determination of reliable geochronological data on the Pleistocene marine remnants. Along the Pacific coast of the Baja California peninsula, amino acid racemization (AAR) stratigraphic analyses yield valuable data that distinguish the last two interglacial deposits from older ones (Keenan, 1982; Keenan et al., 1984, 1987), but in the warmer Gulf of California, this kind of analysis could only contribute late Pleistocene (last interglacial) dates (Ortlieb, 1982a, 1984b, 1987) (Figure 2). In comparison with the results obtained along the west coast of the United States (Masters and Bada, 1977; Wehmiller et al., 1977, 1978; Karrow and Bada, 1980; Wehmiller, 1982), the chronological range, as well as the accuracy, of the AAR stratigraphic results from northwestern Mexico appear to be much more limited; this is a direct consequence of the higher Quaternary temperatures experienced by the southern area.

Environmental and paleoclimatic conditions in the northwestern Mexico coastal areas also probably played a major role in the geochemical complications that affected many Th/U analyses of pelecypod and coral samples. Most of the radiometric analyses of fossil carbonates indicated a last interglacial age (only a few cases were older than the I.S. 5e age), but they are not accurate enough to give reliable absolute ages. In other words, the Th/U age measurements do not permit a clear distinction between the isotopic substages 5a, 5c, and 5e (~85 ka, ~105 ka, and ~125 ka, respectively) of the last interglacial. In the case of pre-I.S. 5e samples, the confidence intervals of the radiometric apparent ages are so wide that the geochronological data are of reduced practical use, even for determining whether the samples are coeval with the penultimate interglacial episode (I.S. 7), or if they are older.

The composition of faunal assemblages and the oxygen isotope composition of marine shell carbonates are two independent and complementary paleoclimatic indicators that help to identify specific episodes of late Quaternary sea level (Valentine and Meade, 1960; Kennedy et al., 1982; Muhs and Kyser, 1986). In California and northwestern Baja California, comparative studies of the composition of marine terrace faunal assemblages provided useful chronostratigraphic data which distinguish earliest last interglacial (I.S. 5e) from younger last interglacial (I.S. 5a/c) localities (Valentine and Meade, 1961; Emerson, 1980; Kennedy et al., 1982, 1986). In the Gulf of California, ^{18}O isotopic analyses of littoral shells permit the identification of early last interglacial (I.S. 5e) localities and their separation from older (middle Pleistocene) deposits, as well as from younger ones (I.S. 5a and 5c) (Ortlieb, 1987).

K/Ar dating of volcanic rocks which have chronostratigraphic relationships with marine terraces was attempted but was not always successful. It should be added that the generally coarse littoral sediments which cover the Pleistocene marine platforms are not suitable for magnetostratigraphic analyses.

Under such conditions, it is apparent that chronostratigraphic interpretations still depend heavily on stratigraphic and geomorphological observations.

Marine Terraces and Reconstruction of Paleosea Levels

On methodological and practical grounds, it must be emphasized that the reconstitution of Pleistocene sea levels involves more than an identification of old marine surfaces and of marine and littoral units. The elevation of any wave-cut surface of some unknown time has by itself no practical significance except to indicate that sea level has once been close to the locality concerned.

The regional correlation of Pleistocene marine features, as well as their chronologic interpretation, can only be made through comparative studies of the relative position of remnants of definable high seastands; those definable levels are coeval with the interglacial maxima. Thus, every effort should be made in the field to reconstruct the position and the elevation of the paleo-sea level at the maximum of every transgressive phase; this is done by paying particular attention to the shoreline angle (back-edge) of the wave-cut platforms, as well as to the morphology, the sedimentology, and the faunal content of the marine deposits (Ortlieb, 1982b, 1987). Commonly encountered difficulties are: the localization of shoreline angles in regions covered with thick alluvial or eolian sediments, the identification of transgression maxima in the case of series of beach ridges or closely spaced marine platforms, and the distinction of interglacial from interstadial high seastands.

In this large study area, analyses of marine terraces and their associated deposits must also take into account regional geomorphic and climatic parameters.

EASTERN AND NORTHERNMOST COASTS OF THE GULF OF CALIFORNIA

Geomorphic Context

The late Cenozoic history of the mainland coast of the Gulf of California is dominated by Plio-Quaternary depositional processes. Notwithstanding the variety of their climatic and geomorphic controls, these active processes of continental sedimentation have led to the same result: a general burial of Pleistocene paleoshorelines.

In the northern Gulf area, the hyperarid conditions of the Sonoran Desert, combined with a generally low relief and the abundance of Colorado River alluvial sediments, are responsible for great accumulations of eolian sands and fluvio-deltaic deposits (Mesa de Sonora, see Figure 1). Along the northeastern coast of the Gulf of California, the Sonoran climate, combined with surface runoff and the typical Basin and Range relief, together controlled a widespread development of bajadas (compound alluvial fans) and piedmonts. In the southeastern part of the Gulf, where the climate becomes tropical, several perennial rivers supply great quantities of alluvial material from the Sierra Madre Occidental to the flat coastal plain and ultimately contribute to the wide continental shelf.

Besides the inland accumulation of terrestrial sediments, another limitation to the study of Pleistocene shorelines comes from the importance of the Holocene littoral processes; the eastern coast of the Gulf of California presents long sequences of beach ridges (in Nayarit and Sinaloa), extensive barrier-islands (in southern Sonora and Sinaloa), abundant coastal dunes (in the northeastern Gulf), and numerous coastal lagoons.

The most suitable areas for gathering data on Pleistocene high sea levels are the coastal ranges between Guaymas and Puerto Lobos, in central Sonora, and some cliffed stretches of the coast near Puerto Lobos and along the southern Mesa de Sonora in the northern extremity of the Gulf (Figure 1).

Late Pleistocene Terrace

Morphostratigraphy

The rocky sectors of the central Sonoran coast show a conspicuous terrace, cut at a few meters above the present MSL. This is a marine platform, with its associated nearshore sediments commonly covered by several meters of alluvium and eolian sands. The shoreline corresponding to the maximum transgression is located between +5 and +7 m (Hertlein and Emerson, 1956; Malpica et al., 1978; Ortlieb and Malpica, 1978; Ortlieb, 1980, 1981a, 1982b). (In this chapter, all elevations are referred to the present MSL, and not to any high-water datum).

The age of this terrace is well constrained by morphostratigraphic and lithostratigraphic criteria, but has caused some problems in geochronological interpretation. On the central Sonoran and Isla Tiburón shores, stratigraphic relationships and geomorphic features clearly show that this is the only marine unit that immediately antedates the late Quaternary bajada deposits. The weak cementation of the littoral sediments and the fair preservation state of the fossil remains, which confirm a relatively young Pleistocene age, provide reliable criteria for regional correlations of the remnants of this unit.

Geochronology

The $^{230}Th/^{234}U$ method of radiometric dating did not yield a clearcut I.S. 5e (~125 ka) age (Bernat et al., 1980; Ortlieb, 1981a) for marine shells from the low terrace. Fourteen of 17 samples of thick-shelled pelecypods provided results ranging from 64 to 129 ka (54 to 142 ka, with a confidence interval of $\pm 1\sigma$ for individual values, Figure 3). This range of apparent ages, from all the Gulf east coast samples, is similar to the range of results (64 to 120 ka) obtained from

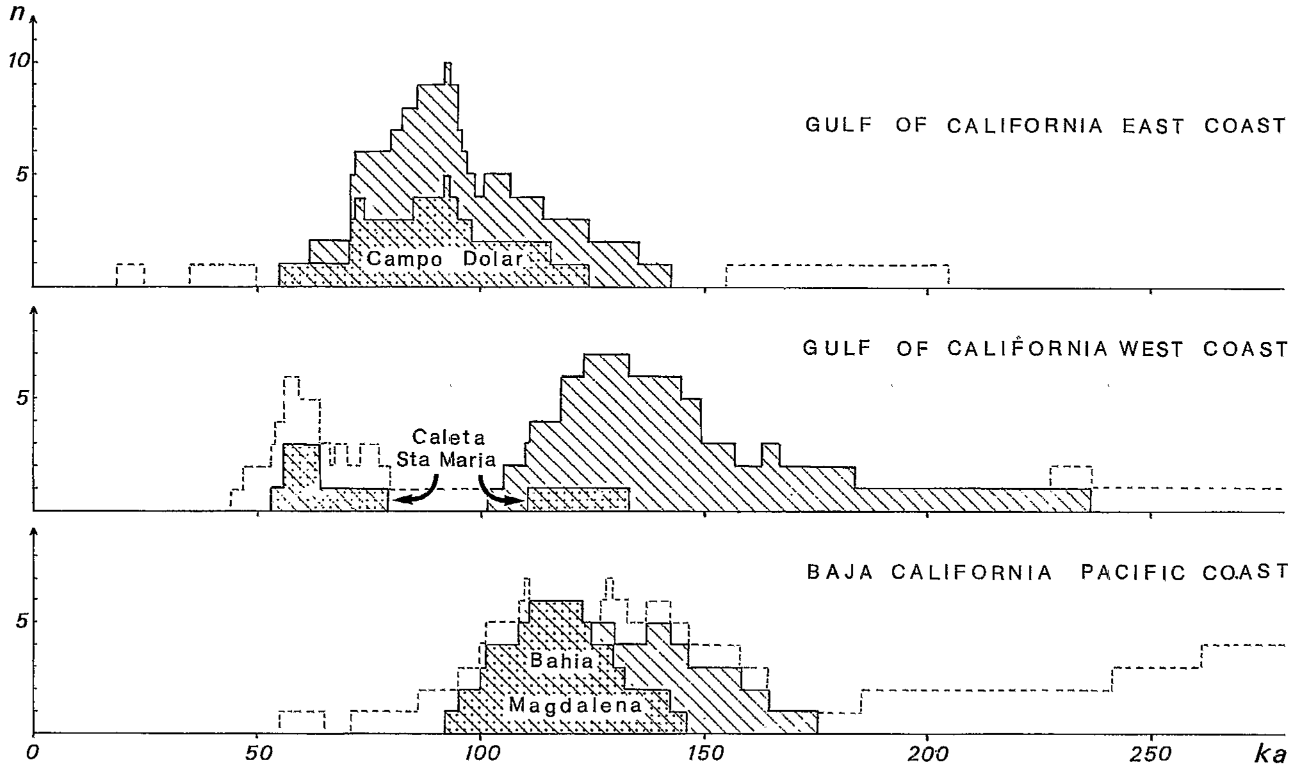


Figure 3—Frequency distribution of uranium-series apparent ages (including confidence intervals of ±1 σ), from late Pleistocene marine shells and corals collected in northwestern Mexico (data from Omura et al., 1979; Bernat et al., 1980; Ortlieb, 1987). Dotted lines designate analytically unreliable results. In each coastal region, one locality provided five or six results from distinct individual samples (dotted and striped areas). Stratigraphical, morphological, and AAR stratigraphic information, as well as oxygen isotope analyses, lead us to assign an Isotopic State 5e age to most of the dated samples, except in Caleta Santa María, where at least some of the samples may be of I.S. 5a/c age.

a series of six samples collected in situ in a single thin sedimentary unit at Campo Dolar (Figure 3). If formerly coexisting shells yield such a wide spread of apparent Th/U ages, one may assume that single Th/U results are of little significance, and that all the radiometric data should not be taken as statistical evidence for more than a single episode of late Pleistocene high-level seastand.

Radiometric dating of comparable low terraces in other parts of the world provided a mean 125 ka age (Bloom et al., 1974; Chappell, 1974, 1981; Kern, 1977). The most probable age of the whole sample set from Sonora and Isla Tiburón is close to the oldest limit (130 ka) of the apparent range, and not its statistical mean (93 ka); this results from a late uptake of uranium by the mollusk shells in the particular paleoclimatic and paleohydrologic conditions that exist along the eastern coast of the Gulf of California. Pelecypod shell material is often considered to provide minimum Th/U ages (Ku and Kern, 1974; Ku, 1976; Stearns, 1980).

On the eastern coast of the Gulf of California, amino acid racemization analyses were performed on 29 fossil shell samples (Figure 2). The data strongly support a late Pleistocene age at practically all localities (Ortlieb, 1982a, 1984b, 1987, in press). Amino acid analyses of individual *Dosinia ponderosa* shells previously submitted for Th/U dating demonstrate the unreliability of most of the individual radiometric ages and confirm that the fossils do not pertain to several episodes of late Pleistocene high seastands.

Age of the Tepopa Paleoembayment: 30 ka by Radiocarbon or 120 ka?

In central Sonora, another kind of geochronological problem with neotectonic implications concerns the reliability of a series of ~30 ka apparent radiocarbon ages. Richards (1973) inferred recent vertical motions of the northeastern coast of the Gulf of California on the basis of four ^{14}C dates of emerged Pleistocene shells from the area of Tepopa; three of the results ranged from 26,770 ±525 y BP to 29,550 ±1115 y BP, and the fourth was apparently older than 42 ka. Eleven additional ^{14}C dates obtained ranged from 24,150 ±150 y BP to 33,800 ±1,500 y BP, and a twelfth result showed 20,150 ±230 y BP (Ortlieb, 1984a, 1987). These dates were measured on shells sampled at distinct littoral units corresponding to various openshore, fluvio-marine and lagoonal paleoenvironments, which all seem to be coeval with a +5 ±1 m Pleistocene transgression.

Thus, 15 dates averaging 30 ka versus a single result of "older than 42 ka" apparently document a correlation of the Tepopa marine and lagoonal units with a last interstadial high seastand (I.S. 3). Many controversial discussions have taken place on the existence (or otherwise), at ~30 ka, of a sea level episode high enough to have left emerged remnants (Mörner, 1971; Thom, 1973; Giresse and Davies, 1980). According to commonly accepted models of late Quaternary sea level variations (Bloom et al., 1974; Chappell and Veeh, 1977), the ~30 ka eustatic sea level was probably as low as 40 m below present datum.

• Lithostratigraphic and paleogeographic interpretations of sequences of littoral deposits (Lecolle and Ortlieb, 1978; Ortlieb, 1984a, 1987) demonstrated that the Tepopa marine and lagoonal series were contemporaneous with the nearby I.S. 5e Campo Dolar locality, and that they are not associated with a distinct episode of late Pleistocene high sea level. Consequently, the radiocarbon data from the Tepopa beds are discarded as evidence of a high I.S. 3 high-level seastand. The 15 of a total of 16 finite ^{14}C apparent ages are interpreted to result from a surprisingly widespread and uniform contamination of the shell carbonates by modern carbon.

Regional Attitude

Between Bahía Adair and Bahía Kino, including the shores of Isla Tiburón, the remnants of the late Pleistocene (I.S. 5e) high sea level are at a uniform elevation of +6 ± 1 m (Figure 4). At Guaymas, the I.S. 5e shoreline seems to be near the present MSL, but southward no data are available. In the northeastern Gulf, in general, the localities where the late Pleistocene shoreline is at more than +7 m are quite exceptional.

In one of those localities, on the east coast of the Infiernillo Channel, the reconstructed I.S. 5e shoreline is uplifted to about +9 m; the littoral sequence crops out along the trace of an inferred fault (Gastil and Krummenacher, 1974, 1977) which was probably active in the late Quaternary (Ortlieb, 1982b, 1984a). A second area where the last interglacial deposits have been significantly uplifted is the northwesternmost Sonoran coast, near the mouth of the Colorado River.

Eastern Side of the Colorado River Mouth

On the eastern side of the Colorado River mouth, a late Pleistocene (I.S. 5e) deltaic sequence that is partly emerged ends with an index bed of *Chione corteziensis* coquina. The correlation of this coquina with the I.S. 5e is established on both morphostratigraphic (widespread, highest-elevated, and well-preserved marine remnants) and geochronological grounds (one 129 ±13 ka Th/U age and three concordant AAR stratigraphic results). A comparative geomorphic and sedimentologic study of the Holocene delta and of the emerged Pleistocene paleodeltaic units (Ortlieb, 1987, in press) permits a reconstruction of recent deformation of the area. The shoreline associated with the coquina is observed at +7 m in northwestern Bahía Adair, at +12 m to the southwest of the same bay, and at +25 m at Punta Gorda, whereas lateral time-equivalents of the coquina crop out at about +10 m on the west bank of the present-day deltaic plain (at the eastern foot of Sierra El Mayor) and at +8 m in the San Felipe area (Figure 5).

The local uplift thus evidenced along the southern boundary of the Mesa de Sonora is directly related to the late Quaternary activity of the Cerro Prieto fault system. A branch of this system, the Punta Gorda fault, shows a strong strike-slip activity which ceased shortly before the deposition of the *Chione corteziensis* coquina (Colletta and Ortlieb, 1979, 1981, 1984). The Cerro Prieto fault system induced flexuring, drag folding, and intense fracturing in a topographic bulge that formed since late middle Pleistocene time in the southwestern part of the Mesa de Sonora near Golfo de Santa Clara (Merriam, 1965; Colletta and Ortlieb, 1979, 1984). Nowadays, almost all seismic activity in the delta region is concentrated along this fault trace (Allen, 1975; Suarez et al., 1981; Gonzalez et al., 1984). This fault seems to represent the plate boundary and constitutes the principal link between the San Andreas system and the Gulf of California.

The fact that at some distance and on both sides of the Colorado River mouth the I.S. 5e shoreline is found at the same elevation (+7/+8 m), indicates that no large vertical motions have occurred recently on either lithospheric plate. The relative vertical motion for the late Quaternary observed on the southern Mesa de Sonora, characterized by a maximum amplitude of 20 m and a maximum uplift rate of 170 mm/10^3y, is limited to a narrow area northeast of the Cerro Prieto fault trace.

Middle Pleistocene Marine Remnants

Remnants of pre-I.S. 5e Pleistocene transgressions are scarce along the northern and eastern coasts of the Gulf of California. Marine deposits and abrasion surfaces of such an age are distinguished from late Pleistocene marine remnants by morphostratigraphic and petrologic evidence. Petrographic differences between middle Pleistocene emerged marine sediments and those from younger marine terraces include a larger degree of cementation, major dissolution or diagenetic recrystallization of aragonitic bioclasts, and predominance of calcitic fossils like oysters, barnacles, echinoids, etc. Moreover, in several localities the composition of the fossil fauna is clearly distinct from that of the I.S. 5e, and from the modern fauna (Ortlieb, 1987).

In several localities (Ensenada de la Cruz, Sierra Bacha, Punta Cirio, Bahía Lobos, Bahía Adair), pre-I.S. 5e marine sediments crop out underneath the last interglacial unit at a relatively low elevation (below +6 m). In most cases, the reconstructed position of these former high seastands lies between +5 and +12 m. Higher middle Pleistocene littoral remnants have only been observed in the Santa Margarita locality (north of Puerto Libertad), where they consist of marine platforms almost devoid of associated sediments, lying at +10, +15, and +23 m (Figure 6).

The age of each of the pre-I.S. 5e marine units is not precisely determined. In the Colorado delta region, a partially emerged marine unit that underlies the late Pleistocene littoral sequence is interpreted to correspond to a relatively young middle Pleistocene high sea level episode (I.S. 7 or 9); in the subsiding tectonic regime of the deltaic area, during Pliocene-Quaternary time, this unit cannot be very old, even if it had been uplifted by faulting. In Bahía Adair and at Santa Margarita (Figure 6), where pre-I.S. 5e deposits crop out at the surface and have not yet been removed by erosion, it is also assumed that they are not older than middle Pleistocene. In other localities from the central Sonora coast, the burial of pre-I.S. 5e marine units below latest (?) middle Pleistocene bajada deposits also suggests a late middle Pleistocene age for the high seastands.

It is noteworthy that Pliocene marine beds have never been described on the coast of Sonora, and that Miocene marine units are only known below sea level from exploratory wells drilled in the Hermosillo coastal plain (Gomez, 1971) and from a few outcrops in western Isla Tiburón (Smith et al., 1985).

In summary, most of the middle (and ? early) Pleistocene marine units that crop out on the east coast of the Gulf of California are relatively low lying, generally at no more than about +10 m. In spite of the erosion and covering up by Quaternary alluvium, the older littoral remnants also support the idea of a lack of important regional vertical motions.

Uplift from latest middle Pleistocene to the present time has been detected in the northern Gulf only and can be associated with deformations of the Cerro Prieto fault system. No definite neotectonic conclusions have been drawn from

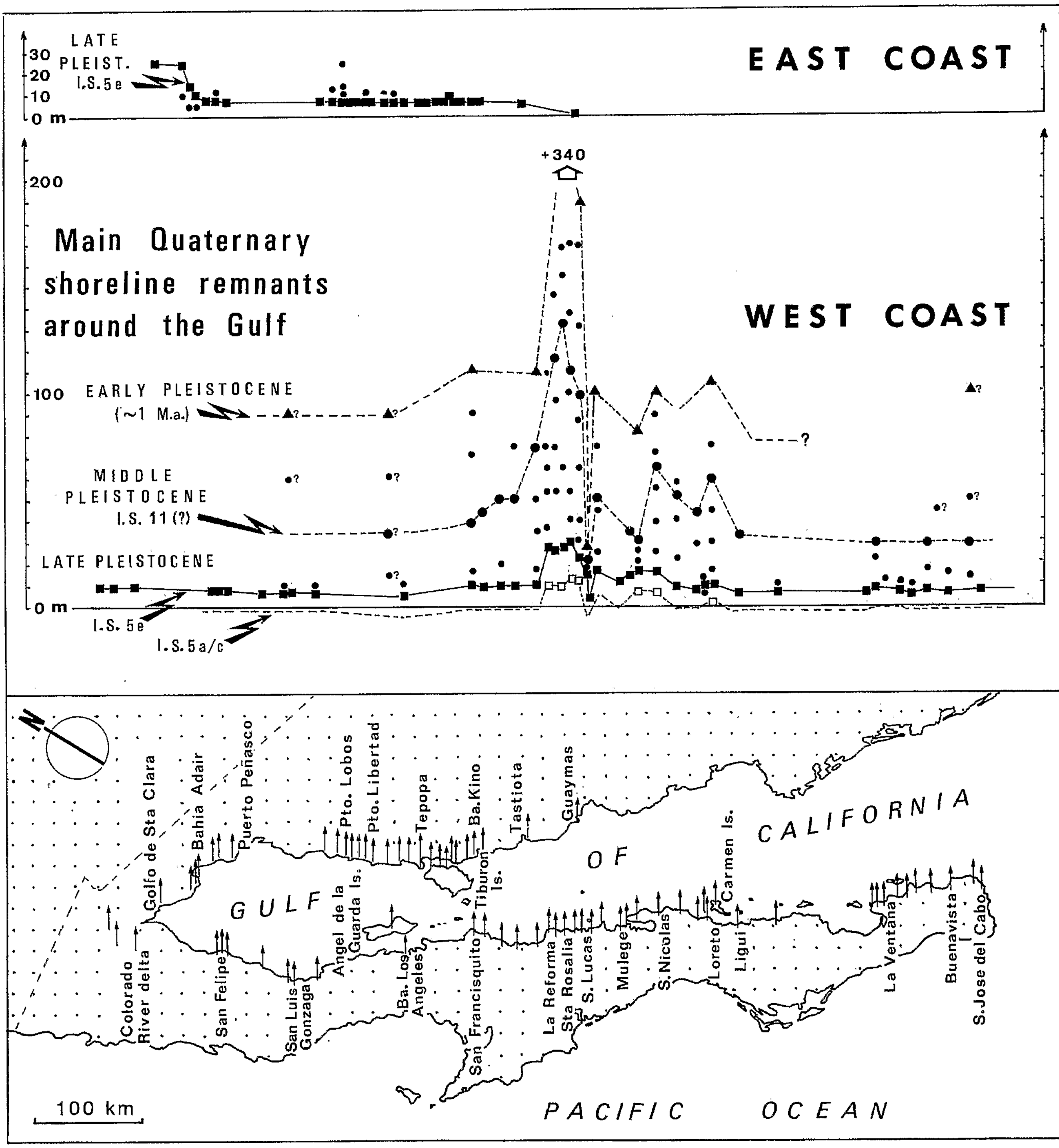


Figure 4—Spatial distribution of Pleistocene marine terraces around the Gulf of California. The regional correlation of late Pleistocene (I.S. 5e and 5a/c) shorelines is based on morphostratigraphic, geochronologic (Th/U and amino acid racemization data), and oxygen isotope data; the tentative correlations of older Pleistocene marine terraces (~1 Ma, and ? I.S. 11) are based on morphostratigraphic and geometric interpretations.

the existence of +10, +15, and +25 m terraces at Santa Margarita; they may be considered as the only preserved remnants of elevated middle Pleistocene high seastands, and in which case would document a slightly higher elevation of the northeastern coast of the Gulf during the middle Pleistocene. They may be the result of vertical displacement of a fault block, perhaps related to the former activity of a southeastern extension of the Cerro Prieto fault system (Figure 6). In either case, the motions involved must have ceased by the end of the middle Pleistocene, inasmuch as the last interglacial shoreline in the Santa Margarita locality is observed at its typical +6 ±1 m elevation.

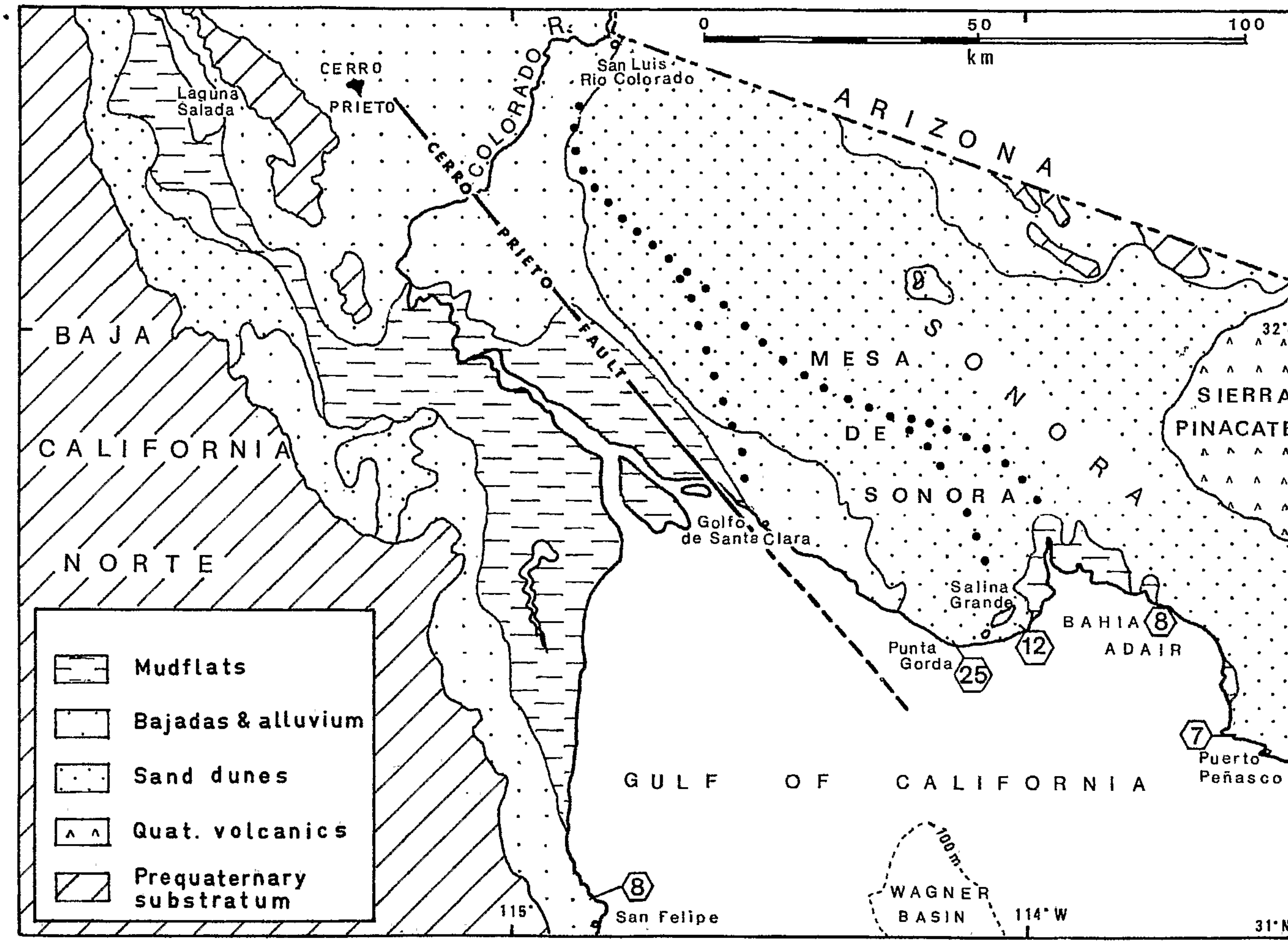


Figure 5—Quaternary geology sketch map of the northern Gulf of California, with location of the Cerro Prieto fault, the main active link between the San Andreas and the Gulf systems. Numbers in small hexagons indicate elevations (in meters above present MSL) of the late Pleistocene (I.S. 5e) shoreline; the coastal border of the Mesa de Sonora has been uplifted (by as much as 17 m at Punta Gorda) in the late Quaternary; but on a larger scale, the Pacific/North American plate boundary does not show evidence of differential vertical motions. Large dots represent a reconstructed former course of the Colorado River during the last interglacial (Ortlieb, 1987).

GULF COAST OF BAJA CALIFORNIA

Geomorphic Context

The eastern coast of the Baja California peninsula is characterized by steep relief due to the regional structural pattern and the volcanic nature of most of the outcropping rocks. Around the eastern peninsula, the continental shelf is particularly narrow and has been described as a typical neo-trailing edge margin (Inman and Nordstrom, 1971). Many offshore faults run parallel to the coastline or make a low angle with it (Rusnak et al., 1964; Moore, 1973; Henyey and Bischoff, 1973; Bischoff and Henyey, 1974).

Coastal plains and bajadas are less numerous and narrower than along the eastern coast of the Gulf or along the Pacific coast of the peninsula. On most of the central and southern Gulf coast of the Baja California peninsula, paleoclimatic and morphodynamic conditions, as well as its largely rock nature, have been favorable to the imprint and subsequent preservation of Pleistocene shorelines; subaerial erosion has generally not been able to destroy the former marine platforms cut in volcanic rocks, and continental accumulation processes have been too slow to produce thick sedimentary covers on the terraces. These relatively favorable conditions are found in the central eastern part of the peninsula (notably in the La Reforma and Bahía San Nicolas areas) and in several nearby islands.

In the northern and southern extremities of the Baja California east coast, very few terraces older than late Pleistocene have been identified. This scarcity of data concerning old Pleistocene terraces is mainly due to distinct climatic regimes and geomorphic parameters, which differ from those of the east central Baja California region. In northeastern Baja California, as in Sonora, the middle Pleistocene shorelines have been concealed under abundant bajada deposits and alluvial fans; in southeasternmost Baja California, the wetter and subtropical climate accelerated the alteration of the old Pleistocene marine remnants.

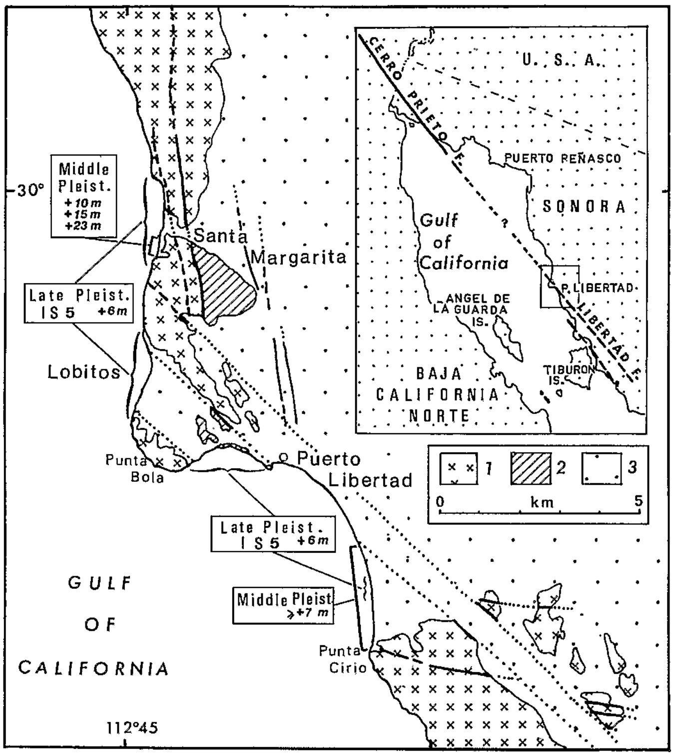


Figure 6—Geologic sketch map of the Puerto Libertad region, eastern coast of the Gulf of California (simplified from Gastil and Krummenacher, 1974), with indication of the elevation of distinct Pleistocene high seastand remnants. The inserted map shows the hypothetical relationship between the Cerro Prieto and Libertad faults (Cerro Prieto lineament of Gastil and Krummenacher, 1977). 1 = Pre-Cenozoic substrate; 2 = Miocene volcaniclastic units; 3 = Quaternary sediments, mainly alluvium.

Late Pleistocene Terrace(s)

Morphostratigraphy and Geochronology

Along the east coast of the peninsula, the last interglacial shoreline is generally well identified, even though there are ambiguities in a few localities. The degree of cementation of the littoral remnants and the state of preservation of the fossils may often, but not always, be used as relative chronologic criteria to distinguish the youngest (late Pleistocene) from the older (late middle Pleistocene) deposits.

A series of amino acid racemization analyses and Th/U age determinations (Figure 2) helped to confirm that, in many instances, the lowest emerged terrace, which is associated with well-preserved fossiliferous sediments, was formed during the I.S. 5e. The AAR stratigraphic analyses cover more than 80 samples, mainly from the east-central coast (Figure 2). High Quaternary temperatures hinder the use of this geochronological tool on the coasts of Baja California Norte and south of Bahía San Nicolas in Baja California Sur, as well as in the closed area of Bahía Concepción. In the belt between Santa Rosalía and Bahía San Nicolas, 40 analyses provided useful data to help separate the last interglacial from earlier middle Pleistocene.

Of 15 Th/U dates for late Pleistocene localities along the Gulf coast of Baja California, 6 results are in the range 122-135 ka and 9 results are in the range 48-87 ka; some of the younger apparent Th/U "ages" are analytically unreliable (Ortlieb, 1987). Unlike the Th/U data from the east coast of the Gulf of California, the statistical mean of radiometric dates (130 ka) clearly designates the low terrace as a remnant of the I.S. 5e seastand (Figure 3). In three localities (Punta Santa María, Bahía Concepción, and Loreto), radiometric analysis was also effective in dating emerged marine deposits as latest middle Pleistocene.

In the area of Santa Rosalía (Figure 7), which shows the best-developed and most complete series of marine terraces (Figures 8, 9), a number of arguments established that the two lower terraces are late Pleistocene (Ortlieb, 1987); the upper terrace (+25 ± 5 m) is correlated with the earliest last interglacial seastand (I.S. 5e), and the lower terrace (+11 ± 1 m) is coeval with a subsequent high sea level episode (I.S. 5a or 5c).

Besides morphostratigraphic and AAR stratigraphic arguments supporting this chronologic interpretation, oxygen-isotope analyses of shell carbonates show that fossils from the upper terrace (~+25 m) have $\delta^{18}O$ values similar to modern shells and significantly lower than other Pleistocene shells, from both higher (older) terraces and from the lower (younger) terrace. These geochemical data indicate on the one hand that the upper terrace is coeval with a climatic maximum, which compares with present-day conditions and, on the other hand, that the lower terrace was formed during a milder "interstadial" episode (I.S. 5a or 5c). The I.S. 5a/c terrace is much narrower than the main last interglacial platform (I.S. 5e).

Remnants of the I.S. 5a/c have not been positively identified outside of the La Reforma-Santa Rosalía area. Nevertheless, littoral notches and narrow benches are observed at elevations between +3 and +6 m, that is, below the well-developed I.S. 5e terrace in Bahía San Nicolas (Figure 10) and in Isla del Carmen; they are probably contemporaneous with the late last interglacial high seastand. The fact that the above-mentioned localities are among those that show the most elevated I.S. 5e shoreline (Figure 4) is certainly not a coincidence: the I.S. 5a/c highstand of sea level was eustatically lower than present MSL, and the emergence of the I.S. 5a/c remnants only occur in coastal areas that have been recently uplifted at mean rates exceeding 100 mm/10^3y.

Regional Attitude

Along the coast of Baja California Norte, the main last interglacial (I.S. 5e) shoreline is observed at +6 to +11 m (Figure 4). If an original +6 m eustatic position is assumed, this shoreline appears to have been uplifted, by a few meters only, from Punta San Francisquito southward.

Between Cabo Virgenes and San Lucas (La Reforma-Santa Rosalía area), this shoreline is generally elevated up to +25 to +30 m, although in the faulted area north of the town of Santa Rosalía, it reaches an elevation of +40 m (section C in Figure 8). Near San Lucas, late Pleistocene and older marine terraces are tilted southward; north of San Lucas lagoon, littoral deposits of late Pleistocene age crop out at up to +14 m, whereas south of the lagoon, the last interglacial shoreline is apparently depressed below present sea level. Tilting and subsidence thus mark the neotectonics of the southern part of the Santa Rosalía Basin. The undeformed low terrace (+9 m) visible all around Isla San Marcos (Figure 7) indicates that this island is structurally distinct from the Santa Rosalía Basin.

Between Chivato Peninsula and the Loreto-Isla del Car-

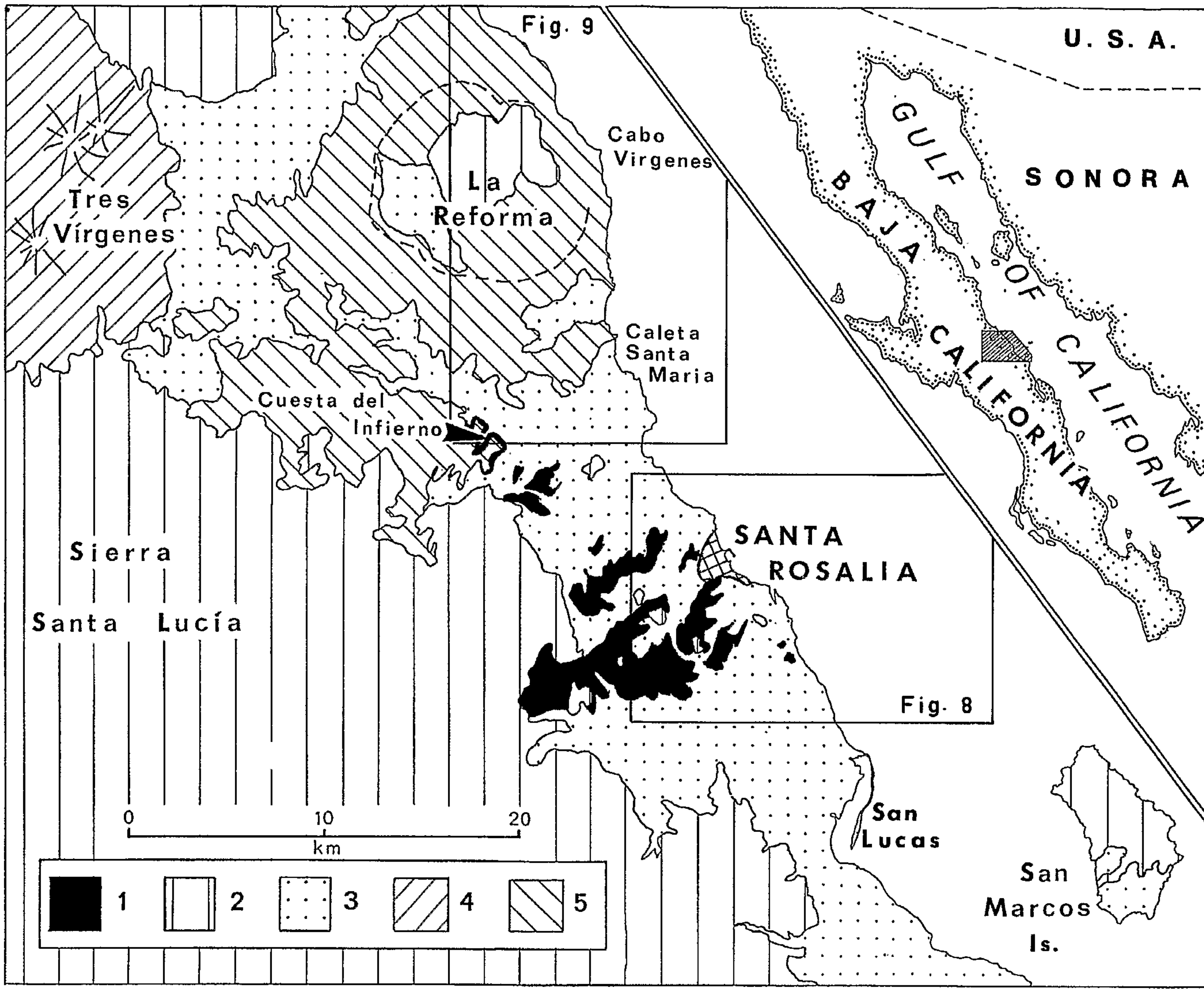


Figure 7—Geological setting of the Santa Rosalía region, on the central east coast of Baja California: 1 = "Upper Mesa," interpreted as the oldest Pleistocene marine terrace (~1 Ma); 2 = Miocene volcanics ("Comondu Formation" or "Andesites of Sierra Santa Lucia"); 3 = Upper Miocene to Quaternary sedimentary units; 4 = Tres Virgenes Plio-Quaternary volcanics; 5 = La Reforma Plio-Quaternary volcanics, including a widespread ignimbritic sheet southwest of the caldera.

men area, the I.S. 5e shoreline is identified at elevations of +9 and +13 m, except at the southeastern tip of Chivato Peninsula and in Concepción Peninsula, where it is slightly more elevated and reaches +15 to +18 m. In Chivato Peninsula, and in northwestern Bahía Concepción, small faults recently deformed and offset (by a few decimeters/meters) late Quaternary and middle Pleistocene marine and continental units. In Isla del Carmen, some recent vertical deformations are inferred from lateral correlation of late Pleistocene shoreline remnants.

In the poorly surveyed coastal segment between Ligui and Bahía de La Paz, the area of Punta San Telmo provided evidence of a late Pleistocene high seastand at less than +10 m (Anderson, 1950; Squires, 1959) (Figure 4).

East and southeast of Bahía de La Paz, the main last interglacial shoreline has been described at +6 to +9 m (Hammond, 1954; Hertlein, 1957; Dowlen and Minch, 1973; Ortlieb, 1982b, 1987; Sirkin et al., 1984). In Bahía de la Ventana and at Buenavista, this shoreline is said to have locally warped up to +17 m (Hammond, 1954) (Figure 4). Along the southern extremity of the Baja California peninsula, scarce marine benches at about +6 m most probably constitute the remnants of the I.S. 5e shoreline.

Middle and Early Pleistocene Terraces

Along the eastern coast of Baja California, the chronostratigraphy and regional correlations of pre-I.S. 5e shorelines are often difficult to establish. Petrographic characteristics and alteration states of the fossils, for instance, are not sufficiently discriminant to separate the middle Pleistocene deposits, such as those that are coeval with the I.S. 7 episode, from older ones (I.S. 9, I.S. 11, etc.). The penultimate interglacial (I.S. 7) shoreline proved to be practically out of reach of the AAR stratigraphic and radiometric methods.

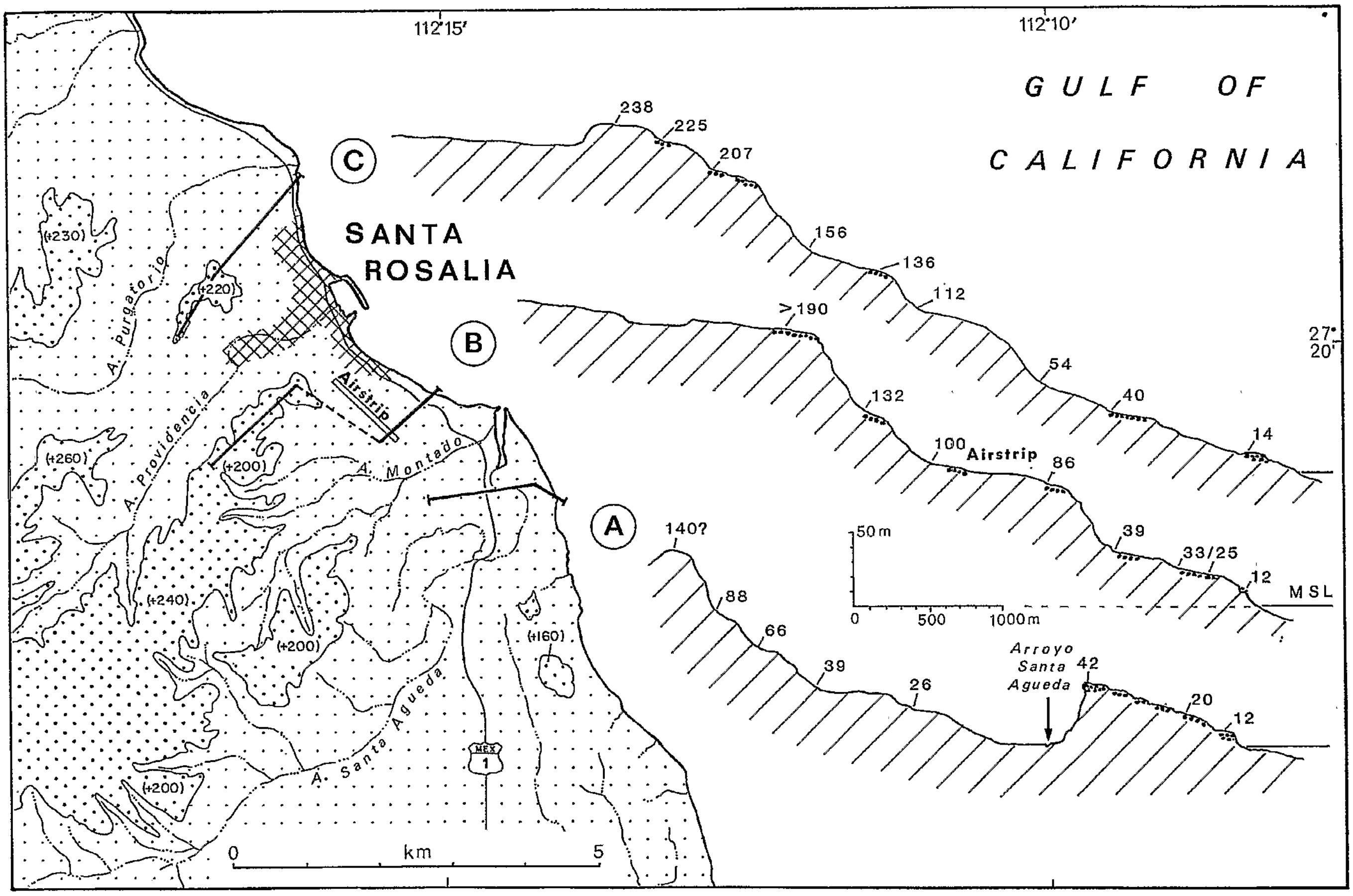


Figure 8—Three sequences of Pleistocene shorelines in the Santa Rosalía region (see location in Figure 7), with elevations in meters above present MSL. In the sketch map, the larger dots show the extension and approximate elevations of the Upper Mesa remnants (oldest marine platform).

In many cases, the marine deposits associated with the I.S. 7 high seastand(s) have been eroded during the subsequent I.S. 5e transgression, and the shoreline position cannot be precisely located. As the eustatic level of the I.S. 7 sea level was most probably several meters lower than the I.S. 5e stand (that is, close to or below the present datum), it may be predicted that the remnants of this transgression can only appear above the I.S. 5e terrace in areas characterized by greater than 50 mm/10^3y mean uplift rates. In fact, terraces assigned with some confidence to the I.S. 7 have only been identified in east-central Baja California at elevations ranging from +10 to +25 m, at a few meters above the I.S. 5e shoreline. In the Santa Rosalía-La Reforma area, the highest I.S. 7 shoreline seems to be located at elevations of +38 to +54 m (Figures 8, 9); a secondary high seastand during the I.S. 7 episode probably coincided with the second lower terrace, that is, with the platform which was subsequently reoccupied by the sea during the I.S. 5e maximum.

Tentative correlations of middle Pleistocene marine terraces with the chronostratigraphic scale of Shackleton and Opdyke (1973) are possible when the Pleistocene terraces are in a staircase arrangement, as in east-central Baja California. The vertical spacing of the terraces, the total number of shore platforms on the same transect, the identification of the I.S. 5e shoreline, and morphostratigraphic data are then taken into consideration to develop this kind of correlation. One particular marine surface provides another criterion in the regional correlations; this wide platform is interpreted to be coeval with the longer-than-usual I.S. 11 interglacial period, as defined in the V28-238 and other deep sea isotopic curves (Shackleton and Opdyke, 1973; Kominz et al., 1979). This wide terrace, thus tentatively assigned to the I.S. 11 (but which might have been prepared during the previous I.S. 13 high seastand), is generally found between +35 and +70 m along the east coast of the peninsula (Bahía Santa Ana, San Lucas, Chivato Peninsula, Bahía Concepción, Bahía San Nicolas, San Bruno Buenavista, Isla del Carmen, etc.; see Figures 1, 4), and between +100 and +130 m in the Santa Rosalía-La Reforma area (Santa Rosalía airport) (Figures 8, 9).

Along the east coast of the peninsula, the most elevated Pleistocene marine remnants are commonly observed between +90 and +110 m (Punta San Francisquito, Bahía San Nicolas, Isla del Carmen) (Figure 4). In the La Reforma-Santa Rosalía area, they are found at +160 to +200 m, at least along the present coastline; a few kilometers inland, at the boundary between the Santa Rosalía Basin and the La Reforma volcanic complex, the oldest marine terrace (Upper Mesa) has been uplifted to more than +200 m (Figure 7) and up to +340 m (Cuesta del Infierno) (Figures 4, 7).

Santa Rosalía Upper Mesa

In the Santa Rosalía Basin, extensive remnants of a wide, even surface cut in Pliocene sedimentary series is known as

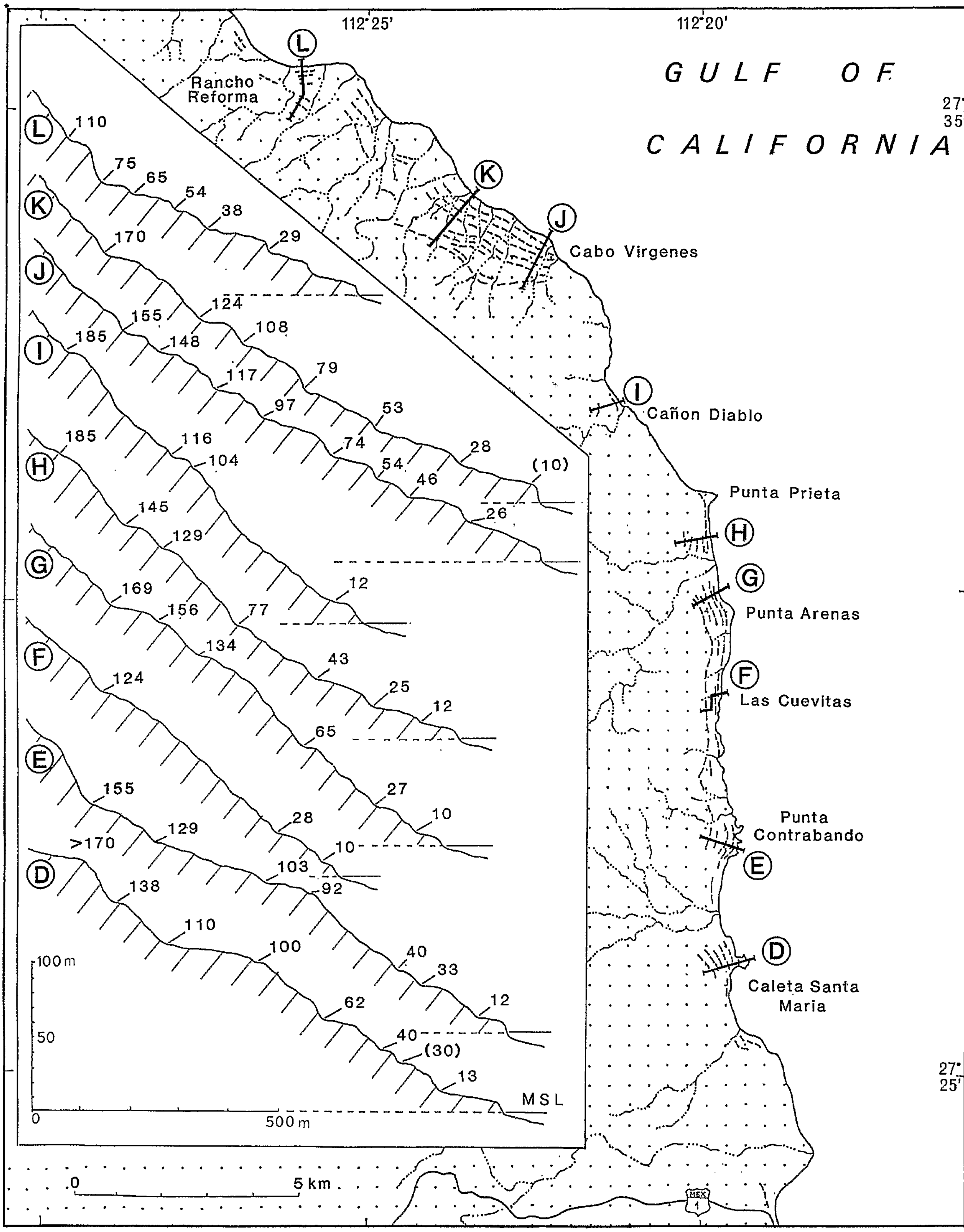


Figure 9—Nine sequences of Pleistocene shorelines and marine remnants along the coastal margin of the La Reforma volcanic complex (see location in Figure 7), with elevations in meters above present MSL.

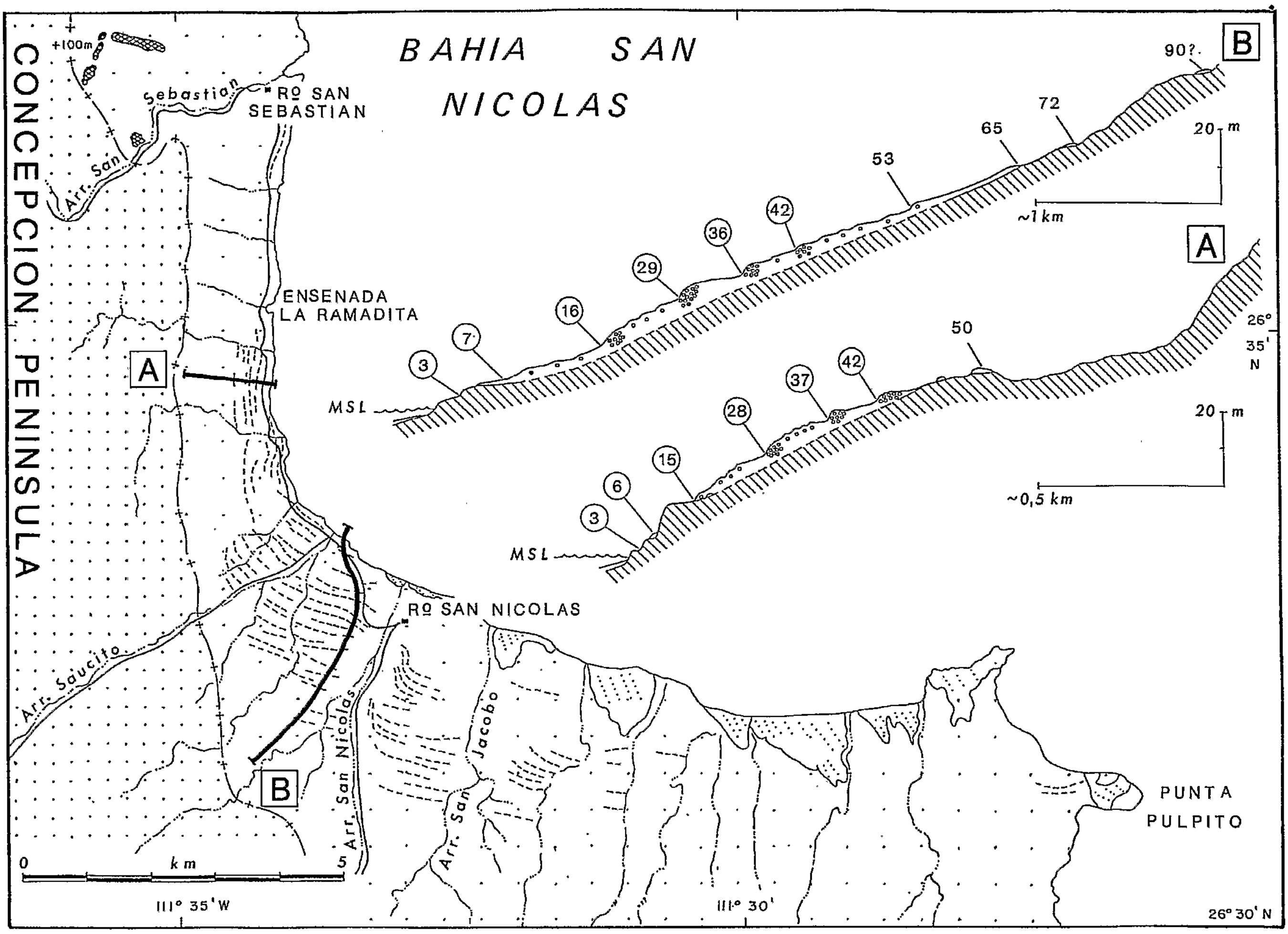


Figure 10—Sequences of Pleistocene shorelines in Bahía San Nicolas, central east coast of Baja California (see location in Figure 1), with elevations in meters above present MSL. Circled numbers designate elevations of the best-defined shorelines, which are tentatively correlated with the main interglacial high seastands of late Pleistocene and late middle Pleistocene age.

the Upper Mesa (Wilson, 1948; Wilson and Rocha Moreno, 1955). This mesa is locally covered with nearshore sediments containing relatively well-preserved fossil shells (thus contrasting with the totally dissolved aragonitic shells from the underlying Pliocene marine beds), and which can be correlated with the Pleistocene Santa Rosalía Formation of Wilson (1948). I interpret the Santa Rosalía Formation as constituting typical marine terrace deposits (Ortlieb, 1981b, 1984a; Ortlieb and Colletta, 1984).

In the western part of the basin, this marine unit is overlain by a 20-m-thick ignimbrite sequence, which resulted from an early Pleistocene explosive event of the La Reforma caldera (Figure 7). No reliable radiometric data could be obtained directly from the ignimbritic rocks, but two K/Ar dates (1.09 ± 0.11 Ma, Schmidt, 1975, and Schmidt et al., 1977; and 1.2 ± 0.1 Ma, Ortlieb, 1987) have been measured on "Aro volcanic" rocks (Schmidt, 1975), an intrusive sequence interpreted to be penecontemporaneous with the main caldera explosive event (Demant, 1981, 1984a). The ignimbrite sheet, which preserves the flat paleotopography of the marine platform, was deposited shortly after the cutting of the Upper Mesa; the base of the volcanic sequence directly overlies the marine sands and conglomerates.

These stratigraphic relationships (and others involving a higher than +170 m terrace deposit at Punta Santa Maria that rests on basaltic flows postdating the ignimbrite emission) tend to indicate that the oldest and most elevated Pleistocene littoral remnants of the Santa Rosalía area are about 1 Ma old. This age estimate fits with the global initiation of the "glacial Pleistocene" regime, characterized by the alternation of interglacial and glacial episodes every 90,000 or 100,000 years. In the chronostratigraphic scale of deep-sea cores V28-238 and V28-239 (Shackleton and Opdyke, 1973, 1976), it would probably correspond to the I.S. 23 episode.

In the locality known as Cuesta del Infierno, at the northwestern end of the Santa Rosalía Basin (Figure 7), the Upper Mesa geomorphic surface and its associated marine sediments reach a maximum elevation of +320 to +340 m. The altitude of the Upper Mesa decreases progressively toward the east and the southeast, down to about +200 m (Santa Rosalía) and +160 m (mouth of arroyo Santa Agueda) close to the present coastline (Figure 8). Beside the normal syngenetic slope of this marine platform, toward the open sea, the Upper Mesa thus appears to have been tilted up in the northwesternmost part of the basin. The net uplift experienced by the Cuesta del Infierno locality amounts to approximately 300 to 350 m (mean rate of 300 to 350 mm/10^3y), and the uplift relative to the Santa Rosalía coastal area is on the order of 150 m (mean relative rate of 150 mm/10^3y).

The wide extent of the Upper Mesa contrasts strongly with the 50- to 200-m width of all the lower marine terraces of the area. It probably owes its exceptional original dimensions (10 km-width along a 15-km-long stretch of coast) to its particular tectonic history, which permitted multiple reoccupations of the same platform by the sea during the early Pleistocene, and which started soon after the deposition of the (? Upper Pliocene) Infierno Formation.

To sum up, the distribution of early and middle Pleistocene marine terraces on most of the eastern coast of the Baja California peninsula documents a general regional uplift. Apart from the La Reforma-Santa Rosalía area, the highest observed Pleistocene shorelines are located at 90 to 110 m; if one assumes that these marine remnants are coeval with the first interglacial high seastands of late early Pleistocene age (about 1 m.y. old), the mean uplift rate of the east coast of Baja California can be estimated to be 100 mm/10^3y.

In the northeastern and southeastern coastal regions of Baja California, only few notes on old Pleistocene marine terraces, at about +90 m, have been made by previous authors (Wittich, 1909, 1911; Arnold, 1957); additional data are needed for these localities (Bahía San Luís Gonzaga, Isla Angel de la Guarda, San José del Cabo; see Figures 1, 4) before they can be correlated with early Pleistocene high seastands. If such correlations were confirmed, it would mean that almost all the eastern Baja California coast (outside the La Reforma-Santa Rosalía area) would have been uplifted at a mean rate of 100 mm/10^3y during the second half of the Quaternary. Alternatively, it could mean that both the northern and southern extremities of the eastern coast have been less uplifted relative to the east-central part. It should be noted that the last interpretation applies to the late Quaternary, inasmuch as the I.S. 5e appears to be uplifted by more than a few meters in the east-central coast (50 to 100 mm/10^3y), and seems to be near its original position in the northeastern and southeastern Baja California coasts (Figure 4).

In the area between Cabo Virgenes, Santa Rosalía, and San Lucas, local deformations were surveyed. Stronger uplift motions, with mean rates between 150 and 350 mm/10^3y, were most probably involved in thermal processes directly related to the magma chamber of the La Reforma caldera. Immediately south of San Lucas, the total lack of emerged marine terraces is attributed to a strong and local downdrop of the southern part of the Santa Rosalía Basin. The widespread southward tilting thus observed between the rim of the La Reforma caldera and San Lucas is still active, as it also affects the late Pleistocene shorelines.

WESTERN COAST OF BAJA CALIFORNIA

Geomorphic Context

The Pacific coast of the peninsula differs greatly from the Gulf of California coastal areas not only in its general structure but also in the variety of its climates and inland morphology. Northwesternmost Baja California is, in many aspects, geomorphically similar to the southwestern California coast; in this more temperate region, Pleistocene marine terraces are generally covered by thick alluvial sediments which prevent the identification of the early shorelines. Between Punta Baja and the 28th parallel, the coast is characterized by a more arid climate, higher inland reliefs, and many rocky cliffs.

The west-central region, including the Ojo de Liebre and San Ignacio lagoons (Figure 1), has wide lowlands where eolian sands, lagoonal sediments, and bajada deposits accumulated throughout Quaternary time. Around the lagoons, the best-preserved Pleistocene marine sediments are of last interglacial age. These areas were subjected to high evaporation, and the older Pleistocene marine deposits are so heavily calichified that they can hardly be distinguished from one another.

The Vizcaíno Peninsula and the region of San Juanico (Figure 11) combine rocky coastal areas where marine platforms can be formed easily and have remained well-preserved, and local nearshore environments that favor accumulations of littoral and marine sediments. As a result, Pleistocene shorelines are numerous and are commonly observed in sequences of staircase terraces (Figures 11, 12). In these areas, geomorphic conditions have limited the covering up of the marine terraces by eolianites and continental sediments.

In the southwestern Baja California peninsula, between La Purisma and Todos Santos (Figures 1, 11), the coastal area has been dominated by the piling up of eolian sediments and terrestrial sediments eroded from the Sierra La Giganta. These wide bajadas, which present many similarities with the southeastern coast of the Gulf of California, are not favorable for the preservation of Pleistocene littoral remnants; even the last interglacial marine deposits are commonly hidden or eroded along extensive stretches of the coast (north and south of Bahía Magdalena, and north of Todos Santos; Figure 1). The southern tip of the peninsula, which consists essentially of granitic and metamorphic rocks, is also unfavorable for the development of Pleistocene shorelines.

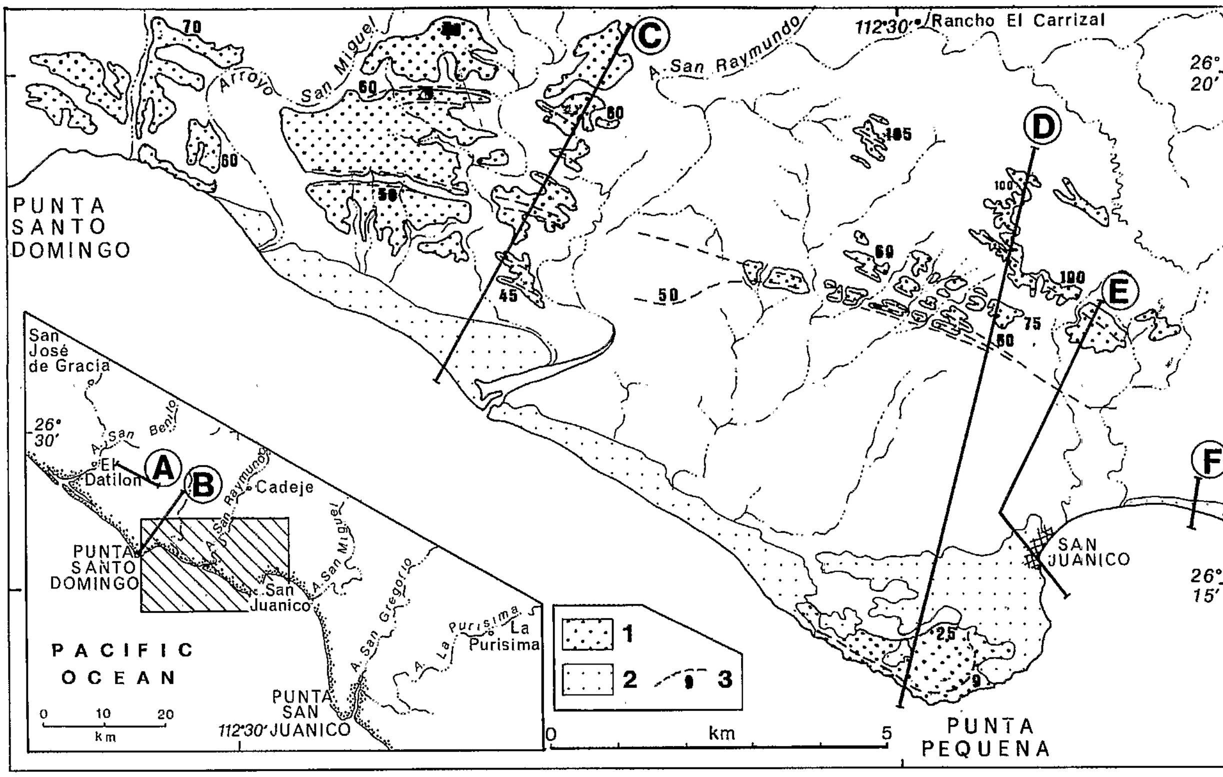
A large variety of Pleistocene marine remnants is observed along the western coast of Baja California. In the south, the remnants of interglacial high seastands resemble the benches cut in batholithic and volcanic rocks from both the eastern and western sides of the Gulf of California. Around the lagoons of west-central Baja California, outcrops of late Pleistocene marine and lagoonal sands measure hundreds of square kilometers. In many localities of western Baja California, particularly southeast and northeast of San Ignacio lagoon, Pleistocene abrasion platforms are especially wide (as much as several kilometers), and the older terraces commonly consist of isolated mesas capped with a thin layer of calichified pebbles and marine sediments. In northwestern Baja California, the Pleistocene marine remnants are more altered, and the terrace morphology is more subdued, as a result of wetter paleoclimates and more active alluviation.

The Pleistocene marine and littoral sediments that crop out along the Pacific coast are generally more abundant, smaller-grained, thicker, and better preserved compared with those of the Gulf of California. It may be mentioned that the reconstruction of former positions of sea level is more precise when based on erosional features than on marine sediment outcrops; in this respect, the determination of the position of Pleistocene shorelines is generally more accurate in the arid, rocky environment of the central east coast of Baja California than on most of the Pacific coast of the peninsula. In the latter region, marine terraces are very wide and conspicuous, but the shorelines coeval with the transgressive maxima are seldom observed.

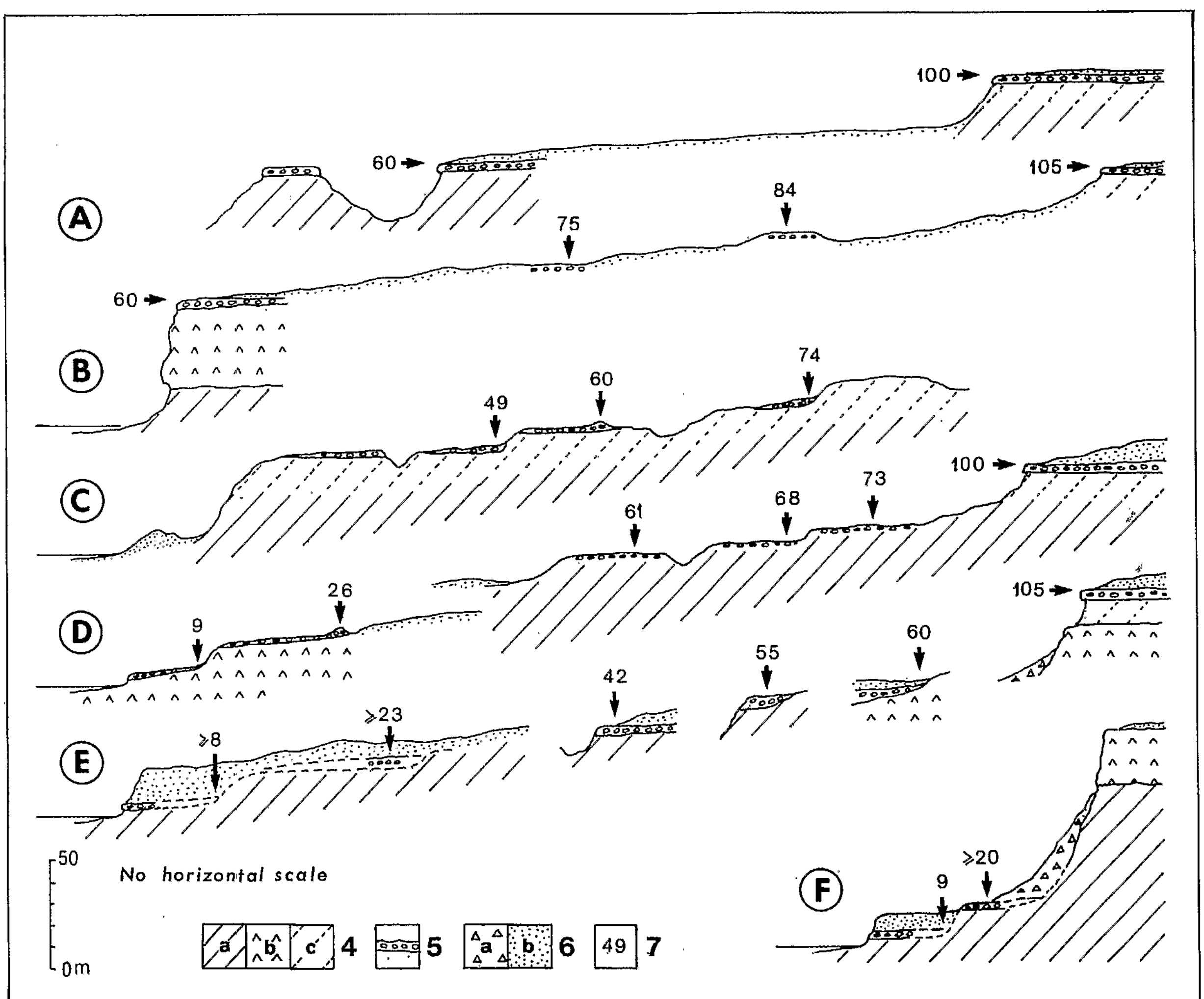
LATE PLEISTOCENE TERRACE(S)

Morphostratigraphy and Geochronology

As in the Gulf of California, the last interglacial marine remnants of the Pacific coast of Baja California consist of a



PUNTA SANTO DOMINGO
Arroyo San Miguel
A. San Raymundo
112°30' Rancho El Carrizal
26° 20'
26° 15'
SAN JUANICO
PUNTA PEQUENA
C
D
E
F
1
2
3
0 km 5
San José de Gracia
26° 30'
A. San Benito
El Datilon
A
B
Cadeje
A. San Raymundo
PUNTA SANTO DOMINGO
San Juanico
A. San Miguel
A. San Gregorio
A. La Purisima
La Purisima
PACIFIC OCEAN
0 10 20 km
PUNTA SAN JUANICO
112°30'



A
B
C
D
E
F
100
60
105
84
75
74
49
61
68
73
26
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42
55
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50
0m
No horizontal scale
a b c 4
5
a b 6
49 7

low platform covered with poorly consolidated nearshore sediments and generally unaltered fossils. In many coastal areas where several Pleistocene marine deposits crop out, the differences in the state of alteration of the sediments and composition of the faunas are distinctive enough so that the identification of each late Pleistocene unit is almost unmistakable. Some localities show stratigraphic sequences with, or without, interstratified continental units where the I.S. 5e sediments clearly overlie an older, probably I.S. 7, marine unit (San Juanico, Laguna San Ignacio, Bahía Asuncion). In distinct stretches of the Pacific coast of the peninsula (Bahía Tortugas, Santa Rosalillita, Punta Baja, San Quintín), the particularly extensive development of the lower marine terrace is interpreted as the result of an inheritance of an I.S. 7 platform. Generally, the youngest middle Pleistocene marine remnants that crop out immediately above the I.S. 5e terrace sediments appear to be older than the I.S. 7 episode (that is, I.S. 9 or 11 episodes).

Radiometric dates and amino acid racemization (AAR) stratigraphic analyses of the last interglacial littoral deposits (Figure 2) cover the Bahía Magdalena region (Omura et al., 1979; Wehmiller and Emerson, 1980), the Bahía Tortugas-Bahía Asuncion area (Emerson et al., 1981; Keenan, 1982; Keenan et al., 1984, 1987; Ortlieb, 1984b), and a few isolated localities from the Baja California Norte coast: Santa Rosalillita (Woods, 1980), Punta Cono (Keenan, 1982; Ortlieb, 1987), Camalu (Valentine, 1980), and Punta Baja (Ortlieb, 1987). On the west coast of Baja California, and in the Vizcaíno Peninsula particularly, AAR data appear to be more reliable than Th/U dating (Ortlieb, 1982a, 1984b, 1987; Keenan et al., 1984, 1987; Ortlieb et al., 1984).

At Bahía Magdalena, Omura et al. (1979) dated two coral and four echinoid samples from the low (+6 m) marine terrace; the Th/U and Pa/U apparent age spread is from 108 to 128 ka (Figure 3). In the Vizcaíno Peninsula, only three samples provided Th/U apparent ages, ranging from 97 to 150 ka. In a few localities, the radiometric ages confirmed presumed assignments of late middle Pleistocene age to marine units morphostratigraphically older than the youngest Pleistocene shoreline.

AAR stratigraphic analyses of western Baja California samples benefited from calibration studies and kinetic modeling applied farther north, in California (Wehmiller et al., 1977; Wehmiller and Emerson, 1980; Kennedy et al., 1982; Wehmiller, 1982), and thus were more useful for chronostratigraphic interpretations (Wehmiller, 1982; Keenan et al., 1984; Ortlieb, 1987). Some problems of interpretation arose as a consequence of differences in analytical procedures and because of uncertainties concerning late Quaternary paleotemperature evolution on the southwestern coast of Baja California. For example, there are some minor disagreements between chronostratigraphic interpretations (Emerson, 1980; Emerson et al., 1981; Ortlieb, 1987) concerning a few last interglacial localities (I.S. 5e and/or I.S. 5a/c remnants) in the Bahía Tortugas region (Figure 13). In some other localities, and particularly on the eastern shore of Laguna San Ignacio, chronological discrepancies between AAR stratigraphic interpretations (Keenan, 1982) and morphostratigraphic observations can be resolved (Ortlieb, 1987) by assuming that diagenetic temperatures were higher than predicted by a regular latitudinal model (such as the one proposed by Wehmiller, 1982).

Regional Attitude

For most of the western coast of Baja California, the last interglacial shoreline appears to be little deformed; its elevation ranges from only +6 to +9 m from the southern tip of the peninsula northward to the Punta Cabras (Figure 1) area (except for the Vizcaíno Peninsula) (Figure 14). Between Punta Cabras and Punta Banda, this shoreline is elevated up to +15 m. From Punta Banda northward to San Diego, two last interglacial high seastands have been recorded: the older one (I.S. 5e) between +40 and +23 m, and the younger one (I.S. 5a/c) between +10 and +18 m (maximum +23 m?) (Figure 14).

Also on the Vizcaíno Peninsula, two sets of last interglacial marine remnants may be correlated with two high seastands. On the southwestern coast of the Vizcaíno Peninsula and on Isla Cedros and Islas San Benito, the I.S. 5e shoreline lies between +12 and +18 m, whereas a more recent Pleistocene shoreline (I.S. 5a/c) is locally described at about +5 to +8 m (Figures 12, 13, 15). Along the northwestern shore of the Vizcaíno Peninsula (Figure 16), the I.S. 5e shoreline has been surveyed at only +9 m, an intermediate elevation between that of the Ojo de Liebre region and the southwestern Vizcaíno Peninsula.

The low position (+5 m) of the I.S. 5e shoreline around Laguna Ojo de Liebre relative to its altitude along the rest of the Pacific coast of Baja California suggests a recent slow subsidence of the area (about 1 m in the last 125,000 years). This negative vertical motion suggests that the "Baja California syncline" (Beal, 1948) is still an active structure.

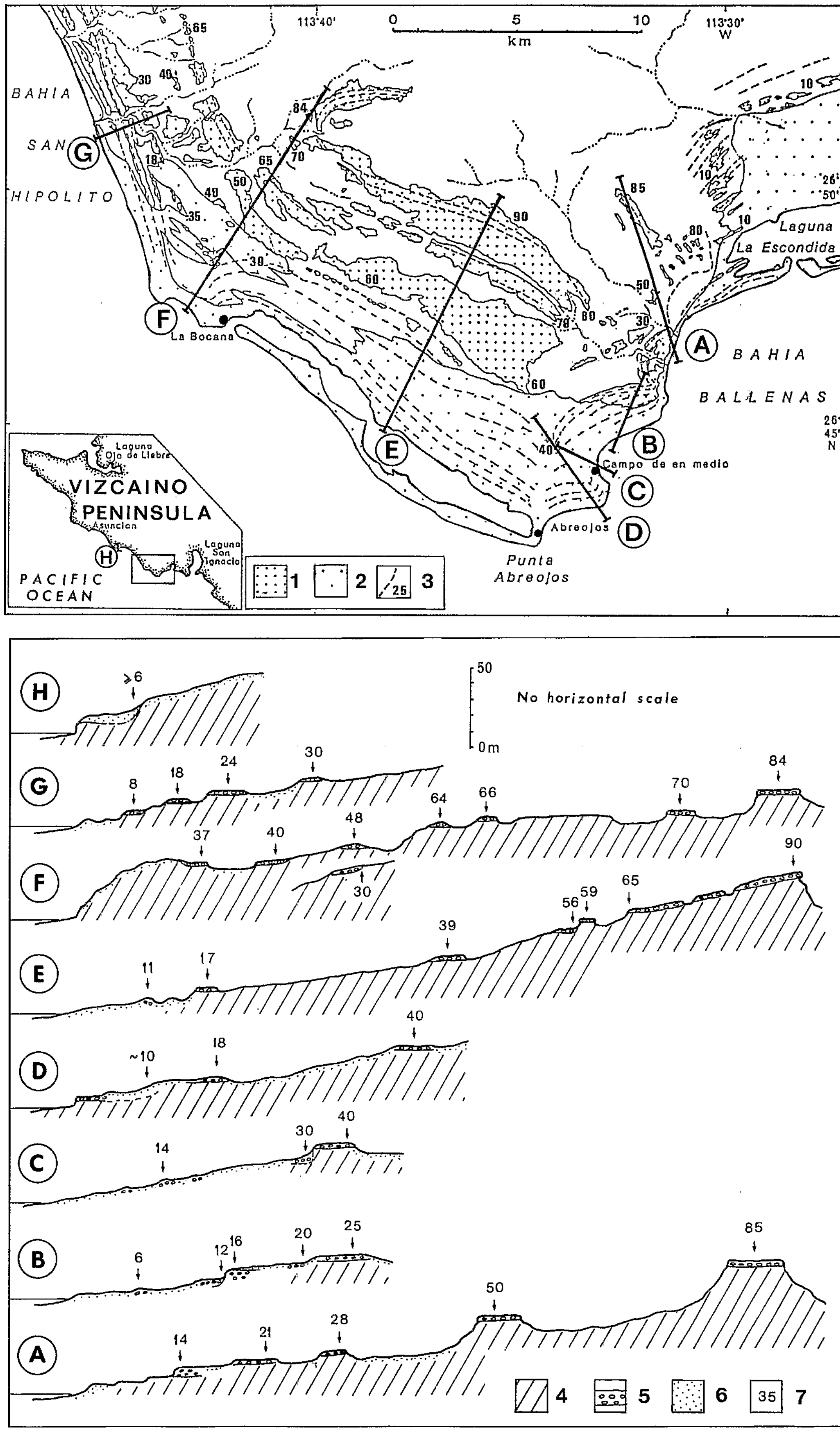
Except for the limited area of the Ojo de Liebre Basin, the late Pleistocene shoreline attitude thus shows that most of the Pacific coast of Baja California has been either "stable" or slightly uplifted, by a few meters only, in the late Quaternary. The limited areas where recent uplift motions have been relatively strong, and where I.S. 5a/c shorelines could be identified, are the Vizcaíno Peninsula (Figure 15) and the northwesternmost part of Baja California, from Punta Banda northward (Figure 14).

Middle and Early Pleistocene Marine Terraces

The Bahía Asuncion area in the Vizcaíno Peninsula is the only region where AAR stratigraphic data can support chronologic interpretations of middle Pleistocene marine deposits (Keenan et al., 1984, 1987). In the remaining part of the Pacific coast of Baja California, tentative chronostratigraphic interpretations rest on geometric and morphostratigraphic grounds.

Along the southwesternmost coast of Baja California,

Figure 11—Sequences of Pleistocene marine deposits, shore platforms, and associated shorelines in the San Juanico region, southwestern coast of Baja California. In sketch map, 1 = Pleistocene marine sediments; 2 = Late Quaternary eolian sands; 3 = Pleistocene shorelines (elevations in meters above present MSL). In cross sections, 4 = Pre-Quaternary substratum (a, Eocene; b, early Pliocene basalts; c, marine Pliocene "Salada Formation"); 5 = Pleistocene marine sediments; 6 = Quaternary (a, alluvium; b, eolian sands) and 7 = Highest elevation of marine deposits, or well-defined shoreline elevation.


113°40'
0 5 10
km
113°30' W
BAHIA SAN HIPOLITO
Laguna La Escondida
BAHIA BALLENAS
26° 50'
26° 45' N
La Bocana
Campo de en medio
Abreojos
Punta Abreojos
Laguna Ojo de Liebre
VIZCAINO PENINSULA
Asuncion
Laguna San Ignacio
PACIFIC OCEAN
1
2
3
No horizontal scale
50
0m
4
5
6
7

I.S. 9 and I.S. 11 ages are assigned to +12 to +15 m and +22 to +30 m shorelines, respectively (Figure 14). Scarce, older terraces, observed between +45 and +60 m, are supposed to be coeval with early middle Pleistocene and late early Pleistocene.

From San Juanico northward (Figure 14), marine terraces are better preserved and document higher regional uplift rates. Some ancient littoral features, at elevations close to that of the I.S. 5e shoreline (less than +12 m), are interpreted to be of I.S. 7 age (Figure 11). The higher main terraces, surveyed at +25 to +30 m and +40 to +50 m, are tentatively correlated with I.S. 9 and I.S. 11 high sea level episodes, respectively. In the San Juanico-Laguna San Ignacio area, still higher elevated terraces, located at +60, +75, +85, +105, and +130 m, are assigned to early middle and late early Pleistocene high seastands (Figures 11, 14). This regular spacing of the terraces suggests that uplift motions have been steady during the Quaternary.

In the wide Ojo de Liebre Basin, where the Pleistocene marine remnants are deeply calichified, there is no record of high seastands in staircase disposition; in some places, Pleistocene marine units are found in normal stratigraphic sequences. Near Ojo de Liebre Lagoon, in the center of the basin, several Pleistocene marine deposits lying at less than +30 m, which are probably coeval with three or more middle Pleistocene interglacial high seastands, crop out on a north-south-oriented, horstlike topographic ridge; if this ridge is an uplifted faulted block, these middle (and early?) Pleistocene interglacial remnants are not significant for the vertical motions of the whole Ojo de Liebre region. Anyway, it can be concluded that the center of the Ojo de Liebre Basin is experiencing much slower vertical motions than the surrounding areas (San Ignacio area and Vizcaíno Peninsula) (Figure 14).

In the Vizcaíno Peninsula, remnants of middle and early Pleistocene high stands of sea level are more numerous than anywhere else. They consist either of a series of marine platforms, or else of partially overlapping units of much-encrusted sublittoral sediments (Troughton, 1974; Robinson, 1975; Ortlieb, 1979a, 1979b, 1987) (Figures 12, 16). Geometric correlations of sequences of terraces and marine outcrops all along the Vizcaíno Peninsula coasts, aided by a few AAR stratigraphic age determinations, lead us to assign I.S. 9 and I.S. 11 ages to high seastand remnants found at +30 to +35 m and +40 to +55 m, respectively (Figure 15). The highest elevated littoral remnants, commonly observed between +100 m and +140 m (for example, at Mesa Grande, near Punta Eugenia, Figure 16, and north of Bahía Tortugas, Figure 17), are most probably of late early Pleistocene age. In the Bahía Tortugas area, early and middle Pleistocene marine sediments are strongly deformed by the active Bahía Tortugas fault system (Figure 17); these units, which locally dip steeply, register intense deformations related to a main active fracture zone (see below).

Along most of the coast of Baja California Norte, between El Tomatal (Woods, 1980) and Punta Banda, two conspicuous marine terraces are found above the lowest one (I.S. 5e), at +24 to +30 m and +60 m (Figure 14); they are tentatively assigned to the I.S. 9 and I.S. 11 high seastands. Two or three more middle Pleistocene shorelines are observed at elevations ranging from +90 m to +150 m (Figure 14).

In northwesternmost Baja California Norte, north of Punta Banda, where conditions of preservation of Pleistocene littoral remnants are less favorable than to the south, available information on the position of middle and early Pleistocene shorelines is sparse (Emerson and Addicott, 1953; Valentine, 1957, 1961; Valentine and Rowland, 1969). The distribution of the few Pleistocene marine remnants in northwesternmost Baja California and in the San Diego region (California) compares with that prevailing south of Punta Banda Peninsula.

Punta Banda Peninsula and Agua Blanca Fault System

The series of terraces described at Punta Banda (Lindgren, 1888; Allen et al., 1960; Ortlieb, 1987) document much higher uplift rates here than in other parts of northwestern Baja California Norte. About 14 terraces, almost regularly spaced with 25 ±5 m height differences between consecutive platforms, are preserved up to approximately +330 m (Figure 18, Table 1). At Punta Banda, I.S. 5e, I.S. 7, and I.S. 9 ages are tentatively assigned to the shorelines surveyed at +33 m, +50 m, and +95 m, respectively. The shorelines observed at +140 m and +160 m, associated with particularly wide platforms, are tentatively correlated with high seastands coeval with the I.S. 11 (and ? I.S. 13) episode(s). The more elevated terraces surveyed between +200 and +330 m have probably been formed during the previous I.S. 15, 17, 19, 21, and 23 episodes of the marine isotopic chronostratigraphic scale.

The regular vertical spacing of the terraces and the fact that north and south of Punta Banda, the highest observed terraces are located at only +120 to +140 m, indicate that the Punta Banda Peninsula has been steadily uplifted throughout the Quaternary. This local uplift involves the Agua Blanca fault system, because the Punta Banda Peninsula is a block limited to the north by the Agua Blanca fault proper, and to the south by the Santo Tomas branch (Allen et al., 1960; Gastil et al., 1975).

The evolution of this major fracture zone, extending from the continental shelf into northwestern Baja California, remains debatable. Allen et al. (1960) have interpreted that, despite the scarcity of precise evidence, maximum strike-slip displacements of the Agua Blanca fault amounted to 22 km, or at least 11 km, since the Cretaceous and to 5 km during the Quaternary. Other authors presented data in favor of some Holocene activity (Armiego [=Armijo] and Suarez, 1981; Hatch and Rockwell, 1986; Hilinsky and Rockwell, 1986); the hydrothermal activity observed in the village of Punta Banda may also be taken as evidence of recent activity of the fault. Nevertheless, neither historical nor present-day seismic activity have been registered (Johnson et al., 1976; Leeds, 1979; Darby et al., 1984). Offshore, bathymetric and geophysical surveys showed close relationships between this fault and both the San Diego Trough-Maximinos and the Coronados Bank active fractures (Legg, 1979; Legg and Wong, 1979; Legg and Luyendyk, 1982).

From the evidence, it seems that the main late Quaternary activity of the Agua Blanca fault has been concentrated in its western and offshore segments. Comparisons of the marine terrace distributions in northwestern Baja California

Figure 12—Eight sequences of Pleistocene marine deposits, shore platforms, and associated shorelines in the Punta Abreojos region, west-central Baja California. In sketch map: 1 = Pleistocene marine deposits; 2 = Quaternary alluvium and eolian sands; 3 = Pleistocene shorelines (elevations in meters above present MSL). In cross sections: 4 = Pre-Quaternary substratum; 5 = Pleistocene marine sediments; 6 = Quaternary alluvium and eolian sands; 7 = Highest elevation of marine deposits, or well-defined shoreline elevation.

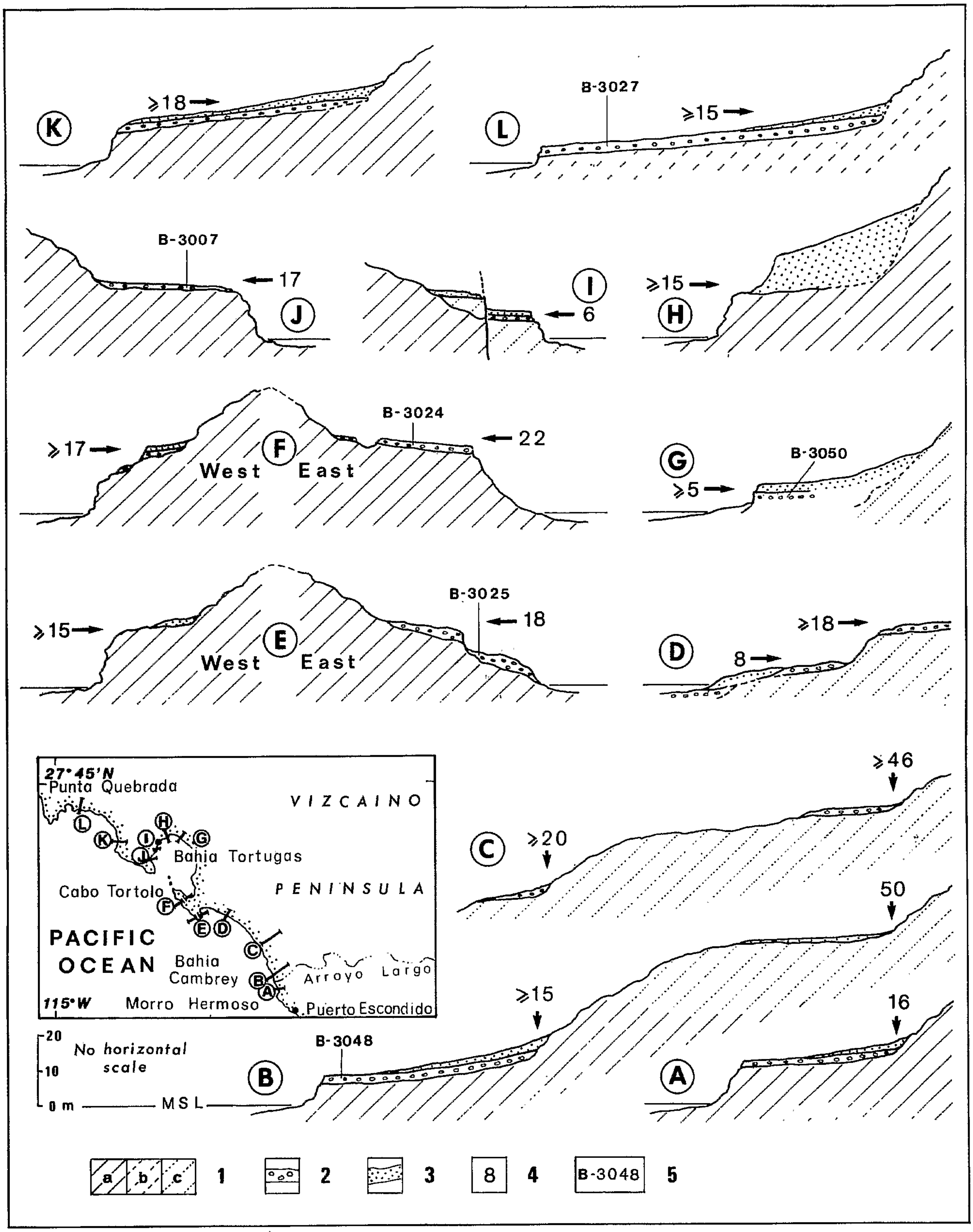


Figure 13—Late and middle Pleistocene marine terraces in the Bahía Tortugas area, west-central Baja California. An I.S. 5e age is assigned to the wide, low platform whose back edge lies at +15/+18 m, except along the trace of the Bahía Tortugas fault (near Cabo Tortolo and Bahía Tortugas), where the platform was tilted or downdropped. 1 = Pre-Quaternary substratum (a, Mesozoic; b, Miocene; c, Pliocene); 2 = Pleistocene marine sediments; 3 = Quaternary alluvium; 4 = Shoreline elevation (in meters above present MSL); 5 = Fossil localities studied by Emerson (1980) and Emerson et al. (1981).

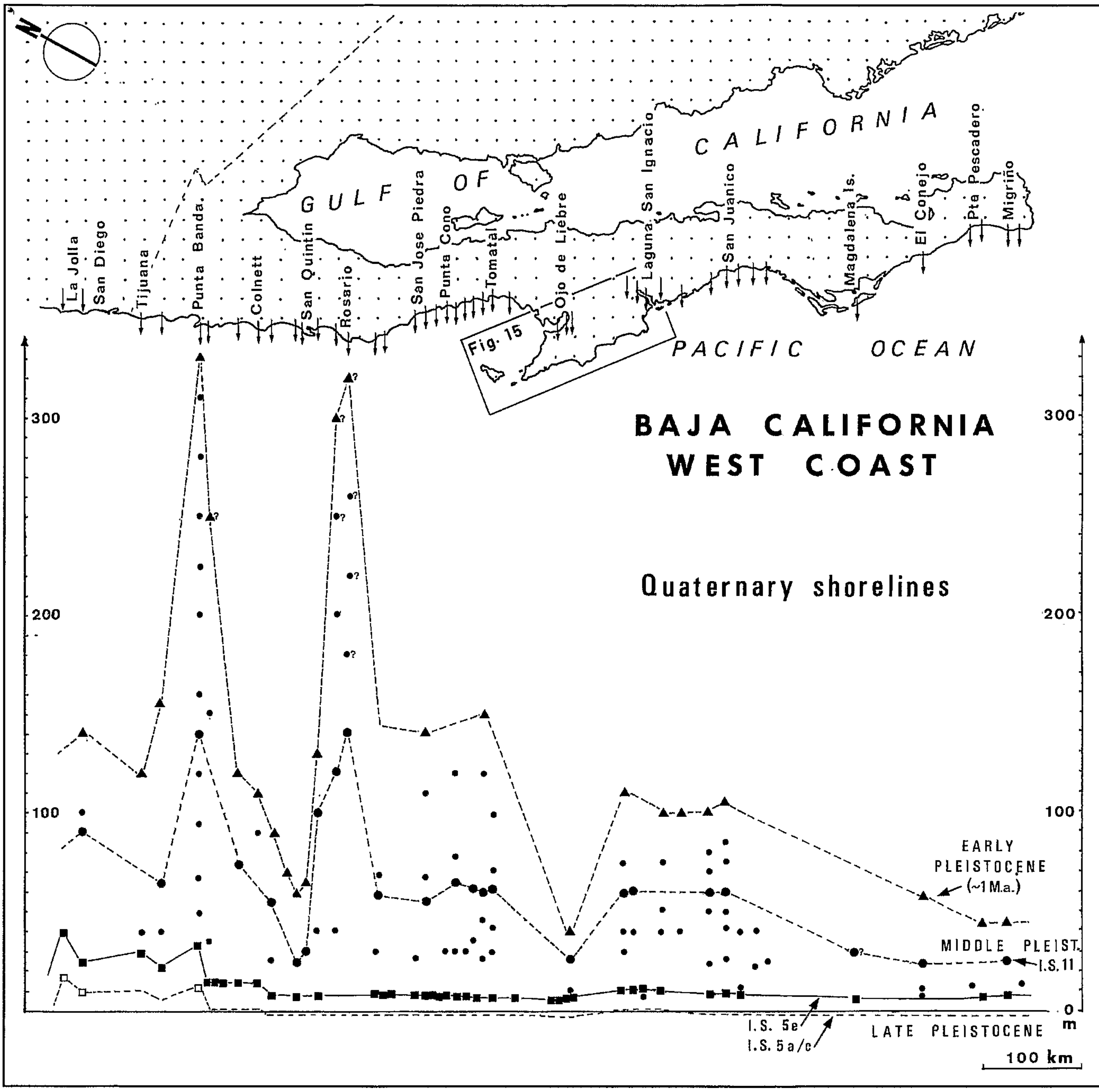


Figure 14—Spatial distribution of Pleistocene marine terraces on the Pacific coast of Baja California. The regional correlation of late Pleistocene (I.S. 5e and 5a/c) shorelines is based on morphostratigraphic and geochronologic (Th/U and amino acid racemization) data; the tentative correlation of older Pleistocene marine terraces (early Pleistocene and ? I.S. 11) are based on morphostratigraphic and geometric interpretations.

show that, beyond the Punta Banda Peninsula structure, the Agua Blanca fault system forms a boundary between two large crustal blocks.

According to the above-mentioned chronostratigraphic interpretation of marine terrace data, the Punta Banda Peninsula appears to have been uplifted during the Quaternary at a mean rate of about 300 mm/10^3y. Yet, even if the vertical motions were continuous, it seems that the uplift rate has not been constant through time; the present position of the presumed I.S. 5e shoreline suggests that since ~120 ka the Punta Banda Peninsula experienced only a mean 220 mm/10^3y vertical motion. In fact, this vertical motion rate is not significantly distinct from those determined in northwesternmost Baja California and southernmost California for the late Quaternary. North of Ensenada, regional correlation of the late Pleistocene terraces (I.S. 5a/c and I.S. 5e) suggests that the area has been uplifted at rates ranging between 170 and 240 mm/10^3y.

In spite of the poor control on the position of the middle/early Pleistocene shorelines in northwestern Baja California and southwestern California, it is assumed that the +120 to +140 m elevated marine surfaces correspond to late

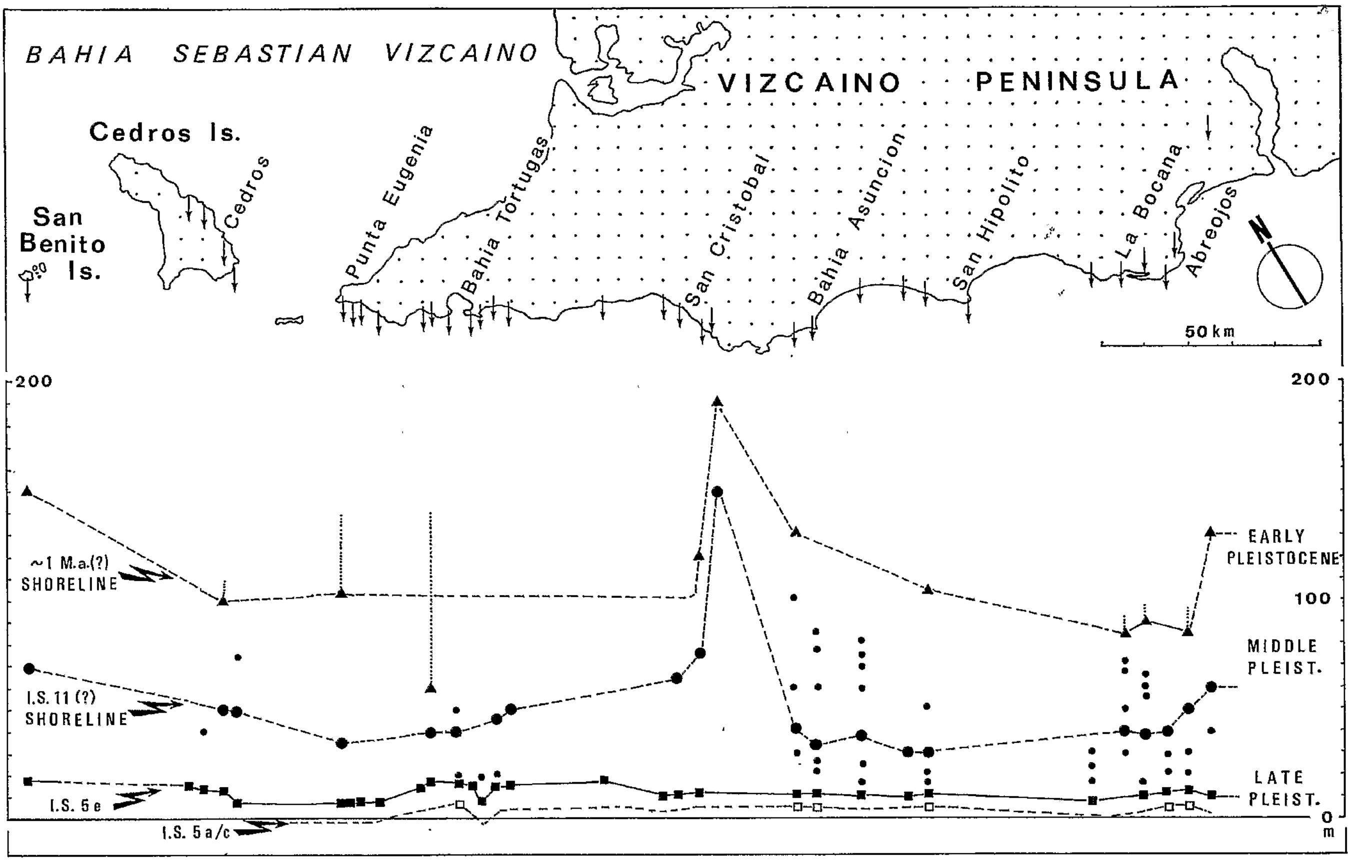
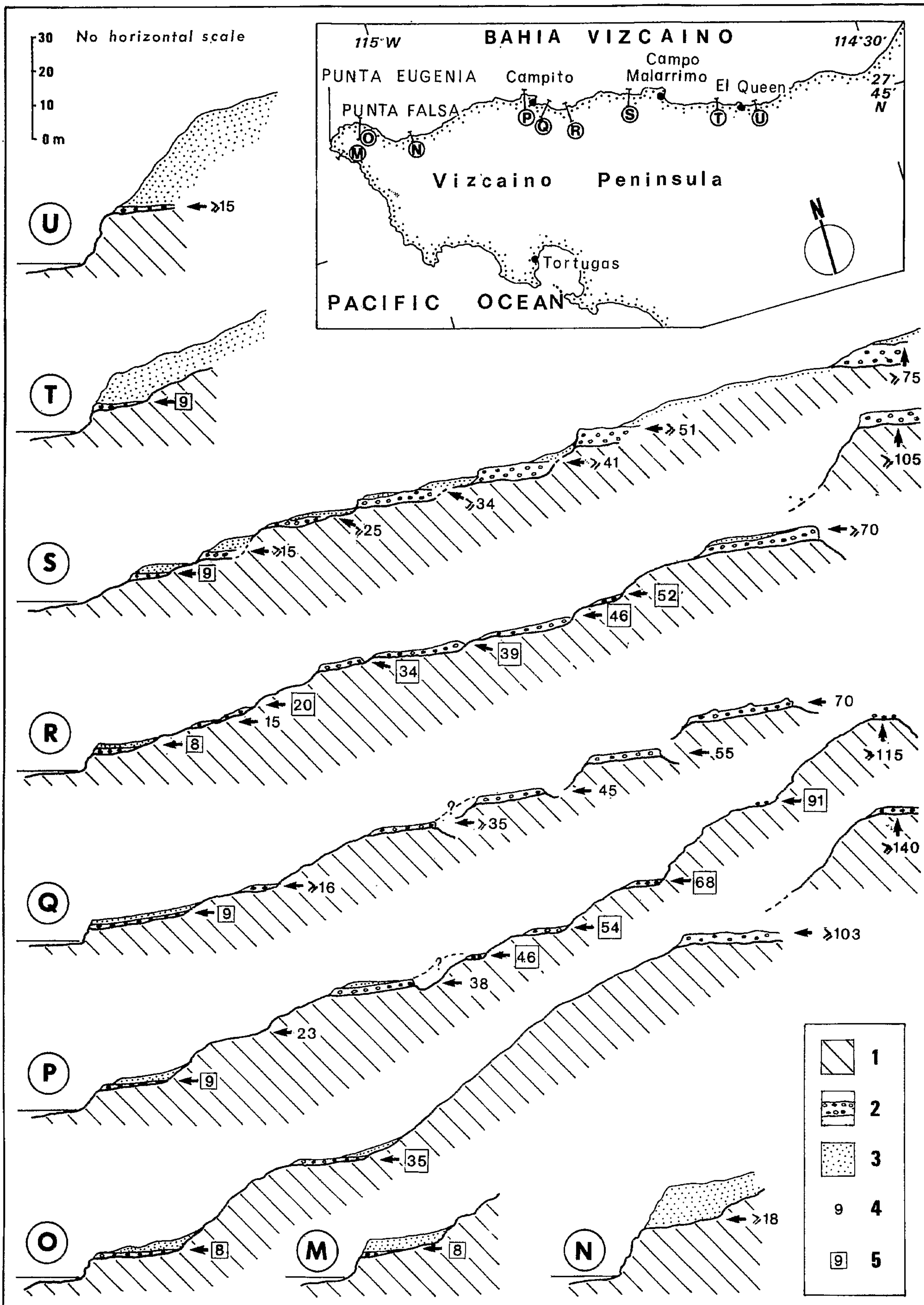


Figure 15—Spatial distribution of Pleistocene marine terraces on the southwestern coast of the Vizcaíno Peninsula, and on Isla Cedros and Islas San Benito (see location in Figure 14). The regional correlation of late Pleistocene (I.S. 5e and 5a/c) shorelines is based on morphostratigraphic and geochronologic (Th/U and amino acid racemization) data; the tentative correlation of older Pleistocene marine terraces (early Pleistocene and ? I.S. 11) are based only on morphostratigraphic and geometric interpretations.

early Pleistocene high seastands; accordingly, mean Quaternary uplift rates were on the order of 130 mm/10^3y, that is, significantly slower than the rates of motion occurring in the last 125,000 years.

High uplift rates may perhaps have occurred in another area of northwestern Baja California, between San Quintín and El Rosario (Figure 14). According to previous reconnaissance by Orme (1972, 1974), this region registered a series of Pleistocene marine terraces that could be compared with those of Punta Banda, and the "Quaternary marine limit" is said to have reached a maximum elevation of +357 m near El Rosario. However, the early Pleistocene age assignment to the highest shorelines examined by Orme needs revision, as paleontologic data suggest that some of the "Quaternary" terraces mentioned by him are probably of Pliocene age (Acosta, 1966; Gastil et al., 1975). The series of hypothetical Pleistocene marine terraces represented in the diagram of Figure 14 correspond to several conspicuous platforms, cut in Upper Cretaceous sandstones and set in successive steps, but which have not yet been positively identified as coeval with Pleistocene interglacial high seastands (Ortlieb, 1987). Aside from the El Rosario area, it may be added that Orme's work suggests stronger Quaternary deformations than those interpreted in the present work. In the region of Camalu, north of San Quintín, for instance, the amplitudes of vertical fault displacements are thought to be smaller than previously determined by Orme (1972, 1974); this author misinterpreted the thickness of a Pleistocene eolian sand unit and thus overestimated (by about 70 m) the downdrop motion of the San Ramon faulted block. It must be stressed that, particularly in northwestern Baja California, the determination of Quaternary coastal deformation is limited by the availability of chronostratigraphic data and field evidence of the oldest Pleistocene shorelines.

Figure 16—Sequences of Pleistocene marine platforms, shore platforms, and associated shorelines on the northern coast of the Vizcaíno Peninsula, west-central Baja California. 1 = Pre-Quaternary substratum; 2 = Pleistocene marine sediments; 3 = Quaternary alluvium and eolian sands; 4 = Highest elevation of marine deposit, or approximate shoreline elevation (in meters above present MSL); 5 = Elevation of well-defined shorelines, probably corresponding to the main interglacial high seastands of late and middle Pleistocene age.


30
20
10
0 m
No horizontal scale
BAHIA VIZCAINO
115° W
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27° 45' N
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PUNTA FALSA
Campito
Campo Malarrimo
El Queen
Vizcaino Peninsula
Tortugas
PACIFIC OCEAN
N
U
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O
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≥15
9
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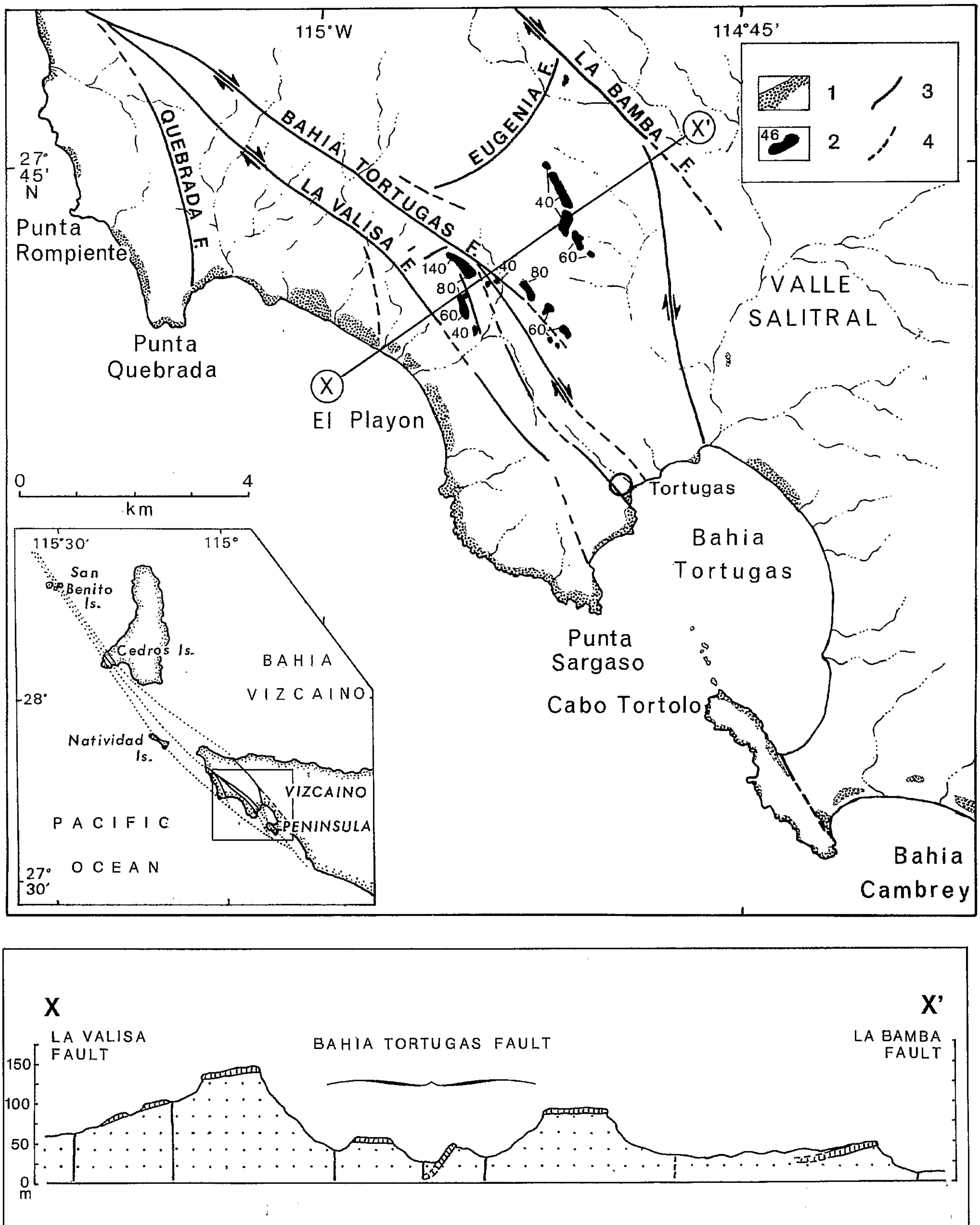

Figure 17—Deformation of Pleistocene marine terraces across the Bahía Tortugas fault system (modified from Robinson, 1979). In sketch map: 1 = Late Pleistocene marine terrace; 2 = Early and middle Pleistocene marine deposits and shore platforms (approximate elevations in meters above present MSL); 3 = Main observed faults; 4 = Inferred faults. Cross section shows the attitude of early (?) and early middle Pleistocene deformed marine deposits.

Table 1. Elevation (in meters above present MSL) of remnants of Pleistocene high seastands in Punta Banda Peninsula, northwestern Baja California (see Figure 18). After Lindgren (1888), Allen et al. (1960), and Ortlieb (1987).

Lindgren (1888)	Allen et al. (1960)	SE of Punta Banda Peak	E of Bahía Papalote	SW of Punta Banda Village	Bahía Arbolitos
12	15	10 ± 3*		22 ± 2·*	14 ± 2·*
	40	33 ± 3*		35 ± 3*	30 ± 3·
54	58	50 ± 2*	49 ± 5*		41 ± 3·
			(67 ± 3)·	68 ± 5·*	
	95	90 ± 3*	97 ± 5·*	100 ± 5*	87 ± 2·*
	125	(120 ± 10)*	122 ± 5·*		
143	134	140 ± 10·	138 ± 3·		140 ± 10*
	162	160 ± 10·	165 ± 5·*		
183	210	200 ± 5·			190 ± 3*
	229	(225 ± 10)·	225 ± 10*		
	262	252 ± 20·	240 ± 5·*		
	284	290 ± 10*	275 ± 10·		
	314	302 ± 10·*			(315 ± 15)·
	348	327 ± 10*			

· = Marine platform
• = Beach ridges and littoral sediments
( ) = Questionable shoreline

GEODYNAMIC SIGNIFICANCE OF QUATERNARY DEFORMATION

Styles of Deformation

The vertical deformation shown in northwestern Mexico through the study of Pleistocene marine terraces may be schematically divided into three categories: large-scale regional deformations probably seated in the upper crust; fault-related displacements; and volcano-tectonic processes. The last-mentioned processes are of limited extent, although they also involve upper crustal deformation. The recent crustal behavior of distinct regions across this plate boundary are deduced from the deformation surveyed along the main fracture zones and from regional comparison of marine terrace elevations.

Volcano-tectonic Motions Near Santa Rosalía

The tectonic features accompanying the Plio-Quaternary evolution of the La Reforma caldera include general doming of the area, intense faulting of the northeastern part of the volcanic complex, and very strong resurgent uplift of the central massif of La Reforma (amplitude of ~800 to 1000 m in the last million years; Demant and Ortlieb, 1981; Demant, 1981, 1984a, 1984b). Pleistocene terrace data document the regional uplift motions that encompass the caldera rim and the Santa Rosalía Basin (Figure 7), an upwarping of the inland boundary of the sedimentary basin, and some fault-related deformation.

The vertical crustal movements, which were apparently continuous during the last million years, most probably result from thermal phenomena of the La Reforma magma chamber. Geochemical arguments suggest that La Reforma and Tres Virgenes calc-alkaline volcanism is not directly associated with Basin and Range extensional tectonics, nor with the recent history of the Gulf of California plate boundary (Demant, 1984b). The closeness of the Quaternary tholeiitic cone of Isla Tortugas (Batiza, 1978) and the Guaymas Basin spreading center might thus be coincidental.

The few normal faults, with displacements of a few meters or less, that offset Quaternary deposits and marine platforms like the Upper Mesa mark an extensional regime and are associated with the Basin and Range structural evolution of the Santa Rosalía Basin (Angelier et al., 1981; Colletta and Angelier, 1981, 1983). Near San Lucas, the southern boundary of the Santa Rosalía Basin is characterized by ongoing Quaternary downwarping and local subsidence.

Although some Plio-Quaternary faulting has been described in the central part of the Baja California peninsula, west of the La Reforma and Tres Virgenes volcanic complexes (Angelier et al., 1981; Chorowicz et al., 1982a, 1982b), no positive evidence supports the existence of any large, recently active, transpeninsular fault which would join Bahía Sebastián Vizcaíno on the Pacific coast and the Santa Rosalía-San Lucas region. Such a fracture zone, which had been suggested by several authors in hypothetical reconstructions of late Cenozoic peninsular block motions (Rusnak et al., 1964; Rusnak and Fisher, 1964; Hamilton, 1971; Orme, 1972; Fife, 1974; Minch, 1975), might be an old structure which remained inactive during the Quaternary.

Faulting and Vertical Motions

The vertical deformation of Quaternary coastal deposits associated with recent fault activity may be divided into two types. Small displacements (a few meters or less) observed along local faults do not compare with the deformations experienced along major fracture zones.

Small faults, commonly the pure dip-slip type, were found in every coastal region: in Sonora (eastern coast of the Infiernillo channel, Isla Tiburón, Puerto Libertad area, etc.), in east-central Baja California (Santa Rosalía, Chivato Peninsula, Mulegé, Isla del Carmen, etc.), and in northwestern Baja California (Camalu, Santa Dominguito, etc.). These faults generally correspond to an extensional regime of Basin and Range style (on both sides of the Gulf of California) or to minor tectonic readjustments.

The fracture zones, which show large strike-slip components, also produce stronger and wider vertical motions than the above-mentioned small normal faults. Three main fracture zones which delineate the peninsular block of Baja California are responsible for some of the major vertical deformation of Pleistocene marine terraces. These main block boundaries are the Gulf of California fault system, the Tosco-Abreojos fault system, and a set of west-northwest- to north-south-striking faults between the international border and the Punta Banda Peninsula. The characteristics and implications of the vertical deformation surveyed along these structural boundaries are discussed below.

Large-Scale Vertical Deformation

If the approximate age of 1 Ma assigned to the highest elevated marine remnants observed in numerous places on the peninsula is correct, and if the 1 Ma sea level was eustatically in approximately the same position as it is now, it may be concluded that the Baja California crustal block has been uplifted with a mean net rate of 100 to 140 mm/10^3y. In contrast, the eastern coast of the Gulf of California does not present evidence of any important vertical motion during the Quaternary.

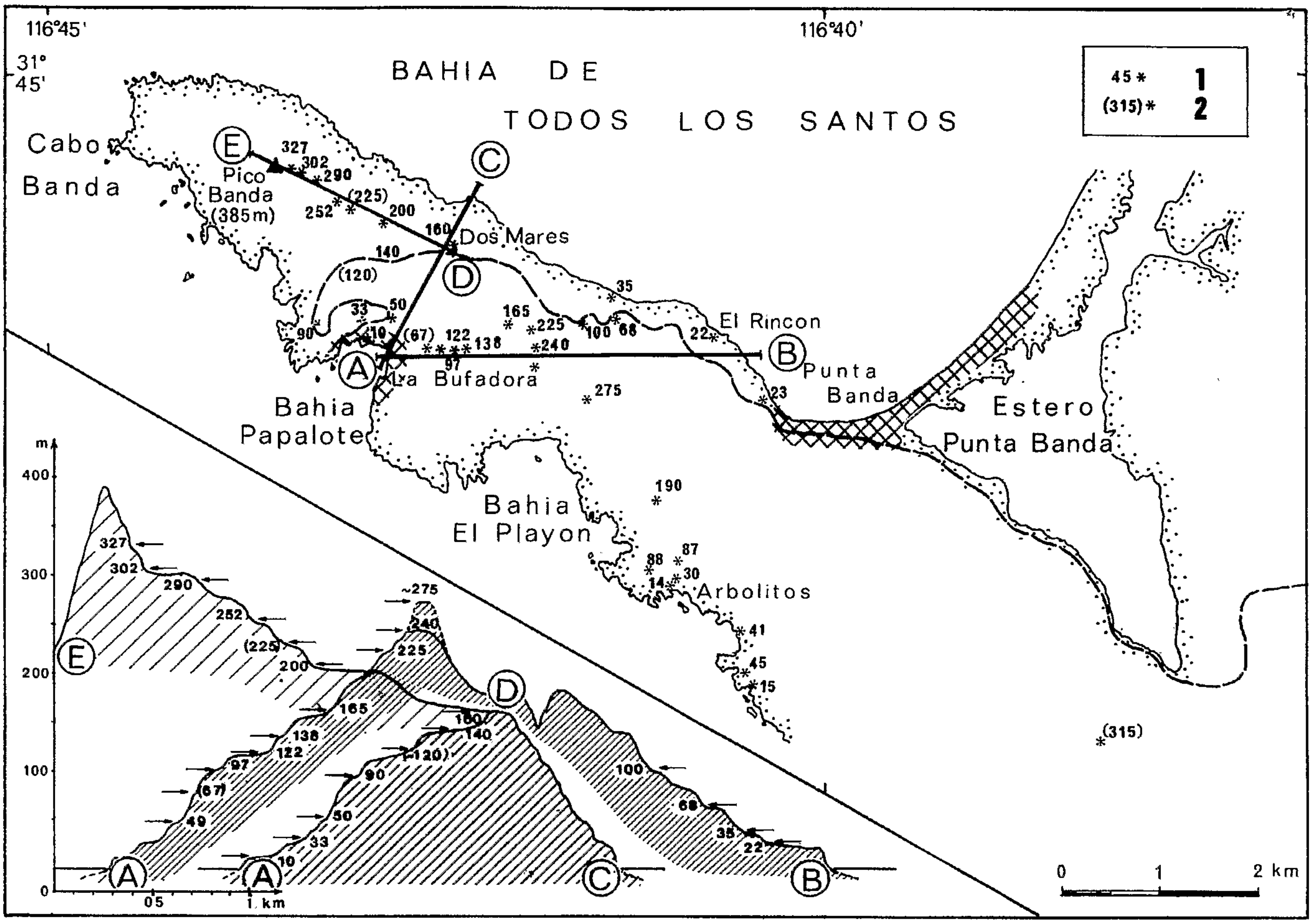

Figure 18—Sequences of Pleistocene marine terraces and associated shorelines in the Punta Banda Peninsula, northwestern Baja California (elevations in meters above present MSL). 1 = Elevation of well-defined Pleistocene shorelines; 2 = Highest elevation of shore platforms, or of marine deposits (minimum shoreline elevation).

In comparison with the high uplift rates determined in coastal California, the peninsula of Baja California thus appears to be in near isostatic equilibrium. The most actively deformed areas, which show uplift rates not exceeding 300 mm/10^3y (still an order of magnitude less than some regions of California) are found only near the fracture zones bounding the peninsular block or in the volcanic area of Santa Rosalía.

The survey of the late Pleistocene shoreline elevations, seen over the whole region (Figures 4, 14, 15), indicates that many areas of the peninsula have remained almost stable during the late Quaternary (northwestern and southwestern Gulf coasts, southwestern and west-central Pacific coasts). Other areas experienced uplift motions on the order of 100 mm/10^3y, or slightly less (east-central coast of Baja California, Vizcaíno Peninsula, and northwestern Baja California south of Punta Banda).

The widely accepted idea that the peninsular block is still being tilted toward the Pacific ocean is not supported by Pleistocene marine terrace data. A regional tilt developed in Miocene time contemporaneously with the emission of a large volume of volcanics ("Comondu Formation"). This broad crustal motion was due to thermal expansion and to rifting processes that accompanied the formation of the "protogulf" of California. Since the Pliocene, and particularly since the major plate boundary was transferred into the Gulf, volcanic activity has been greatly curtailed in the peninsula. In the last few million years, the peninsular block has been slightly uplifted, but without any conspicuous differential motion along the eastern side of Baja California. Outcrops of Pliocene marine units are found at appreciable elevations (up to ~+300 m) along the coasts of the Baja California peninsula, but they are not significantly more elevated on the eastern side than on the Pacific coast. As far as Quaternary movements are concerned, it may be concluded from the oldest marine terrace data that it is rather the northern half of the Pacific coast which has been uplifted more, relative to the rest of the peninsula. Definitely, there has been no westward tilting of the peninsular block, at least in the past million years, nor probably in all of Plio-Quaternary time.

Vertical Deformation Along the Baja California Crustal Block Boundaries

The recent vertical motions inferred from the Pleistocene marine terrace survey provide interesting clues for the definition of the Baja California structural block ("miniplate"?). These data support the hypothesis that the Pacific/North

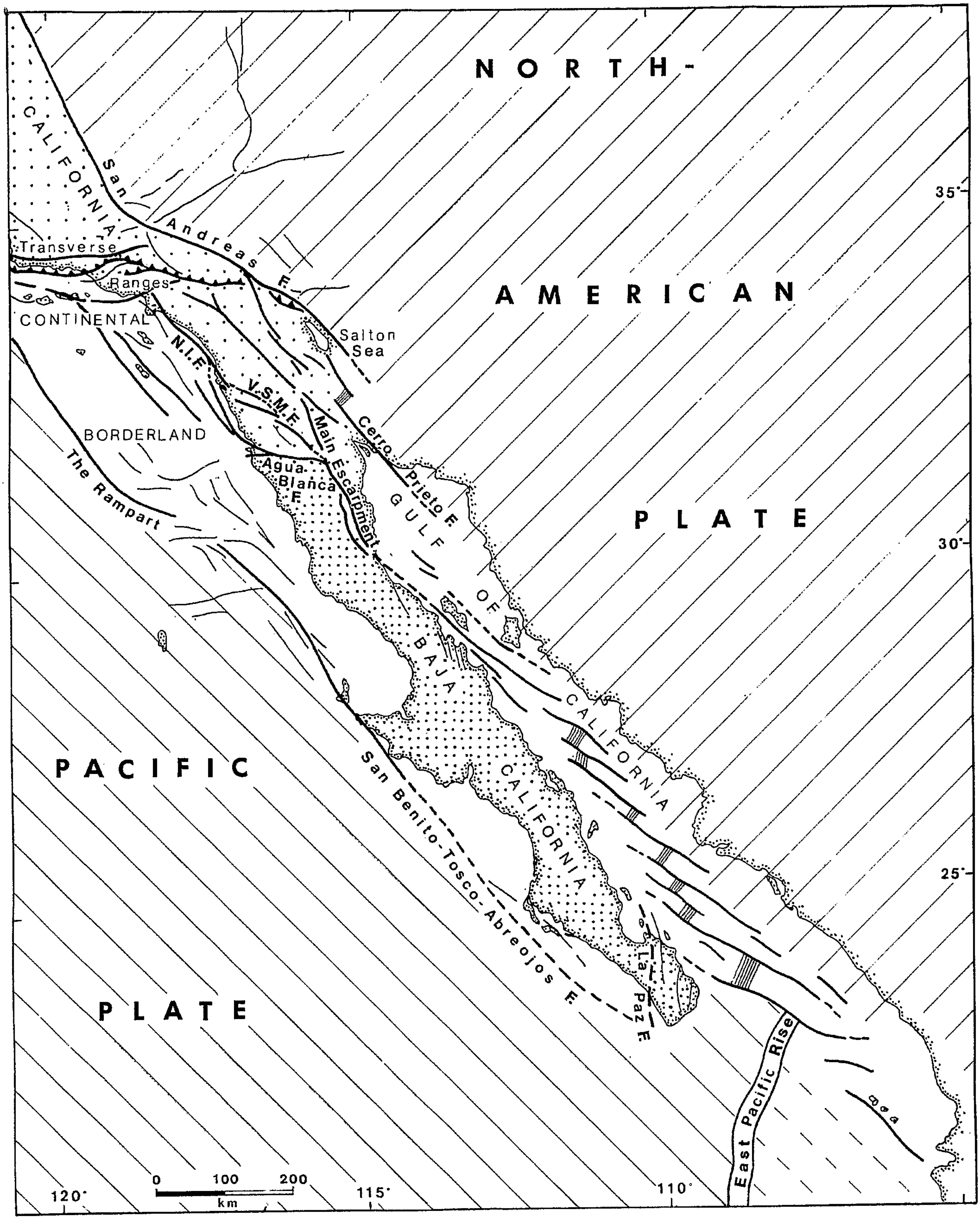

Figure 19—Structural map of the Pacific/North American plate boundary in northwestern Mexico and southwesternmost USA. The Baja California peninsular block is limited to the north by the Agua Blanca fault system. The Quaternary marine terrace data support the geodynamic model according to which the plate boundary is not restricted to the Gulf of California transform faults system, but also includes the San Benito-Tosco-Abreojos fault, as well as the active Newport-Inglewood-Rose Canyon (NIF) and Vallecitos-San Miguel (VSMF) faults. North of the Agua Blanca fault, the Quaternary vertical motions have been altogether stronger and more irregular than those which affected the Baja California block.

American plate boundary is not strictly limited to the San Andreas-Gulf of California system, but that it also involves some structural features to the west of the present shoreline, off southern California and Baja California.

Gulf of California Fault System

To the east of the peninsula, the major "Pacific"/North American plate boundary is defined by a series of en echelon transform faults which link the spreading centers seated in the deep basins of the Gulf (Moore and Buffington, 1968; Henyey and Bischoff, 1973; Moore, 1973; Bischoff and Henyey, 1974).

At the northern end of the Gulf of California, the plate boundary is represented by the Cerro Prieto fault. Lateral displacements along this fracture zone, throughout the Quaternary, may be estimated to be about 100 km (if one accepts a mean relative plate motion of 50 to 60 mm/y, according to Larson et al., 1968; Atwater, 1970; Minster and Jordan, 1978).

In addition, the Plio-Quaternary tectonic and sedimentary history of the Colorado River delta area is also marked by steady subsidence. Plio-Quaternary deltaic sequences are found at considerable depths below the surface. Exploratory well data indicate that at Yuma, the Pliocene Bouse Formation is identified between depths of 960 and 1630 m (Eberly and Stanley, 1978), and that offshore Punta Gorda (Pemex wells Extremeño 1 and 301), an early-to-late Pleistocene marine sequence reaches a depth of at least 3300 m (Trinidad Reyes and Rueda Gaxiola, 1982; Viñas Gomez, 1982, 1984). The relatively young uplift motion experienced by the southern limit of the Mesa de Sonora, between the Colorado River mouth and Bahía Adair, and documented by deformation of fluvio-deltaic and marine units of latest (?) middle and early late Pleistocene age, thus appears contrary to the general, long-lasting regional subsidence. This uplift, corresponding to some drag-folding, or transpressive folding, is directly related to the Cerro Prieto fault activity; it was initiated at the end of the middle Pleistocene and probably continues today.

Along the eastern Baja California coast, the only vertical deformation of Pleistocene emerged marine units, which is probably controlled by the plate boundary structure, was detected in the eastern tip of the Chivato Peninsula and in Concepción Peninsula, relatively close to the deep fault system of the Gulf. These fault-controlled uplifts, which only amount to a few meters in the last 120,000 years, are considered as recent, inasmuch as the middle and early Pleistocene terraces observed in the Chivato and Concepción Peninsulas are not significantly higher than in other localities of the central east Baja California coast.

Finally, it should be noted that the late Pleistocene shoreline appears to be preserved at the same (original) elevation along the eastern coast of the Gulf of California and on the northeastern and southeastern Baja California coasts. These data show that no large-scale differential motions are occurring across the main Pacific-North American plate boundary.

San Benito-Tosco-Abreojos Fault System

The western boundary of the peninsular crustal block, located almost entirely offshore on the Pacific shelf, is the San Benito-Tosco-Abreojos fault system (Figure 19). This complex fracture is inherited from the Miocene subduction zone, which evolved into a transform fault before the main Pacific/North American plate boundary was transferred to the Gulf of California (Atwater, 1970; Normark, 1977; Spencer and Normark, 1979; Normark and Spencer, 1980).

Onshore expression of the Tosco-Abreojos system consists essentially of strike-slip faults cutting the westward land projections formed by Bahía Magdalena and the Vizcaíno Peninsula. In Isla de Santa Margarita (Bahía Magdalena area), Yeats and Haq (1981) described features related to the Alcatraz fault with late (?) Quaternary activity. The strongest deformations of Pleistocene marine units known in Baja California are observed in Bahía Tortugas (Figure 17). Late Quaternary activity of the Bahía Tortugas fault (Robinson, 1979) involved combined strike-slip and dip-slip motions and induced local tilting of the earliest last interglacial platform (Allison, cited by Emerson, 1980; Angelier et al., 1981; Ortlieb, 1987). Earlier Quaternary activity of the Bahía Tortugas fault is evidenced by vigorous tilting and folding of well-cemented early/middle Pleistocene marine units (Figure 17).

According to some theoretical tectonic reconstructions, cumulative right-lateral displacements along the same fault system since the Miocene amounted to 50 km (Robinson, 1979). The Bahía Tortugas fault is interpreted as a crustal fracture which delineates a still-active major boundary between the Pacific plate and the Baja California peninsular block (Figure 19).

Toward the northwest, data on deformation of marine terraces from the Islas San Benito (Cohen et al., 1963) indicate that the Bahía Tortugas fracture zone can be traced through southwestern Isla Cedros to the Islas San Benito (Figure 17). A preliminary survey of marine terrace distribution on Isla Cedros (Figure 15) leads to the assumption that the island has been tilted toward the south, at least during the late Quaternary (Ortlieb, 1987).

Northwestern Structural Boundary of Baja California

A complex fault system including the Agua Blanca fault and several other faults in northwesternmost Baja California seems to constitute a northern structural boundary of the peninsular crustal block (Figure 19). The Agua Blanca fault proper is an old structure which does not show any important present activity inland, but is associated with the highest Quaternary uplift motion detected along the coasts of Baja California (Punta Banda); furthermore, this fault system is linked with active offshore fractures (Legg and Luyendyk, 1982).

The precise relationships between the Newport-Inglewood-Rose Canyon fault, the Vallecitos-San Miguel fault, and the Agua Blanca fault remain to be determined (Figure 19). The activity of the Newport-Inglewood-Rose Canyon fault, which is responsible for strong recent vertical offsets in southwesternmost California (particularly at La Jolla; Kern, 1977), has probably been involved in large right-lateral crustal displacements (10 to 20 mm/y; Humphreys and Weldon, 1984; Weldon and Humphreys, 1986). The Vallecitos-San Miguel fault concentrates most of the seismicity presently registered in northwestern Baja California (Gastil et al., 1975; Reyes et al., 1975; Harvey, 1986).

The fact that the late Pleistocene shorelines (I.S. 5e and 5a/c) reach significantly higher altitudes from Punta Banda northward than along the remaining Pacific coast of Baja California is attributed to major ongoing crustal deformation. This uplift motion, involving altogether the Agua Blanca, Newport-Inglewood-Rose Canyon and Vallecitos-San Miguel fault systems, may be relatively recent because middle and early Pleistocene marine terraces, which are well-documented in the Punta Banda Peninsula (up to +320 m), are not known at high elevations in the San Diego-Tijuana area (Figure 14).

In the Punta Banda Peninsula, long-term Quaternary uplift motion rates decreased from a mean of ~300 mm/10^3y to a late Quaternary 220 mm/10^3y value, which compares with that for the San Diego-Tijuana area (170 to 240 mm/10^3y). The marine terrace data lead to the conclusion that the Punta Banda Peninsula behaved as a steadily rising block during the major part of the Quaternary, and since the late (?) middle Pleistocene it lost its independence and integrated a major deformed block limited to the north by the Rose Canyon segment of the Newport-Inglewood-Rose Canyon fault system.

The region limited by the Agua Blanca fault and the Newport-Inglewood-Rose Canyon and Vallecitos-San Miguel faults is thus interpreted as constituting a recently active deep fracture zone separating the Baja California peninsular block from the southern California block (Figure 19). This boundary probably existed throughout the Quaternary and explains why the peninsula experienced uplift motions significantly slower than the major part of coastal California. The eastern termination of this fracture zone remains to be studied. There may be an active structural link between the eastern end of the Agua Blanca fault and the Canal de Ballenas area, through a fault system involving the Main Escarpment feature (San Pedro Martir lineament of Gastil et al., 1975) (Figure 19).

CONCLUSIONS

One of the main conclusions of this study, based on relative positions of distinct Pleistocene shorelines, is that the Baja California peninsula has experienced relatively slow and uniform vertical motions in the Quaternary. The peninsula has been uplifted at a mean rate of 100 ±50 mm/10^3y over the last million years. In several parts of the peninsula, these uplift rates seem to have decreased through the Quaternary.

Only on the northwesternmost peninsula and in the region surrounding the Plio-Quaternary La Reforma caldera has there been significantly more uplift (maximum rates of about 200 to 300 mm/10^3y).

In comparison with the California coast, the recent vertical motions of Baja California thus appear to have been much slower, locally by an order of magnitude. The vertical deformation data suggest that the structural boundary between the U.S. and Mexican Californias is formed by a major fracture zone encompassing both the Agua Blanca, Newport-Inglewood-Rose Canyon, and Vallecitos-San Miguel fault systems (Figure 19).

The eastern coast of the Gulf of California behaved as a vertically "stable" margin in the Quaternary, although some subsidence may have occurred in its southern part.

In the Colorado River delta area, more than 3000 m of Pleistocene deltaic and marine sediments point to a long-term, mainly tectonic, subsidence. Nevertheless, local positive vertical motions have been active since the end of the middle Pleistocene on the eastern compartment of the main fracture zone linking the Gulf of California and the southern San Andreas fault system (Cerro Prieto fault).

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