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STRATIGRAPHIC AND TECTONIC EVOLUTION OF LA PURISIMA AREA (BAJA CALIFORNIA, MEXICO) DURING LATE OLIGOCENE AND MIOCENE: IMPLICATIONS FOR THE PACIFIC MARGIN EVOLUTION

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Riassunto. Lo studio delle sequenze neogeniche affioranti nella regione di La Purisima, situata lungo la costa occidentale della Bassa California Meridionale (Messico), ha permesso il riconoscimento di discordanze regionali che separano i principali corpi sedimentari ivi presenti. Sulla base dei dati stratigrafici, paleontologici e strutturali ottenuti, gli autori propongono un nuovo quadro stratigrafico basato sulla definizione di sequenze deposizionali.

La Sequenza Sedimentaria Inferiore (Formazione San Gregorio Auctorum) è composta principalmente da argilliti silicizzate contenenti noduli fosfatici e livelli vulcanoclastici subordinati. La sequenza è fortemente deformata in numerose località e mostra pieghe con asse NE-SW, piccoli sovrascorrimenti ciechi e faglie normali a direzione N-S riferibili alla formazione di un bacino di pull-apart. La Sequenza Sedimentaria Intermedia (Formazione Isidro e parte basale della Formazione Comondù Auctorum) è costituita da arenarie fossilifere di mare basso, contenenti livelli cineritici ed è chiusa a tetto da una potente successione di arenarie vulcanoclastiche legate ai lobi di progradazione di una conoide alluvionale. Piccoli sovrascorrimenti e pieghe, orientati entrambi E-W, associati a sistemi di pieghe aperte di dimensioni chilometriche orientate da NNW-SSE a NW-SE, indicano l'attivazione di una zona di taglio NW-SE a carattere trascorrente, probabilmente legata all'impostazione del sistema di faglie trascorrenti destre di Tosco-Abreojos lungo la costa occidentale della penisola. La Sequenza Sedimentaria Superiore è costituita da arenarie e conglomerati a giacitura suborizzontale, che rappresentano le facies distali di ampi ventagli alluvionali derivati dallo smantellamento della Formazione Comondù affiorante lungo la parte assiale della penisola. Calcari coquinoidi associati a conglomerati e arenarie vulcanoclastiche sono stati osservati in affioramenti discontinui tra la Sequenza Sedimentaria Inferiore e quella Intermedia e rappresentano probabilmente una ulteriore unità allostratigrafica.

I risultati delle analisi stratigrafiche e strutturali appaiono in accordo con la presenza di un complesso regime trascorrente, attivo durante parte del Neogene lungo il margine Pacifico della Bassa California.

Abstract. The study of the Neogene sequences outcropping in the La Purisima area, Baja California Sur, Mexico, has demonstrated the presence of regional unconformities separating the main sedimentary bodies. On the basis of stratigraphic and structural analyses, we propose a new stratigraphic framework in terms of depositional sequences.

The Lower Sedimentary Sequence (San Gregorio Formation Auctorum) is mainly composed of silicized shales with phosphatic nodules and subordinate tuffites.

The sequence is heavily deformed at several sites, and shows N-S trending folds, thrusts and normal faults. The Middle Sedimentary Sequence (Isidro Formation and lowermost Comondù Formation Auctorum)

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consists of shallow marine fossiliferous sandstones with cineritic beds, capped by a thick fan of volcaniclastic sandstones. Small E-W trending thrusts and folds are associated to huge NNW-SSE and NW-SE open folds. The Upper Sedimentary Sequence is made of sub-horizontal sandstones and conglomerates probably representing the distal facies of the enormous alluvial fans of the Comondù Formation. Coquinoid limestones associated with volcaniclastic sandstones and conglomerates have been observed in between the lower and middle sequences, and are supposed to constitute a further allostratigraphic unit.

The combined analysis of the stratigraphic and tectonic evidences is consistent with complex active wrenching along the Pacific margin.

1. Introduction.

The tectonic history of the Pacific margin along the Baja California Peninsula is represented during Oligocene and Miocene by a change from active to transform plate boundary (Atwater, 1970). Several oceanographic surveys have been carried out along the Californias Continental Borderland in order to investigate the evolution of the margin (Krause, 1965; Yeats & Haq, 1981; Spencer & Normark, 1979; Crouch, 1981; Mammerickx & Klitgord, 1982). In spite of the relative abundance of information about the offshore region, few structural data exist about the Oligocene-Miocene sedi-

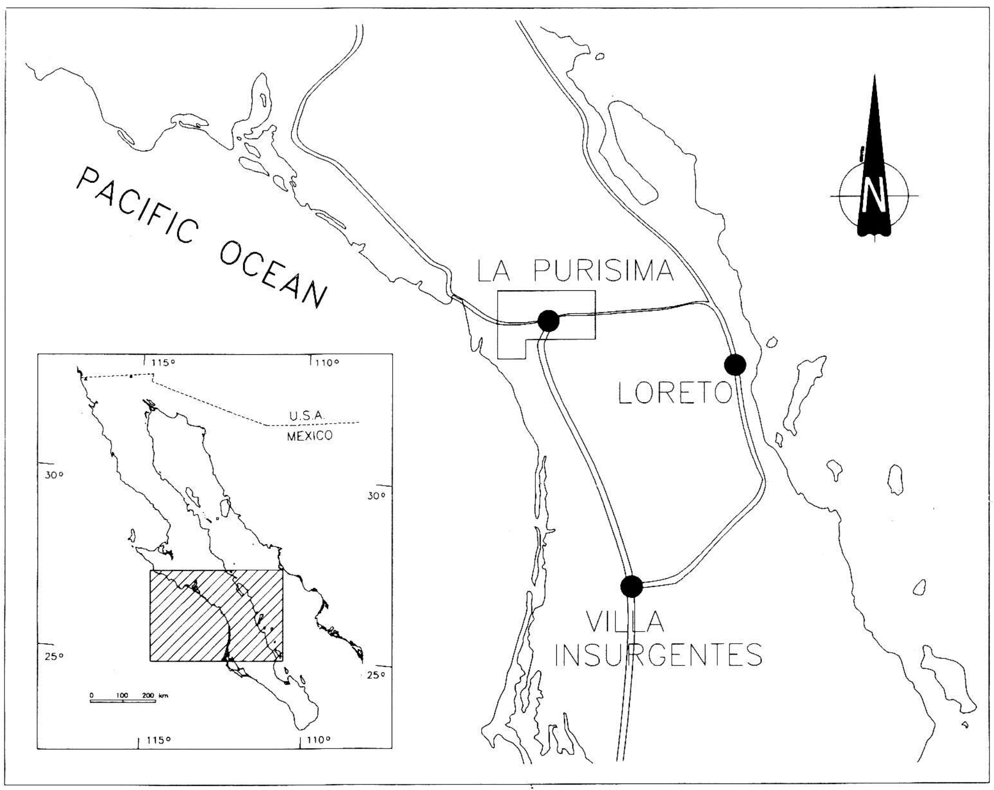

Fig. 1 - Location of the study area.

mentary units outcropping on the west coast of Baja California.

This work represents the first attempt to study the tectonic evolution of the Continental Borderland analyzing the onshore sediments which crop out in the La Purisima region, located on the west coast of Baja California Sur (Fig. 1). The La Purisima area is one of the classical localities along the Pacific margin where the Oligo-Miocene sedimentary sequences are widely and continuously exposed. Moreover, tectonic structures are present within different stratigraphic units, allowing the characterization of some phases of the evolution of the Pacific margin. During the last decade several American geologists have re-examined the sedimentary units (Hausback, 1984; Smith, 1984; Applegate, 1986; McLean et al., 1987), providing an accurate geological and stratigraphical framework of the area. Although some considerations were made about the presence of unconformities and tectonic structures, none of the previous authors carried out a detailed structural analysis.

The present paper summarizes the results of new stratigraphical and structural analyses. Three sedimentary sequences have been recognized, which are bounded by angular unconformities and are regarded as allostratigraphic units; their relationships with the tectonic evolution of the Continental Borderland are presented and discussed. Field work was carried out in 1984, 1987 and 1988.

2. The sedimentary sequences.

Many of the previous authors have tried to distinguish the Oligo-Miocene formations outcropping in Baja California Sur on the basis of their lithological characteristics. This being the approach, several correlation problems are to be faced due to the presence of repeated interfingering of units which merge into one another. McLean et al. (1987) have suggested a general stratigraphic framework, giving little weight to the presence of widespread angular unconformities linked to tectonic deformation.

A somewhat different stratigraphic distinction is proposed herein, based on the reconnaissance of sedimentary sequences separated by regional unconformities, and intended as allostratigraphic units.

2.1. Lower Sedimentary Sequence (San Gregorio Formation Auctorum).

Previous authors. The Late Oligocene San Gregorio Formation (Hausback, 1984), originally proposed by Beal (1948) for the rocks exposed at Arroyo La Purisima, was referred by several authors (Darton, 1921; Heim, 1915, 1921, 1922; Mina, 1957; Ojeda-Rivera, 1979) to as the younger Miocene Monterey Formation of California because of lithological similarities. Until recently, the San Gregorio Formation was believed to crop out in the San Hilario and San Juan regions of Baja California too, but Applegate (1986) has restricted its areal distribution to La Purisima and neighbour areas, proposing the new Oligocene to Early Miocene El Cien Formation for the rocks of the San Hilario region.

At La Purisima, the San Gregorio Formation consists of phosphatic and siliceous shales, tuffites, diatomite, pelletoidal phosphatic sandstones and rhyolite tuff, with an exposed thickness of 72 m at least (Hausback, 1984). K-Ar radiometric ages of 23.9 and 23.4 Ma have been determined from the tuff beds at La Ventana, and 25.3 Ma in the Pump House area nearby La Purisima (Hausback, 1984). Moreover, the diatoms indicate a Late Oligocene age (McLean et al., 1987). The foraminiferal assemblages suggest an upper bathyal environment (McLean et al., 1984, 1987).

Original data. The Pump House site of Hausback (1984) in the La Purisima valley has been revisited by the present authors (site L35, see Fig. 2). At site L35, the formation is about 60 m thick. It can be divided into two parts: a lower one characterized by black and white silicized shales, and an upper part made of yellow and green silicized shales. At site L35, the San Gregorio Formation directly onlaps over a strongly weathered aphiric andesite lava flow of unknown age; a breccia with lavic boulders included into a yellow-reddish matrix is present between the two units and is probably due to subaerial erosion and pedogenesis. A deformed and folded unconformity separates the sequence from the overlying Isidro Formation.

The lower lithozone is composed of black and white silicized shales (35 m); decimetric packstone interlayers bear phosphatic nodules with oolitic structures. The

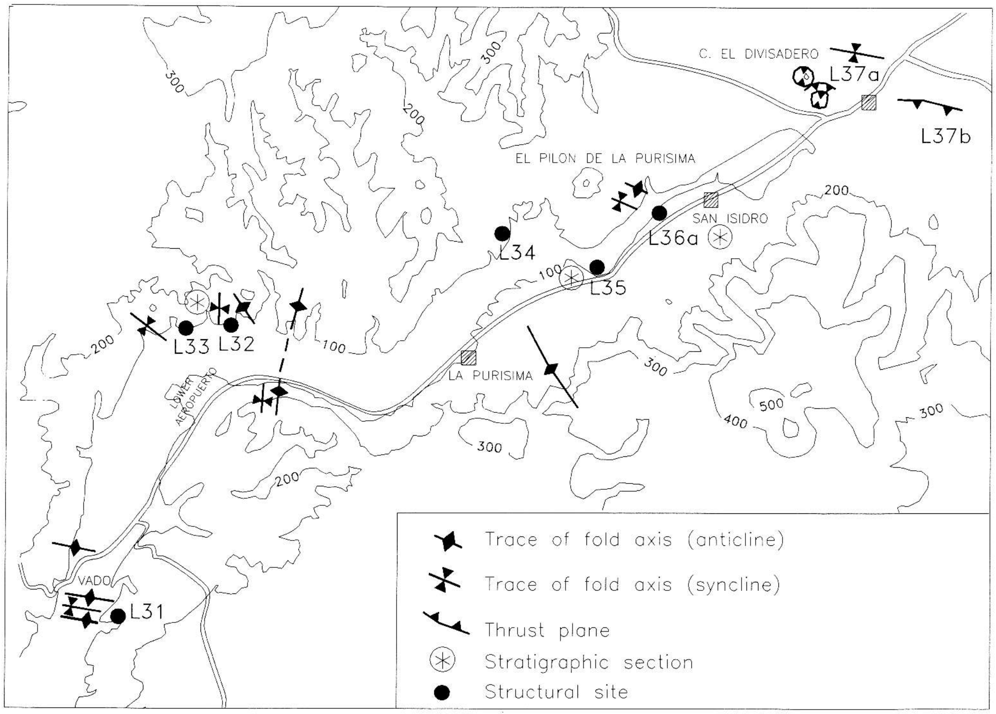

Fig. 2 - Index map of the study area showing location of site.

black shales contain abundant fish scales but rare skeletal remains, and show dense burrows at the top of the individual beds, infilled with the phosphatic nodules of the overlying levels. The nodules were also observed to form aligned and thin, discontinuous horizons inside the shale layers. The calcareous beds exhibit a normal grading of turbiditic origin, and gradually pass upward to the black shales. Reddish levels made of reworked pyroclastic sandstone are observable in the upper part of the lithozone.

The upper lithozone comprises yellow and green silicized shales (25 m) interbedded with three main calcilutitic (wackestone) levels regularly bedded or in horizons of aligned nodules few centimetres thick. These levels contain abundant bivalve bioclasts, sponge spicules, benthic and planktonic foraminifera, diatoms and algal fragments.

A diatom assemblage was recovered from a wackestone layer in the topmost part of the upper lithozone. J. A. Barron (personal communication to I. Premoli Silva) identified *Actinoptychus undulatus*, *Actinoptychus* cf. *splendens*, *Cestodiscus pulchellus*, *Coscinodiscus marginatus*, *Coscinodiscus* cf. *monicae*, *Coscinodiscus obscurus*, *Paralia sulcata*, *Stephanopyxis* cf. *grunowii*, *Stephanopyxis spinosissima*, *Synedra jouseana linearis*, *Thalassiothrix longissima*. He considered the assemblage indicative of a Late Oligocene age, thus confirming the previous age assignments.

The recognized lithological assemblages do not differ from those described by previous authors. However, the depositional environment can be reconsidered on the basis of the following evidences:

- the sharp boundary between the subaerial regolitic lava breccias and the basal shales of the sequence indicate a sudden transgressive event above a quickly subsiding area;

- the oolitic structures of the phosphatic nodules suggest the presence of nearby shoals where phosphatization occurred;

- the normal grading of the phosphatic nodules bearing limestones points toward an intrabasinal resedimentation in a trough from the shoals;

- the fossil contents, biogenic structures and the sediment fabric suggest recurrent dysaerobic conditions in a relatively deep borderland basin.

2.2. The Coquinoid Limestone.

This previously unrecorded lithotype is exposed at site L33 and 200 metres south of site L35 (Fig. 2). It consists of coquina limestone in beds averaging 1 m in thickness, and includes small bivalves (primarily cardiids, mactrids, tellinids, venerids) as well as hard substrate gastropods; the fossil contents being heavily re-crystallized, no attempt was made to identify species. The limestone is associated with volcaniclastic sandstones forming planar beds of 60-70 cm; reworked pyroclastics including pomiceous pebbles 1-5 cm in size and conglomeratic levels are intercalated. The exposed thickness of this unit has been estimated to be roughly 15-20 m at site L33, a few metres at site L35 where the coquina limestone only crops out. At site L35 the limestone seems to lay above the Lower Sedimentary Sequence (Fig. 3). The contact, however, is not exposed because of a debris cover horizontally extending for about 200 m between the Lower Sequence and the considered limestone. The strong difference of respective attitude, however, suggests a possible unconformity in between. The upper contact is well exposed at both sites, represented by a marked angular unconformity separating the coquina levels from the Middle Sedimentary Sequence (Fig. 3).

The Coquinoid Limestone and the associated lithotypes may either represent the topmost part of the Lower Sedimentary Sequence, or be a distinct sequence. Of course, the topping unconformity is against their assignment to the Middle Sequence (Isidro Formation Auctorum, cf. McLean et al., 1987). As regards the relationships with the Lower Sedimentary Sequence, the reason in favour of a separation is twofold. Firstly, a strong discrepance is to be noted concerning the respective environmental meaning. In fact, the Lower Sedimentary Sequence is currently regarded as being of upper bathyal environment, whereas the coquina limestone appears to have been deposited in shallow water, quite possibly a beach environment. Secondly, the thick, relatively proximal pyroclastic deposits differ markedly from those of the Lower Sedimentary Sequence, which are thin layered and reflect a quite faraway source, probably related with the volcanism of the Sierra Madre Occidental (Gastil et al., 1979; Hausback, 1984). The pyroclastic deposits of the considered sequence indicate the beginning of important local volcanic activity, probably related to the inception of the "Comondù-related" volcanic arc. Finally, the present unit suggests the settlement of shallow shelf conditions that lasted later on during Miocene.

2.3. Middle Sedimentary Sequence (Isidro Formation and lowermost Comondù Formation Auctorum).

Previous authors. The Isidro Formation has been recognized in several localities of Baja California Sur, where the outcrops of La Purisima represent the northernmost exposures. In the study area, the formation is composed of bioturbated, yellow to brown, fine-grained tuffaceous sandstones and siltstones attaining a total thickness of 80 m. Both fossils and sedimentary structures suggest an inner shelf shallow environment (Smith, 1984; Hausback, 1984). The cited authors mentioned the interfingering with the lowermost Comondù Formation. The age of the formation is constrained by K-Ar dates: in the La Purisima area, the Isidro Formation unconformably overlies the San Gregorio Formation of 23.4 Ma, and, at La Purisima Vieja 16 km northwest, the Isidro Formation grades upward into nonmarine Comondù beds containing a 14.5 Ma basalt flow (Hausback, 1984). Similar stratigraphic relationships between the Isidro and Comondù Formations have been reported on for other sites of the peninsula, in the San Hilario and San Juan de la Costa areas (Gastil et al., 1979; Hausback, 1984). Applegate (1986), in the frame of an accurate stratigraphic and sedimentologic study, reconsidered the fossiliferous and tuffaceous sandy layers exposed in the San Hilario and southernmost peninsular areas, previously referred to the Isidro Formation. He

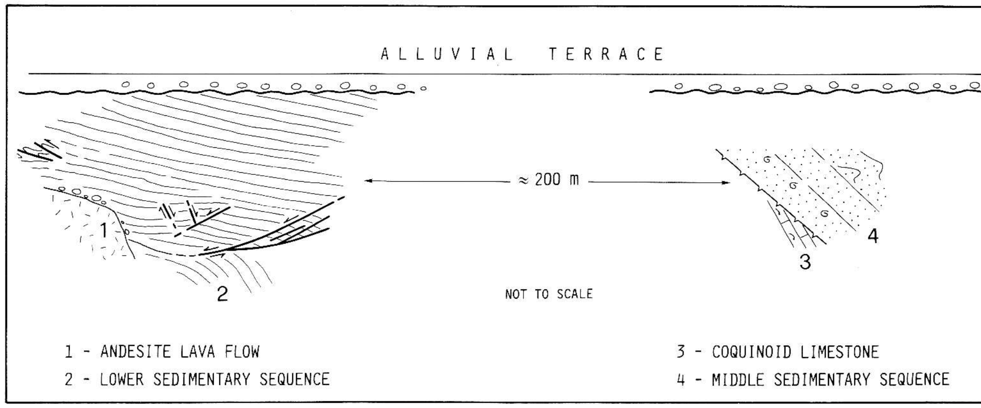

Fig. 3 - Stratigraphic relationships among the Lower Sedimentary Sequence (San Gregorio Formation), Coquinoid Limestone and Middle Sedimentary Sequence observable at the Pump House (site L35), on the left bank of Arroyo La Purisima.

noted that these deposits are older than those of the type-area, and separated them to form the Cerro Colorado Member of the El Cien Formation.

Original data. The lowermost part of the sequence was recognized and measured at the Pump House site (Fig. 2). Moreover, two significant stratigraphic sections have been studied: the first one is exposed at the site named Lower Aeropuerto, 200 m west of a small ranch located on the right bank of the Arroyo La Purisima; the second section is few hundred metres east of the village of San Isidro (see Fig. 2 for locations).

At the Pump House site (Fig. 3), as already said, the Middle Sedimentary Sequence is bounded at the base by an angular unconformity that separates it from the Coquinoid Limestone. The basal Isidro Formation crops out, represented by 10 m of grey-green, bioturbated sandstones followed by a few metres of light-grey, thin bedded marl. In the uppermost part of the sandstone level some fossiliferous horizons were observed which succeed each other as follows. A bryozoan bearing layer with well preserved eschariform and celleporiform colonies in growth position, sparse or in clusters. G.P. Braga (pers. comm.) identified the cheilostomatous genera *Pentapora*, *Porella*, *Escharoides*, *Celleporaria*. A 0.5 m thick oyster bed built up by *Hyotissa haitensis* (Sowerby) and sparse bryozoans. A layer with a transported assemblage including *Aequipecten plurinominis* (Pilsbry & Johnson), *Rapana imperialis* Hertlein & Jordan and the sand dollar *Vaquerosella fairbanksi santanensis* (Kew). The topmost layer contains large barnacles.

The Aeropuerto Section is bounded by two angular unconformities (Fig. 4). The 50 m thick lower part mainly consists of well stratified bioclastic sandstones and siltstones; cross-lamination and burrowing are frequently observed. The basal part includes a 8 m thick layer of reworked greenish to yellowish ash. The lowermost level yielded *Anadara (Anadara) topangaensis* Reinhart, *Hyotissa haitensis* (Sowerby), *Ostrea (Ostrea)* sp., *Parvilucina (Parvilucina) approximata* (Dall), *Macoma (Macoma)* sp., *Donax* sp., *Dosinia (Dosinia) whitneyi (Gabb), Chione (Chionopsis) richtofeni* Hertlein & Jordan, *Corbula (Caryocorbula)* aff. *praenasuta* (Olsson), *Corbula (Caryocorbula)* sp., *Turritella altilira* Conrad, *Turritella bicarina* Loel & Corey, *Turritella* sp., undeterminable cypreids, naticids and pyramidellids, the small echinoid *Vaquerosella andersoni* (Twitchell) and barnacles.

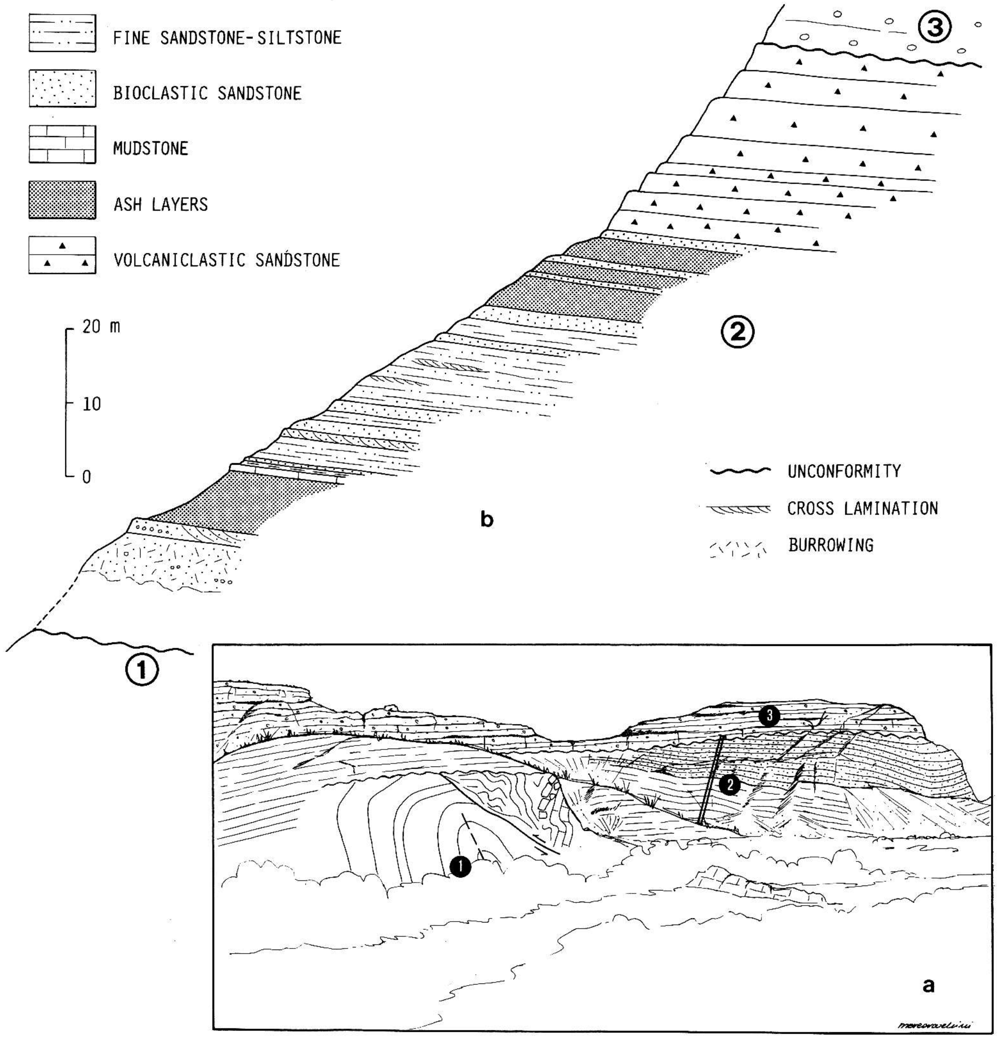

Fig. 4 - Lower Aeropuerto (site L32/L33). a) Stratigraphic relationships among the considered sedimentary sequences observable right of Arroyo La Purisima, 5 km downstream from the town of La Purisima. 1) Coquinoid Limestone, 2) Middle Sedimentary Sequence, 3) post-Comondù fluvial terrace. b) Stratigraphic section of the Middle Sedimentary Sequence (location shown in the bottom part).

The upper part is characterized by two main volcaniclastic bodies. The lowest one, 12 m thick, is composed of well stratified yellowish tuffitic sandstones and siltstones. The uppermost one, about 20 m thick, contains reddish-violet volcaniclastic sandstones that form clear, thickening upward beds. The sandstones pinch out a few hundred metres laterally, thus indicating a progradational lobe of a deltaic system.

In the San Isidro Section (Fig. 5), the base of the Middle Sedimentary Sequence is not exposed; an angular unconformity due to erosional truncation makes the top. The section includes two main units separated by a successive N-S trending normal fault with a small slip. The lower unit consists of brownish-greish and grey fossiliferous sand that includes turritellids, *Lyropecten pretiosus* (Hertlein), *Spondylus scotti* Brown & Pilsbry, *Chione* sp., barnacles and shark teeth. The sand is capped by two oyster beds 1.5 and 0.8 m thick respectively, separated by 0.60 m of grey clayey silt bearing a transported turritellid assemblage. The latter layer yielded *Turritella bicarina* Loel & Corey, *Turritella ocoyana* Conrad which is found by the thousands, *Lyropecten pretiosus* (Hertlein), *Amussiopecten vanvlecki* (Arnold) and barnacles. The upper oyster bed is entirely made of variously sized whole shells of *Hyotissa haitensis* (Sowerby) cemented to one another, and represents a true oyster bank. The exposed thickness of this lower unit is 27.9 m.

The 33 m thick upper unit is composed of greish-brownish sandstones forming wedge-shaped beds, and with parallel, cross, occasionally fish-bone lamination. At the very base abundant megafossils occur with varying preservation, from good to poor: *Aequipecten plurinominis* (Pilsbry & Johnson), *Argopecten* sp., *Spondylus scotti* Brown & Pilsbry, *Ctenoides* sp., *Ostrea vespertina* Conrad, *Miltha (Miltha) sanctaecrucis* (Arnold), *Cardita* sp., *Pitar (Lamelliconcha)* sp., *Dosinia (Dosinia)* sp., *Turritella bicarina* Loel & Corey, *Turritella ocoyana* Conrad, *Strombus* sp., undetermined vermetids and naticids. It is of note that the bulk of the bivalves is represented by internal casts of whole shells. Fossiliferous sandstones with at least two burrow systems, the largest ones referable to *Ophiomorpha* sp., characterize the upper part of the unit. Small lavic and pomiceous pebbles, arranged in rows or forming thin lenticular layers, are widespread throughout. The local occurrence of mud-cracks was noted as well.

The fossils from the basal part of the sequence (Pump House site) point toward an Early Miocene "Vaqueros" age which is consistent with the K-Ar dates. The fauna recovered at the very base of the Aeropuerto Section indicates an early Middle Miocene age; the presence of *Vaquerosella andersoni*, that occurs abundantly, may support the correlation of this level with the Relizian Buttonbed Sand Member of the Temblor Formation in California. The assemblages obtained from the San Isidro Section suggest a Mid-Miocene "Temblor" assignment of the topmost part of the lower unit. The occurrence of the early Late Miocene to Pliocene *Ostrea vespertina* at the base of the upper unit could indicate an earliest Late Miocene age for this latter, but this is not in agreement with the 14.5 Ma date of the basalt flow interbedded with the basal Comondù Formation at La Purisima Vieja. We conclude that the upper part of the Middle Sedimentary Sequence is of Middle Miocene age; *Ostrea vespertina* should have

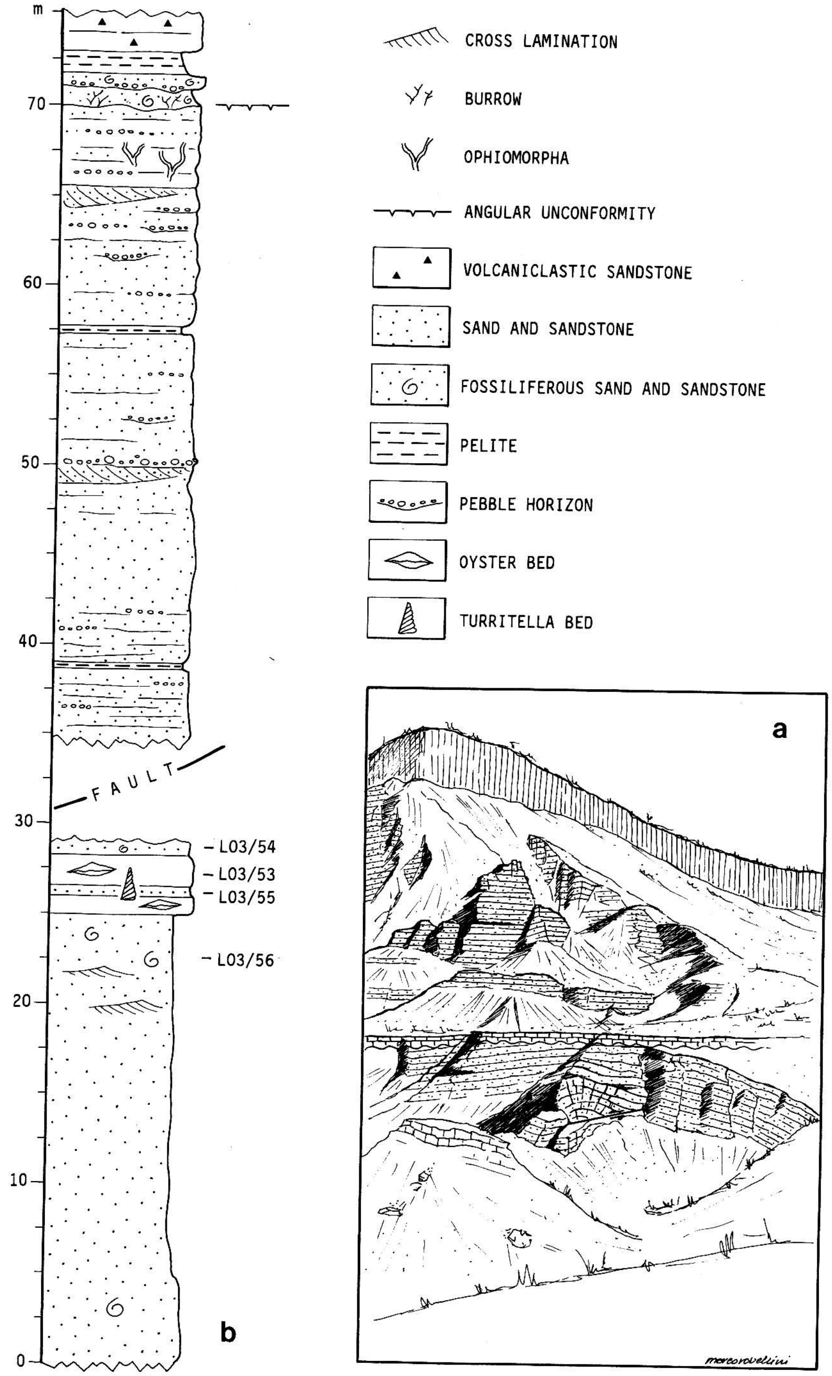

Fig. 5 - San Isidro. a) Stratigraphic relationships between Middle and Upper Sequences separated by angular unconformity observable at the village of San Isidro. b) San Isidro Section.

appeared in the considered area earlier than in other northward Californian localities.

The fossiliferous lower part of the Middle Sedimentary Sequence provides evidence for a shallow water environment with incidental volcanic supply related to faraway explosive activity. The upper part is characterized by volcaniclastic sandstones and lava pebbles indicating a marginal marine environment controlled by important volcanic input linked to the erosion of a nearby volcanic arc. The lower part of the sequence, observed in the analyzed sections, perfectly conforms to the typical facies of the Isidro Formation as intended by the authors. As regards the upper part, the abundant volcaniclastic arenaceous supply has led the previous authors to include this facies into the Comondù Formation, regarded to interfinger with the marine Isidro Formation. It is worthy of note that, on the basis of our recent field work in the La Purisima region, the volcaniclastic arenaceous deposits resulted to be truncated at the top by an erosional angular unconformity, and that a thick arenaceous sequence referred to the Comondù Formation too lies upon the same unconformity.

2.4. Upper Sedimentary Sequence (middle-upper Comondù Formation Auctorum).

The Upper Sedimentary Sequence is exposed along the San Isidro Section (Fig. 5) and develops unconformably above the fossiliferous limestones of shallow marine environment at the top of the Middle Sequence. The section is composed upward by 150 m of monotonous pinky-brownish volcaniclastic sandstones. The sequence is capped by a lava-flow of the Mesas. Similar lava-flows range in age from 12.5 to 6 Ma (Hausback, 1984; Hagstrum et al., 1987). In the Lower Aeropuerto Section, alluvial sandy conglomerates outcrop too, but are quite possibly related to a post-Comondù fluvial terrace fed with reworked material from the Comondù Formation s.s. (Fig. 4).

3. Tectonic evolution of Baja California continental margin.

According to the current view herein briefly resumed, the Cenozoic evolution of the North American Pacific margin is characterized by three main geodynamic events (Fig. 6).

The oceanic lithosphere subduction under the North American Plate was active since the Cretaceous up to the Miocene (Atwater, 1970). The prosecution of the subduction phenomena caused the Pacific-Guadalupe spreading center to intersect with the American Margin at about 29 Ma. Two triple junctions were then created: the Mendocino and Rivera junctions, migrating north and south respectively.

Between Oligocene and Miocene three main plate reorganizations occurred along the Baja California margin, as testified by the presence of abandoned spreading ridges (Mammerickx & Klitgord, 1982). The first reorganization started at 29 Ma, culminating at 25 Ma, and is constrained by a clockwise rotation of the Pacific-Farallon spreading center. At the same time, the major Farallon plate broke up into several

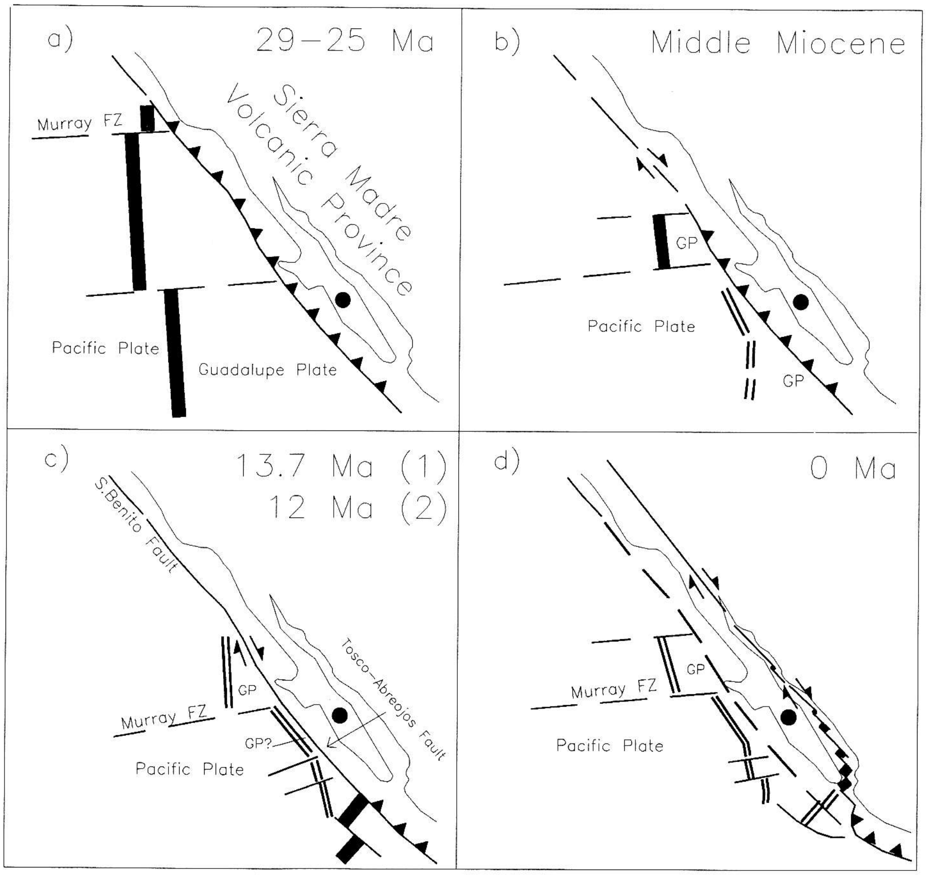

Fig. 6 - Palinspastic restoration of Baja California and western Mexico between 29 Ma and Recent. Present-day outlines of Baja California are shown for reference. Solid black) active ridge; double lines) abandoned ridge; black circle) study area. In part c): 1. data from Mammerickx & Klitgord (1982); 2. from Yeats & Haq (1981); redrawn from Mammerickx & Klitgord (1982).

smaller parts, and the Guadalupe plate formed between the Mendocino and Murray fracture zones.

Subsequently to the Late Oligocene reorganization, the plate configuration remained relatively stable 10 Ma long. Between 29 and 12.5 Ma, the Pacific-Guadalupe spreading center was progressively consumed eliminating the subduction between the Murray Fracture Zone and a minor zone located 29°30'N. Further south the spreading ridge rotated anticlockwise becoming parallel to the continental margin at 12.5 Ma. The magnetic anomalies between 29°30'N and 27°N show a 12.5 Ma ridge preserving a small fragment of the Guadalupe plate on its eastern side.

A major plate reorganization occurred during Middle Miocene, between 12.5 and 11 Ma. After that reorganization, the Pacific-Guadalupe spreading center became totally inactive between 29°30'N and 23°30'N. It is still dubious whether the abandoned ridge was partly consumed in a trench or was abandoned offshore, leaving small fragments of the Guadalupe plate along the Baja California margin. South of the peninsula the Pacific-Guadalupe ridge was active up to 12.5 Ma rapidly rotating clockwise. A transform boundary developed at that time along the western Baja California, between the Pacific and North American plates, departing from the new trench-ridge-transform triple junction located at the southern tip of Baja California. A continuous NW-SE trending fault zone, the Tosco-Abreojos transform fault, extending between the Vizcaino Peninsula and the tip of Baja California, was recognized by Spencer & Normark (1979) and interpreted as the transform boundary between 14-12 and 4.5 Ma. The northward prosecution of that transform boundary is represented by the San Benito fault zone recognized by Crouch (1981). During the same span of time the "Protogulf of California" opened (Karig & Jensky, 1972; Angelier et al., 1981; Dokka & Merriam, 1982; Zanchi, 1989a, b) in connection with the westward propagation of the Basin and Range Province.

The East Pacific Rise propagated northward between 11 and 6.5 Ma, causing the opening of the present-day Gulf of California at 3.5 Ma. Since then the transform plate boundary jumped from the Tosco-Abreojos fault zone to the Gulf, leaving the Pacific margin in a rather inactive intraplate setting (Fig. 6).

4. The tectonic structures in the La Purisima area.

A detailed structural analysis was carried out in the units outcropping in the Arroyo La Purisima, between Carambuchi (Cuba) and the "Vado" of the road to San Juanico (Fig. 2). Several structures of different kind were observed, including folds, thrusts and normal faults. Folds have been measured according to Ramsay & Hubert (1987). Faults and fractures have been analyzed collecting a representative number of measurements for each outcrop. Faults have been interpreted using simple geometrical criteria (Hancock, 1985; Hancock et al., 1987) because of the lack of slickenside lineations. Most of the structures seem to have developed in still soft deposits, due to synsedimentary deformation. Megascopic data concerning the major structures are summarized in the structural map of Fig. 2.

4.1. The Lower Sedimentary Sequence.

One representative site (L35; Fig. 2), where complex structures of difficult interpretation are exposed, was analyzed in this sequence. It corresponds to the Pump House locality of Hausback (1984, table 1) and to the outcrop figured by McLean et al. (1987, Fig. 6). The site is a few metres from the main road connecting San Isidro to la Purisima, near a small lake on the east bank of Arroyo La Purisima.

Some small centimetric to metric thrusts were observed on the eastern side of the outcrop (Fig. 7A, 8). The structures are outlined by a reddish tuffitic level, probably that dated 25.3 Ma by Hausback (1984). Deformation is characterized by blind thrusting; the small NE-SW trending thrusts (Fig. 7A, L35-TH) are embricated and opposite-facing (Fig. 8 a, 9). Faulted centimetric pop-up anticlines and ramp folds are associated to the main slip surfaces (Fig. 8a, b). Similar megascopic structures have been recognized in several thrust belts (see for a short summary Dunne & Ferril, 1988), but blind thrusting, as a deep expression of superficial folding, has been also identified along major strike-slip structures (Stein, 1985). For example, the Coalinga earthquake of 1983, located near the San Andreas Fault System, seemed to be as-

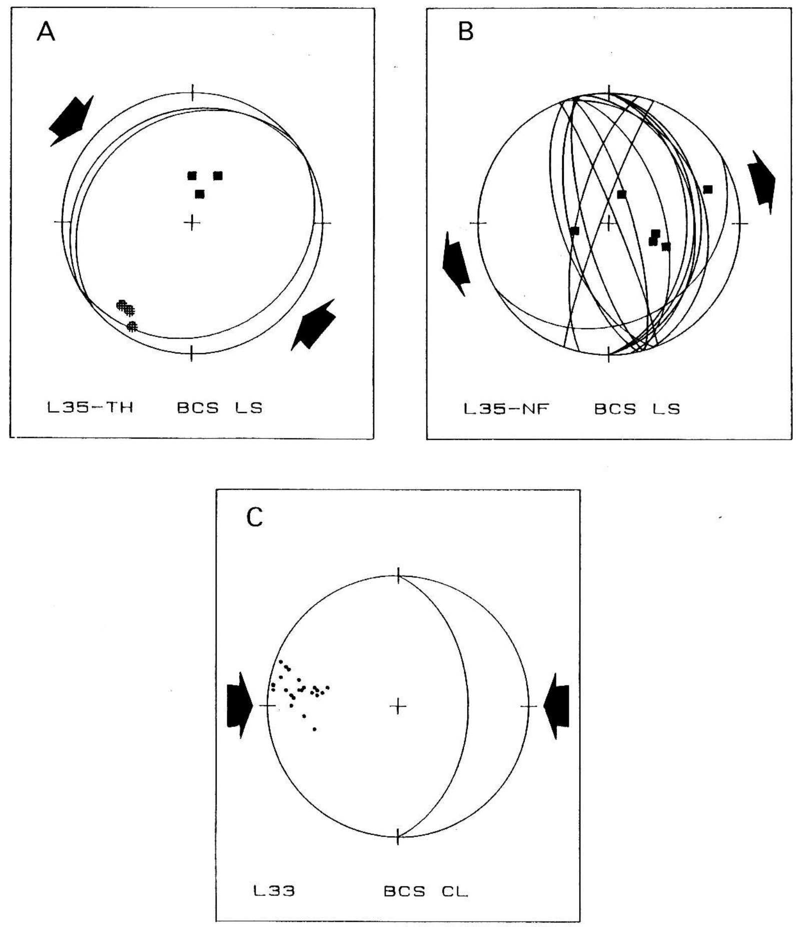

Fig. 7 - Stereographic projections of structures observed in the Lower Sedimentary Sequence - lower Schmidt's hemisphere. Thin lines represent fault planes; black squares are poles to bedding; small dots are poles to bedding in folds; gridded circles are fold axes; arrows represent stress directions as deduced from the structures. A) Thrust planes in the Lower Sedimentary Sequence; B) normal faults in the Lower Sedimentary Sequence; C) folds and thrust planes in the Coquinoid Limestone.

sociated to blind faulting at depth, due to propagation of a thrust plane. Other examples of blind thrusting associated to wrench faults were recognized for the El Asnam earthquake of 1970, and for the Armenian earthquake of 1988 (Stein & Yeats, 1989).

On the back side of the outcrop, several fault planes consisting of complex systems of N-S trending normal faults (Fig. 7B, L35-NF) cross the sequence overlying the lava flow. The beds are crossed by two major listric faults connected by strongly

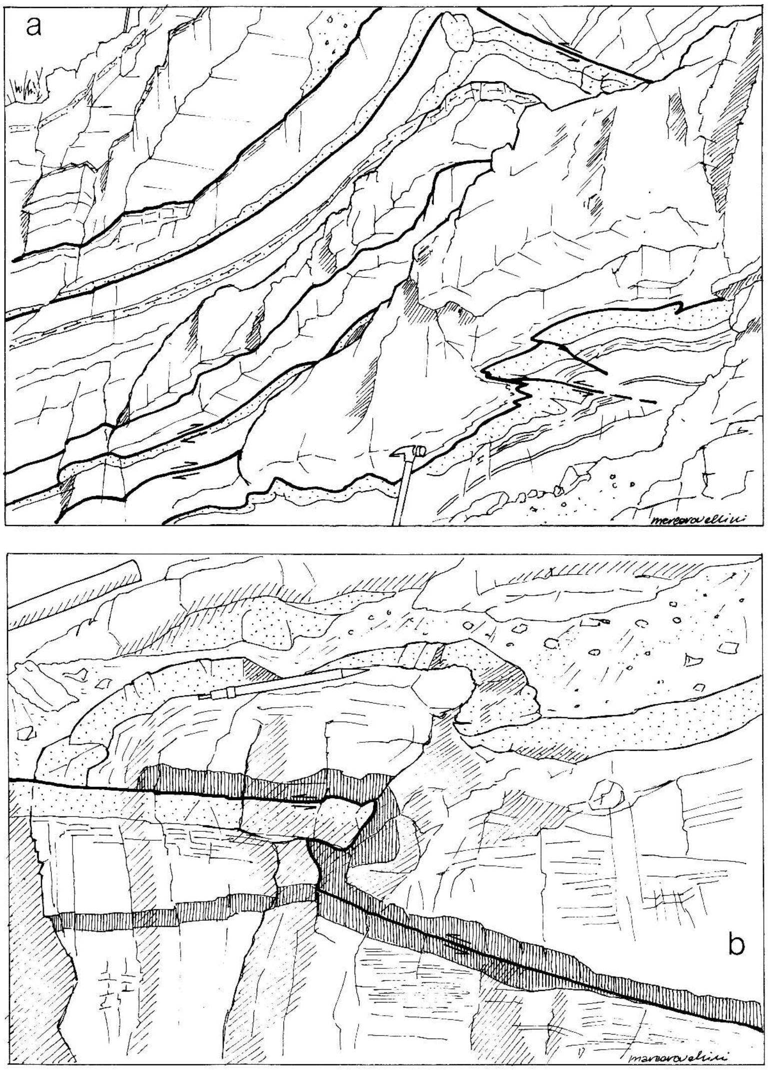

Fig. 8 - Blind thrusts in the Lower Sedimentary Sequence at Pump House (site L35). A) Opposite facing blind thrusts; a faulted pop-up anticline is shown in the lower right. B) Ramp fold associated to a centimetric blind thrust.

rotated and extended duplexes. Bedding is tilted and previously formed normal faults appear as high angle reverse faults. Although the structures are only partially exposed, the rates of extension seem to be important. In this case, deformation occurred in hydroplastic conditions too, the fault planes displaying plastic dragging and sqeezing of the sediments.

A characterization of the tectonic setting indicated by the structures observed within this sequence is uncertain, mainly because of the small investigated area. On the basis of the above said examples, blind thrusting as well as normal faulting can be related to the different effects of releasing and restraining bends along a strike-slip shear zone. The importance of normal faulting suggests the probable formation of a N-S trending pull-apart basin. On the contrary, N-S folds were recognized in the area by Hausback (1984) and McLean et al. (1987) who described open folds due to a gentle deformation of the San Gregorio beds.

4.2. The Coquinoid Limestone.

The two small exposures of the Coquinoid Limestone both show impressive deformation. The volcaniclastic and bioclastic beds at site L33 indicate a strong compressive deformation. A decametric overturned fold (Fig. 4a, 7C) was formed under a thrust plane above which small chevron folds are recognizable among chaotic blocks. The structures are sharply cut by a marked angular unconformity. The fold is the same figured by McLean et al. (1987, fig. 21) and regarded to affect the Isidro Formation. Poles of Fig. 7C refer to the lower fold, the cyclographic projection to the main thrust plane. The structures are consistent with an E-W compression and westward tectonic transport. Although striations and fractures are present in the contorted beds, the chaotic setting partly displays plastic structures referable to a prediagenetic deformation.

Similar volcaniclastic and bioclastic layers crop out further west along the small cliff of site L35. Subvertical bedding suggests the presence of close folds in that place too.

4.3. The Middle Sedimentary Sequence.

The beds of the Middle Sedimentary Sequence show several tectonic structures all along the La Purisima Valley. At site L31, right south of the Vado, E-W trending heptometric open folds are observable in the river (Fig. 9A, 9B); kilometric open folds deform the sequence and are cut by the upper unconformity at site L32 (Fig. 4a, 9C). The diagram of Fig. 9C refers to the broad syncline depicted in the drawing of Fig. 4a. The axes of these structures are subperpendicular to those of the previous ones. The folds cross the valley and are still exposed in the high clives of its left side. Site L34 shows slump-like folds and probable thrust planes interlayered among undeformed

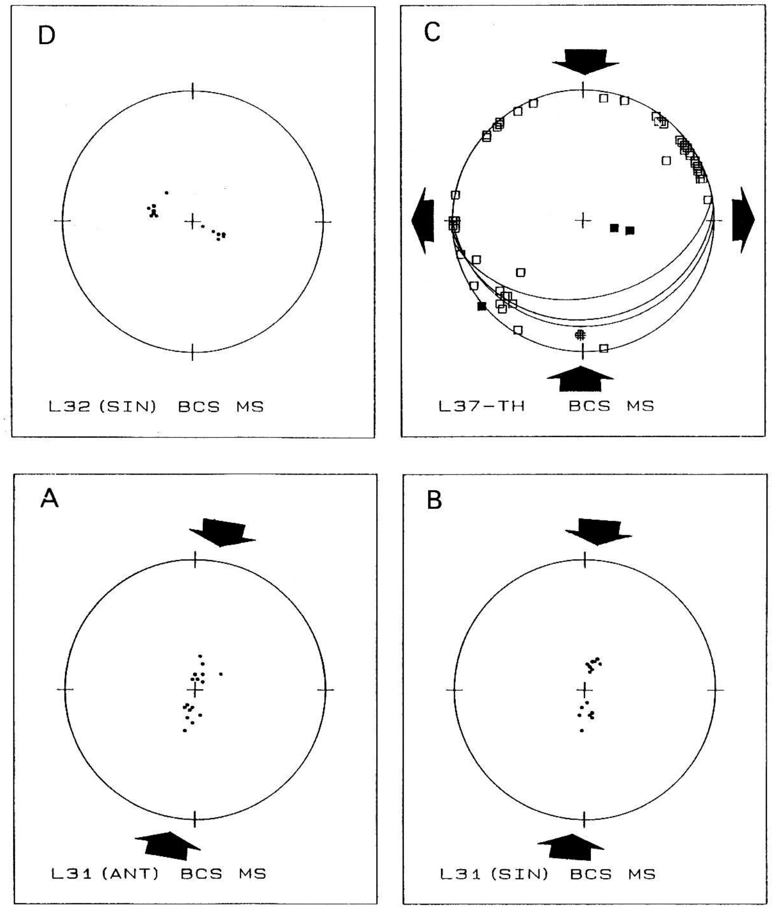

Fig. 9 - Stereographic projections of the structures observed in the Middle Sedimentary Sequence - lower Schmidt's hemisphere. Empty squares are poles to extensional joints; other symbols as in Fig. 7. A) and B) open folds outcropping near the "Vado"; C) broad syncline of Fig. 4; D) thrust planes and extensional joints at Cerro El Divisadero (see also Fig. 10).

beds. Fold axes range from E-W to WNW-ESE trends. NW-SE folds and contorted strata outcrop at site L36a in front of the village of San Isidro, along the right bank of the river, and are easily observable from the "Gasolinera Station". Folds and thrusts are present under the upper unconformity just south of that village, where the stratigraphic section of Fig. 4b was measured.

The most impressive structures of the valley occur at site L37 corresponding to the small isolated relief of Cerro El Divisadero. There, E-W trending folds and thrust planes display an embricated thrust fan (Fig. 9D, 10). Thrusts are mainly low angle ramps (20°-30°) crossing sub-horizontal strata. Bedding is locally upturned by high

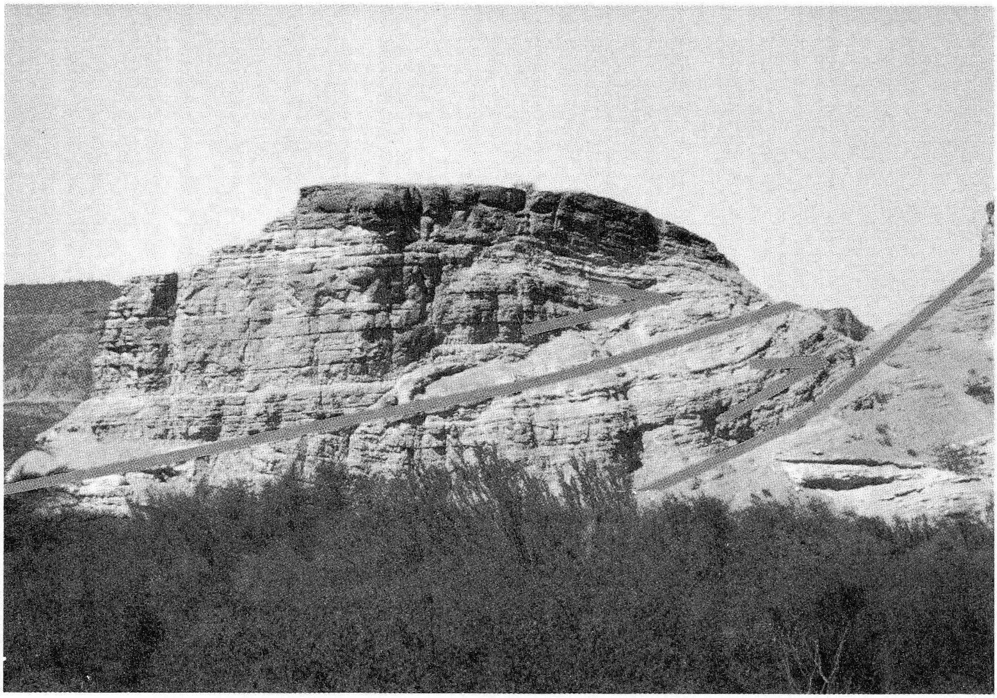

Fig. 10 - Embricated thrust planes in the Middle Sedimentary Sequence at Cerro El Divisadero (site L37).

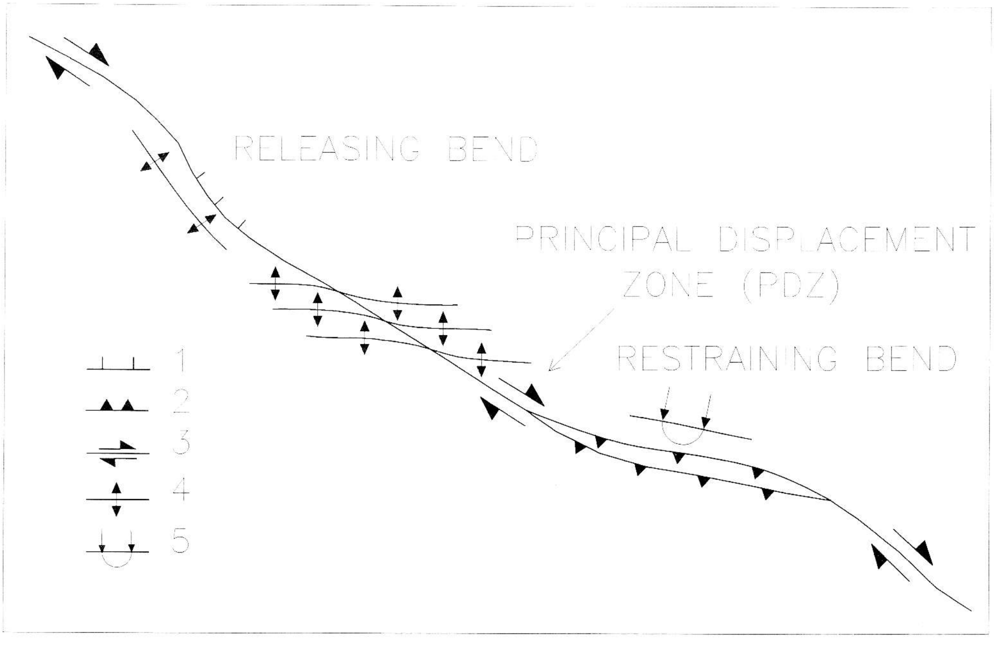

Fig. 11 - Idealized structures along a major NW-SE dextral strike-slip fault. After Christie-Blick & Biddle (1985).

angle reverse folds. Folds and contorted beds of bioclastic limestone and sandstone are present along thrust surfaces, especially along the floor thrust. A full joint spectrum (Hancock et al., 1987) measured in the upper klippe indicates a N-S trending horizontal $\sigma 1$ axis consistent with the E-W fold axes. Net slips are not precisely evaluable, but are supposed not to exceed a few hundred metres. The prosecution of these structures has been observed east of Cuba. Other E-W trending folds are exposed along the river north of Cuba.

Surprisingly, McLean et al. (1987) interpreted the structures of the same outcrop (their figures 19 and 20) as linked to slumping along a normal fault. As indicated in many works concerning the deformation along strike-slip faults (Wilcox et al., 1973; Crowell, 1974; Reading, 1980; Crouch, 1981; Ron & Eyal, 1985; Christie-Blick & Biddle, 1985; Biddle & Christie & Blick, 1985), the structures displayed by the Middle Sedimentary Sequence can be referred to a strike-slip shear zone. Folds and thrust planes are consistent with a NW-SE trending dextral strike-slip fault. The idealized structures associated with a right-slip fault are represented in Fig. 11; the en échelon folds and thrust trends fit in with the ones measured in Arroyo La Purisima, although the major shear zone is not exposed in the area. The presence of slump-like structures indicate that this tectonics could have been already active during the sedimentation.

4.4. The Upper Sedimentary Sequence.

Structural data were not obtained from the flat lying Upper Sedimentary Sequence in the La Purisima valley because of the lack of evident tectonic structures. Some minor fault planes have been observed near La Purisima Vieja, consisting of NW-SE trending normal faults and extensional joints. The structures can be related to the extensional phenomena connected with the opening of the Protogulf of California (Angelier et al., 1981) that affected the western side of the peninsula too (Zanchi, 1989b).

5. Discussion and conclusions.

The analyses carried out in the La Purisima area have led to a new tectono-stratigraphic framework of the evolution of the Pacific margin in the study region (Fig. 12). Four sedimentary bodies have been distinguished which can be considered allostratigraphic units being bounded by regional unconformities accompanied by erosional truncation. Some doubt does exist as regards the unconformity between the Lower Sedimentary Sequence and the Coquinoid Limestone because of poor exposure.

The Lower Sedimentary Sequence corresponds to the Late Oligocene San Gregorio Formation of the authors. It represents the infilling of a deep, anoxic basin quickly subsiding and supplied from nearby shoals where phosphatization occurred. The sequence is strongly deformed showing NE-SW blind thrusts and N-S normal

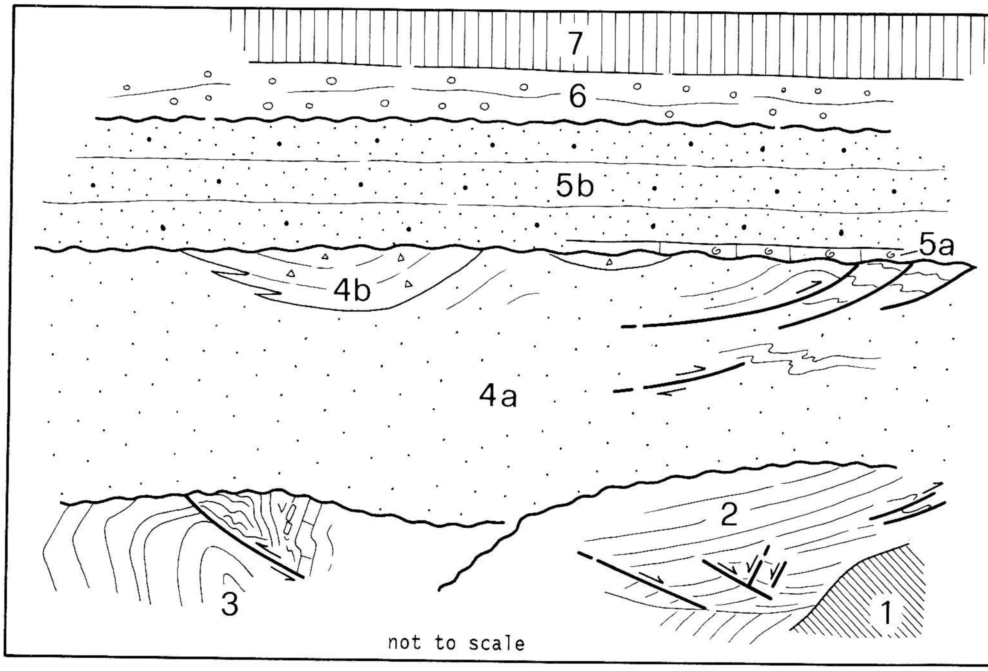

Fig. 12 - Tentative tectono-stratigraphic scheme of the La Purisima area. 1) Andesitic lava flow at the bottom of the Lower Sedimentary Sequence; 2) Lower Sedimentary Sequence; 3) Coquinoid Limestone; 4) fossiliferous beds (a) and volcaniclastic sandstones (b) of the Middle Sedimentary Sequence; 5) bioclastic sandstones (a) and alluvial sandstones (b) of the Upper Sedimentary Sequence; 6) post-Comondù alluvial deposits; 7) capping lava flows of the Mesas.

faults, both moving in still soft sediments. Such an association of structures can be related to wrench tectonics probably in connection with oblique convergence along the Pacific margin. The environmental meaning of the sequence and the observed tectonic structures are consistent with deposition in pull-apart basin.

The Coquinoid Limestone and the associated volcaniclastics indicate the beginning of shallow shelf conditions influenced by local strong volcanic supply, possibly linked to the "Comondù-related" arc. The individuality of this unit, already considered, is further supported by its tectonic features. In fact, the N-S trending folds indicate a possible change of the stress field in the region. The lack of physical continuity with the underlying unit is the unique reason why we abstain from esplicitly propose the considered body as a fully distinct sedimentary sequence. On the basis of the stratigraphic position, an earliest Miocene age can be inferred.

The Middle Sedimentary Sequence corresponds to the Isidro Formation of the authors and is here intended to include the interfingering sandstones of the Comondù Formation as well. In our opinion, the name Comondù strictly applies to those volcaniclastic sandstones that represent the westernmost progradational lobes of the alluvial fans linked to the erosion of the Miocene andesitic volcanic arc developed in the area presently occupied by the Gulf of California (Hausback, 1984; Sawlan & Smith, 1984). The sedimentary features and the fossil contents of the Isidro Formation suggest definitely shallow, tidal-influenced and beach environments. The volcaniclastic sandstones of the uppermost part enhance the regressive trend of the sequence. The Middle Sedimentary Sequence, on the basis of the K-Ar dates (Hausback, 1984: McLean et al., 1987) and the encountered fossils results to be of Early-Middle Miocene age. The basal part can be Early Miocene or early Middle Miocene in age according to places; the topmost part should be Upper "Temblor" (Serravallian in terms of Mediterranean stage ages). The Middle Sedimentary Sequence is bounded by angular unconformities, clearly observable in the La Purisima area. The tectonic structures observed in the sequence are generally due to a N-S compression and are here interpreted as related to the activation of a NW-SE dextral strike-slip fault zone.

The Upper Sedimentary Sequence basically corresponds to the mid-upper part of the Comondù Formation as intended by Hausback (1984). It starts with a short-lasting transgressive event, and quickly evolves toward debris flow dominated alluvial deposits. The angular unconformity at the base of the sequence makes unreliable the assignment of this lithosome to the Comondù Formation. In fact, a given formation cannot be based on lithosomes having an unconformity accompanied by an erosional truncation in between. Accordingly, a new lithostratigraphic definition is to be proposed for this sequence. It is of note that also younger terrace deposits have been uncorrectly included into the Comondù Formation (McLean et al., 1987). K-Ar ages of immediately underlying and overlying lava flows are 14.5 and 7-8 Ma respectively and establish the age of this sequence as late Middle Miocene to early Late Miocene.

In the tectono-stratigraphic framework here proposed, we enhance the importance of the unconformities bounding the recognized sedimentary sequences as related to regional geodynamical events. The lowermost unconformity occurs between Late Oligocene and Early Miocene and can be related with the Late Oligocene plate reorganization culminating at about 25 Ma and causing the inception of oblique convergence between the North-American and Guadalupe Plates (Fig. 6a). This event was responsible for the end of deep marine conditions along the present western coast of the Baja California Peninsula.

The upper unconformity is well time constrained in the Late Middle Miocene prior to 14 Ma, and is coincident with the activation of the NW-SE Tosco-Abreojos dextral transform fault, indicating a change from active to transform plate boundary along the North-American Plate. This permits to anticipate the inception age of the Tosco-Abreojos Fault Zone as previously proposed by Yeats & Haq (1981) (Fig. 6).

In conclusion, the tectono-sedimentary scenario reconstructed for the La Purisima region is consistent with a predominant wrench regime controlling the evolution of the study area from Late Oligocene to Middle Miocene at least, as already recognized in the Californian Continental Borderland (cf. Howell et al., 1980).

APPENDIX

Anadara (Anadara) topangaensis. Two shells and 36 loose valves are in hand; the material is variously preserved, but all features are observable. The specimens conform to the figures and the description given by Moore (1983). According to this author, *Anadara topangaensis* is a Miocene species recovered from Alaska, southern California and Baja California Norte. Californian occurrences are from the Topanga and Rosarito Beach formations. The Topanga Formation was reported to be largely of Relizian age by Ingle & Barron (1978); according to Berggren et al. (1985), the Relizian stage spans from 17.5 to 16.5 Ma, thus being correlative of early Middle Miocene. The Rosarito Beach Formation was assigned a Middle Miocene (Temblor) age too, mainly on the basis of the marine mollusc fauna (Minch et al., 1970).

Aequipecten plurinominis (Pl. 41, fig. 1). *Aequipecten plurinominis* occurs commonly in the Early and Middle Miocene deposits of the Caribbean Region (Mongin, 1968), in the Mid-Miocene Agueguexquite Formation of Mexico (Perrilliat, 1976) and Progreso Formation of Ecuador (Marks, 1951). It is of note that Duque-Caro (1990) has reported the latter formation as well as the Gatun Formation of Panama (several occurrences from the lower and middle parts) as being of Early Pliocene age.

Lyropecten pretiosus (Pl. 41, fig. 2). *Lyropecten pretiosus* is reported to be a Miocene species, ranging from Southern California to Baja California Sur; it occurs in the Temblor "Horizon" and is common in the Isidro Formation (Moore, 1984). According to Addicott (1977), the Temblor stage correlates with the late Early Miocene-Middle Miocene time interval.

Amussiopecten vanvlecki (Pl. 41, fig. 3). The species is distributed from Southern California to Baja California Sur and ranges in age from Oligocene to Miocene (Moore, 1984). The latest known occurrence is from the Saltos Shale Member of the Monterey Formation (Barker's Ranch fauna) which is referable to the late Early Miocene-Middle Miocene Temblor stage (Addicott et al., 1978).

Spondylus scotti. The species was based on shell material from La Boca Formation of Panama that was currently assigned an Early Miocene age (Woodring, 1982); however, it is not unlikely that the formation is younger, possibly Middle or Late Miocene in age. Smith (1984) reported on the occurrence of *Spondylus scotti* in the Isidro Formation and regarded it as an index species.

Hyotissa haitensis (Pl. 41, fig. 4). The species is widely distributed throughout the Caribbean region, and ranges in age from Late Oligocene to Pleistocene (Woodring, 1982). Records from Ecuador and Peru refer to the Daule and Montera Formations respectively, which were assigned a latest Miocene-Early Pliocene age (Duque-Caro, 1990). *Ostrea wiedeyi* Hertlein, recovered from the Late Oligocene-Early Miocene Vaqueros Formation, quite possibly is a synonym of *Hyotissa haitensis.* If so, the Pacific range of *Hyotissa haitensis* would extend northward to Southern California. It is of note that *Hyotissa haitensis* has been quoted by Smith (1984) from the Isidro Formation.

Ostrea vespertina (Pl. 41, fig. 5). Five variously preserved specimens are in hand; the largest, complete shell strongly resembles those from the Paso Robles Formation figured by Addicott & Galehouse (1973) and referred to as *Ostrea vespertina* Conrad. According to Moore (1987), the species is distributed from middle California to Mexico, and ranges from Miocene to Pliocene. The earliest occurrence is from the Santa Margarita Formation which represents the lower part of the Late Miocene (Addicott, 1977). The present record from the Isidro Formation of Baja California Sur predates the first appearance of the species to Mid-Miocene prior to 14.5 Ma.

Ostrea (Ostrea) sp. The small specimens in hand do not match the characters of any Californian ostreid dealt with in the extensive report by Moore (1987). Instead, they appear to be strictly related to *Ostrea wiedenmayeri* Hodson, described from Venezuelan deposits originally regarded as of Oligocene age, but quite possibly younger (Early or Middle Miocene). In fact, the left attached valve has basically the same shape, and bears numerous, closely spaced radial riblets such as that species. It is not unlikely that the present material belongs to Hodson's taxon, but a decision in this respect must await the direct comparison of relevant specimens.

Parvilucina (Parvilucina) approximata. The species is distributed from southern California to Baja California Sur, and ranges in age from Miocene to Holocene; the modern representatives occur intertidally and down to depths exceeding 1000 m, from middle California to Panama (Moore, 1988). It is of note that the oldest record refers to the Middle Miocene Comondù Formation of Baja California.

Miltha (Miltha) sanctaecrucis. The species has been recorded from middle and southern California (Moore, 1988); Smith (1984) listed *Lucinoma* cf. *sanctaecrucis* from the Tortugas Formation of Baja California Sur. The age range spans from Oligocene to Pleistocene; the lowest stratigraphic occurrence is from the basal part of the Temblor Formation.

Dosinia (Dosinia) whitneyi. The specimen in hand perfectly conforms to the figures of Gabb's species given by Moore (1963), Addicott (1973), and Moore & Addicott (1987). In California, *Dosinia whitneyi* ranges from Late Oligocene to Middle Miocene.

Chione (Chionopsis) richtofeni. The available specimens are more or less damaged, but the diagnostic characters are observable. They fully agree with the figure and description of the holotype (Hertlein & Jordan, 1927; Smith, 1984). The species was recorded from the Isidro and San Ignacio formations of Baja California Sur. In northern Baja California and northward, it is replaced by the closely related *Chione (Chionopsis) temblorensis* (Anderson), reported to range from late Early Miocene to Middle Miocene (Addicott, 1965; Minch et al., 1970).

Turritella altilira. One fragment of the spire, poorly preserved. It is assigned to Conrad's species on account of the two strong, noded primary spirals, the adapical one unequally doubled. *Turritella altilira* was recorded from Peru, Ecuador, Panama, continental Mexico, and resulted to have an Early Miocene to Pliocene range. The more precise correlation of the units in the northwestern corner of South America (Duque Caro, 1990) points toward a first appearance of the species not earlier than the Middle Miocene. Worthy of note is the record of *Turritella* aff. *altilira* from the Isidro Formation (Smith, 1984).

Turritella ocoyana. The species occurs from middle California to Baja California Sur; Perrilliat (1987) recorded it from the Middle Miocene Ferrotepec Formation of West Mexico. *Turritella ocoyana* was currently regarded as an index species of the Temblor Stage (Adegoke, 1969) which is correlative with the latest Early Miocene-Middle Miocene time span (Addicott, 1977). It is of note that *Turritella ocoyana* has a middle-upper Temblor range in the Kern River area (Addicott, 1965).

Turritella bicarina (Pl. 41, fig.6). Two defective specimens which compare satisfactorily to the plesiotype of *Turritella inezana bicarina* from Purisima Vieja, illustrated by Loel & Corey (1932, pl. 59, fig. 5) and Merriam (1942, pl. 25, fig. 12). The species is reported to occur from middle California to Baja California Sur, and is currently assigned a Vaqueros age (Late Oligocene-Early Miocene). Smith (1984) listed *Turritella* aff. *bicarina* from the Middle Miocene San Ignacio Formation: this, quite possibly, is the same form.

Turritella sp. One fragment of the spire that bears a quite superficial resemblance to the Peruvian *Turritella abrupta* Spieker.

Rapana imperialis. This distinctive species ranges from southern California to Baja California Sur; Smith (1984) recorded it from the Isidro Formation. Californian records refer to the Vaqueros Stage.

Vaquerosella andersoni. Several variously preserved specimens that conform to the illustrations of Twitchell's species given by Loel & Corey (1932) and Addicott (1972). *Vaquerosella andersoni* was reported to have a Vaqueros to Temblor range, i.e. Early to Middle Miocene. The last occurrence seems to be from the Buttonbed Sand Member of the Temblor Formation which was assigned a Relizian age (Addicott, 1972), correlative of the early Middle Miocene (Berggren et al., 1985).

Vaquerosella fairbanksi santanensis (Pl. 41, fig. 7). The subspecies resulted so far to be confined to the Vaqueros Stage of southern California; it is commonly associated with *Rapana imperialis.*

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PLATE 41

Fig. 1 - *Aequipecten plurinominis* (Pilsbry & Johnson, 1917). Length 26.0 mm (preserved part). Pump House (Site L 35), LO3/50.

Fig. 2 - *Lyropecten pretiosus* (Hertlein, 1925). Length 39.5 mm. San Isidro Section, LO3/55.

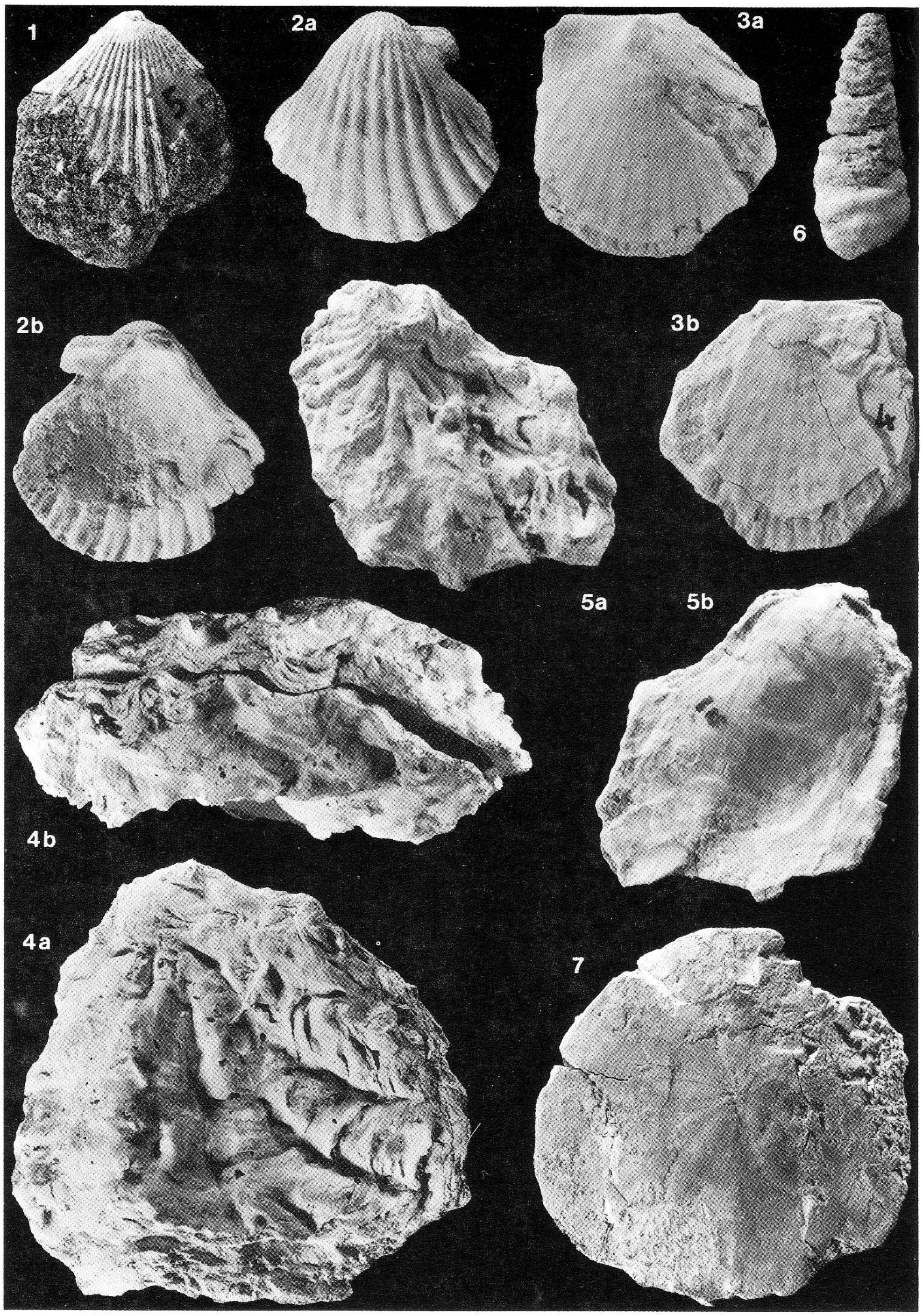
Fig. 3 - *Amussiopecten vanvlecki* (Arnold, 1907). Length 41.5 mm. San Isidro Section, LO3/55.

Fig. 4 - *Hyotissa haitensis* (Sowerby, 1950). Length 111.5 mm. San Isidro Section, LO3/53.

Fig. 5 - *Ostrea vespertina* (Conrad, 1854). Length 42.5 mm. San Isidro Section, LO3/54.

Fig. 6 - *Turritella bicarina* Loel & Corey, 1932. Height 35.0 mm. San Isidro Section, LO3/54.

Fig. 7 - *Vaquerosella fairbanksi santanensis* (Kew, 1920). Antero-posterior diameter 76.0 mm. Pump House (Site L35), LO3/50.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