STRATIGRAPHY, DEPOSITIONAL ENVIRONMENTS AND FORAMINIFERA OF THE MIOCENE TORTUGAS FORMATION, BAJA CALIFORNIA SUR, MEXICO

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RESUMEN

La Formación Tortuga (Mioceno Inferior a Superior) se encuentra expuesta ampliamente en la parte noroccidental de la Península de Vizcaino, Baja California Sur, México. Esta formación contiene un registro claro de la evolución de una cuenca localizada en el extremo austral de la provincia fisiográfica conocida como "Continental Borderland". Los sedimentos diatomáceos de esta formación se asemejan en muchos aspectos a la "Lutita Monterey" de la Alta California, con la cual se correlacionan.

El estudio integrado del contenido de foraminíferos y diatomeas, así como de las características sedimentológicas de una sección de la Formación Tortugas de 400 m de espesor, que se encuentra en un bloque afallado localizado al este de Punta Quebrada, ha permitido la subdivisión de esta unidad en cuatro miembros diferentes, cada uno de los cuales refleja cambios en paleobatimetría, ambientes de depósito y eventos climáticos y/o tectónicos. El miembro 1 (estratigráficamente el más bajo) abarca del Mioceno Inferior al Medio (Saucesiano) y consiste en 60 m de lodolitas limosas que contienen foraminíferos de ambiente batial medio. El miembro 2 está compuesto por 65 m de areniscas espículas intercaladas con arenas tobáceas y lodolitas limosas que representan depósitos de un abanico submarino durante parte del Mioceno Medio (Reliziano y Luisiano), así como erosión de los sedimentos previamente depositados en el fondo de la cuenca; este miembro también refleja la presencia de actividad volcánica y una disminución en la profundidad de la cuenca en ese tiempo. Los miembros 3 y 4 fueron depositados durante la parte superior del Mioceno Medio y la parte inferior del Mioceno Superior (Mohniano inferior) estos miembros están compuestos por 300 m de porcelanitas (muy abundantes en los 50 m inferiores) que alternan con lodolitas diatomáceas, representando sedimentación en una cuenca sellada, anóxica, en un ambiente batial superior.

El estudio de una sección de la misma formación, localizada hacia el este de la pista aérea de Bahía Tortugas, ha permitido el dividir a esta secuencia en dos miembros. El miembro basal (A) está compuesto por 45 m de areniscas líticas que contienen pellas de fosforita y moluscos fósiles de edad Mioceno Temprano a Medio (Saucesiano Superior a Realiziano), y que representan una facies de sedimentación nerítica que es contemporánea con la parte superior del miembro 1 y el miembro 2, los cuales representan condiciones batiales en la sección de Punta Quebrada. El miembro B consiste en 95 m de lutitas diatomáceas y limosas que contienen foraminíferos que indican un ambiente de depósito en una cuenca sellada, anóxica, semejante a la que se reconoce en los miembros 3 y 4 de la sección de Punta Quebrada.

En resumen, se reconocen tres etapas en la evolución geológica de la cuenca Tortugas: 1) Subsistencia rápida durante el Mioceno Temprano (Saucesiano) que llevó al área de un

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régimen de erosión subaérea hasta profundidades de ambiente batial medio con una acumulación lenta de sedimentos; 2) Levantamiento durante el Mioceno Medio (Reliziano—Luisiano) que originó el depósito de turbiditas en las partes profundas de la cuenca; 3) Hundimiento renovado con velocidades de subsidencia y sedimentación esencialmente iguales durante la parte temprana del Mioceno Tardío (Mohniano); estas condiciones dieron como resultado el depósito de sedimentos finos en un ambiente batial superior caracterizado por una deficiencia de oxígeno en el agua.

La secuencia depositada en la cuenca Tortugas fue levantada tectónicamente durante el intervalo Mioceno—Plioceno. La deformación estructural del área se continuó durante el Pleistoceno.

ABSTRACT

The Lower through Upper Miocene Tortugas Formation is widely exposed on the Vizcaino Peninsula of Baja California Sur, Mexico, and provides a clear record of the evolution of a southern continental borderland basin. The diatomaceous sediments of this formation are similar in many respects to the correlative Miocene Monterey Shale of Alta California.

The integrated study of foraminifera, diatoms, and sedimentologic characteristics through a 400 m thick section of the Tortugas Formation located in a faulted block east of Punta Quebrada, has allowed this unit to be subdivided into four members reflecting variations in paleobathymetry, depositional environments, and tectonic and/or climatic events. The lowermost member 1 consists of 60 m of Lower to Middle Miocene (Saucesian) silty mudstones containing middle bathyal foraminifera. Member 2 is composed of 65 m of interbedded spicular sandstones, tuffaceous sands, and silty mudstones, representing submarine fan deposition and erosion of previously deposited sediments on the basin floor during Middle Miocene time (Relizian—Luisian). Member 2 also reflects the presence of volcanic activity and an uplift event during that period. Members 3 and 4 are composed of 300 m of alternating porcellanites (mainly found in the lower 50 m) and diatomaceous mudstones representing deposition in an anoxic, middle bathyal, silled basin during late Middle and early Late Miocene (Mohnian) time.

Study of a second section through the Tortugas Formation located east of the airfield at Bahia Tortugas allowed the division of this sequence into 2 members. The basal member A consists of 45 m of lithic sandstones containing pelletal phosphorite and neritic mollusks of Early to Middle Miocene age (upper Saucesian to Relizian?) and representing a neritic facies correlative with the upper part of member 1 and with member 2 representing bathyal conditions in the Punta Quebrada section to the north. Member B consists of 95 m of silty, diatomaceous shales containing foraminifera indicative of a silled anoxic basin environment similar to the environment recognized in members 3 and 4 of the Punta Quebrada section.

In summary, three stages in the geologic evolution of the Tortugas basin are recognized: 1) Early Miocene (late Saucesian) rapid subsidence from subaerial to a middle bathyal depth of a low rate of sediment accumulation; 2) A Middle Miocene (Relizian—Luisian) uplifting event that triggered deposition of turbidites in the deeper part of the basin, and 3) Renewed subsidence and equal rate of sedimentation in the Late Miocene (early Mohnian) resulted in a low oxygen environment at upper bathyal depths.

Uplift of the Tortugas basin sequence occurred during the Miocene—Pliocene interval with further structural deformation of this area during Pleistocene time.

INTRODUCTION

Neogene rocks of the Baja California Peninsula are dominated by Miocene volcanic units commonly

included in the Comondú Formation (Beal, 1948; Gastil and Lillegraven, 1974). Alternately, Neogene marine units are limited in distribution and thickness, Allison, (1964). Taken together, these rocks

contain a little studied record of the later development of the Baja California Peninsula and adjacent Pacific margin and Gulf of California. Significantly, Miocene marine rocks have been reported mainly from the western half of the Peninsula and assigned to the San Gregorio, Isidro, San Ignacio, Monterey Superior and Inferior, Tortugas, and Rosarito Beach Formations (Beal, 1948; Mina, 1946; Allison, 1964; Minch, 1970; Minch *et al.*, 1976; Lozano, 1975). Although the relationships between these various units are unclear in detail, they have a general similarity in age range and lithologic character with various portions of the Monterey Shale, Rincon Shale, and Vaqueros Formation of Alta California and contain a similarly valuable but little known record of Pacific borderland history. This report focuses on the depositional history of

the Lower through Upper Miocene Tortugas Formation of the Vizcaino Peninsula (Fig. 1).

Miocene rocks assigned to the Tortugas Formation are widely exposed in the western side of the Vizcaino Peninsula, Robinson (1975) and in Cedros Island, Kilmer (1969). The Tortugas rocks studied for this report crop out in an area immediately north of Bahia Tortugas (Fig. 1). This stratigraphic unit represents an uplifted portion of bathyal diatomaceous sediments deposited in a subsiding Neogene basin located along the southern margin of the Southern California Continental Borderland Province, Blake *et al.* (1978).

The two sections studied were displaced by post-Miocene faulting. This action brought these sequences closer together relative to their original locations.

Fig. 1. Location and geology of the Bahia Tortugas area, Baja California Sur, Mexico (geology by J. Helenes, 1979).

The strata of the Tortugas Formation are Early to Late Miocene in age, and resemble the well known Monterey Shale of California and similar deposits around the Pacific margin. The similarity in lithology, age, and depositional history of these deposits suggests a similar origin, in turn implying regionally widespread Miocene tectonic, paleoceanographic, and paleoclimatic events, Ingle (1973).

OBJECTIVE AND METHODS

The purpose of this report is to describe the lithology and fossil content of the Miocene Tortugas Formation exposed at two localities of the Bahia Tortugas area (Fig. 1) in order to define the age and depositional history of this important unit. A firm correlation of these strata with regional tectonic and sedimentological events is proposed for at least one of the sections.

In order to achieve these objectives, a reconnaissance geologic map of the area was prepared and two key sections through the Tortugas Formation were measured and sampled (Fig. 1). Samples were collected at irregular intervals with regard for changes in microfossil content and preservation, as well as lithologic characteristics.

Lithologic variations through the Tortugas Formation were determined on the basis of field observations together with limited petrographic descriptions in the laboratory.

Emphasis in the study is placed on quantitative analysis of fossil foraminifera within the Tortugas Formation. Samples were mechanically broken and then boiled in water with Quaternary-O. Washed samples were sieved using a No. 230 mesh (opening in mm = 0.063) screen to eliminate silt and clay sized material. The remaining coarse fractions were then scrutinized for foraminifera. Generally, 250 or more specimens of fossil foraminifera were randomly picked from 32 of the prepared samples found to contain these microfossils. However, due to the low numbers of foraminifera in some of the samples, the mean number of specimens picked is 192.

Approximate boundaries between the various paleoenvironments identified in this report represent the top or the base of important water mass boundaries commonly impinging along continental margins, including the surface layer and the oxygen minimum layer, Ingle (1975). Thus, the assignment of species to an environment or biofacies implies

an approximate depth range. The depth ranges indicated by the use of qualitative environmental designations are the following: Upper Neritic, 10–50 m; Lower Neritic, 50–150 m; Upper Bathyal, 150–500 m; Middle Bathyal, 500–2000 m; Lower Bathyal, 2000–4000 m.

A paleobathymetric curve was constructed (Fig. 5) using the deepest dwelling forms present in each sample, yielding a minimum depth of deposition (Ingle, in press) for each portion of the Tortugas Formation exposed at Punta Quebrada.

PREVIOUS WORK

The earliest references to Miocene rocks in the Bahia Tortugas area are those by Hanna (1926) who described thick deposits of "light, gray-colored shales" overlying "a sandy layer in which we found numerous shark teeth, some sea lion teeth and pectens". He correlated these layers with the Upper Miocene of Kern County, California. Jordan and Hertlein (1926) also described Miocene strata in the Bahia Tortugas area "which are several hundred feet thick. The base of the Miocene is a layer containing bones and shark's teeth". The rest of the series was reported to be composed of white siliceous shale and soft fine grained sandstone, ashes and impure diatomite. Later, Hertlein and Jordan (1927) described several localities of Miocene exposures near Bahia Tortugas, and assigned these rocks to the Middle Miocene (Temblor stage) on the basis of mollusks and shark teeth.

In 1933, Hertlein collected a diatomite in the northern end of Bahia Tortugas bay, and according to Dr. G. D. Hana's identification of the diatoms, the sample was placed in the Upper Miocene.

The Tortugas Formation as such, was first named by Mina, (1956) for the Miocene rocks exposed about three kilometers north of Bahia Tortugas (Locality 9 in Fig. 1). He assigned to this unit a Middle to Upper Miocene age on the basis of questionable faunal content.

In 1960, Durham and Allison mentioned diatomaceous and tuffaceous rocks of the Tortugas Formation that contain Middle Miocene foraminifera and gastropods. In addition, Allison (1964) described the Tortugas Formation as composed of cherts and diatomaceous rocks, and assigned the unit to the Middle Miocene Luisian stage of Kleinpell (1938).

A masters thesis by Robinson (1975) provides the most comprehensive account of the Tortugas Formation to date. He correlates this unit with similar exposures near Asuncion (Fig. 1), with rocks from the Bahia San Cristobal area (in between Bahia Tortugas and Asuncion) reported by G. Troughton (M.S. thesis, 1975), with Miocene shales exposed on Cedros Island, Kilmer (1969), and with a 2000 m thick submarine section composed of "Miocene and post-Miocene sediments" reported by Normark *et al.* (1969) and based on seismic reflection studies in an area located southwest of the Vizcaino Peninsula.

STRATIGRAPHY

Field work

The geologic map shown in Fig. 1 was prepared from aerial photographs (DETENAL, Mexico;

1:50,000), and by field reconnaissance of the units. One of the sections under study is located at approximately 2 Km north of the town of Bahía Tortugas, and 300 m east of the local airfield (Locality 9; Figs. 1 and 2), this section will be termed the Airfield Section in this report. Locations 1, 2, 3, 4, 7 and 8 (Fig. 1) east of Punta Quebrada are termed the Punta Quebrada Section. This last section can be traversed from the lower to the upper contact by walking west of Loc. 3, but in order to construct a column, a number of short sections in different localities within this area were chosen with regard for better fossil content, clarity of exposures of the strata, and ease of measurement of the sections (Figs. 1, and 2).

Regional geology

Both Mesozoic and Cenozoic sedimentary rocks crop out in the Bahia Tortugas area (Fig. 1, map C) along with a basement complex of Triassic to Early

Fig. 2. Stratigraphic columns through the Miocene Tortugas Formation, Bahia Tortugas Airfield and Punta Quebrada sections.

Jurassic ophiolitic rocks. These basement rocks have yielded a potassium/argon date of 187 ± 1.4 m.y.b.p. (Robinson, op. cit.). The oldest sedimentary unit in the area is the Late Jurassic to Early Cretaceous Eugenia Formation, which is overlain unconformably by the lower and middle members of the Cretaceous Valle Formation. Paleogene rocks are unknown in the area, but the Neogene is amply represented by the Tortugas Formation (Early to Late Miocene), the Almejas Formation (Middle to Late Pliocene) and the marine terraces (Late Pliocene to Pleistocene).

According to Robinson (op. cit.), "the structural pattern of the area consists of large northwest-trending, right lateral slip faults with subordinate northeast-trending faults".

The Tortugas Formation unconformably overlies (low-angle, angular unconformity) the Cretaceous marine rocks of the Valle Formation at both the Punta Quebrada and the Airfield sections (Fig. 1). The upper part of the Tortugas Formation is in faulted contact with the Jurassic-Cretaceous Eugenia Formation in the Punta Quebrada area, whereas it is unconformably overlain by the Pliocene Almejas Formation or covered by alluvium elsewhere.

Lithostratigraphic units

Stratigraphic sections through the Tortugas Formation at both the Punta Quebrada and Airfield localities are presented in Fig. 2. The major lithologic changes in both sequences allow the subdivision of the formation into several members, these are (from bottom to top) as follows:

A) Punta Quebrada Section

Member 1. Rocks of this sub-unit comprise the basal portion of this section (Locality 1: samples 4–20). The lower contact of this member in this locality is defined by an angular unconformity separating the Tortugas Formation from the concretionary sandstones of the middle member of the Cretaceous Valle Formation.

Member 1 consists of approximately 54 m of mainly medium hard, greenish gray, light-gray weathering, medium to thin bedded, slightly siliceous, silty mudstone. Some layers are massive and contain yellow chert concretions whereas others are laminated. The strata contain sparse and small fragments of pelletal phosphorite and volcanic glass shards. In this member, as throughout the entire sequence, secondary layers of gypsum up to 15 cm

in thickness are locally abundant. The fossil content of the sub-unit includes foraminifera, fish scales, diatoms, sponge spicules, and statocysts of mysids; the abundance of sponge spicules increases toward the top of the unit.

The upper contact of the member is defined by the first appearance in the section of a sandy siltstone.

Member 2. This sub-unit was measured at localities 2, 3, and 4 (samples 21–31), and conformably overlies rocks assigned to member 1.

The resistant sandy strata of this sub-unit form ridges that stand out higher than the softer rocks of the adjacent units. These characteristic sediments consist of approximately 65 m of soft, massive, brown, weathering, sandy mudstones (~49 m) interbedded with hard, massive to well stratified (medium to thick bedded), greenish gray to tan weathering, silty, fine sandstones (~16 m) located mainly in the lower portion of the member. A white-gray horizon of volcanic ash, about 35 cm in thickness, and a bioturbated layer (2 m) of tuffaceous sandstone occur near the middle portion of this sub-unit. The sandstones of member 2 are composed of sponge spicules (20–40 %), quartz (~20 %), minor amounts (<5 %) of pelletal phosphorite and a clayey to silty matrix (~20 %). The mineral grains are mainly sub-angular. The fossil content includes sponge spicules (tri-tetrahedral), foraminifera, statocysts of mysids, fish scales, shark's teeth and vertebrae, marine mammalian bones, and molds of diatoms, ostracods and pelecypods.

The upper contact of this member is defined by the first appearance of a hard, tan to gray porcellanite.

Member 3. This sub-unit (Locality 4: samples 32–42) conformably overlies member 2.

Member 3 consists of approximately 75 m of alternating hard, tan to gray, medium to thin bedded porcellanite and medium soft, brown-gray, massive mudstone. The mudstone varies from massive silty mudstone to laminated diatomaceous mudstone with the abundance of diatoms increasing toward the top of the unit. A 30 cm thick layer of white-gray volcanic ash is present in member 3 (sample 27). The fossil content includes diatoms, foraminifera, statocysts of mysids and sponge spicules. The porcellanite layers contain rare molds of pelecypods.

The upper limit of member 3 is defined by the

first appearance of a white, laminated diatomite in the section.

Member 4. The sub-unit includes the youngest Miocene marine strata exposed in the Punta Quebrada area (Locality 7, 8; samples 43–58) and conformably overlies member 3.

Member 4 consists of at least 213 m of soft, massive, brown weathering, diatomaceous silty mudstone containing individual cyclic sequences of soft, white, laminated diatomite and hard, tan, thin to medium bedded porcellanite. This sub-unit also contains one prominent 60 cm thick, white-gray layer of volcanic ash along with some other, thinner, ash horizons. One 35 cm thick layer of friable, yellowish, lithic sand is present whereas yellowish weathering chert nodules are scattered throughout the unit. The fossil content includes diatoms, foraminifera, radiolarians, statocysts of mysids, fish scales, sponge spicules and ostracods.

The uppermost portion of this sub-unit is structurally complex due to the activity of an adjacent fault (Fig. 1), hence the total thickness could not be determined. However, 30 to 40 m may be a reasonable estimate of the stratigraphic thickness missing between the last measured point (Loc. 7; sample 58 = Loc. 8; sample 70) and the upper contact of member 4 with the Jurassic–Cretaceous Eugenia Formation.

B) Airfield Section

Member A. Exposures of this member are restricted to the area adjacent to the Airfield Section (Locality 9; samples 29, 73–79). The lower contact of this member is defined by an angular unconformity with the underlying sandstones of the Cretaceous Valle Formation (~5°).

The rocks of member A have a yellow-gray color on fresh surfaces which weathers to brown. The sub-unit has an approximate thickness of 45 m and consists of alternating hard, medium bedded strata (~5 m) and soft, massive layers (~40 m) of silty, fine to medium grained, lithic sandstones indurated by a calcareous cement (40–60 %/o). The detrital fraction consists of subangular to subrounded grains of metaquartz (~35 %/o), quartz (~30 %/o), feldspars (~20 %/o) and variable amounts of pelletal phosphorite (1–30 %/o). Nuclei of the pellets are composed of quartz and metaquartz. Fossils present include silicified shells of gastropods and pelecypods, as well as spines of echinoderms.

At locality 9, member A is conformably overlain by strata assigned to member B. The contact between these two members, is defined by the change from brown weathering sandstone to greenish-gray, siliceous slightly arenaceous mudstones.

Member B. This member overlies conformably the strata of member A. During the field work pertinent to this project the rocks of member B were not systematically sampled nor its thickness determined, but Robinson (op. cit.) reports a thickness of approximately 95 m.

Spot samples collected from the lowermost strata of member B indicate that it is composed mainly of light gray weathering, greenish-gray, medium hard, medium to thin bedded, silty, siliceous mudstone, which is sandy near the contact with the member A. Lenses and horizons of yellow to gray porcellanite are interbedded with the siliceous mudstones.

The upper part of member B is generally covered by alluvium or unconformably overlain by the Pliocene Almejas Formation.

Based on the stratigraphic position of member B, it is tentatively correlated with the middle part of the Punta Quebrada Section (member 3, 4?); this correlation is also suggested by the presence of the benthonic foraminiferal species *Globobulimina montereyana* (Kleinpell) in at least one of the samples taken from member B.

BIOSTRATIGRAPHY AND AGE

LOCAL FORAMINIFERAL ZONES

The quantitative study of the benthonic foraminifera contained in the rocks of the Punta Quebrada section, allows the subdivision of this section into five local zones (Fig. 3). From bottom to top of the section, the proposed zones are:

A) *Rectuvigerina* ("Siphogenerina") *mayi* Zone

The base of this zone is marked by the presence of: *Rectuvigerina mayi* (Cushman and Parker), *Plectofrondicularia miocenica* Cushman, *Buliminella californica* Cushman, and *Valvulinaria casitasensis* Cushman and Laming. The first three species are found throughout the entire zone, while *V. casitasensis* is only found in the lower part of it (samples 4–12).

The top of this zone is defined by the last occurrence in the section of the following species: *R. mayi* (Cushman and Parker), *P. miocenica* Cushman and Parker.

Fig. 3. Stratigraphic ranges of selected benthonic foraminifera, and selected diatom species in the Punta Quebrada section of the Miocene Tortugas Formation.

man, *Buliminella californica* Cushman, *Bolivina floridana* Cushman, and *Planularia luciana* Kleinpell.

The following species range within the limits of the zone, and occasionally are abundant (>10 %): *Fursenkoina californiensis* (Cushman), *Buliminella subfusiformis* Cushman, *Bolivina obliqua* Barbat and Johnson, and *Bolivina californica* Cushman. In the upper part of the zone, the following species are common: *Planularia luciana* Kleinpell, *B. floridana* Cushman, and *Uvigerinella californica* (Cushman).

Finally, the following species are common and even abundant in this zone, but they range into overlying strata: *Bolivina marginata* Cushman, *Bulimina dubia* (Barbat and Johnson), *Nonion labradoricum* (Dawson), and *Cassidulina williamsi* Kleinpell.

B) *Cibicides floridanus* Zone

The base of this zone is marked by the first occurrence in the section of *Buccella* cf. *B. peruviana* (d'Orbigny). The top of this zone is defined by the last occurrence of the same species and of *Cibicides fletcheri* Galloway and Wissler.

This zone is characterized by the great abundance of the two aforementioned species and the presence of *Cibicides lobatulus* (Walker and Jacob), and *Cibicides floridanus* (Cushman).

C) *Bulimina uvigerinaformis* Zone

The bottom of this zone is defined as the first appearance in the section of: *Epistominella gyrodinaformis* (Cushman and Goudkoff), *Uvigerina segundoensis* Cushman and Galliher, and *Bulimina uvigerinaformis* Cushman and Kleinpell. The first two species are confined to the lower part of the

zone, but *B. uvigerinaformis* is also found in the upper part of it.

The top of this zone is marked by the last occurrences of the following species: *Globobulimina montereyana* (Kleinpell), *Bolivina directa* Cushman, *Bolivina granti* Rankin, and *Bolivina seminuda foraminata* R.E. and K.C. Stewart.

The upper part of this zone is characterized by the high abundance of species indicative of low oxygen conditions, such as: *Suggrunda kleinpelli* Bramlette, *Bolivina seminuda* Cushman, and *Globobulimina ovula pedrouna* (Kleinpell). *Florilus mediocostatus* (Cushman) appears for the first time in the upper part of the zone becoming abundant higher in the section.

D) *Bolivina girardensis* Zone

The base of this zone is marked by the first occurrence in the section of: *Bolivina girardensis* Rankin, *Bolivina imbricata* Cushman, and *Bolivina rankini* Kleinpell. The top of this zone has not been yet defined due to the lack of foraminiferal evidence in the uppermost strata of the section. However, the first appearance in the higher portions of the section of *Bulimina delreyensis* Cushman and Galliher, and *Valvulineria ornata* Cushman mark the upper part of this zone.

This zone is also characterized by the abundance of specimens assigned to the species *Valvulineria miocenica* Cushman, and *Florilus mediocostatus* (Cushman), although they also range down into the underlying zone.

DIATOM ZONES

The study of the abundant diatom flora contained in the upper strata (members 3, 4) of the Punta Quebrada section (Fig. 3) served as a basis for the correlation with estimated radiometric ages (Fig. 4). The diatom zonation utilized in this report, as well as the estimated radiometric ages assigned to the datum surfaces are those proposed by barron (in press).

The concurrent presence of *Denticula lauta*, *D. hustedtii* (abundant), *Coscinodiscus plicatus*, and *C. endoi* throughout both members, indicate that this part of the section is included into the *Denticula hustedtii/Denticula lauta* Zone, which is correlated with a late Middle to early Late Miocene age. The age assignment of the members is further supported by the ubiquitous presence of *Denticula punctata hustedtii* and *Actinocyclus ingens*.

The base of member 3 is correlated with the bottom of subzone B (Fig. 4) on the basis of the first occurrence of *Denticula praedimorpha*, and the concurrent last appearance of *Denticula nicobarica* (Fig. 3). The concurrent presence of these two species, has been dated as old as 13 Ma (Middle Miocene), and in this section it is located just below sample Num. 32 and above sample Num. 31.

The base of Subzone C, which is defined by the first appearance of *Rhizosolenia barboi*, and coincides closely with the last occurrence of *Mediaria splendida* (Fig. 4), has not been located positively in the section, but is believed to be placed in between samples Num. 43 and 37. Due to this uncertainty, this datum was not utilized in the calculations of the rates of sediment accumulation and subsidence of the basin.

The base of Subzone D (Fig. 4) is marked by the first appearance of *Denticula dimorpha* s. str. after the occurrence of *Denticula praedimorpha*. This subzone is also characterized by the presence of *Thalassionoema hirosakiensis*, which appears for the first time in the upper part of this subzone. The base of this subzone has been assigned an age of 11.0 Ma (Barron, in press), marking the beginning of the Late Miocene. In the section it is located close to sample Num. 49.

The uppermost samples of the section contained both species, *Denticula hustedtii* (very abundant), and *Denticula dimorpha* s. str. (very rare), hence the rest of the section is encompassed within Subzone D, and correlated with the lowermost Late Miocene. The top of Subzone D is defined by the last occurrence of *Denticula dimorpha* s. str., and *Denticula lauta*, and has been assigned an age of 9.8 Ma. So the top of the section has a tentative age of at least 10.0 Ma.

REGIONAL CORRELATION

A) Punta Quebrada Section

According to the stratigraphic ranges of selected benthonic foraminifera (Fig. 3) as defined in California (Kleinpell, 1938; Bandy and Arnal, 1969), the lower part (member 1) of this section is correlated with the Saucian Stage (Fig. 2). This correlation is based mainly on the presence of *Rectuvigerina mayi*, and *Valvulineria casitasensis*.

Planktonic foraminifera found in this member are poorly preserved and exhibit low diversity, hence it has not been possible to utilize them for

AGE (Ma)	EPOCH	SERIES	DIATOM ZONES	KNOWN RANGES OF SELECTED DIATOM SPECIES	CALIFORNIA STAGES	NEOGENE ZONES
6			Denticula kantshatica		UPPER MOHNIAN	N-17
7			Denticula hustedtii			
8			Denticula hustedtii			
9						
10						
11			Denticula hustedtii		LOWER MOHNIAN	N-15
12			Denticula hustedtii			N-14
13			Denticula hustedtii			N-13
14			Denticula hustedtii			N-12
15			Denticula hustedtii			N-10-11
16			Denticula hustedtii			
17			Denticula hustedtii			
18			Denticula hustedtii			
19			Denticula hustedtii			
20			Denticula hustedtii			
21			Denticula hustedtii			
22			Denticula hustedtii			
23			Denticula hustedtii			
24			Denticula hustedtii			
25			Denticula hustedtii			
26			Denticula hustedtii			
27			Denticula hustedtii			
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99			Denticula hustedtii			
100			Denticula hustedtii			

Fig. 4. Absolute ages of the Miocene diatom zones (after Barron in press), and their correlation with California Stages (Kleinpell, 1938; Warren, 1972), and with standard Neogene planktonic foraminiferal zones (Blow, 1969; Berggren and van Couvering, 1974).

precise correlations with the standard Neogene Zones (Verggren and Van Couvering, 1974). However, it should be noted that the presence of *Catapsydrax* (?) cf. *C. dissimilis* and the high abundance of *Globigerina praebuloides* among the planktonic forms, suggests an Early to Middle Miocene age (Blow, 1969; Ingle, 1973).

Calcareous nannofossils within member 1 allow correlation (Milow, pers. comm., 1980) with the following Cenozoic nannofossil zones (Bukry, 1978): *Triquetrorhabdulus carinatus* Zone (samples Nums. 4-7), *Helicopontosphaera ampliaperta* Zone (samples Nums. 8-10), and *Sphenolithus heteromorphus* Zone to *Coccolithus miopelagicus* Subzone of the *Discoaster exilis* Zone (samples Nums. 11-20).

The estimated absolute ages (Roth, 1974) assigned to the limits of these zones indicate that the

lowermost 20 m of this section represent deposition during Early Miocene times (21 to 15 Ma), while the remainder of member 1 (samples Nums. 11-20) were deposited during the earliest Middle Miocene age (15.5 to 13.4 Ma).

Most of the strata of member 2 are tentatively correlated with the Relizian and Luisian stages of Kleinpell (op. cit.) on the basis of their stratigraphic position between well dated Saucanian and Mohnian faunas (Fig. 3). This equivalence is partially supported by the presence in the strata of member 2 of *Cibicides floridanus*, and *Bolivina tumida cuneata*.

The calcareous nannofossils in these strata indicate that the lower part of member 2 (samples Nums. 21-23) can be correlated (Milow, pers. comm.) with the interval *Catinaster coalitus* Zone to *Discoaster kugleri* Subzone of the *D. exilis*

Zone, Bukry (1978), which has an estimated minimum age Roth (1974) of 13.2 Ma (Middle Miocene). The upper part of member 2 (samples Num. 24-30) can be correlated with the interval *D. kugleri* Subzone of the *D. exilis* Zone to *D. hamatus* Zone, hence it is only possible to assign a Middle Miocene age to these strata.

The uppermost strata of member 2 and members 3 and 4 (Fig. 3) are assigned to the lower Mohnian stage of Kleinpell (op. cit.) based on the presence of *Bulimina uvigerinaformis*, *Epistominella gyroldinaformis*, *Bolivina girardensis*, and *Bulimina delreyensis*.

Calcareous nannofossils identified in the uppermost strata of member 2 and member 3 are correlated with the interval from *D. kugleri* Subzone of the *D. exilis* Zone to the *D. hamatus* Zone (Milow, pers. comm.); these zones are assigned a Middle Miocene age. This correlation is further supported by the assignment of sample Num. 32 to a Middle Miocene age on the basis of the radiolaria (Kling, pers. comm., 1980) contained in it (undifferentiated *Cannartus pettersoni* and *Dorcadospyris alata* Zones).

The species of calcareous nannoplankton contained in the strata of member 4, only allow the correlation of this member with the Middle Miocene to Pliocene interval.

Study of the planktonic diatoms (Fig. 3) contained in the strata of members 3 and 4 indicate correlation with the Subzones *B*, *C*, and *D* of the *Denticula hustedtii/Denticula lauta* Zone (Fig. 4) as proposed by Barron (in press). These subzones encompass an interval of at least 3 million years (from 13 to 10 Ma).

The correlation of sample Num. 43 with the Subzone *C* (Middle Miocene) and the assignment of a Late Miocene age to sample 49 (Subzone *D* of the *D. hustedtii/D. lauta* Zone), together with the correlation of samples Num. 48 and 54 with the *Ommatartus antepenultimus* Zone (Kling, pers. comm., 1980) of tropical Cenozoic radiolarians (Riedel and Sanfilippo, 1978) which indicates a Late Miocene age for the strata of member 4, allows the placement of the boundary between Middle and Late Miocene within samples Num. 43 (Middle) and 48 (Late) (Fig. 2).

B) Airfield Section

Although foraminifera have not been recovered to date from the lower member A, larger invertebrates are common and include the following spe-

cies indicative of a late Early to early Middle Miocene age (W.O. Addicott, pers. comm., 1979).

Turritella ocoyana Conrad

Turritella inezana Conrad

Leptopecten cf. *L. andersoni* (Arnold)

Nuculana sp. — fragments

Eucidaris sp. — spines

This fossil fauna allows the correlation of the lower 15 m of this member with the uppermost Vaqueros stage and the rest of the member with the Temblor stage of California, Weaver, *et al.* (1944). This megafaunal stages are equivalent to the upper Saucian to Luisian (Fig. 2) foraminiferal stages, Addicott (1972).

The siliceous mudstones of the overlying member B are tentatively assigned to the lower Mohnian stage (Fig. 2) of Kleinpell (op. cit.), on the basis of their stratigraphic position and the presence of the benthonic foraminifera *Nonionella miocenica*, and *Globobulimina montereyana*. The presence of these species of foraminifera suggests correlation with the *Bulimina uvigerinaformis* Zone of the Punta Quebrada section (Fig. 2). Further study of the faunas in these strata is necessary in order to establish a precise correlation.

BIOFACIES AND PALEOENVIRONMENTS

Quantitative analysis of foraminifera (Fig. 5) together with qualitative analysis of other fossil groups and sedimentologic characteristics of the Tortugas Formation have provided a basis for the interpretation of paleoenvironments represented within this unit. In general, the methods and criteria for biofacies assignments are those discussed by Bandy and Arnal (1960, 1961), and Ingle (1967, 1975, in press).

Slope biofacies

The slope biofacies is characterized by the relative abundance ($>10\%$) of the following species thought to characterize middle to lower bathyal environments:

Bolivina floridana Cushman

Bulimina carnerosensis Cushman and Kleinpell

Plectofrondicularia miocenica Cushman

Rectuvigerina mayi (Cushman and Parker)

Uvigerinella californica (Cushman)

Fig. 5. Paleobathymetry, benthonic foraminiferal biofacies, percentages of planktonic species, and percentages of species indicative of low oxygen environments (Ox. Min. spp.).

This biofacies is also characterized by the greater diversity of the benthonic fauna, as well as the higher percentages of planktonic foraminifera compared with shallower or deeper biofacies represented in the Tortugas Formation. This is the deepest biofacies recognized in the Tortugas Formation and is only found in member 1 of the Punta Quebrada section.

Bulimina carnerosensis, *Uvigerinella californica*, and *Plectofrondicularia miocenica* are particularly diagnostic of middle and lower bathyal environments based upon homeomorphy with Recent species characterizing these depths (Bandy, 1960; Bandy and Arnal, 1969). For example, *Bulimina carnerosensis* is morphologically similar to the modern species *Bulimina rostrata* commonly living in middle to lower bathyal environments (500–2000 m).

The thin bedded and laminated silty mudstones of member 1 containing this biofacies are also

compatible with a middle-to-lower slope or basin plain environment. Rare pelletal phosphorite in this unit, along with up to about 75 % of upper bathyal species also point towards downslope displacement of material. The laminated portions of member 1 may represent a response to lower oxygen conditions in the Miocene basin, but diagenetic changes in these beds obscures detail and has likely destroyed many siliceous tests and frustules previously present. Planktonic foraminiferal faunas present in these biofacies are dominated by *Globigerina*, representative of surface temperature as cool or cooler than those now prevailing at 28° N latitude, in the northeastern Pacific, in turn suggesting vigorous upwelling and productivity, resulting in a well developed oxygen minimum layer.

SUBMARINE FAN BIOFACIES

This biofacies is characterized by a high relative

abundance (60 ‰) of displaced neritic species of foraminifera, along with *in situ* species indicative of middle to lower bathyal environments (10 ‰). Hence, displaced faunas in this biofacies differ markedly from those indicative of slope environment in the slope biofacies. The mixed fauna in this submarine fan biofacies is interpreted to be the result of downslope displacement of the shelf-dwelling species into a bathyal environment.

Fossils found in the upper part of the strata containing this biofacies include shark's teeth and vertebrae, fragments of marine mammalian bones, and traces of megafossil burrowing (generally oblique to the stratification).

Species considered as neritic (Bandy and Arnal, 1969), include the following:

- Buccella* cf. *B. peruviana* (d'Orbigny)
- Buliminella elegantissima* (d'Orbigny)
- Cibicides fletcheri* Galloway and Wissler
- C. lobatulus* (Walker and Jacob)
- Florilus incisus* (Cushman)

Species considered as indicative of the *in situ* bathyal environment include:

- Bulimina carnerosensis* Cushman and Kleinpell
- B. carnerosensis mahoneyi* Cushman and Kleinpell
- B. uvigerinaformis* Cushman and Kleinpell
- Epistominella gyroldinaformis* (Cushman and Goudkoff)
- Uvigerina segundoensis* Cushman and Galliher
- Uvigerinella obesa* (Cushman)

The fan biofacies is recognized in member 2 of the Punta Quebrada section (Fig. 5). Significantly, the high abundance of sponge spicules, as well as the presence of middle bathyal species suggest that the lower part of member 2 was deposited in a middle bathyal environment with an influx of terrigenous and biogenic neritic material via turbiditic currents, representing a base of slope or submarine fan sedimentary facies.

The upper part of member 2 also contains layers of tuffaceous sandstones bearing the megafauna noted above along with abundant trace fossils. Although these features suggest deposition in a shallower (neritic) environment, the tuffaceous beds are enclosed by spicular sandstones with abundant middle bathyal microfaunas. Thus, these beds in-

cluding the tuffaceous, bioturbated sandstones are viewed as gravity transported from shallower neritic environments similar to those represented by member A of the Airfield section.

SILLED BASIN BIOFACIES

The main characteristics of this biofacies are: a) high content of benthonic species of foraminifera that indicate low oxygen conditions (50 ‰), b) low percentages of planktonic foraminifera (< 5 ‰) and c) a high abundance of diatoms (Fig. 5).

The species here considered to indicate low oxygen conditions include:

- Bolivina imbricata* Cushman
- B. seminuda* Cushman
- B. seminuda foraminata* R.E. and K.C. Stewart
- Cassidella delmonteensis* (Cushman and Galliher)
- Globobulimina montereyana* (Kleinpell)
- G. ovula pedroana* (Kleinpell)
- Suggrunda kleinpelli* Bramlette

Analogous Recent low oxygen faunas have been described from the Santa Barbara basin off southern California (Harman, 1964; Phleger and Soutar, 1973), in the Gulf of California (Bandy, 1961), off Central America (Smith 1963, 1964), and off South America (Ingle, Keller and Kolpack, in press). Of special significance is the fact that *Bolivina bicostata*, *B. seminuda*, *Globobulimina pacifica*, and *Suggrunda eckisi* comprise the dominant species in these modern low oxygen biofacies (Ingle, pers. comm., 1980). Miocene homeomorphs of these species form the Silled Basin Biofacies noted above, comprising from 40 ‰ to 60 ‰ of the species present in members 3 and 4 of the Punta Quebrada Section, implying low oxygen conditions in this Mohnian silled basin.

The deepest dwelling forms observed in this biofacies are middle bathyal species such as:

- Bolivina girardensis* Rankin
- Bulimina carnerosensis* Cushman and Kleinpell
- B. delreyensis* Cushman and Galliher
- B. uvigerinaformis* Cushman and Kleinpell
- Uvigerinella obesa* (Cushman)

This biofacies is present throughout all of members 3 and 4 of the Punta Quebrada Section, with the highest percentages of species indicative of

low oxygen conditions found in the lower part of member 3 (Fig. 5). Member B of the Airfield Section also contains foraminifera representatives of this biofacies.

*In addition to faunal evidence, the presence of laminated diatomite and altered porcellanites within these parts of the Tortugas Formation, suggest that most of these sediments were deposited below sill depth in a low oxygen environment (0.1 to 1.0 ml/l) analogous to the modern silled basins off southern California and in the Gulf of California (Calvert, 1964).

The high content of diatomaceous material, indicates that the basin was located in an area of upwelling of nutrients with a very high organic productivity and extremely low influx of terrigenous material, to dilute the diatom frustules being deposited.

Diatoms in this sequence are best correlated with high latitude zonations such as those proposed by Scharader (1973) and Barron (1976, in press). These floras imply the presence of a cool or cold oceanic current in the area during Middle to Late Miocene times, similar to the modern California Current.

The very high content of porcellanites in the strata of member 3 reflect a very low influx of terrigenous material in an environment with an oxygen content of less than 0.5 ml/l; as dissolved oxygen values of less than 1.0 ml/l characterize oxygen minima, with laminated sediments preserved as a function of little or no bioturbation when dissolved oxygen is less than 0.5 ml/l (Calvert, 1964). Cyclic sequences of laminated diatomites and porcellanites scattered in the thick mass of homogeneous, diatomaceous mudstones in the upper portion of member 4, suggest the following potential variables affecting cyclic sedimentation of this member: a) an increase in the influx of fine terrigenous material to the basin; b) a generally higher content of oxygen in the water (0.5 – 1.0 ml/l) than in the period of sedimentation of the strata of member 3; c) periodic decreases in the amount of dissolved oxygen to lows of 0.1 ml/l, caused by high primary productivity associated with more energetic upwelling conditions. These conditions are likely associated with paleoceanographic events during climatic colder intervals of the Late Miocene.

The presence of the volcanic ash in member 3 (Punta Quebrada) and member B (Airfield) indi-

cates volcanic activity near the area mainly during late Middle Miocene.

Shelf biofacies

This biofacies is characterized by the presence of common neritic mollusks and echinoderms, and the total absence of deeper dwelling forms. The neritic mollusks are the only paleontological evidence utilized to define this biofacies, and the strata of member A of the Airfield section are the only ones where this biofacies is recognized.

The pelletal phosphorite and the megafauna contained in the lithic sandstones of this member indicate that these beds were deposited in a middle to outer neritic environment with water depths between 20 and 100 m. The likely sources of material for this unit were the Franciscan type strata of the Eugenia Formation and the sandstones of the Valle Formation.

The presence of pelletal phosphorite in Miocene neritic sequences of California and western Mexico presents an interesting and as yet not completely understood phenomenon (Dickert, 1966; Anglejan, 1967; Lowe, 1969; Manheim, *et al.*, 1975).

BASIN EVOLUTION

Sediment accumulation and subsidence of the basin

In order to develop a quantitative model of the tectonic and sedimentary evolution of the Miocene Tortugas Basin as represented by the Punta Quebrada section, the absolute ages estimated for this section (Fig. 6), as well as the minimum depths of deposition deduced from the biofacies analysis (Fig. 5), are treated as precise data; in reality they represent best estimates.

The measured thicknesses of this section are the basis for calculating the original thicknesses of the sediments; in making these determinations, a maximum of compaction of the beds was obtained by assuming the compaction of an equal thickness of sediments with a composition of 100 % shale and with the same depth of burial (Van Hinte, 1978, p. 216).

The average rate of accumulation (RA) of the strata bounded by the assigned ages, is calculated with the following equation:

$$RA = \frac{T_o}{10^6 I}$$

Fig. 6. Estimated radiometric ages, paleobathymetry, rates of sediment accumulation (RA) and subsidence (RS) of the basin, as calculated for the strata of the Punta Quebrada section.

Where RA is the average rate of sediment accumulation in the basin and is given in cm/1000 years; To is the original thickness of the sediments and is given in meters; and I is the time span of the interval between two age assignments and is given in Megayears ($MA = 10^6$ years).

When calculating the RA of the porcellanite-rich part of member 3, an age was calculated for the top of that part (sample No. 39). This was accomplished by assuming the same RA for the uppermost 268 m of the section (measured thickness between samples 39 and 58), then determining the time interval represented by the 26 m (measured thickness) between the top of the porcellanite-rich unit and the level with an assigned age of 11.0 Ma (between samples 43 and 48).

In calculating the amount of subsidence, the assumption was made that if the estimated water depth remains the same from bottom to the strati-

graphic top of a given paleoenvironmental unit, the amount of subsidence is equal to the original thickness of that unit (Bandy and Arnal, 1960) but if the water depth changes, the subsidence equals the original thickness of the sediments less the change in water depth. This same reasoning is applied to the estimated rates of subsidence (RS), hence the rate of subsidence was calculated using the following equation:

$$RS = \frac{To - (\Delta D)}{10 I}$$

Where:

RS = Average Rate of Subsidence with respect to sea level (cm/1000 yrs).

ΔD = Total change in water depth (m). Upward movement of the sea floor is considered as positive.

Table I. Rates of sediment accumulation and subsidence of the basin, at the Punta Quebrada section.

SAMPLES NUM.	I (Ma)	Tp (m)	To (m)	RA (cm/10 ³ yr)	RA (cm/10 ³ yr)	D (m)
58-39	1.15	268	311	27	27	0
39-32	1.85	50	75	4	4	0
32-21	0.40	74	110	28	-22.5	+200
20-4	7.60	57	98	1.3	14.5	-1000

I = Time span of the Interval (Ma=10⁶ years).

Tp = Present (measured) Thickness of the strata (m = meters).

To = Original (estimated) Thickness of the sediments (m = meters).

RA = Average Rate of Accumulation of the sediments (centimeters per 1000 years).

RS = Average Rate of Subsidence of the basin with respect to sea level (centimeters per 1000 years).

AD = Total Change in Water Depth (m meters). Upward movement of the sea floor is considered positive.

SAMPLES NUM. = Portion of the Section enclosed by the samples indicated.

NOTE: Negative values of RS indicate uplifting.

Fig. 6 illustrates the rates of accumulation of sediments and subsidence of the basin, while Fig. 7 shows a model for the tectonic and sedimentary evolution of the area; this model was constructed following the idea of Van Hinte (1978). Both figures 6 and 7, were constructed with the data given in Table I.

DEPOSITIONAL HISTORY

As indicated by the facies represented in the two sections studied, and considering a palinspastic reconstruction of the fault bounded blocks of the area, similar to the reconstruction made by Robinson (1979), it is proposed here that at the time of deposition, the block containing the Punta Quebrada section (Fig. 1) was located farther southwest from the source of sediments than the block containing the Airfield section (Fig. 1). Furthermore, from late Early to early Middle Miocene (Saucesian to Luisian), the Punta Quebrada section represents a deeper facies of deposition in the basin. So, taking into consideration that the forces that affected

the area during that time came from the west, the different tectonic events triggered by those forces most likely affected more severely the block containing this section than the block containing the Airfield section, as suggested by the more dramatic changes in depth of deposition represented in the Punta Quebrada sequence.

From late Middle to Late Miocene (Mohnian), both sections represent essentially the same environment of deposition, with obvious implications for the evolution of basin configuration and bathymetry.

Study of the paleobathymetric curve, the rates of sediment accumulation and subsidence (Fig. 6), and the proposed model of the evolution of the basin as indicated by the strata of the Punta Quebrada section (Fig. 7), as well as the sedimentary characteristics of both sections, indicate that three different stages in the evolution of the Miocene Tortugas basin are represented in the two sections. These stages (summarized in Table II) are the following:

Fig. 7. Proposed Model of the Tectonic Evolution of the area, as represented in the strata of the Punta Quebrada section.

TABLE II. Stages in the evolution of the Miocene Tortugas basin.

STAGES	CHARACTERISTICS OF THE BASIN
I. Late Saucian (20-15 Ma)	-- Rapid subsidence of the basin to middle bathyal depths. Rate of sedimentation less than rate of subsidence.
II. Realizian - Luisian (15-13 Ma)	-- Uplifting event and vigorous filling of the basin. Turbidite units appear in the section.
III. Early Mohnian (13-10 Ma)	-- Rate of subsidence equals rate of sedimentation. Deposition in a low oxygen silled basin with upper batyal depths.

STAGE I. During Saucian times, the western part of the area subsided rapidly ($RS = 14.5 \text{ cm}/1000 \text{ yr}$) from a non-marine environment where peneplanation of the Cretaceous strata of the Valle Formation was taking place, to a depth of at least 1000 m (Fig. 6) where the middle to lower bathyal sediments of member 1 were deposited.

The deposition ($RA = 1.3 \text{ cm}/1000 \text{ yr}$) of these deep water sediments after the Paleocene-to-Lower Miocene hiatus possibly represents the result of tectonic subsidence of the area. This subsiding event was probably related to the right lateral displacements occurring along the western side of the North American continental margin after the collision of the East Pacific Rise with the North American plate in southern California, prior to 29 Ma (Atwater, 1970; Atwater and Molnar, 1973).

The widespread formation and development of Neogene basins in the western side of both Alta and Baja California have been related (Blake *et al.*, 1978) to the compressional forces that probably appeared in the area as a result of a change in azimuth of relative shear between the Pacific and North American plates during the interval between 21 and 10 Ma (Fig. 8).

STAGE II. The Middle Miocene interval (Relizian-Luisian) is represented by deposition of neritic, sandy sediments in the more stable eastern part of the area, and middle to upper bathyal fine grained sediments and sandy turbidites ($RA = 28 \text{ cm}/1000 \text{ yr}$) in the deeper parts of the Tortugas Basin to the west. The coarse grained turbidites eroded part of the fine sediments previously deposited, as indicated by the sudden change in the foraminiferal fauna in some of the strata of member 2 (Fig. 3), with time telescoped within the spicular sandstones of this same member. The high content of pelletal phosphorite in the neritic sandstones (member A) and the lower content of it in the turbiditic strata (member 2), also suggest a provenance relationship between these two different facies.

During Middle Miocene, a suggested uplifting event ($RS = 22.5 \text{ cm}/1000 \text{ yr}$) took place in the area (Fig. 7), but it seems to be represented only in the Punta Quebrada section, suggesting that the block containing this section was affected more severely by the tectonic activity than the block containing the Airfield section.

This Middle Miocene uplifting event might represent the pivoting (Menard, 1978) of the triple

junction (ridge-trench-transform) against the Sebastian Vizcaino Block at about 13.5 Ma, and is probably also related with the presence of volcanic ashes in this part of the section (just below sample Num. 30).

STAGE III. During late Middle Miocene (early Mohnian), the subsidence of the eastern side of the basin and sediment accumulation in the west allowed both areas to reach similar depths (500 m), and the formation of an effective sill allowing low oxygen conditions to prevail throughout the basin. The silled nature of the basin remained the same, with the rate of subsidence essentially equal to the rate of sediment accumulation ($RA - RS = 27 \text{ cm}/1000 \text{ yr}$), at least through the early Late Miocene.

While the inferred geochemical characteristics of this Mohnian basin indicate a strong similarity with the Recent Santa Barbara Basin off Southern California (Degens *et al.*, 1961), the rates of sediment accumulation in the Tortugas Basin were much lower ($27 \text{ cm}/10^3 \text{ yrs}$ as max.) than those reported by Emery (1960) as prevailing on the bottom of the modern basin ($114 \text{ cm}/10^3 \text{ yrs.}$).

The low rates of sediment accumulation during Mohnian times indicate either a very low influx of land-derived material, or a relatively large influx of terrigenous sediments and a low rate of deposition in the area due to bypassing of the sediments towards deeper levels in the basin.

The second possibility (bypassing of sediments) is proposed as the one prevailing in the Mohnian basin, as it resembles the actual situation at the San Diego Trough (Emery, *op. cit.*; Degens *et al.*, 1963) in which the rate of sediment accumulation has an average of $15 \text{ cm}/10^3 \text{ yrs}$. This bypassing hypothesis is supported by the presence of a section "2000 m thick, composed of Miocene and post-Miocene sediments" trapped in between ridges of the sea floor and located offshore the Sebastian Vizcaino Peninsula, south of Cedros Island (Normark, *et al.*, 1969).

So, from late Middle to early Late Miocene (from 13 to about 10 m.y.b.p.), both Tortugas Airfield and Punta Quebrada sections represents landward depocenters or fringes of a basin, while a deeper center (or centers) of deposition was (were) located farther south to southwest.

From Late Miocene to Middle Pliocene (from around 10 to about 3 m.y.b.p.), the sedimentary record shows a break, which is interpreted as evidence of uplift in the area, as an angular uncon-

formity separates the uppermost strata of the Tortugas Formation from the lowermost Almejas Formation. Posterior subsidence allowed the area to reach neritic conditions during Late Pliocene times, as evidenced by the neritic deposits of the Almejas Formation overlying the upper bathyal sediments of the Tortugas Formation.

Miocene–Pliocene uplift in this area is regarded as the culmination of local deformation related to the transference of slices of the North American plate to the Pacific plate. This event was directly related to the evolution of the San Andreas fault system and the opening of the Gulf of California, during which the triple junction (transform, trench

Fig. 8. Schematic tectonic evolution of the southwestern continental margin of North America, in relation to the Miocene Tortugas Basin. Data compiled from Atwater (1970); Blake et al, (1979).

and rise) formed by the Pacific, North American, and Farallon (now Rivera and Cocos) plates (Fig. 8) migrated toward the south (Dickinson, 1979).

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