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Part 1

NEOGENE MICROFOSSILS FROM THE SANTIAGO DIATOMITE, BAJA CALIFORNIA SUR, MEXICO

By

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ABSTRACT

A biostratigraphic study of the Santiago Diatomite—the diatomaceous outcrops in southernmost Baja California—was carried out using benthic and planktonic foraminifera and calcareous nannoplankton. The Santiago Diatomite is considered to be latest Miocene to middle Pliocene in age and to be associated with nearby upper Pliocene beds. The sediment was deposited during a transgressive event which resulted from local tectonic spreading of the Gulf of California. A paleobasin with its major depocenter at the Santiago site was formed.

Micropaleontological information suggests an upper bathyal paleodepth for the Santiago Diatomite, with an assemblage characteristic of transitional water masses—California current and the North Equatorial System—converging at this site.

In general, normal marine conditions existed, with the exception of some levels of laminated sediments that suggest decreased oxygen content. Dissolution of calcareous microfossils could be indicative of deposition near the carbonate compensation depth, or local upwelling.

Reconstruction of the evolution of the Santiago paleobasin suggests a probable association with a subaerial canyon that existed prior to this time, with later submersion and, finally, a regressive event during late Pliocene-Pleistocene time.

Key words: micropaleontology, Neogene, Baja California Sur, Mexico.

RESUMEN

El estudio bioestratigráfico de los sedimentos diatomíticos que afloran en la parte más austral de Baja California, para el cual se utilizó foraminíferos planctónicos, bentónicos y nannoplancton calcáreo, permite asignar una edad de miocénica tardía a pliocénica media a la Diatomita Santiago, que aflora cerca de capas del Plioceno superior. Estos sedimentos fueron depositados durante un evento transgresivo, como resultado de la apertura tectónica local del Golfo de California que formó una paleobahía, cuyo máximo centro de depósito fue el área de Santiago.

La información micropaleontológica obtenida indica, para la Diatomita Santiago, una paleoprofundidad batial superior, con un conjunto transicional característico de masas de agua asociadas a la corriente de California y al sistema Nordecuatorial, las cuales convergen en esta área.

En términos generales, se puede considerar que predominaron condiciones marinas normales durante el depósito, con excepción de algunas capas de sedimentos laminados, que sugieren decremento en el contenido de oxígeno. La ausencia de algunos taxa, así como la presencia de microfósiles calcáreos parcialmente disueltos, puede atribuirse a depósitos cercanos al límite de compensación del carbonato o a una surgencia local.

Se interpreta la evolución de la paleobahía Santiago, la cual señala una probable asociación con un cañón subaéreo preexistente, la posterior sumersión y finalmente un evento regresivo durante el Pleistoceno.

Palabras clave: micropaleontología, Neógeno, Baja California Sur, México.

INTRODUCTION

Geological reconnaissance of Baja California represents a major contribution in the reconstruction of the detailed tectonic and marine history of the Gulf of California. No major published studies have been made on marine Neogene sediments from Baja California Sur, and only few studies have been reported from the northern part of Baja California.

Recent reports have been largely involved with geological and geophysical marine investigations on the origin and evolution of the gulf: several hypotheses attribute the origin of the Gulf of California to ocean-floor spreading and transform faulting (***e.g.***, Larson ***et al.***, 1968; Moore and Buffinton, 1968; Atwater, 1970; Moore, 1973).

Moore and Curray (1982) reconstructed the history of the Gulf of California and proposed a single two-phase process: the late diffuse extension phase which is still occurring in the central northern gulf, following a phase characterized by a jump of the plate edge from transform motion off the west coast to approximately the back or the northeastern side of the coastal batholith.

Different reports point out the existence of a protogulf prior to latest Miocene (Gastil *et al.*, 1968; Ingle, 1973, 1974; Moore, 1973), and suggest that marine deposition in the northern portion of the gulf began during middle Miocene (Ingle, 1973) and that the initiation of the major period of basin formation and initial rifting on the trough might have started during early Miocene (Gastil *et al.*, 1968). Although Moore and Curray (1982) stated that the first opening was completed at about 3.5 Ma, they suggested that, other than shelf deposits, no sediments older than 5.5 Ma (latest Miocene) would be found associated with the gulf. Applegate (personal communication) suggests that evidence exists for a seaway between what is now the Peninsula of Baja California and the mainland of Mexico from the upper Oligocene to the Holocene. This concept would eliminate the necessity of a protogulf.

At present, the Neogene marine deposits recognized in southernmost Baja California are poorly studied and apparently represent littoral environments; these allow a partial view of the evolution of the marine events. Analysis of the vertical variation of planktonic foraminifera and coccoliths of the diatomaceous shale that crops out at Santiago, Baja California Sur, when compared with other nearby areas, marine and terrestrial deposits began in the gulf prior to 5.5 Ma. Data obtained from planktonic microfossils and benthic faunas provide some additional paleobathymetric and paleoceanographic information.

STUDY AREA

On the right side of road No. 1, in its part from San José del Cabo to La Paz, about 8 km from Santiago, Baja California Sur (Figure 1), there are several isolated exposures of marine diatomaceous shale, here called Santiago Diatomite.

This area, located at the tip of Baja California, is physiographically known as the Los Cabos Region. It forms the southern part of the peninsula; to the west, it is bounded by the Gulf of California; to the north by the La Paz isthmus region; and to the east and south by the Pacific Ocean.

The La Paz fault is a major structural feature; the rocks to the north are completely different from those to the south; therefore, the presence of Comondú volcanics has not been demonstrated to the south of La Paz fault.

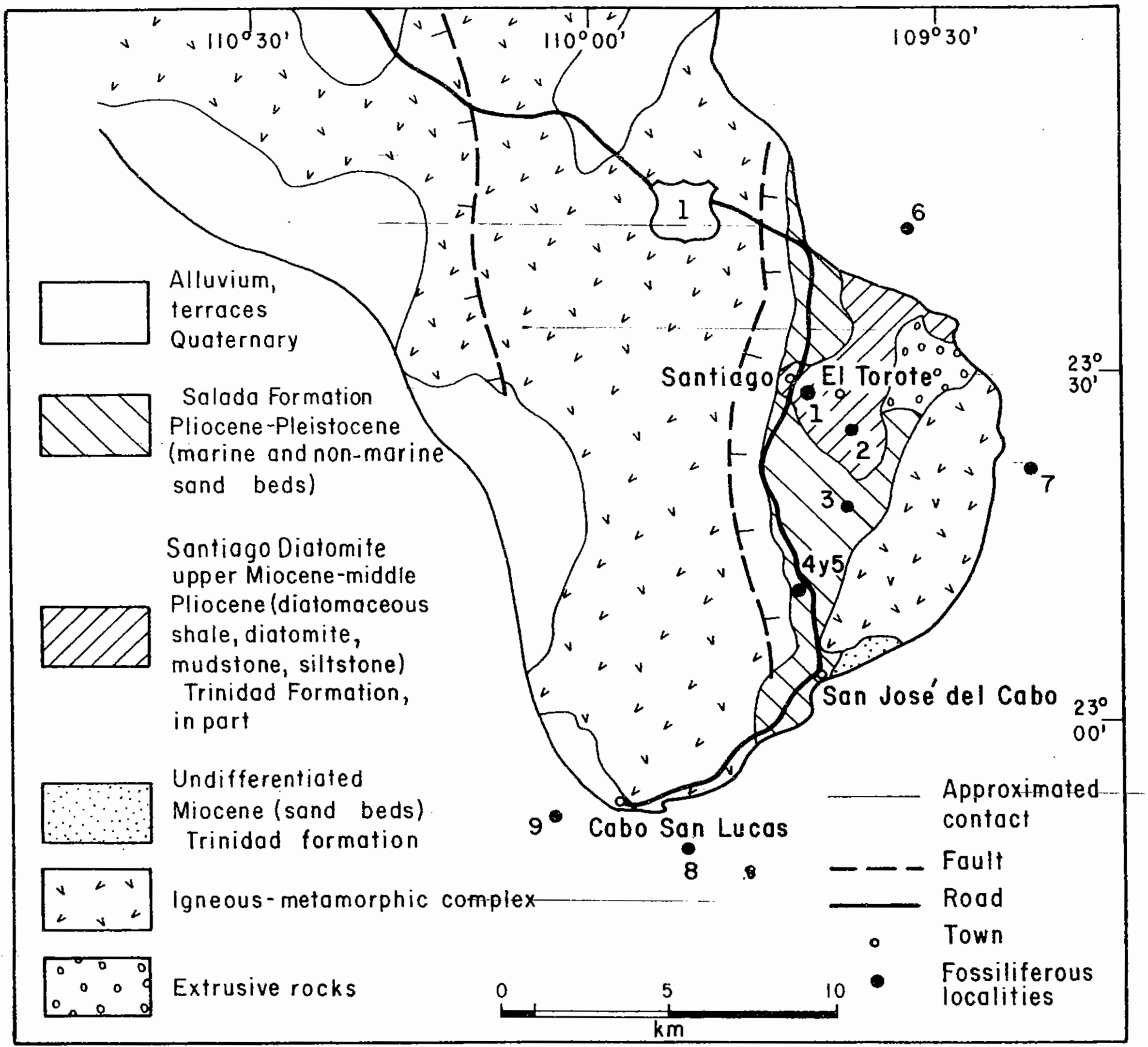

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Figure 1.- Generalized geological map and paleontological localities mentioned in this study. Faults mostly normal, recognized on the field are not mappable. 1—Santiago Diatomite section; 2—El Refugio (Hertlein, 1966); 3—Las Tunas (Miller, 1980); 4 and 5—Rancho Algodones area (Espinosa-Arrubarrena, 1979; Torres-Roldán, 1980; localities from Shepard, 1964); 6—BAC 53 (Sample 104) 23°42.1'-109°36.7' (Santiago canyon); 7—BAC 17 (Sample 36) 23°22.6'-109°23.3' (Los Frailes canyon); 8—BAC 60 (Sample 115) 22°46.9'-109°52.9' (Cardonal canyon); 9—BAC 64 (Sample 111) 22°49.8'-110°3.9' (Vigía canyon).

This area is underlain by Cretaceous granitic batholithic rocks, which form the western range at the Los Cabos Region. The structure is dominated by northeast trending normal faulting, which has produced a series of horsts and grabens, at the southeastern edge of the continental block. On the southeastern side of the tip metasediments and granites exist which may have at one time been connected to the batholiths.

The geology of the tip of Baja California is poorly studied. The Neogene formations, as described by Heim (1922), include Comondú, Isidro and Salada; Beal (1948) described San Gregorio; Mina (1957) described San Zacarías, Santa Clara, Zorra, San Ignacio, San Raymundo, Tortugas and Atajo Comondú, and Pantoja-Alor and Carrillo-Bravo (1966) described Trinidad. Except for the last formation, the rest of them is not recognized in the Los Cabos Region (Figure 2).

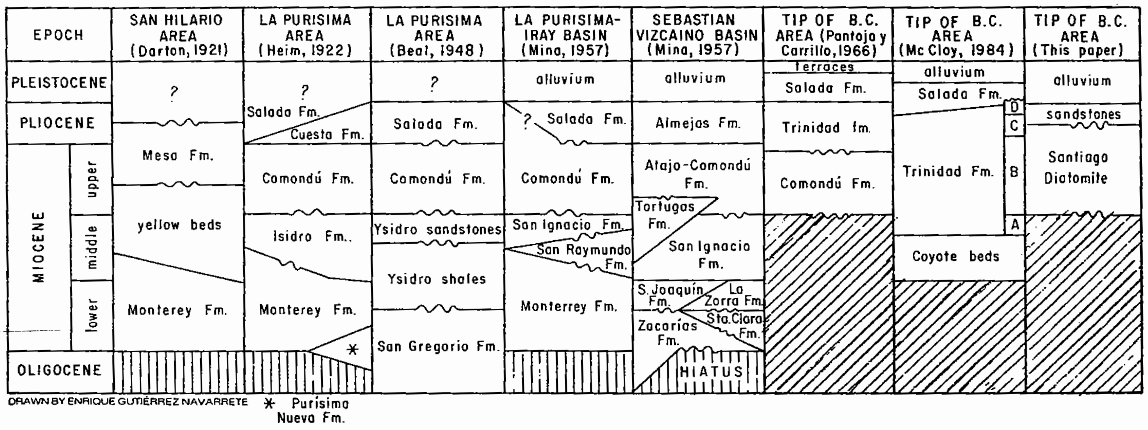

Figure 2.- Generalized stratigraphic correlation chart showing the section studied with respect to Baja California formations.

Normark and Curray (1968) pointed out that "The identification of Comondú, at the southern tip, is based only on lithological similarities, while the reflection profiles show no suggestion of sediments under the volcanic, as defined for the tip of Baja, Ysidro Formation, of Beal". For these authors, the Beal's Ysidro Formation, defined by Pantoja-Alor and Carrillo-Bravo (1966) as the Pliocene Trinidad formation, is combined with the Comondú volcanics.

The arroyo Santiago, the head of the Santiago's Valley inland (where the study area is located), is aligned with the Santiago submarine canyon (Shepard, 1964); this author indicates that the formation of the Santiago's granitic canyon took place when the Los Cabos Region stood higher than now above sea level. The granitic rocks of the Los Cabos block range from 54–88 Ma (Gastil ***et al.***, 1976); on the other hand, after Hausback (1984), the granitic Los Cabos province was probably already upheaving along the La Paz fault, prior to the early Miocene Comondú deposition. After 12 Ma, the same author suggests that the movement along the La Paz fault probably includes the downdropping of the Los Cabos block and significant left-lateral strike-slip faulting.

Despite the scarcity of geological information, paleontological work has been carried out, because of the abundance of fossiliferous localities. Some isolated localities have been reported by Hertlein (1966). On the other hand, Shepard (1964) reports a shale (sample 104) from the west wall of the Santiago canyon, where this canyon joins the Palmas canyon, dredged during the Bacanyon Sea Expedition. The dredged shale is partly laminated and partly nodular and it has a manganese coating. From this shale, F. L. Parker (*in* Shepard, 1964) identified foraminifera of probable Miocene age. Pliocene ***Pecten*** specimens were dredged (sample 36) in the northern wall of the Los Frailes canyon.

A sample from the eastern side of the Los Cabos Region (sample 115) in the northern wall of the canyon yielded diatomite and laminated shale; the diatoms suggest a Miocene age, but the silicoflagellates indicate a probable Pliocene age, while south of Cabo San Lucas, in the western wall of the Vigía canyon, foraminifera from a laminated shale (sample 111) appear to be Pliocene or Pleistocene in age. Location of all these samples is shown in Figure 1.

At Rancho El Refugio, approximately 15 km south of the study area, middle Pliocene sands and silts contain mollusks (Hertlein, 1966). Previous work in diatom assemblages (Hanna and Brigger, 1966) in the Santiago area—probably some of these outcrops—suggests an age equivalent to the late part of the Miocene (Delmontian).

Nine kilometers to the southeast of Santa Anita, a locality known as Rancho Algodones contains a large and diverse fauna. Espinosa-Arrubarrena (1979, 1980) suggested an age equivalent to middle?-late Pliocene for the marine sediments that contain shark's teeth; Durham (*in* Espinosa-Arrubarrena, 1979) deduced a similar age for the same beds on the basis of invertebrate fauna. He suggested the possibility of a younger age based on the time scale of Berggren and Van Couvering (1974). The vertebrate fauna found in Rancho Algodones indicates a Blancan age (Torres-Roldán, 1980).

Miller (1980) assigned a Blancan age to the Las Tunas local fauna, located 14 km to the northeast of Santa Anita and approximately 30 km to the south of Santiago (Figure 1). Moreover, Addicott (*in* Miller, 1980) indicated that this assignment, when used as Durham (1950) and Hertlein (1966) did, might well be middle Pliocene.

Recently, McCloy (1984), from evidence in the overlying beds—considered as Trinidad formation—assigned to the Coyote beds an age not younger than middle Miocene. The same author, based on the presence of ***Anadara patricia*** (*sic*) in the subunit A of the Trinidad formation, suggested a middle Miocene age and, because of the association with other genera of mollusks, she extended the range of those beds to the upper Miocene. Unfortunately, there is no evidence to consider ***Anadara grandis patricia*** as a restricted marker of the middle Miocene. After Woodring (1973), this species is considered as a part of a brackish water group from the Caribbean region, with a range from the middle Miocene to lower Pliocene, while the associated genera (***Melongena*** sp., ***Cerithidea*** sp. and ***Theodoxus*** sp.) reach the Holocene.

Based on radiolaria, Pérez-Guzmán (1985) gave a late Miocene age to the ***Didymocyrtis antepenultima*** and ***D. penultima*** Zones (after Riedel and Sanfilippo, 1978) of some of the diatomaceous sediments that crop out near Rancho El Torote.

The above discussion shows that a great deal of careful work is needed before the exact ages of the beds within this area are known with confidence.

METHODS

The 248 m of the measured section (Figure 3) are lying unconformably under Cretaceous granites. The sequence consists of shaly siltstone, siliceous shale, micaceous mudstones and silty shale. In some levels, the micaceous mudstones grade into a very tuffaceous massive or laminated diatomites. This sequence is overlain unconformably by Quaternary alluvium. This section probably corresponds to McCloy's (1984) subunits B and C previously discussed, and therefore to the Trinidad formation also.

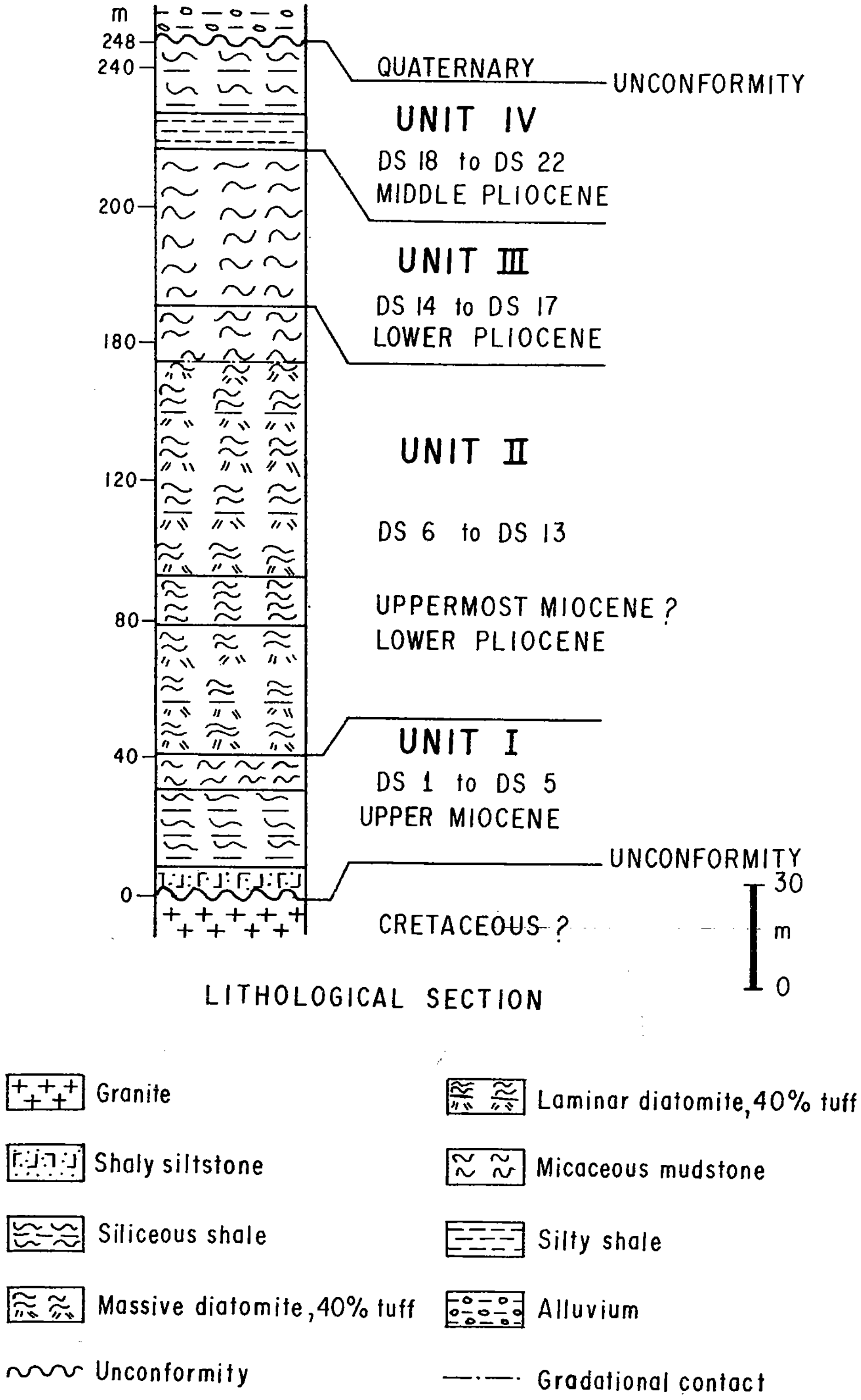

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Figure 3.- Composite columnar section of the outcrops studied at the Santiago area here called Santiago Diatomite.

A 200 gram portion (dry weight) of each sample was soaked in water and sieved through a 200 mesh Tyler screen. The benthic and planktonic populations of each sample were counted separately. A modified Otto microsplitter was used to obtain practical but stratigraphically significant fractions of 200 to 300 benthic and planktonic individuals. The entire population within a sample was counted when total specimens numbered less than 200. Planktonic and benthic foraminifera are rare to common, with evidence of signs of dissolution. In portions of the diatomite, the nannoplankton is scarce and poorly preserved. There are abundant diatoms, silicoflagellates and radiolarians, and, in some horizons, abundant fish remains. Relative abundances of foraminifera are presented as percentage of the total planktonic or benthic population in a sample (Figure 4).

Calcareous nannoplankton species abundances were recorded as the logarithm of the abundance in a smear slide viewed at x 1,000 (Figure 5).

AGE ASSIGNMENT

The whole section is characterized by a transitional microfauna, that consists of many forms generally associated to warm water and many others that could be associated or transported by cold-water flows. Due to this mixture, the age assignment is based, as far as possible, on planktonic (Bolli, 1970; Bolli and Bermúdez, 1965; Bolli and Premoli-Silva, 1973; Bolli and Saunders, 1985), benthic foraminifera (Kleinpell, 1938) and calcareous nannoplankton (Martini, 1971) warm-temperate zonal schemes. Furthermore, in the case of planktonic foraminifera, the prevailing coiling pattern of selected species in each level was taken into account (Figure 4). In some levels, absence of one or more of those groups, caused difficulty in making a zonal assignment.

Low latitude index microfossils are missing in the major part of the Santiago Diatomite, possibly due to dissolution or dilution. In the case of dilution, the rare occurrence of calcareous microfossils may suggest a relatively low productivity as well as a higher rate of terrigenous influx, similar to the Holocene shallower coastal basins of the Gulf of California.

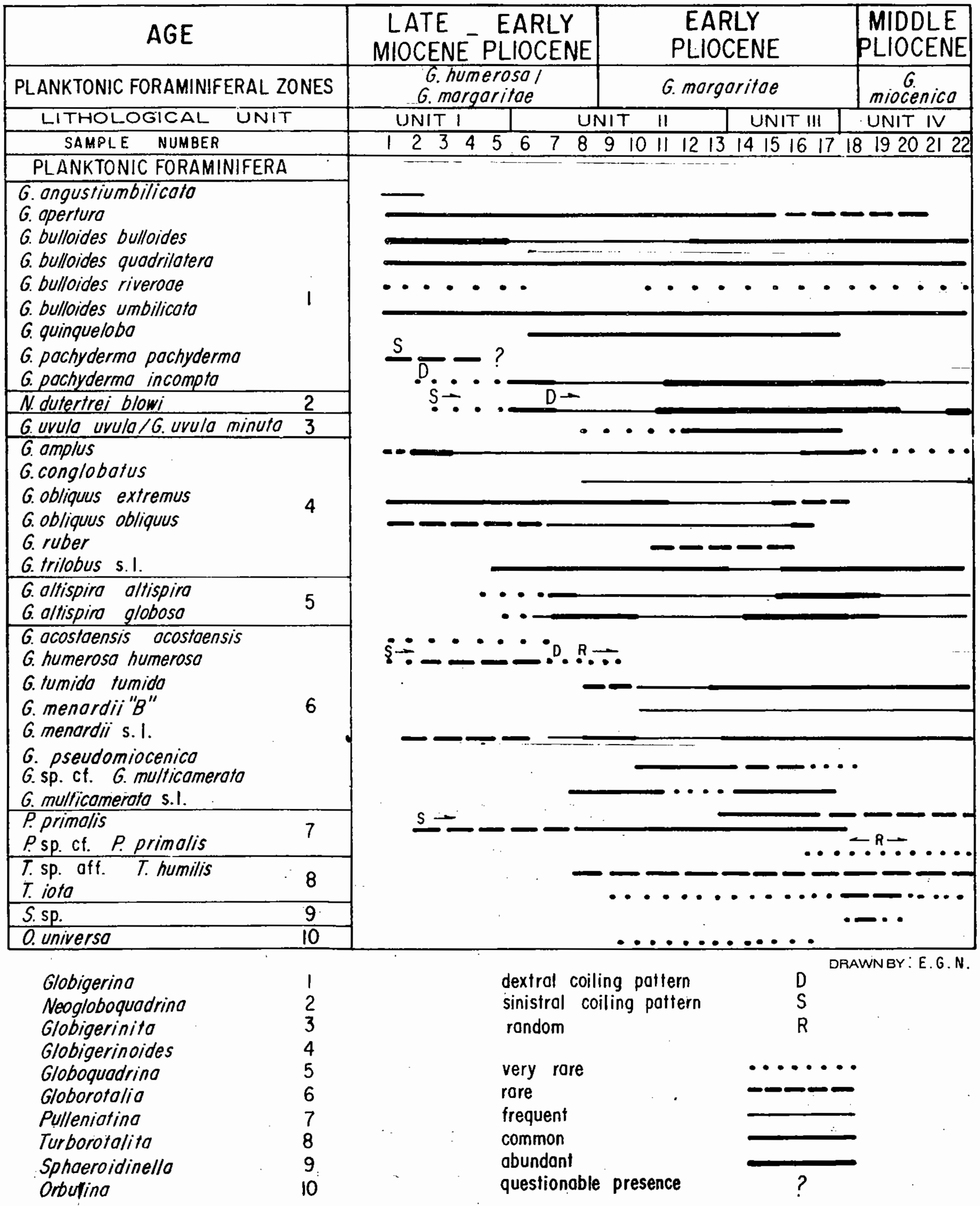

Figure 4.- Planktonic foraminiferal distribution, relative abundance and coiling pattern direction of selected species throughout the Santiago Diatomite section.

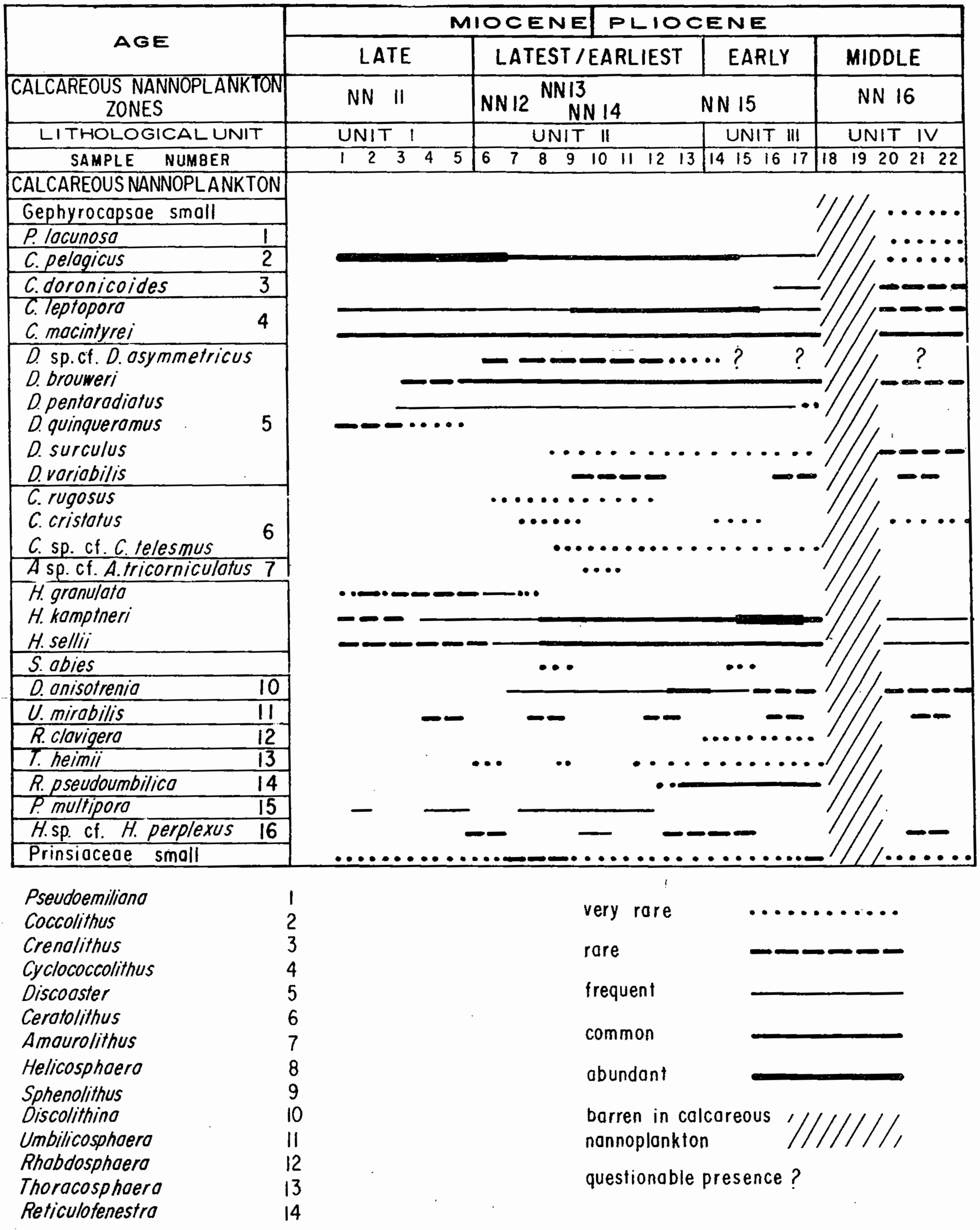

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Figure 5.- Distribution and relative abundance of calcareous nannoplankton throughout the Santiago Diatomite section. Species abundances are recorded in the table as the logarithm of the abundance in a smear slide viewed at x 1,000; +1= tens of specimens in a single field of view; 0= a single specimen in a field of view; -1= a single specimen of the species found in 10 fields of view; -2= a single specimen in 100 fields of view.

The population structure in the Santiago Diatomite is not constant. The base of the section (samples 1 to 6) contains only calcareous microfossils; on top of the section, the siliceous microfossils become more frequent, constituting the dominant elements in the levels of "light layers" diatomites, in rapport with the "dark layers" containing more abundant calcareous microfossils except in sample 18 and 19, where calcareous nannoplankton was not recorded.

The presence or absence of one or more species from one level to another and their frequency are more closely related to paleoclimatic or tectonic conditions, than to stratigraphic range.

At the base of the measured section (samples 1 to 8), index planktonic foraminifera are missing, most of them are longest-ranging species corresponding to the time span around the N17 (***Globorotalia humerosa***) and N18 (***Globorotalia margaritae***), upper Miocene-Pliocene zones. Moreover, the presence in samples 1 to 5 of common to rare ***Discoaster*** sp. cf. ***D. quinqueramus*** Gartner—the central knobs are generally shorter than in ***D. quinqueramus***—suggests a latest Miocene age for this part of the section, while in sample 6 to 8 ***Discoaster*** sp. cf. ***D. quinqueramus*** is absent. The benthic foraminifera assemblage consists mostly of large, robust species of ***Valvulineria*** and ***Nonion*** associated with scarce ***Bolivina obliqua*** and minor species of ***Bolivina***, that could be assigned to the top of the Mohnian or to the base of the ***Bolivina obliqua*** Zone of Kleinpell (1938).

Amaurolithus and ***Ceratolithus*** are not particularly abundant, but their presence is considered meaningful; however ***Amaurolithus*** sp. cf. ***A. tricorniculatus*** Gartner and ***Ceratolithus rugosus*** Bukry and Bramlette, together with forms very close to ***Discoaster asymmetricus*** Gartner become frequent in samples 6 to 8. These facts are indicative of a mixture between the NN12 ***Ceratolithus tricorniculatus***, NN13 ***Ceratolithus rugosus*** and NN14 ***Discoaster asymmetricus*** Zones of Martini (1971) of the latest Miocene-early Pliocene.

Up on the section (samples 9 to 18), the assemblage is characterized by numerous and varied planktonic foraminifera. Some levels, less affected by dissolution, contain keeled menardiiforms ***Globorotalia*** with strong affinities to ***Globorotalia menardii*** B (of Bolli and Premoli-Silva, 1973), ***Globorotalia pseudomiocenica*** Bolli and Bermúdez and

Globorotalia multicamerata Cushman and Jarvis characteristic of lower-latitude lower Pliocene assemblages (***Globorotalia margaritae*** Zone).

Benthic foraminifera are scarce and less varied than the planktonic; the most frequent species are ***Bolivina obliqua*** Barbat & Johnson, ***B. churchi almgreni*** Kleinpell, ***B. rankini*** Kleinpell, ***B. subadvena*** Cushman, ***Nonion multicameratum*** Kleinpell, ***Buliminella subfusiformis*** Cushman and ***Sphaeroidina bulloides*** d'Orbigny, which indicate the Kleinpell's (1938) ***Bolivina obliqua*** Zone from the uppermost Delmontian stage of California. After Barron (1976), this benthic foraminiferal zone is correlatable, at least in part, with the temperate ***Distephanus speculum speculum*** Zone of Bukry, 1973 (Pliocene DSDP Site 173 in the Pacific). In fact, siliceous microfossils become frequent in this part of the section, but no attempt was made to carry on a detailed study of them; nevertheless, it was possible to note that the ***Distephanus speculum*** (Ehrenberg) and ***Mesocena circulus*** (Ehrenberg) groups are the dominant species of the silicoflagellate assemblage.

On the other hand, Berggren and coworkers (1985) consider that the base of the ***Bolivina obliqua*** Zone could be correlated to the ***Stichocorys peregrina*** (Riedel) FAD. Trápaga-Martínez (1985), in a similar study of the same samples, suggests, for this part of the section, a late Miocene age (***Stichocorys peregrina*** Zone of Riedel and Sanfilippo, 1978); nevertheless, Sanfilippo and coworkers (1985) place the ***Stichocorys peregrina*** Zone from the uppermost Miocene to the lower Pliocene and consider that ***Didymocyrtis avita*** (Riedel) is restricted to the Pliocene ***Spongaster pentas*** Zone, where ***Spongaster tetras*** (Ehrenberg) has its first occurrence. Trápaga-Martínez (1985) reports ***Stichocorys peregrina***, ***S. delmontensis*** (Campbell and Clark) and ***Anthocyrthidium ehrenbergii*** (Stohr), radiolarians on which this author based the age assignment; nevertheless, he also reports associated to these species ***Didymocyrtis avita*** and ***Spongaster tetras***, indicative, at least, of an early Pliocene age.

In this part of the section and in the next younger unit, the calcareous nannofossils consist mostly of the outer rims of coccolith shield; the center of the rims has been removed by dissolution, so that few good markers could be identified; consequently, no stratigraphic subdivisions are possible. In spite of this, the common taxa present ***Discoaster pentaradiatus*** Tan, ***D.*** sp. cf. ***D. asymmetricus*** (no typical forms were identified due to stronger dissolution), ***D. brouweri*** Tan, ***D. surculus*** Martini and Bramlette, ***Reticulofenestra pseudoumbilica*** (Gartner), ***Helicosphaera kamptneri*** Hay and Mohler and ***H. sellii*** Bukry and Bramlette, and may suggest the NN14 ***Discoaster asymmetricus*** Zone or/and NN15 ***Reticulofenestra pseudoumbilica*** Zone of Martini (1971), indicative of an early Pliocene age.

The upper part of the Santiago Diatomite (samples 19 to 22) contains impoverished calcareous microfossils. The calcareous nannoplankton is practically absent in two levels of impure diatomite, except for some unidentified fragments; the benthic foraminifera are sparse and poorly preserved. In general, the same species of the precedent unit were found.

Planktonic foraminifera show signs of intense dissolution; many keel fragments were found. Common fragments—in general the last chamber—of ***Sphaeroidinella*** and the occasional record of a delicate and poorly preserved ***Globorotalia miocenica*** Palmer suggest a correlation at least equivalent to the lower part of the ***Globorotalia miocenica*** Zone of Bolli and Premoli-Silva (1973). The scarcity of ***Reticulofenestra pseudoumbilica*** associated with ***Discoaster surculus***, and the doubtful presence of ***Pseudoemiliana lacunosa*** (Kamptner) [not found in the scanning electron microscope, but recorded in cross-polarized light], primitive, very small and sporadic Gephyrocapsae probably of the ***Gephyrocapsa sinuosa*** Hay and Beaudry-***G. aperta*** Kamptner type, suggest at least the lower part of the NN16-***Discoaster surculus*** Zone of Martini (1971).

Pérez-Guzmán (1985) assigns to this part of the section (her samples 1 to 4) an age equivalent to that of the ***Didymocyrtis antepenultima-Didymocyrtys penultima*** Zones; nevertheless, the presence of ***Spongaster tetras*** could be indicative, after Sanfilippo, Westerberg-Smith and Riedel (1985), of an upper ***Spongaster pentas*** Zone or the ***Pterocanium prismatum*** Zone of the middle-lower upper Pliocene.

Not surprisingly, benthic and planktonic foraminifera and calcareous nannoplankton differ slightly on their placement as late Miocene-early Pliocene age; this could be basically due to the delayed arrival of many tropical index morphotypes, in response to the critical low sea-surface temperatures (Ingle, 1967) and in the case of the Miocene and Pliocene stages of California, and that some of the benthic foraminifera commonly used to recognize these stages are time transgressive, as has been demonstrated by several authors, like Crouch and Bukry (1979).

Certainly, the effect of temperature, associated with other physical factors, caused the transitional character of the Baja California Sur assemblage. Tentatively, the Santiago Diatomite ranges from the uppermost Miocene to at least the base of the middle Pliocene—or base of the upper Pliocene ***sensus*** Martini (1971).

ENVIRONMENT

As noted before, the Santiago Diatomite contains laminated horizons in contrast with the massive character of other beds. They support the suggestion of deposition within the upper reaches of the oxygen minimum zone (Calvert, 1964). The presence of epibathial species, associated with a characteristic fauna of a restricted impoverished basin (***Bolivina obliqua***), strengthens this interpretation. Thus the massive diatomaceous shales, which grade into micaceous mudstone, could represent deposition adjacent to a submarine canyon and/or a slope complex, admitting sediments from surrounding areas.

As noted by Gorsline and Emery (1959) and Bandy (1964), cumulative percentages of benthic foraminifera in the whole section indicate that the displaced fauna comprises about 75 % of the total, indicating much downslope sediment displacement. The faunal displacement involves taxa from shallow horizons as ***Lenticulina cushmani*** Galloway and Wissler and ***Buliminella elegantissima*** (d'Orbigny), that have been transported to bathyal depths, in a more or less restricted basin. This interpretation is supported by absence of other benthic groups, particularly ostracodes.

The planktonic foraminifera throughout the Santiago Diatomite section show a remarkable mixture of cold-, temperate- and warm-water species, that includes transitional assemblages. This is probably due to the influence of the California current, which turns west near Cabo San Lucas to become part of the westward-flowing North Equatorial current.

The dominant planktonic foraminifera species ***Globoquadrina altispira altispira*** Cushman and Jarvis, ***G. altispira globosa*** Bolli and

Neogloboquadrina dutertrei blowi Rögl and Bolli, suggest a (slightly) tropical-subtropical character, essentially for the uppermost Miocene. In the Pliocene, this same assemblage, associated with other minor temperate to warm-water foraminifera, as keeled menardiiforms ***Globorotalia***, ***Globigerinoides trilobus*** s.l. Reuss and scarce ***Globigerinoides ruber*** (d'Orbigny), marks an interval of increasing, but always oscillating, surface temperature. The whole section contains significant percentages of ***Globigerina pachyderma pachyderma*** (Ehrenberg), only in the uppermost Miocene, ***G. pachyderma incompta*** Cifelli, ***G. bulloides*** plexus, and minor accessory species like ***Globigerina quinqueloba*** Natland, and ***Globigerinita uvula uvula*** (Ehrenberg), which at this latitude today represent characteristic biofacies of the California current (Bradshaw, 1959; Ingle, 1967). This implies a slight influence of cool-water masses or intensity decrease of the North Equatorial current.

Similar ratios between ***Neogloboquadrina dutertrei blowi*** and ***Globigerina pachyderma incompta*** in the Santiago Diatomite assemblage support the foregoing interpretation, based on Arikawa's work (1983), in which it is postulated that similar percentages of the former species clearly indicate disturbed areas with a prominent thermocline. In the Santiago Diatomite, there is just a slight tendency of ***N. dutertrei blowi*** to be more abundant (less than 10 %). This could indicate at this site that the North Equatorial current looses its indigenous character (such as high temperature and salinity) through cold water mixing with the California current.

The fact that the sinistrally coiling ***Globigerina pachyderma pachyderma*** is practically absent, with exception of occasional uppermost Miocene records, indicates that since the Pliocene the influx of colder water masses has diminished.

The same transitional character observed for the planktonic foraminifera is also valid for the calcareous nannoplakton.

There is definitely a warm interval, as indicated by the presence of abundant ***Discoaster***, particularly ***D. brouweri*** and ***Cyclococcolithus macintyrei*** Bukry and Bramlette. An increase of ***Helicosphaera*** since the early Pliocene reflects warmer surface water conditions, with an optimum between 20 to 28°C (Roth and Berger, 1975). These species, associated to other warm-water indicators, such as ***Hayaster*** sp. cf. ***H. perplexus***

(Bramlette and Riedel), seem to confirm a warm-water influence. The abundances of cool-water species, such as ***Distephanus speculum speculum***, ***D. speculum pentagonus*** (Lemmermann) and ***Mesocena circulus*** (the most abundant of the silicoflagellates) are not dominant, but rather represent a significative percentage within the microfossils. The constant presence of ***Discoaster variabilis*** Martini and Bramlette which, after Bukry (1971), represents a cool temperate element in the basal lower Pliocene assemblages from the area of the cool California current west of northern California (Leg 5, Sites 32 through 37), suggesting a mixture of different water masses, in this case a colder influx, which confirms the interpretation discussed for the planktonic foraminifera.

The relationship between warm-water and cool-water microfossil species of the Santiago Diatomite indicates a paleotemperature of 20°C. This paleoenvironmental interpretation considers that the cool water influx was probably associated with an intensification of the California current that disturbed the control factor of the subtropical Pacific and Gulf of California water masses.

On the basis of abundance and preservation of calcareous microfossils, two facies zones are distinguished: The first comprises abundant and well-preserved planktonic foraminifera and nannoplankton, suggesting that deposition took place well above the carbonate compensation depth (CCD). The second facies zone is characterized by less abundant planktonic foraminifera and calcareous nannoplankton with evident signs of dissolution, suggesting that deposition took place near the CCD. Another interpretation for the second facies is explained by the abundant siliceous microfossil occurrence, such as diatoms, radiolarians and silicoflagellates, suggesting an ancient upwelling of cold-water masses, besides deposition near or below the CCD. Within the facies, ***Amaurolithus*** were observed as occasional components of the assemblages. ***Amaurolithus*** are open-ocean forms; therefore, it is not surprising that they were poorly represented at an early stage of the gulf spreading, and not because they were deposited near the CCD.

Braarudosphaera, a widespread genus, was not recorded at all in any of the studied samples, which would therefore suggest normal marine conditions without continental water dilution and absence of stress conditions; these last conditions, however, were probably present near the basal middle Pliocene, because of the absence of ostracoda and sparse ***in situ*** occurrences of benthic foraminifera. The above mentioned evidence indicates unfavorable living conditions at the sea floor, caused by factors such as high sedimentation rate and low oxygen content. The whole benthic assemblage also includes shelf and upper-slope reworked specimens, probably transported to the bottom by turbidity currents.

All the calcareous species mentioned in the text and also most of the microfossil assemblage is illustrated in Plates 1 to 6.

DISCUSSION AND CONCLUSIONS

Based on the groups presented in this study, age relationships at this locality are somewhat equivalent. These include the following: (1) on the basis of benthic foraminifera, it was only possible to recognize the ***Bolivina obliqua*** Zone of the upper Delmontian, 6.9 Ma old (after Berggren ***et al.***, 1985; the base of this one is close to that K-Ar date); (2) planktonic foraminifera suggest an equivalent age for the ***Globorotalia humerosa*** Zone, in part, to at least the lower part of the ***Globorotalia miocenica*** Zone, or between 5.5 to 3 Ma; and (3) the calcareous nannoplankton goes from the ***Discoaster quinqueramus*** Zone, in part, to the ***Discoaster surculus*** Zone, in part; that is, from 5.5 to 3 Ma.

Age differences are basically related to tectonism and sedimentary control, due to bathymetry and water temperature paleovariations. It can be speculated that many of these ranges or zones are not consistent time equivalents. Moreover, as Bandy (1966) pointed out, the initial appearance of critical morphotypes is not always synchronous at high and low latitudes.

The above mentioned zones are both a product of evolution and ecologically induced migration species. At this latitude, the zones are represented by elements of the California current system planktonic microbiota, as well as components of the North Equatorial current, along with the incursion of species from neighboring water masses of the Gulf of California itself.

The induced species migration is associated with the time and environmental transgressive nature of some foraminiferal assemblages (as noted by several authors, like Natland [1950], and later compiled by Ingle [1967]).

On the basis of age relationships, it is concluded that the Santiago Diatomite ranges between 6.9 and 3 or possibly 2.5 Ma, which agrees with the tectonic framework and historical geology of the Gulf of California.

Biostratigraphic data from the area indicate that toward the west, sediments decrease in age, while paleoecological evidence offers for the Santiago Diatomite a more or less shallow environment at the base and, later up on the section a much more deeper paleobathymetry with subsequent erosion and, in general for the Santiago valley toward the west and southwest, the environment is shallower.

The paleoenvironmental evidences and ages obtained in previous works for each locality and the information from the Santiago Diatomite micropaleontological study are in agreement with Espinosa-Arrubarrena's (1979) proposal, on the existence of a paleobasin located at Rancho Algodones and to the southwest. It is suggested that this paleobay began its development at basal late Miocene, probably with a shallow seaway to the south and a preexisting river canyon to the east.

During early Pliocene, the paleobasin was located to the NE and SW of the Santiago valley, and reached the Rancho Algodones area during middle-late Pliocene. The deeper side of the bay (the canyon area) was on the northeast, and it was shallower at Rancho Algodones; to the south, the terrestrial data (Miller, 1980; Torres-Roldán, 1980) offer evidence for a Pliocene and post-Pliocene regressive event, probably associated with the sea level fluctuations and subaerial erosion. In the Algodones area, the granite topographic expression is comparatively steep hill with rounded boulders, a characteristic of aerial erosion; these hills are flanked by marine upper Pliocene sediments, that definitely prove aerial erosion prior to submergence.

During middle?-late Miocene, submergence occurred as a result of the Gulf of California diffuse-extension spreading process; the Santiago complex became part of the Neogene cycle of basin formation constituting a depocenter.

Subsequently, during and after submergence, a marine process reshaped the granitic boulder complex (oldland valley) to produce the present submarine canyon type, with gorge heads as a product of recent erosion. This reconstruction of the tip of Baja California disagrees with Anderson's (1971) proposal that it might have been a true island between 25–3 Ma. Miller (1980) suggests that the contact with the mainland was maintained until 4 Ma. The author believes, on the other hand, that the Pliocene faunas are best explained by migrations down a paleopeninsula which was connected to the mainland in a similar way as today. At times, part of this peninsula was separated by seaways, such as the one that existed in the isthmus of La Paz during the Pleistocene, which accounts for the subspecific diversity of the present faunas.

Curray and coworkers (1982) pointed out that the first phase of the gulf opening started 5.5 Ma and that there is no evidence for the 400 to 500 km of opening required to place Baja California's tip at a side of Cabo Corrientes, Jalisco. Moreover, these authors stated that the peninsula essentially separated from the mainland as a unit.

This model is also supported by paleobiogeographic and genetic herpetofauna studies (Murphy, 1983), which suggest that Miller's data support instead of a mainland attachment maintained until 4 Ma, the concept of a continuous unit between the Los Cabos Region and the rest of the peninsula by the Pliocene. Such a connection would allow the interchange of subtropical thorn-scrub and ***chaparral*** herpetofauna; besides, Murphy (1983) suggests that the spreading of the Gulf of California yielded two isolated subpopulations, one in the Los Cabos Region and other in the mainland. This is a transgulfian vicariance and considers Baja California as an evolutionary center, instead of a refuge harboring a relict herpetofauna.

For the foregoing, a great number of studies is needed to understand the complexity of this area.

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PLATES 1–6

PLATE 1

PLANKTONIC AND BENTHIC FORAMINIFERA

Figure 1. ***Lenticulina cushmani*** (Galloway and Wissler), lateral view x 47, sample 1.

—— 2. ***Buliminella subfusiformis*** (Cushman), lateral view x 98, sample 1.

—— 3. ***Nonionella miocenica*** Cushman, umbilical view x 57, sample 1.

—— 4. ***Reusella pacifica*** Cushman and McCulloch, lateral view x 50, sample 1.

—— 5. ***Siphonodosaria insecta*** (Schwager), lateral view x 53, sample 1.

—— 6. ***Bolivina rankinii*** Kleinpell, lateral view x 122, sample 1.

—— 7. ***Laterostomella*** sp., lateral view x 122, sample 1.

—— 8. ***Buliminella elegantissima*** (d'Orbigny), lateral view x 135, sample 1.

—— 9. ***Bolivina subadvena*** Cushman, lateral view x 63, sample 1.

—— 10. ***Bolivina interjuncta bicostata*** (Cushman), lateral view x 43, sample 1.

—— 11. ***Bolivina obliqua*** Barbat and Johnson, lateral view x 63, sample 1.

—— 12. ***Bolivina tongi*** Cushman, lateral view x 76, sample 1.

—— 13. ***Bolivina cochei*** Cushman and Adams, lateral view x 67, sample 1.

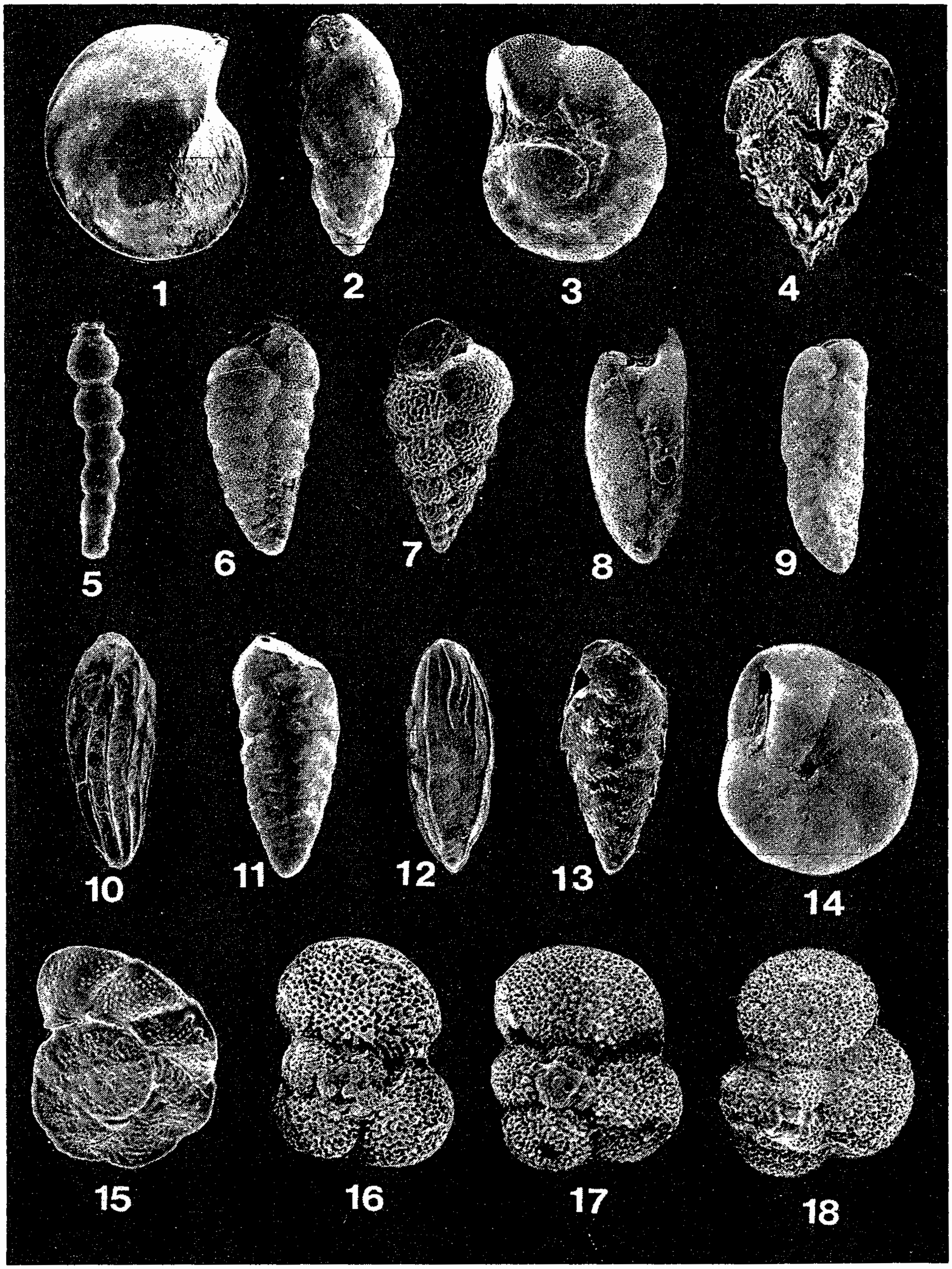
—— 14. ***Epistominella pacifica*** (Cushman) var., umbilical view x 151, sample 1.

—— 15. ***Discorbis campanulata*** (Galloway and Wissler), spiral view x 85, sample 1.

—— 16. ***Globigerina bulloides bulloides*** d'Orbigny, spiral view x 103, sample 2.

—— 17. ***Globigerina apertura*** Cushman, spiral view x 90, sample 2.

—— 18. ***Globigerina bulloides riveroae*** Bolli and Bermúdez, spiral view x 88, sample 2.



PLANKTONIC AND BENTHIC FORAMINIFERA

PLATE 2

PLANKTONIC FORAMINIFERA

Figure 1. *Globigerina bulloides quadrilatera* Galloway and Wissler, spiral view x 94, sample 2.

—— 2. *Globigerina bulloides umbilicata* Orr and Zaitzeff, spiral view x 178, sample 2.

—— 3. *Globigerinita uvula uvula* (Ehrenberg), spiral view x 178, sample 4.

—— 4. *Globigerina pachyderma incompta* Cifelli. (a) spiral view x 110; (b) umbilical view x 106; sample 7.

—— 5. *Globigerina pachyderma pachyderma* (Ehrenberg). (a) spiral view x 92; (b) umbilical view x 100; sample 1.

—— 6. *Globorotalia humerosa humerosa* Takayanagi and Saito, spiral view x 65, sample 6.

—— 7. *Globigerina quinqueloba* Natland. (a) umbilical view x 151; (b) spiral view x 110; sample 4.

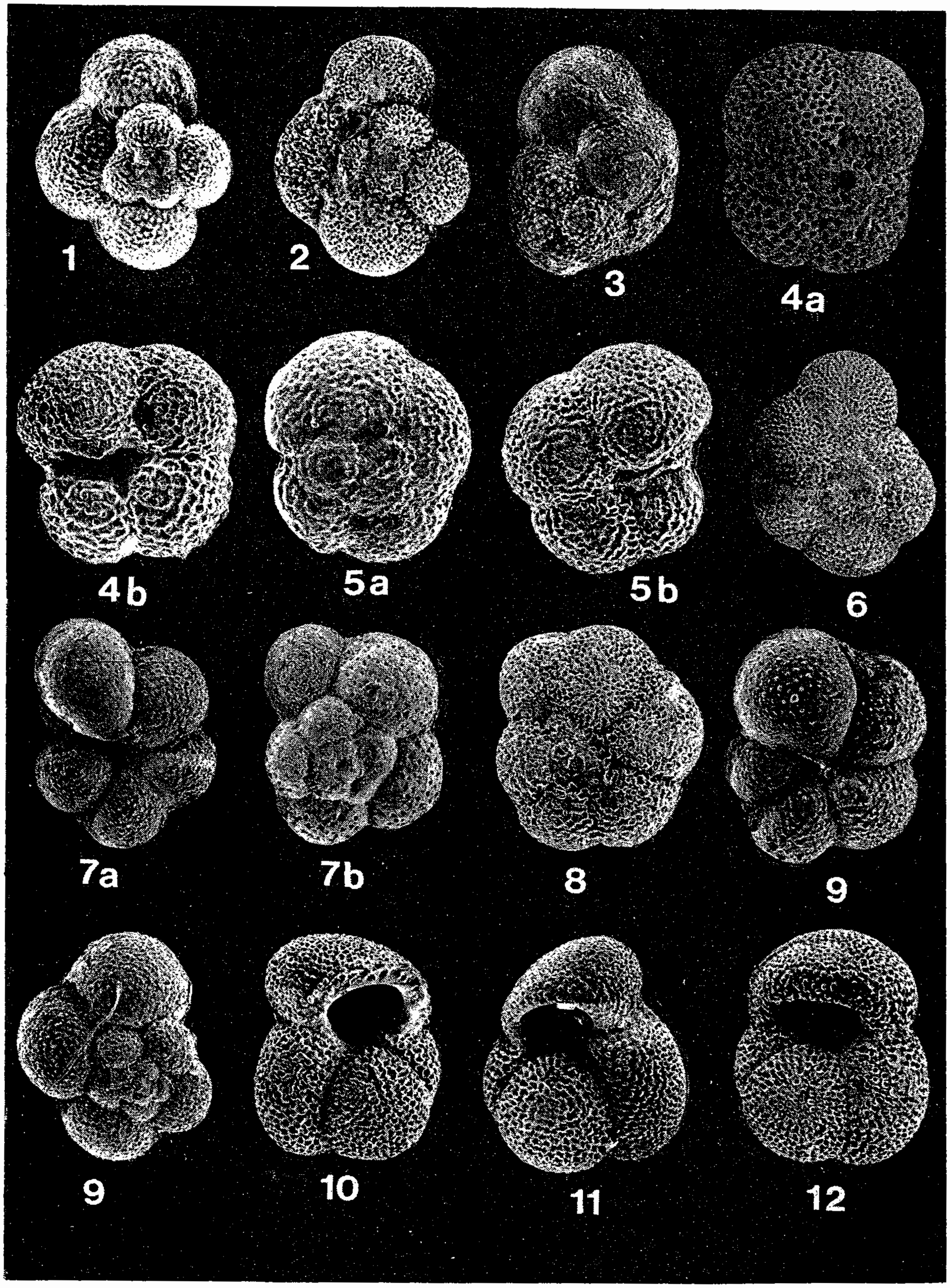
—— 8. *Neogloboquadrina dutertrei blowi* Rögl and Bolli, spiral view x 85, sample 5.

—— 9. *Turborotalita iota* (Parker). (a) umbilical view x 79; (b) spiral view x 65; sample 4.

—— 10. *Globigerinoides obliquus extremus* Bolli and Bermúdez, umbilical view x 75, sample 1.

—— 11. *Globigerinoides obliquus obliquus* Bolli, umbilical view x 80, sample 1.

—— 12. *Globigerinoides ruber* (d'Orbigny), umbilical view x 66, sample 3.



PLANKTONIC FORAMINIFERA

PLATE 3

PLANKTONIC FORAMINIFERA

Figure 1. *Globigerinoides amplus* Perconig, umbilical view x 67, sample 3.

—— 2. *Sphaeroidinella* sp. (a) fragment of the last chamber, outside view x 79; (b) inside view x 81.5; sample 20.

—— 3. *Pulleniatina primalis* Banner and Blow, spiral view x 77.7, sample 3.

—— 4. *Globoquadrina altispira altispira* Cushman and Jarvis. (a) spiral view x 67; (b) umbilical view x 82; sample 5.

—— 5. *Globorotalia tumida tumida* (Brady), spiral view x 53, sample 10.

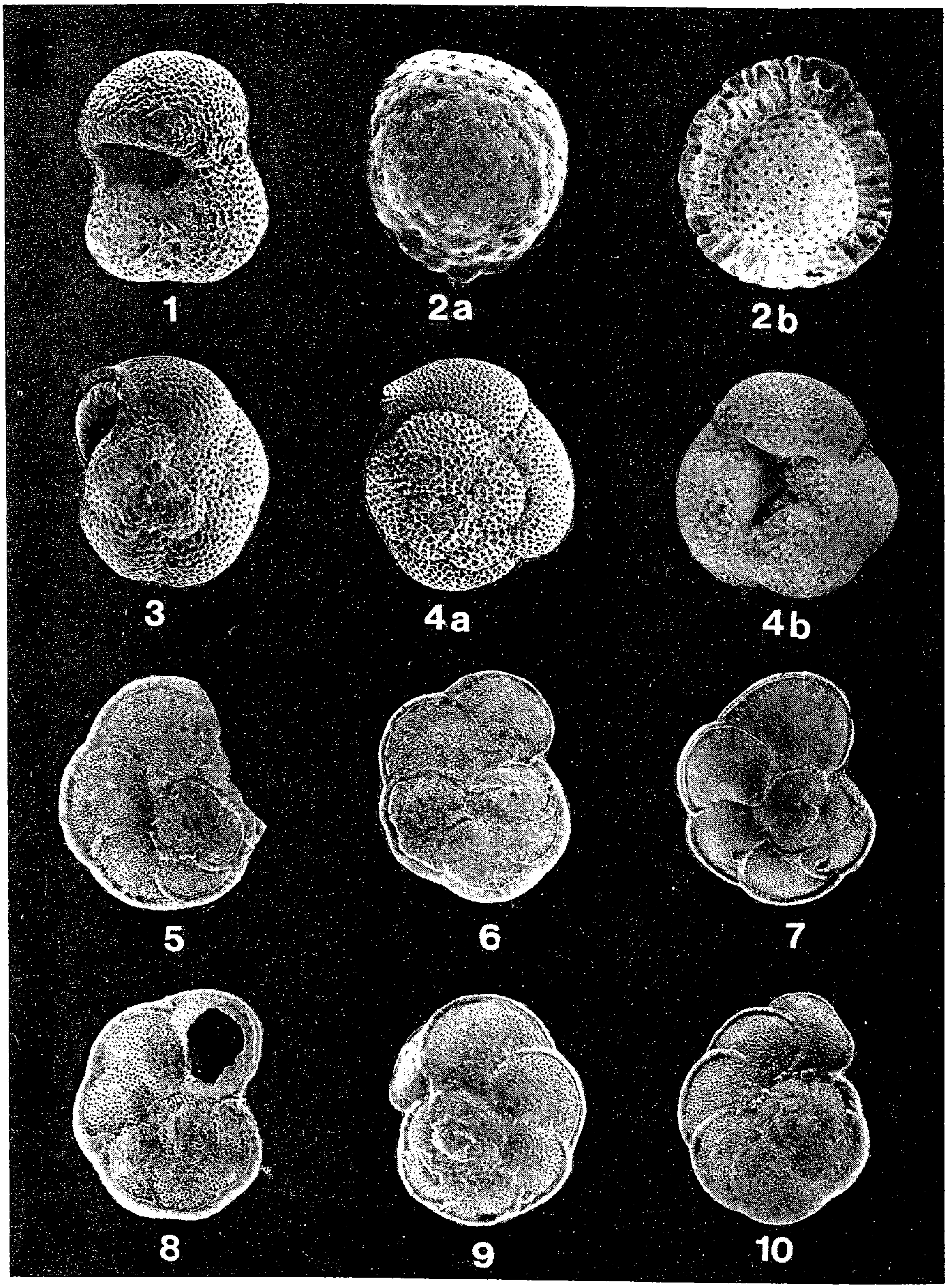
—— 6. *Globorotalia menardii* s.l. (Parker, Jones and Brady), spiral view x 53, sample 10.

—— 7. *Globorotalia pseudomiocenica* Bolli and Bermúdez, spiral view x 54, sample 16.

—— 8. *Globorotalia miocenica* Palmer, spiral view x 72, sample 20.

—— 9. *Globorotalia menardii* "B" of Bolli and Premoli-Silva, 1973, spiral view x 60, sample 19.

—— 10. *Globorotalia multicamerata* s.l. Cushman and Jarvis, spiral view x 50, sample 16.



PLANKTONIC FORAMINIFERA

PLATE 4

CALCAREOUS NANNOPLANKTON

Specimens in cross-polarized light, approximately x 2,000.

Figure 1. *Thoracosphaera heimii* (Lohmann), sample 7.

—— 2. *Rhabdosphaera clavigera* Murray and Blackmann, sample 9.

—— 3. *Ceratolithus* sp., sample 10.

—— 4. *Sphenolithus abies* Deflandre, sample 10.

—— 5. *Ceratolithus* sp. cf. *C. telesmus* Norris, sample 10.

—— 6. *Pontosphaera multipora* (Kamptner ex. Deflandre), sample 9.

—— 7. *Cyclococcolithus leptopora* Murray and Blackmann, sample 9.

—— 8. *Discolithina anisotrenia* Kamptner, sample 9.

—— 9. *Cyclococcolithus macintyrei* (Wallich), sample 9.

—— 10. *Coccolithus pelagicus* (Wallich), sample 5.

—— 11. *Helicosphaera kamptneri* Hay and Mohler. (a) sample 12; (b) + 45°, sample 16.

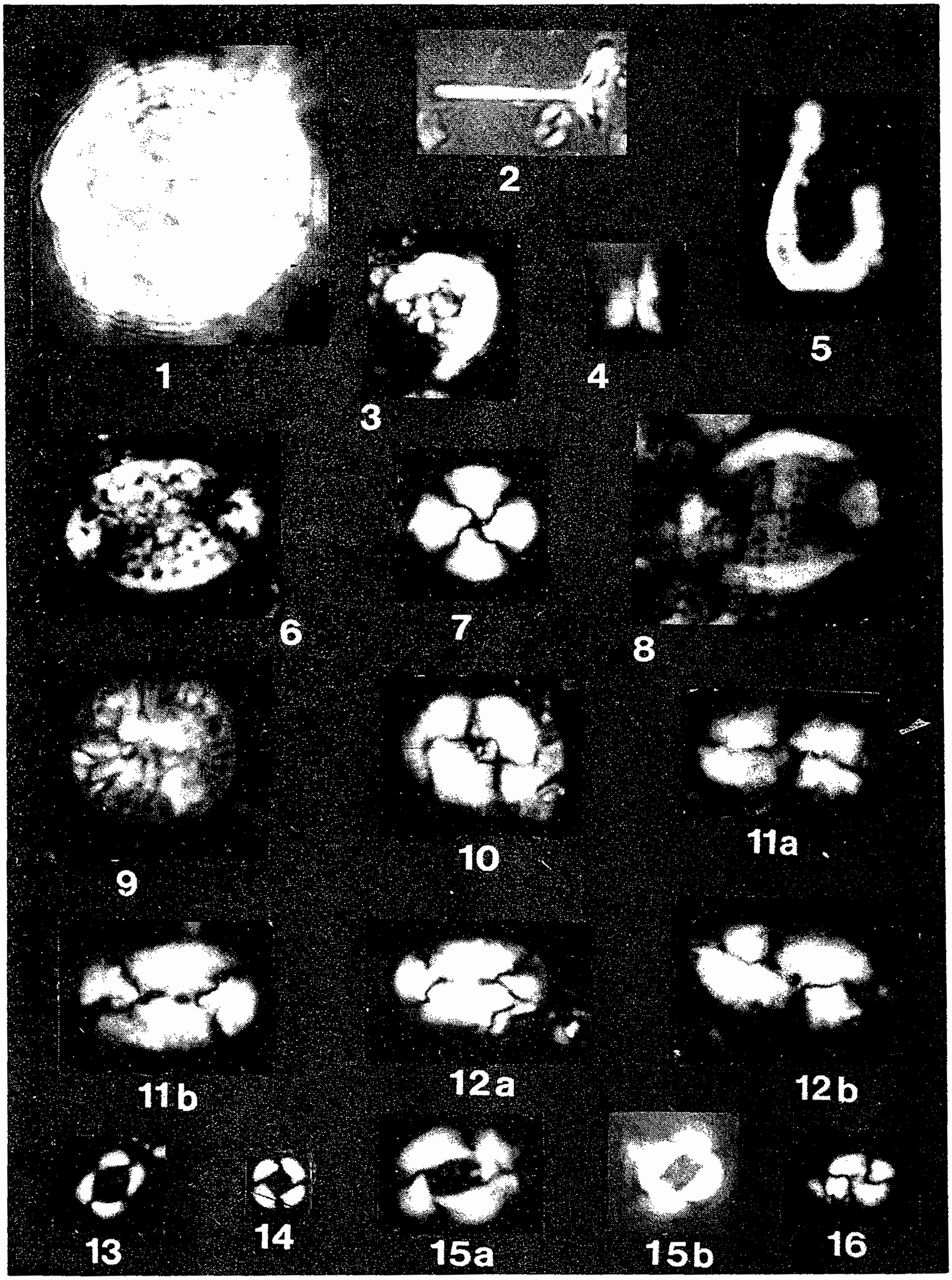
—— 12. *Helicosphaera sellii* Bukry and Bramlette. (a) sample 13; (b) + 45°, sample 12.

—— 13. *Pseudoemiliana lacunosa*? (Kamptner), sample 20.

—— 14. *Umbilicosphaera mirabilis* Lohmann, sample 18.

—— 15. *Reticulofenestra pseudoumbilica* Gartner). (a) sample 16; (b) + 45°, sample 16.

—— 16. *Gephyrocapsa*? small, sample 20.



CALCAREOUS NANNOPLANKTON

PLATE 5

CALCAREOUS NANNOPLANKTON

Figure 1. ***Helicosphaera granulata*** Bukry and Percival, proximal side x 7,800, sample 2.

—— 2. ***Helicosphaera kamptneri*** Hay and Mohler, proximal side x 8,600, sample 12.

—— 3. ***Gephyrocapsa***? small, distal side x 1,000, sample 20.

—— 4. ***Helicosphaera sellii*** Bukry and Bramlette, proximal side x 1,000, sample 12.

—— 5. ***Cyclococcolithus macintyrei*** (Bukry and Bramlette), distal side x 1,000, sample 8.

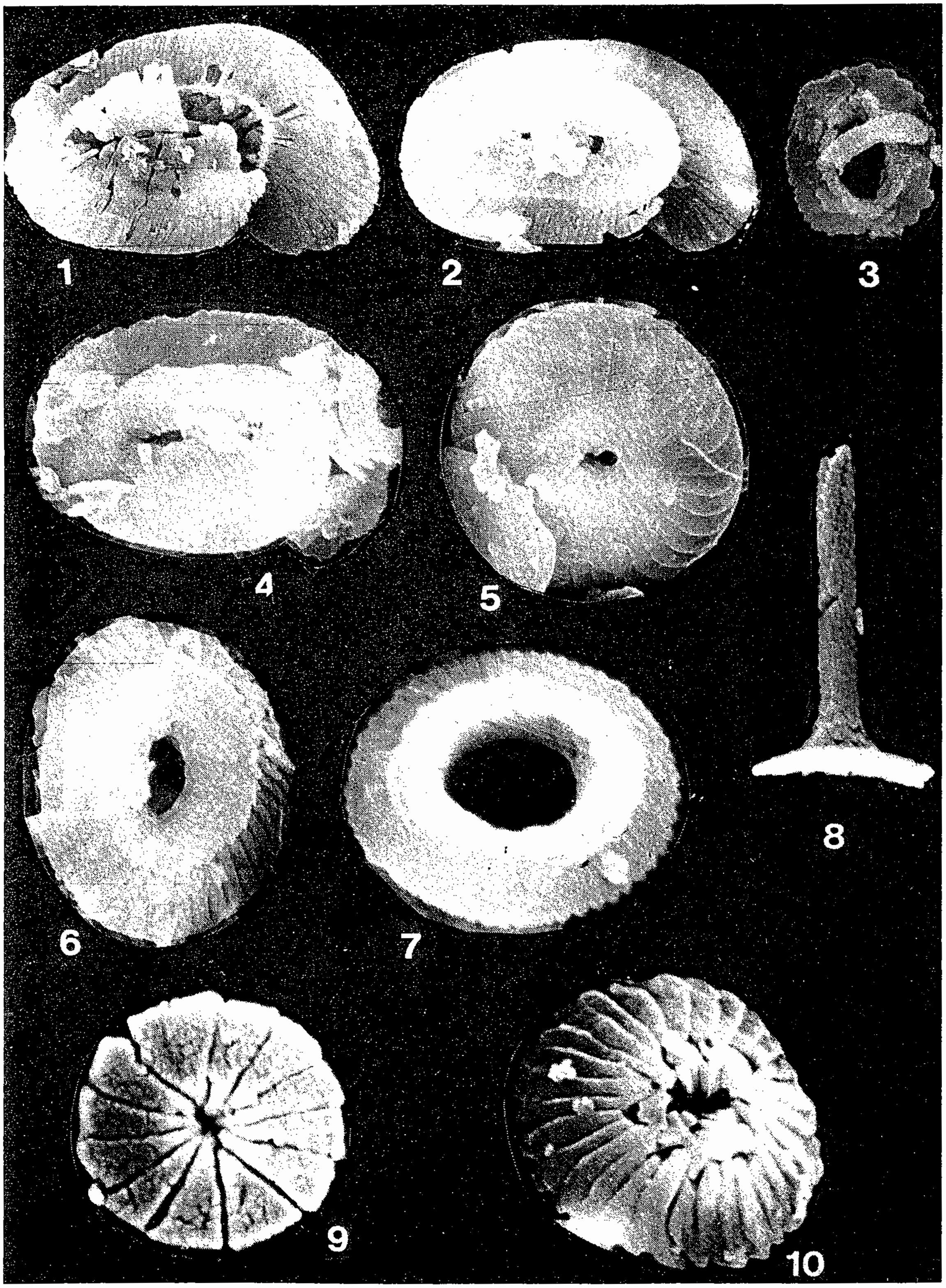
—— 6. ***Coccolithus pelagicus*** (Wallich), distal side x 1,000, sample 5.

—— 7. ***Reticulofenestra pseudoumbilica*** (Gartner), distal side x 6,000, sample 16.

—— 8. ***Rhabdosphaera clavigera*** Murray and Blackmann, side view x 3,500, sample 7.

—— 9. ***Hayaster*** sp. cf. ***H. perplexus*** (Bramlette and Riedel), distal side x 9,400, sample 16.

—— 10. ***Crenalithus doronicoides*** Black and Barnes, distal side x 6,000, sample 16.



CALCAREOUS NANNOPLANKTON

PLATE 6

CALCAREOUS NANNOPLANKTON

Figure 1. *Discoaster surculus* Martini and Bramlette, distal side x 5,400, sample 21.

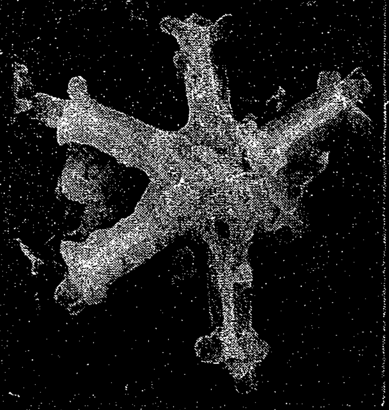
—— 2. *Discoaster brouweri* Tan, distal side x 6,500, sample 16.

—— 3. *Discoaster quinqueramus* Gartner, distal side x 6,600, sample 2.

—— 4. *Discoaster pentaradiatus* Tan, distal side x 4,800, sample 8.

—— 5. *Discoaster* sp. cf. *D. asymmetricus* Gartner, phase contrast, distal side x 2,000, sample 2.

—— 6. *Discoaster variabilis* Martini and Bramlette, distal side x 3,000, sample 16.



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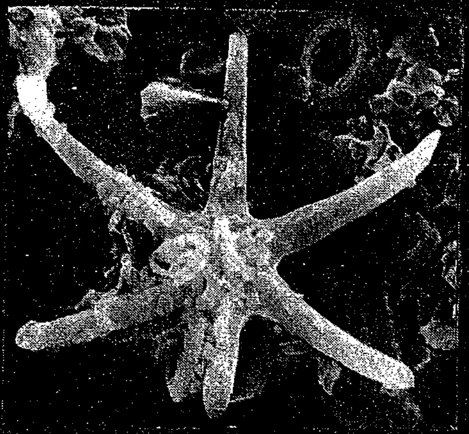

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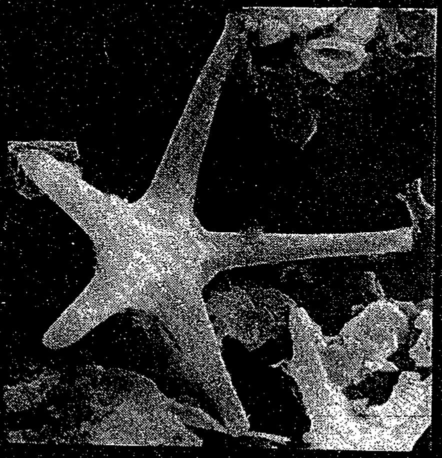

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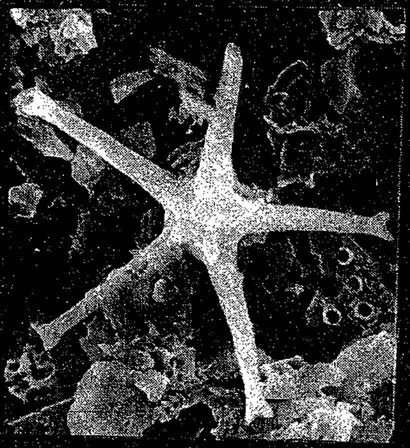

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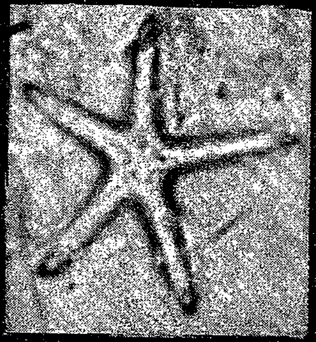

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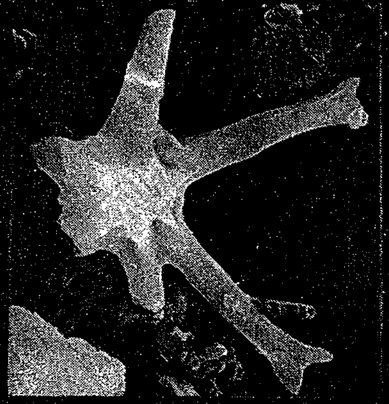

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CALCAREOUS NANNOPLANKTON