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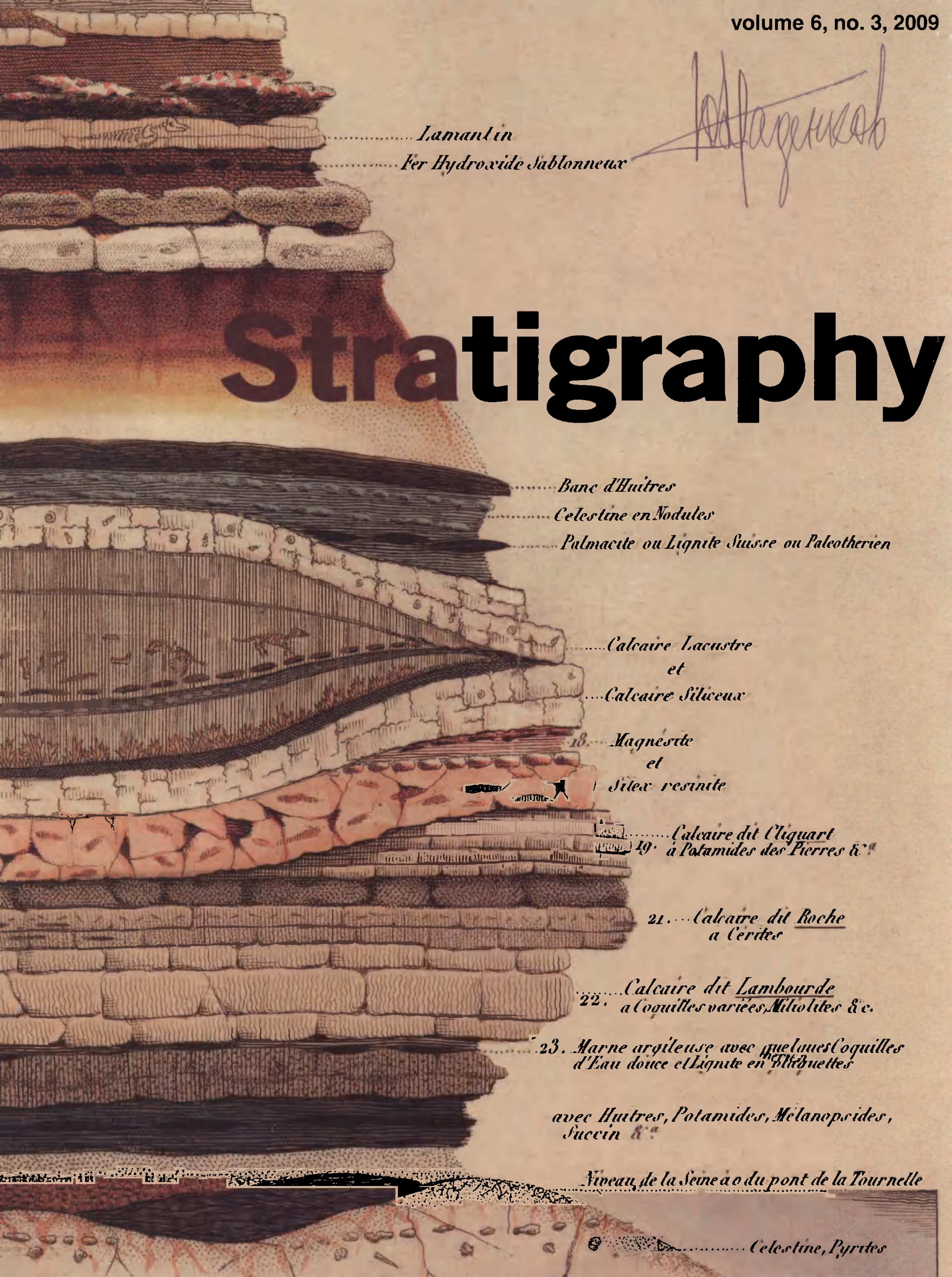
Stratigraphy



The Jurassic-Cretaceous boundary: new data from North America and the Caribbean

Emile A. Pessagno, Jr.[1], Abelardo Cantú-Chapa[2], James M. Mattinson[3], Xiangying Meng[1], and Seyed Mohsen Kariminia[1]

[1]*Programs in Geosciences, University of Texas at Dallas, P.O. Box 830688, Richardson, Texas 75083-0688 (Contribution No. 1096)*
[2]*Instituto Politecnico Nacional, Escuela Superior de Ingenieria y Arquitectura, Unidad Zacatenco, Section de Estudios de Posgrado e Insvestigacion, Fuente de Mirador No. 20, Lomas Tecamachalco, C.P. 53950, Mexico, D. F., Mexico*
[3]*Department of Geological Sciences, University of California, Santa Barbara, California 93106*
email: pessagno@utdallas.edu

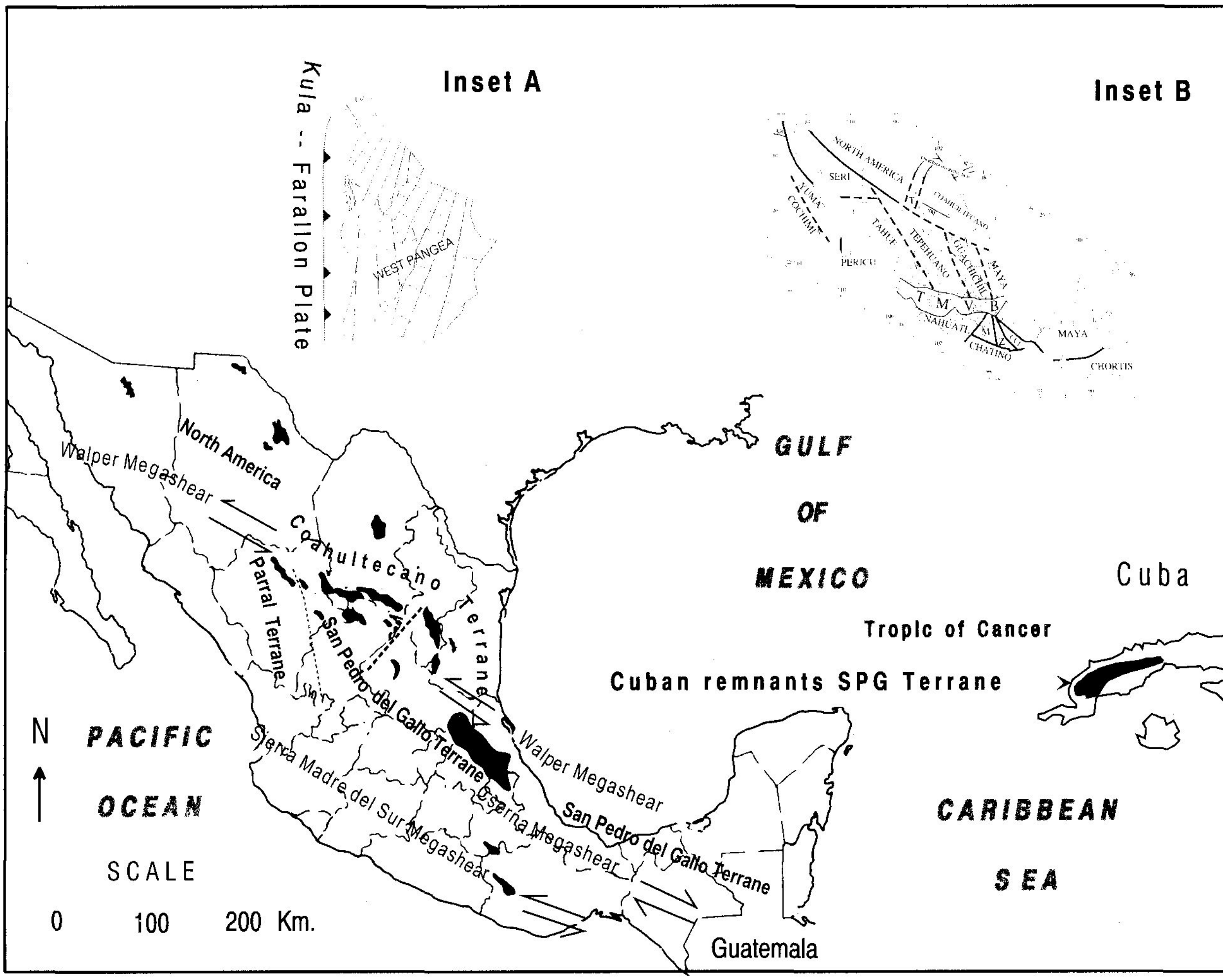
ABSTRACT: The Jurassic-Cretaceous boundary is the most problematic of all Phanerozoic system boundaries. Its definition is obscured by almost imperceptible faunal and floral change, nomenclatural problems resulting from the poor definition of its bounding stages, the over reliance of calpionellids for correlation, and the provinciality of ammonite zones in the European type area. The unfortunate decision of ammonite stratigraphers to use Calpionella Zone B to mark the base of the Berriasian set back the resolution of the Jurassic-Cretaceous boundary problem by thirty-five years in Europe, North America, and elsewhere. In this report a more detailed radiolarian zonation for the Upper Jurassic is introduced. The radiolarian biostratigraphy has been integrated with that of the North American ammonite, *Buchia*, calcareous nannofossils, and calpionellids as well as with new and existing U-Pb geochronometry. Investigations focused on uppermost Jurassic to lowermost Cretaceous successions in central Mexico, Baja California, California, and the West Indies have recognized four new subzones in both radiolarian **Zones 2** and **4**. Pillow basalt at La Désirade dated at 143.734ma ± 0.060ma [0.042%] (U-Pb zircon age on coeval plagiogranite) is intercalated with red ribbon chert containing an upper **Subzone 4 beta$_2$** radiolarian assemblage with corporeal taxon *Neovallupus* spp. This horizon likewise occurs in Mexico, where it can be directly related to ammonite-bearing strata occurring slightly below the boundary between Imlay's **Kossmatia-Durangites** and **Substeuero-ceras-Proniceras assemblages**, and can be recognized in Argentina and Antarctica as well. The composite data from the North American record indicate that the European calpionellid biozones are diachronous between Europe and the Western Hemisphere. The boundary between **Zone 4, Subzone 4 alpha$_2$** and **Zone 5, Subzone 5A**, which corresponds to the traditional Jurassic-Cretaceous boundary, is well represented at Grindstone Creek in the California Coast Ranges in the upper part of the **Buchia sp. aff. B. okensis Zone**. In view of our findings, however, it also may be desirable to consider two other alternatives for the placing the Jurassic-Cretaceous boundary: one at the base of new Radiolarian **Subzone 4 alpha$_1$** and the ammonite ***Substeuerocas-Proniceras* assemblage**, and the other at the base of the Valanginian. The traditional boundary horizon as well as the two alternatives can all be related to new and existing U-Pb geochronometric data. Nomenclatural problems surrounding formational units in the Mexican Upper Jurassic have been addressed. Four new members for the La Caja Formation; two new members for the Taman Formation; and one new formational unit, the Santa Rosa Formation have been introduced.

INTRODUCTION

The boundary between the Jurassic and Cretaceous is the most problematical of all Phanerozoic system boundaries. Moreover, it is an untidy problem that mars the development of an accurate geochronologic ("time") scale for the Mesozoic and, as a consequence, effects the dating of important events in earth history such as the Nevadan Orogeny in the Cordilleran Region of North America.

The Cretaceous System was first formally described in 1822 by d'Halloy for strata cropping out in the Paris Basin whereas the Jurassic System was first introduced by Brongniart (1829) for strata cropping out in the Jura Mountains in eastern France and Switzerland. Subsequently, Thurmann (1836) referred the strata overlying the Jurassic deposits in the Jura Mountains to the Neocomian. In 1852 d'Orbigny placed the Jurassic-Cretaceous boundary between the Portlandian and Neocomian and divided the Neocomian into two substages. The lower of these two substages corresponds to the present-day Berriasian, Valanginian, and Hauterivian (Saks et al. 1975, p. 4). In 1853, Desor established the Valanginian stage at the base of the Cretaceous at the Neuchâtel canton of Switzerland. Saks et al. (1975, p. 4) indicated that Desor "—matched the lower boundary of the Valanginian (and accordingly of the whole system) with the position of the roof of the freshwater sediments of the Purbeckian which crown the section of the Jurassic in the Anglo-Paris and Fraconian basins and, in particular, underlie the marine Valanginian in the stratotype section." In 1865 Oppel established that the upper horizons of the Jurassic system in Southern Europe consisted of marine strata. Oppel (1865, p. 535) included these marine strata in his new Tithonian stage. Unfortunately, he failed to designate a stratotype. In 1867 Pictet introduced the name *Berriasian* for a limestone horizon in southern France near the village of Berrias. He placed the Berriasian at the base of the Cretaceous.

The term *Tithonian* has been used by a variety of investigators with completely different meanings. At the moment, the Tithonian is defined by ammonite zones (text-figure 1). In the Tethyan Realm the top of the Tithonian is defined by the top of the **Durangites Zone** in Southern Europe and by the **Transitorius/Microacanthum Zone** in southeast France and Germany (text-figure 1). In the Boreal Realm the top of the Tithonian is frequently correlated with the top of the **Preplicomphalus Zone** (Geyssant

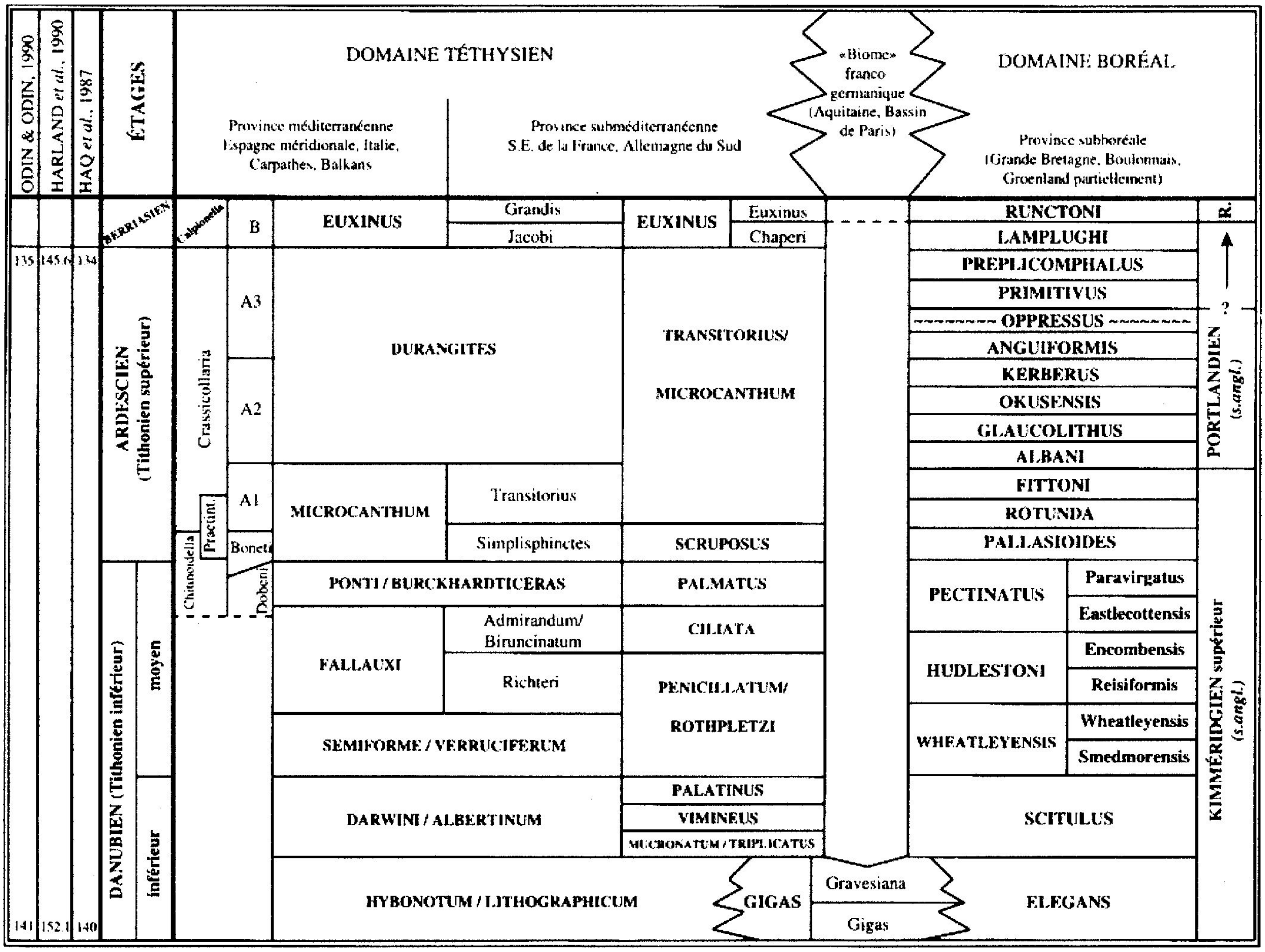


TEXT-FIGURE 1
Map showing distribution of terranes referred to in text. Distribution of megashears largely follows that of Longoria (1994). Off-set of Walper Megashear differs based on re-analysis of stratigraphic data during current study. **Inset A:** View of western Pangea showing geometric fit of Atlantic continents. The position of Mexico is outlined to illustrate overlap with South America. Approximately 70 to 80 percent of Mexico is overlapped by South America. Most workers utilize large strike-slip faults to bring Mexico to its present overlap position in their plate tectonic reconstructions. **Inset B:** Terrane map of Mexico of Sedlock et al. (1993). From Pessagno et al. (1999).

and Enay 1991; Geyssant 1997). As opposed to the Tithonian, the overlying Berriasian stage possesses a stratotype in southern France (Pictet 1867; Kilian 1890; LeHegarat 1973). In the central and southern Tethys the base of the Berriasian is marked by the base of the **Euxinus Zone** (Zeiss 1984, p. 104). However, the base of the **Euxinus Zone** is not exposed at the stratotype at Berrias in southern France; lowermost **Euxinus Zone** strata lack ammonites (Cope 2008). As a consequence, the Berriasian is a stage with a floating base. Workers are at liberty to use what ever criteria they wish to define its base.

It is perhaps ironic to note that chronostratigraphy (d'Orbigny 1840(41) p.600 [1850]) and biostratigraphy (Oppel 1856-1858, 1865) were both born in the Jurassic and Cretaceous systems. Although other criteria that have time significance are used today (e.g., magnetostratigraphy), d'Orbigny, Oppel, and other earlier stratigraphers, stressed the fossil content of the strata for defining stages. Since the day of Oppel, ammonite biozones have been utilized to define Jurassic and Cretaceous stage boundaries.

Stages are the cornerstone of chronostratigraphy; in essence, stage boundaries define system boundaries. Most system boundaries are characterized by marked faunal change. In the Mesozoic, for example, catastrophic faunal change occurs at the top of the Triassic and the Cretaceous. In contrast, faunal and floral changes that occur at the Jurassic-Cretaceous boundary are barely discernible (Cope 2008). In theory, system boundaries should coincide with major rather than minor changes in the paleontologic record. This sort of reasoning led Newell (1966, p. 75) to propose that Jurassic and Cretaceous strata be included in a single supersystem. Wiedmann (1973, p. 177), in an excellent report dealing with changes in the ammonite assemblage at Mesozoic system boundaries, found no evidence for a sharp faunal break either above or below the Berriasian. He proposed (ibid., p. 180) that the Jurassic-Cretaceous boundary be placed instead between the Berriasian and Valanginian and stated that "—it would be placed in analogy to the Triassic-Jurassic boundary-between the final extinction of the Tithonian perisphinctids (Berriasellidae) and the origin of Neocomian perisphinctids (Neocomitinae) and the origin of Cretaceous Ammonitina (Desmoceratacea)." In a

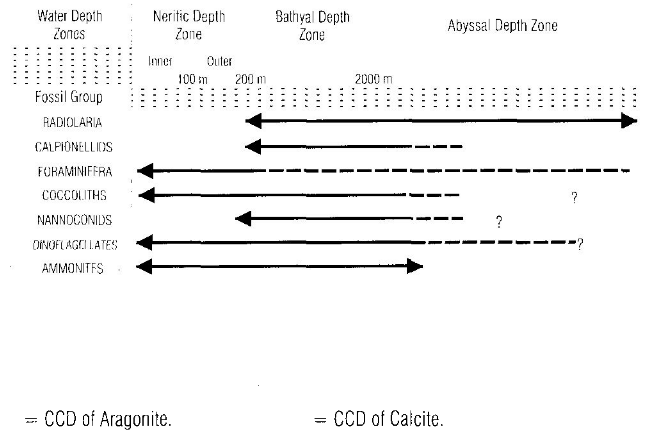


TEXT-FIGURE 2
European ammonite and calpionellid correlations from Geyssant (1997).

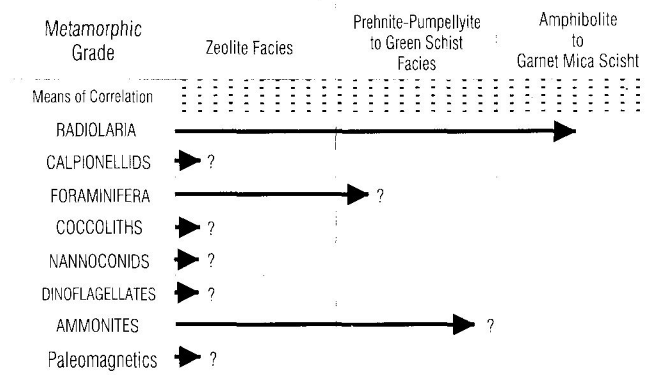
later report Wiedmann (1980) included the Berriasian as the uppermost substage of the Tithonian and placed the Jurassic-Cretaceous boundary at the base of the Valanginian.

The Jurassic-Cretaceous boundary problem is further complicated by the provincial nature of ammonites in highest Jurassic and lowest Cretaceous strata which, in turn, inhibits correlation between the Tethyan Realm and the Boreal Realm in the European type area. In addition, until recently, there has been little international agreement on what to call the terminal stage of the Jurassic (i. e., Tithonian, Volgian, or Portlandian). The name for the final stage of the Jurassic and where its type section was to be located became embroiled in international geopolitics. The English favored using the name "Portlandian" and wanted the type section to be in England; the Russians favored the name "Volgian" and wanted the type section to be in Russia; and the continental Europeans favored the name "Tithonian". However, after considerable debate, the International Subcommission on Jurassic Stratigraphy (ISJS: September 1990) endorsed the use of *Tithonian* for the final stage of the Jurassic. Moreover, the ISJS proposed that the Kimmeridgian be restricted to the French usage (*sensu gallico*) rather than the English usage (*sensu anglico*). At this time, the ISJS also determined that the "Volgian" still can be utilized in the Boreal Realm as the equivalent of the Tithonian. The selection of the Tithonian as the final stage for the Jurassic is by no means without its problems as well in that the Tithonian lacks a stratotype (see above). As noted above, the Berriasian possesses a stratotype, albeit an unsatisfactory one, in Southern France. However, as in the case of the Tithonian, correlations with ammonites between the Boreal and Tethyan Realms in the European type area are by no means certain because of ammonite provincialism.

The lack of dramatic change in the ammonite assemblage in the upper Tithonian and lower Berriasian has led many ammonite biostratigraphers to embrace the base of calpionellid Zone B to mark the base of the Berriasian and to delimit the Jurassic-Cretaceous boundary (Colloque sur la limite Jurassique/Cretacé de Lyon-Neuchâtel, 1973; Geyssant 1997, p. 97). The base of this calpionellid zone had been correlated with the base of the *Berriasella jacobi* Zone (Text-figure 1). Although this undoubtedly seemed like an excellent decision at the time, it is fraught with many difficulties in correlating Tethyan strata between Europe and North America. Moreover, it has hindered rather than helped the placement of the Jurassic-Cretaceous boundary. These problems will be addressed in detail elsewhere this report.



TEXT-FIGURE 3
Stratigraphic potential of various groups of pelagic fossils with respect to water depth.



TEXT-FIGURE 4
Chronostratigraphic potential of various groups of pelagic fossils and paleomagnetics with respect to metamorphism.

It is apparent that the resolution of the Jurassic-Cretaceous boundary problem requires the utilization of all methods of correlation that have chronostratigraphic significance (e.g., ammonites, planktonic microfossils, paleomagnetic reversals, geochronometry, and geochemistry). The purpose of this report is to present data from North America and the Caribbean that will hopefully aid future workers in placing the Jurassic-Cretaceous boundary. Much of this data is new and is derived from on-going studies in Mexico, California, and the Caribbean. Successions bearing ammonites and co-occurring Radiolaria from Argentina and Antarctica are also discussed.

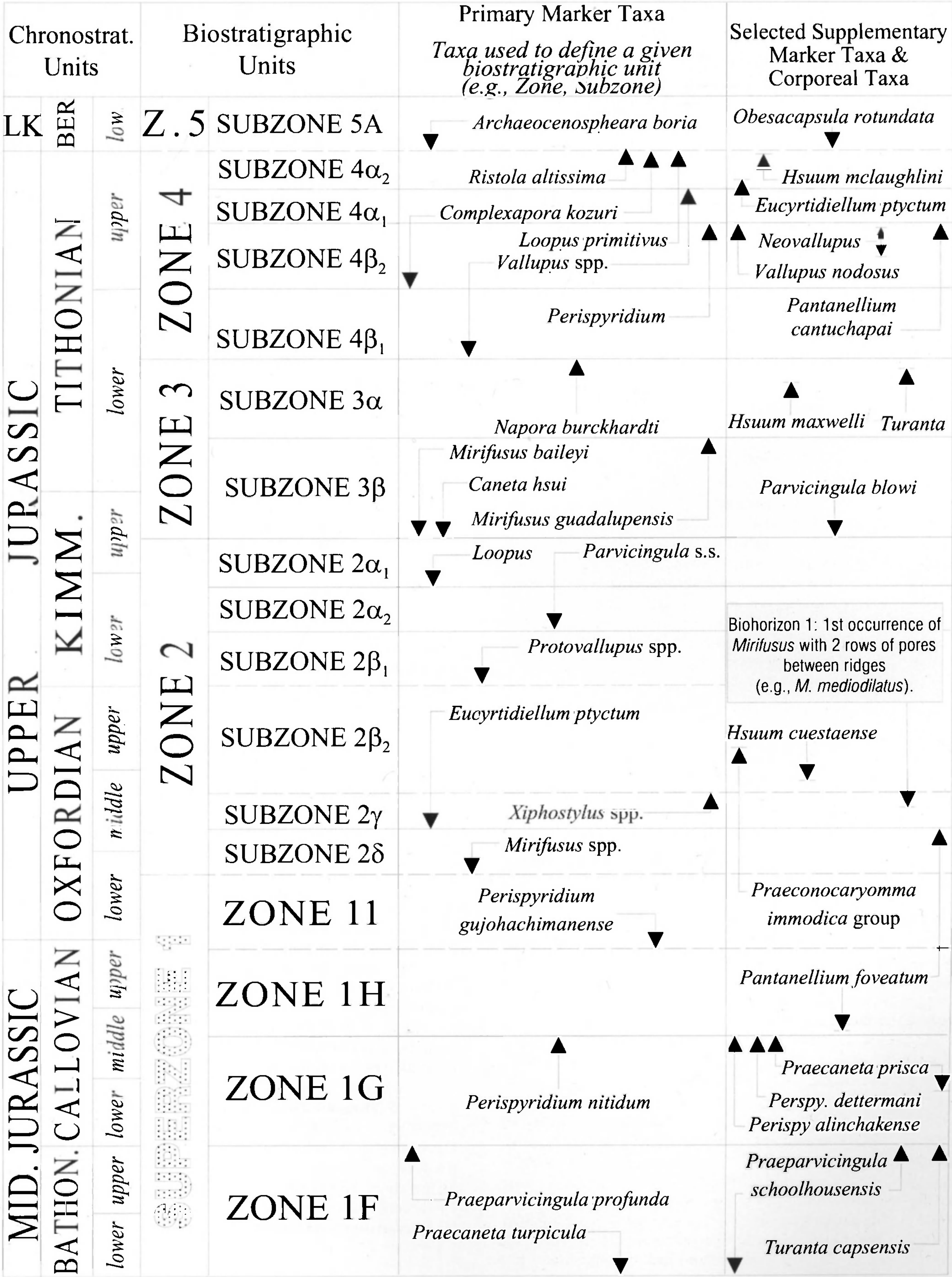
ASSESSMENT OF THE TOOLS OF CHRONOSTRATIGRAPY

In the Mesozoic ammonites and, to a lesser degree, bivalves have been the primary biostratigraphic tools for defining stage boundaries. Planktonic microfossils such as Radiolaria, planktonic foraminifera, dinoflagellates, and calcareous nannofossils have been underutilized in the Mesozoic for this purpose.

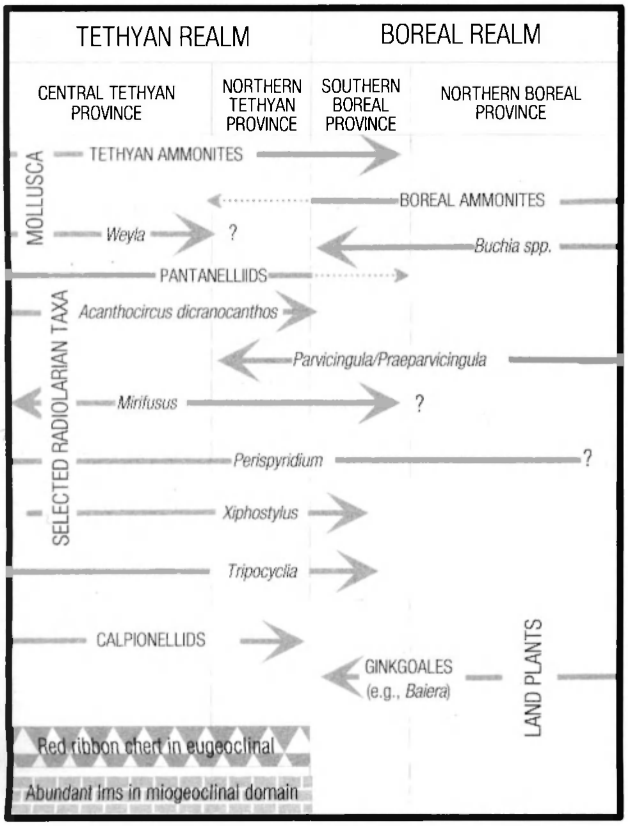
Assessment of fossil groups useful in defining chronostratigraphic units is presented in Text-figures 2 and 3. It is apparent from an examination of these text-figures that given the metamorphic grade of many ammonite-bearing successions in North America and elsewhere in the world, Radiolaria offer the best means of correlation with ammonite biozones among the planktonic microfossils. It has been the experience of the senior author that strata exposed to prehnite-pumpellyite to greenschist facies metamorphism contain well-preserved Radiolaria. This is documented by studies in the Klamath Mountains (Western Klamath Terrane. *See* Harper 1984, p. 1011; Pessagno and Blome 1988, 1990; Pessagno et al. 1993) and in the Eastern Alps (Kiessling 1992). Poorly preserved, but still identifiable, Upper Triassic Radiolaria have been observed by the senior author in samples from Baja California Sur together with conodonts having a CAI (conodont alteration index) of 8. According to Epstein et al. (1977, pp. 7-8; Text-figure 7) conodonts with an alteration index of CAI 8 occur in marble interbedded with garnet mica schist and amphibolite. In contrast, strata exposed to low grade zeolite grade metamorphism from the Izee Terrane (east-central Oregon) lack dinoflagellates and coccoliths. Because Radiolaria occur in strata exposed to zeolite to amphibolite-garnet-mica schist facies metamorphism, their stratigraphic utility extends far beyond that of other Jurassic and Cretaceous microfossils. Detailed radiolarian zonal schemes now exist for the Jurassic and Cretaceous (*e.g.*, Zonations of Baumgartner 1987; Baumgartner et al. 1987, 1995b; Pessagno et al. 1993; and Matsuoka 1986, 1992; Matsuoka and Yao 1986). The zonation proposed by Pessagno et al. (1987a, 1993; *emended herein: See* Appendix 1 *and* Text-figures 4, 33 herein) has been well-calibrated by ammonite chronostratigraphic data. Furthermore, because of the association of radiolarian chert with ophiolite complexes in North America and the Caribbean, it is often possible to relate radiolarian zonal data directly or indirectly (by superposition of strata on ophiolites) to radiometric dates. Interpillow radiolarian chert is commonly associated with pillow basalt in the upper volcanic member of a given ophiolite (e.g., See La Désirade herein).

The development of the M-sequence magnetic polarity time scale for the Late Jurassic to Early Cretaceous interval has advanced over the past two decades. Magnetic field reversals occur very rapidly, taking only approximately 5000 years; they are global in nature and, when properly calibrated biostratigraphically, can provide a precise chronostratigraphic tool across faunal and floral realm boundaries. Ogg et al. (1991) noted that there are no apparent changes in the relative spreading rates during the proposed Jurassic-Cretaceous boundary interval (M16 through M20). Larson and Hilde (1975) placed the Jurassic-Cretaceous boundary near M16; subsequent investigators have argued for a location near the old edge of M17 (Lowrie and Channell 1984) or near the base of reversed-polarity chron M18r (Lowrie and Ogg 1986; Ogg and Steiner 1988). Bralower et al. (1990, p. 70) suggest that the Ogg and Steiner proposal is logical because it is based on correlation between ammonite stratigraphy and magnetostratigraphy at the Berriasian stratotype. Unfortunately, the basal Berriasian strata at Berrias lack ammonites. Although magnetostratigraphy is a useful tool in chronostratigraphic studies, it is, for the most part, entirely dependent on a biostratigraphic foundation.

Few chemostratigraphic investigations have been undertaken involving the Jurassic-Cretaceous boundary. Nevertheless, studies by Jones (1992) of Sr geochemistry of the Late Jurassic and Early Cretaceous marine strata appear to be promising. These studies determined that the $^{87}Sr/^{86}Sr$ ratios of Late Jurassic and Early Cretaceous marine carbonates display a rapid increase from approximately 160ma to 130ma (0.70680 to 0.70745, respectively).



TEXT-FIGURE 5
Latest version of Middle and Upper Jurassic radiolarian zonation.



TEXT-FIGURE 6
Multiple criteria for recognizing Tethyan and Boreal realms.

Geochemical investigations, however, just like paleomagnetic investigations are entirely dependent on biostratigraphy.

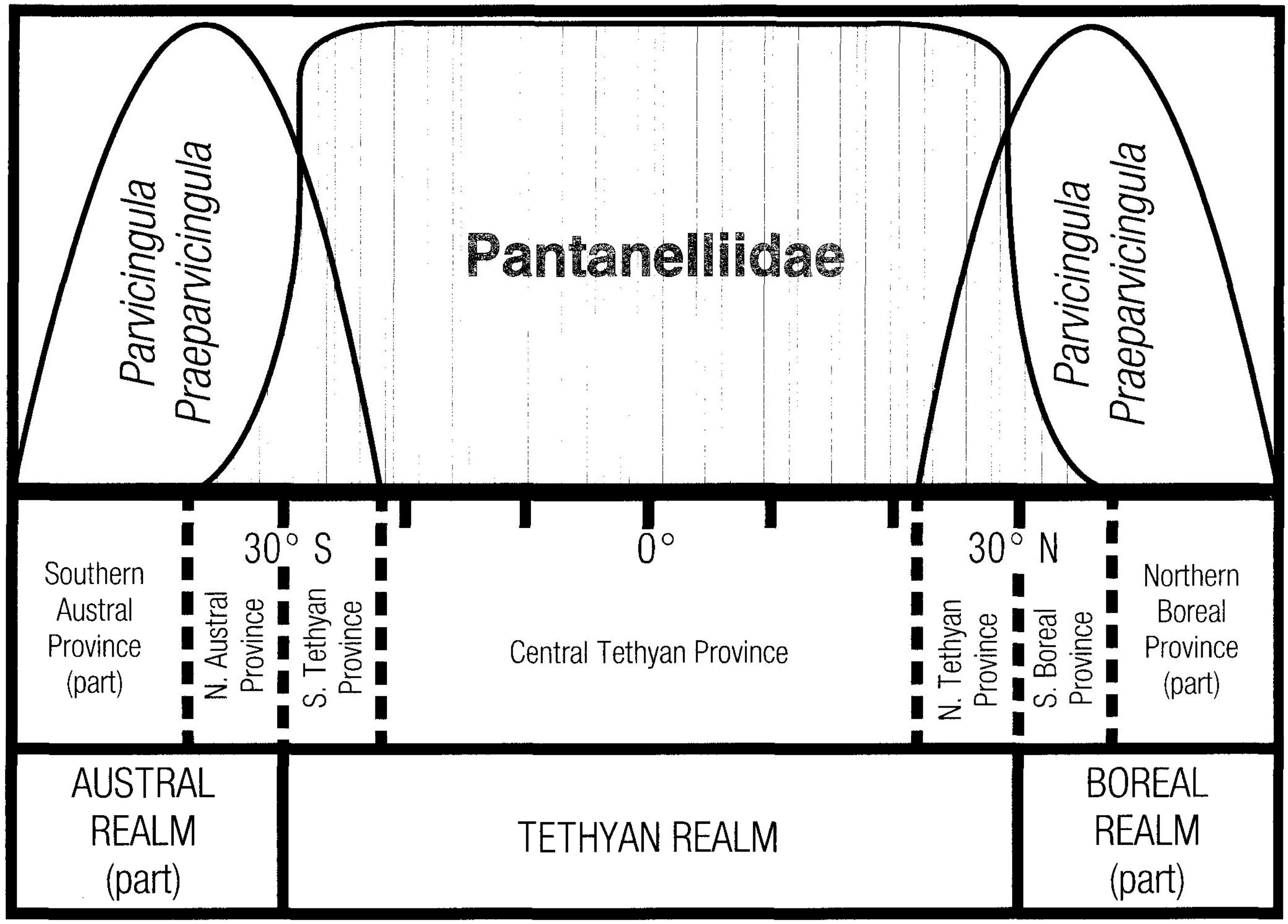
AMMONITE AND CALPIONELLID BIOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY IN EUROPE

Text-figure 1 shows biostratigraphic and chronostratigraphic correlations for the Tithonian stage in Europe by Geyssant (1997). Paleogeographically, Geyssant discussed the Tithonian of Europe within the framework of a Tethyan Domain and a Boreal Domain. The Tethyan Domain is divided into a Mediterranean province which includes southern Spain, Italy, the Carpathians, and the Balkans and a Submediterranean province which includes southeastern France and southern Germany. As noted previously, the provincial nature of the ammonite assemblage in the highest Jurassic and lowermost Cretaceous inhibits correlation of Tethyan strata in southeastern France and southern Germany with Boreal strata in England.

The Tithonian has been informally divided into three informal divisions: lower, middle, and upper by some workers (e.g., Arkell 1956) and two informal divisions: lower and upper by other workers (e.g., Imlay 1980; Enay 1964; Enay and Geyssant 1975; Geyssant 1997). These later workers utilized the first occurrence of calpionellids *s.l.* [= base of **Chitinoidella Zone** of Remane (1969, 1978, 1985)] to define the base of the upper Tithonian. Subsequently, Pessagno et al. (1984, p. 7) stated that this was a poor criterion to follow because this biohorizon is difficult to recognize in many Tethyan successions. *Chitinoidella* Doben possesses a microgranular test wall whereas true calpionellids such as *Calpionella* Lorenz possess a hyaline test wall comprised of radially arranged calcite crystals. These workers concluded that *Chitinoidella*, because of its test structure, does not lend itself to being preserved in limestone that has been even mildly altered. In contrast, calpionellids with hyaline tests are not as susceptible to diagenetic changes. As a consequence, Pessagno et al. (1984, p. 7) choose to utilize the first occurrence of hyaline calpionellids to mark the base of the upper Tithonian. This biohorizon corresponds to the base of the **Crassicollaria Zone** of Remane (1969, 1978, 1985). Geyssant (1997, Table 13, p. 100; see Text-figure 1 herein) did not correlate the boundary between the **Chitinoidella Zone** and the **Crassicollaria Zone** with the base of the upper Tithonian, but, instead, placed it in the lower part of the upper Tithonian. Unfortunately, as will be subsequently borne out in this report, the first occurrence of hyaline calpionellids event/base of **Crassicollaria Zone** is diachronous between Europe and North America and occurs in the upper part of the lower Tithonian rather than either at the base of the upper Tithonian or in the lower part of the upper Tithonian. Geyssant (1997, p. 97. See Text-figure 1 herein) divided the Tithonian into two substages: the Danubian and the Ardescian corresponding respectively to the lower and upper Tithonian. The Danubian was first proposed by Rollier (1909) whereas the Ardescian was proposed by Toucas (1890). Since these substage names have not been formally endorsed by the International Subcommission on Jurassic stratigraphy, the informal terms "lower Tithonian" and "upper Tithonian" will be utilized in the present report.

In the Mediterranean Province Geyssant (1997) included the upper Tithonian in a lower **Microcanthum Zone** and an upper **Durangites Zone**. The **Microcanthum Zone** is subdivided into a lower **Simplisphinctes Subzone** and an upper **Transitorius Subzone.** The **Microcanthum Zone** and its lower subzone overlie the **Ponti/ Burckhardticeras Zone** of the lower Tithonian (*See* Text-figure 1). In the Mediterranean Province of Geyssant the **Durangites Zone** marks the top of the Tithonian and is overlain by the **Euxinus Zone** of the lowermost Berriasian. As noted above, however, it can not be established that the base of the **Euxinus Zone** is exposed at the stratotype at Berrias in Southern France. In the Submediterranean Province Geyssant (1997 p. 98-99) correlated the base of the upper Tithonian with the base of the **Scruposus Zone**. The **Scruposus Zone** overlies the **Palmatus Zone** of the lower Tithonian. The remainder of the upper Tithonian was placed by Geyssant in the **Transitorius/Microacanthum Zone**. This zone marks the top of the Jurassic and the top of the Tithonian and underlies **Euxinus Zone, Chaperi Subzone** of the lower Berriasian.

In the Boreal Domain Geyssant (1997) correlated the base of the upper Tithonian in England with the base of the **Pallasioides Zone** (= upper Kimmerdigian *sensu anglico*). This zone overlies the **Pectinatus Zone, Paravirgatus Subzone** of the lower Tithonian (= upper Kimmeridigian *sensu anglico*). According to Geyssant (1997, Table III) (see Text-Figure 1 herein) the top of the Jurassic and accordingly, the top of the Tithonian is marked by the top of the **Preplicomphalus Zone** whereas the base of the Cretaceous and the base of the Berriasian is marked by the base of the overlying **Lamplughi Zone** (= Portlandian *sensu anglico*).



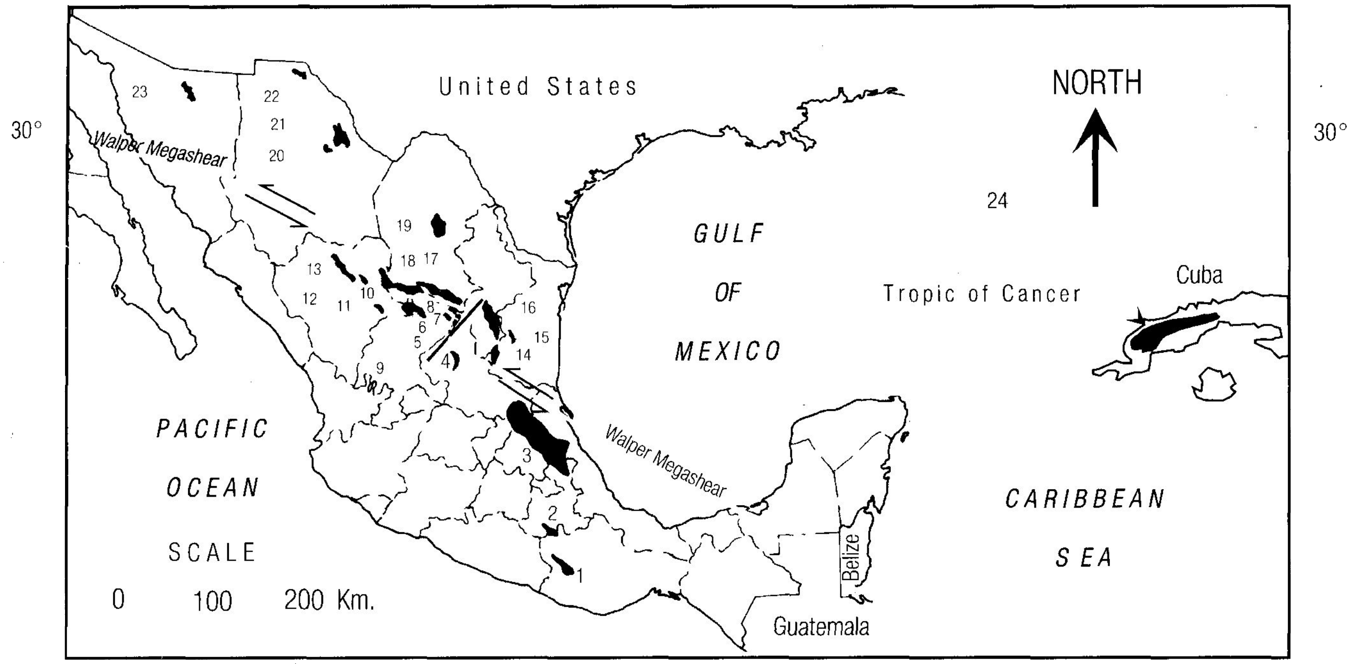
TEXT-FIGURE 7
Pessagno—Blome radiolarian model.

AMMONITE, CALCAREOUS NANNOPLANKTO, CALPIONELLID, RADIOLARIAN, AND BUCHIID BIOSTRATIGRAPHY IN NORTH AMERICA, THE CARIBBEAN, ARGENTINA, AND THE ANTARCTIC PENINSULA

Faunal and Floral Realms and Provinces

In Europe extremely rapid faunal change between the Tethyan Realm and Boreal Realm inhibits biostratigraphic and chronostratigraphic correlation of uppermost Jurassic and lowermost Cretaceous strata. In strong contrast, the faunal change between the Tethyan Realm and Boreal Realm in North America and the Caribbean is not as pronounced. It is perhaps fortuitous that this gradual transition in faunal change is for the most part related to plate tectonics rather than paleooceanography (See below).

Pessagno and Blome (1986), Pessagno et al. (1987a, 1993a, 1993b, 1999, 2001), Pessagno and Martin (2003), and Pessagno (2006) established a paleogeographic model for the Jurassic based not only on the presence of microfossils such as Radiolaria and calpionellids, but also on megafossils such as ammonites and *Buchia* as well as paleolatitudinal data from magnetostratigraphic investigations. These workers divided Tethyan Realm into three provinces: **(1)** A **Southern Tethyan Province** (~ 22° to 29° S); (2) a **Central Tethyan Province** (21° S to 21° N); and (3) a **Northern Tethyan Province** (~22° N to 29° N). The boundary between the Tethyan Realm and the Boreal Realm in the Northern Hemisphere was placed at 30° N. Moreover, they divided the Boreal Realm into a **Southern Boreal Province** and a **Northern Boreal Province** and the **Austral Realm** into a **Northern Austral Province** and a **Southern Austral Province** (Text-figures 5-6). The Northern Tethyan Province includes microfossils and megafossils that are dominantly Tethyan in nature as well as those that make their first appearance at Northern Tethyan paleolatitudes and increase progressively in abundance in the Southern Boreal Province (e.g., the radiolarian genera *Praeparvicingula* and *Parvicingula*) (*See* Text-figure 6). The Southern Boreal Province is characterized by a mixture of both Boreal and Tethyan microfossils and megafossils (e.g., calpionellids, rare members of the radiolarian Family Pantanelliidae Pessagno and Blome, and ammonites such as *Durangites* and *Dichotomosphictes*). In their analysis of the North American Jurassic radiolarian assemblage, Pessagno and Blome (1986) and Pessagno et al. (1993a, 1999) demonstrated that the Southern Boreal Province is characterized by a sharp decline in pantanelliid abundance and diversity and by the abundance and diversity of species of *Parvicingula/Praeparvicingula* (Text-figure 6). In contrast, these workers found that

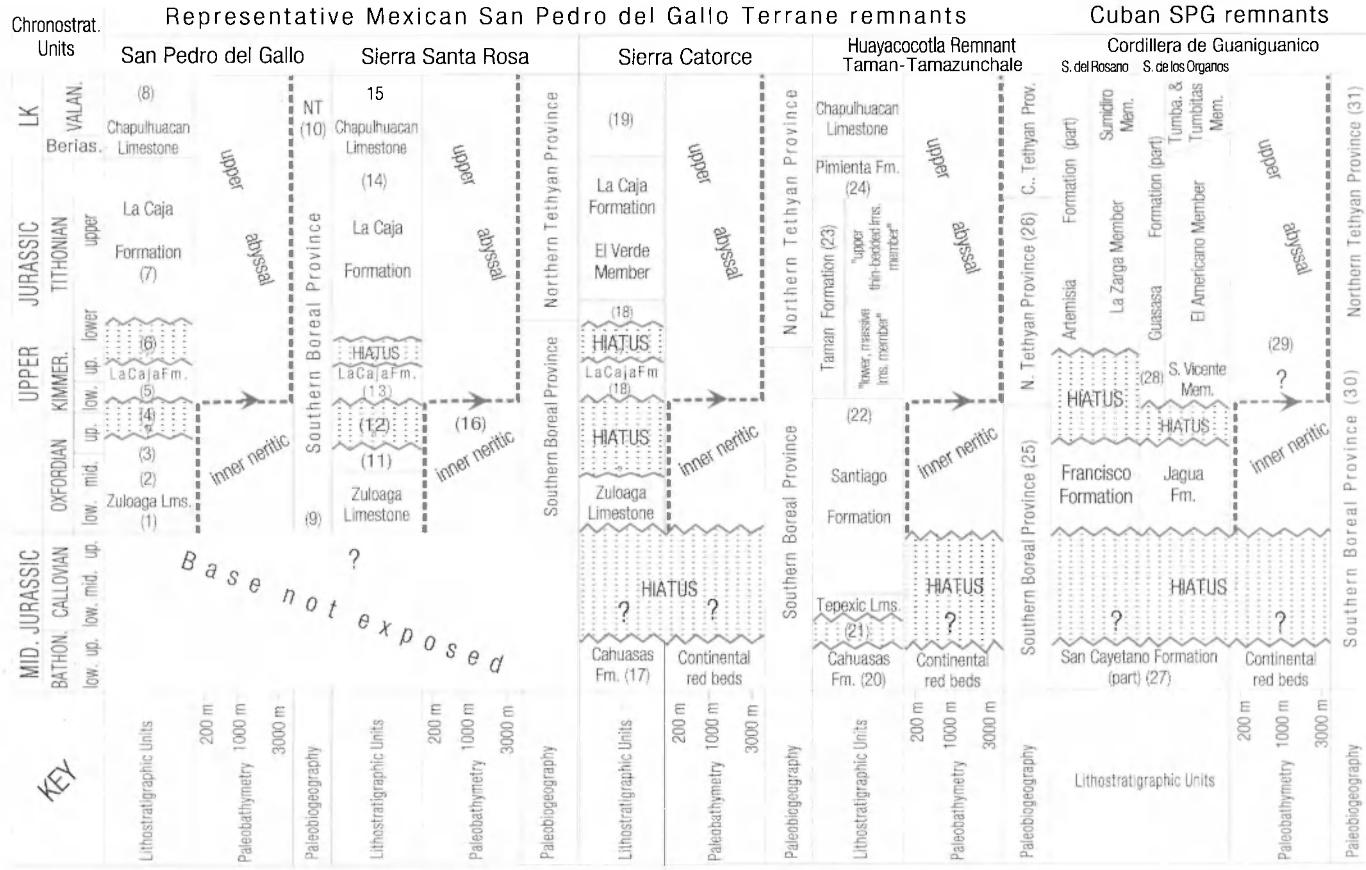


TEXT-FIGURE 8
Index map showing important Jurassic localities in Mexico and Cuba. The most important localities for this report are 3-18, 24. Key to localities: 1 = Tlaxiaco: Sierra Madre del Sur, Oaxaca. 2 = Pletalcingo: Sierra Madre del Sur, Puebla. 3 = Huayacocotla Anticlinorium: Taman- Tamazunchale, SanLuis Potosi; Huayacocotla, Veracruz; Huachinango, Puebla. 4 = Sierra Catorce, San Luis Potosi. 5 = Mazapil. Canyon San Matias Sierra Santa Rosa, Zacatecas. 6 = Sierra de la Caja, Zacatecas. 7 = Sierra Cadnelaria, Zacatecas. 8 = Sierra Sombretillo and Sierra Zuloaga, Zacatecas. 9 = Sierra de Ramirez, Zacatecas-Durango. 10 = Sierra de Chivo, Durango. 11 = Sierra de Palotes, Durango. 12 = San Pedro del Gallo, Durango. 13 = Santa Maria del Oro, Sierra de La Zarca, Durango. 14 = Sierra Vieja-Arroyo Doctor, Tamaulipas. 15 = Huizachal Anticlinorium, Tamaulipas. 16 = Sierra Galeana-Iturbide, Nuevo Leon. 17 = Sierra de Parras, Coahuila. 18 = Sierra de Jimulco, Coahuila. 19 = Sierra Menchaca, Cohuila. 20 = Sierra Plomosas—Place de Guadalupe, Chihuahua. 21 = Sierra El Cuchillo Parado, Chihuahua. 22 = Sierra de Samalayuca, Chihuahua. 23 = Sierra de Cucurpe, Sonora. 24 = Cordillera de Guaniguanico, Cuba. Base map partly derived from that in Salvador et al. (1992). 7 = Sierra Cadnelaria, Zacatecas. 8 = Sierra Sombretillo and Sierra Zuloaga, Zacatecas. 9 = Sierra de Ramirez, Zacatecas-Durango. 10 = Sierra de Chivo, Durango. 11 = Sierra de Palotes, Durango. 12 = San Pedro del Gallo, Durango. 13 = Santa Maria del Oro, Sierra de La Zarca, Durango. 14 = Sierra Vieja-Arroyo Doctor, Tamaulipas. 15 = Huizachal Anticlinorium, Tamaulipas. 16 = Sierra Galeana-Iturbide, Nuevo Leon. 17 = Sierra de Parras, Coahuila. 18 = Sierra de Jimulco, Coahuila. 19 = Sierra Menchaca, Cohuila. 20 = Sierra Plomosas—Place de Guadalupe, Chihuahua. 21 = Sierra El Cuchillo Parado, Chihuahua. 22 = Sierra de Samalayuca, Chihuahua. 23 = Sierra de Cucurpe, Sonora. 24 = Cordillera de Guaniguanico, Cuba. Base map partly derived from that in Salvador et al. (1992).

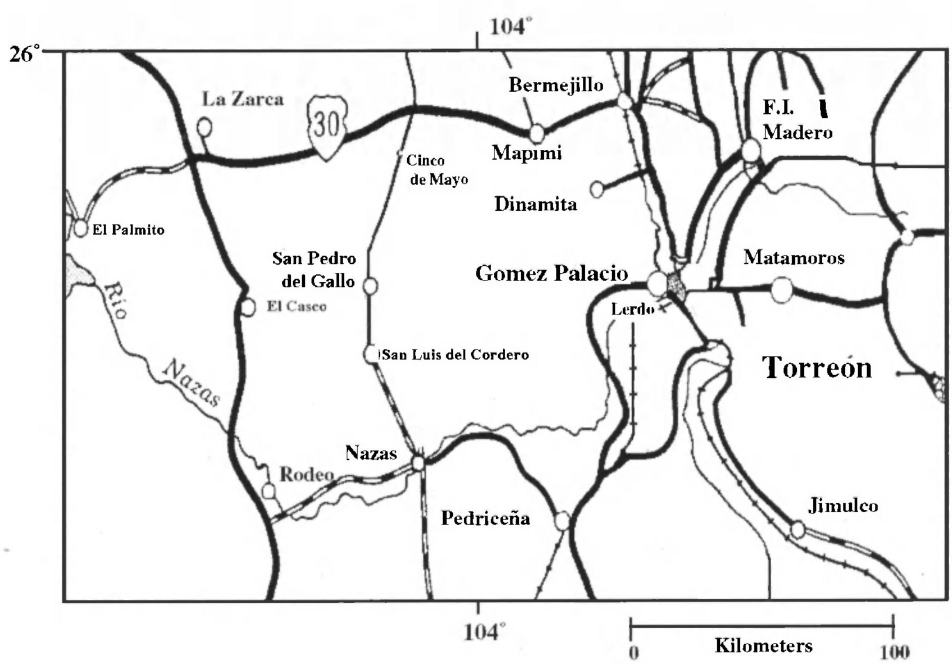
the Northern Boreal radiolarian assemblage is distinguished by abundant *Parvicingula/ Praeparvicingula* and by its total lack of pantanelliids. Both the Southern Boreal and Northern Boreal faunal and floral assemblages are marked by the presence of megafossils such as the ammonites *Kepplerites* and *Amoeboceras*, the bivalve *Buchia*, and land plants such as the Ginkgoales (e.g., *Baiera*) that only occur in the Boreal Realm (*See* Text-figure 5). The equivalent of the Northern Tethyan and Southern Boreal Provinces appears to be missing in the Tithonian and Berriasian strata of Spain, France, Germany, and England. The senior author suggests that the presence of well-developed transitional provinces in the Jurassic of Cuba, Mexico, California, and Oregon are related to plate tectonics in the Eastern Pacific and the tectonic transport of geologic terranes in a northerly or southerly direction along megashears (e.g., Longoria 1985a, 1985b, 1986, 1987, 1994; Pessagno and Blome 1986; Pessagno et al. 1999, Pessagno and Martin 2003, Pessagno 2006). This thesis is supported by the tectonic transport of the San Pedro del Gallo terrane (SPG) in a northwest to southeast direction along the Walper Megashear from higher to lower paleolatitudes during the Late Jurassic (Pessagno et al. 1999). Pessagno et al. noted that, though varying in detail, each succession that has been examined to the southwest of the Walper Megashear shows evidence of tectonic transport from higher latitudes to lower latitudes during the late Middle Jurassic, the Late Jurassic, and the Early Cretaceous (See discussion for San Pedro del Gallo terrane below).

Problems in correlating uppermost Jurassic and lowermost Cretaceous North American strata

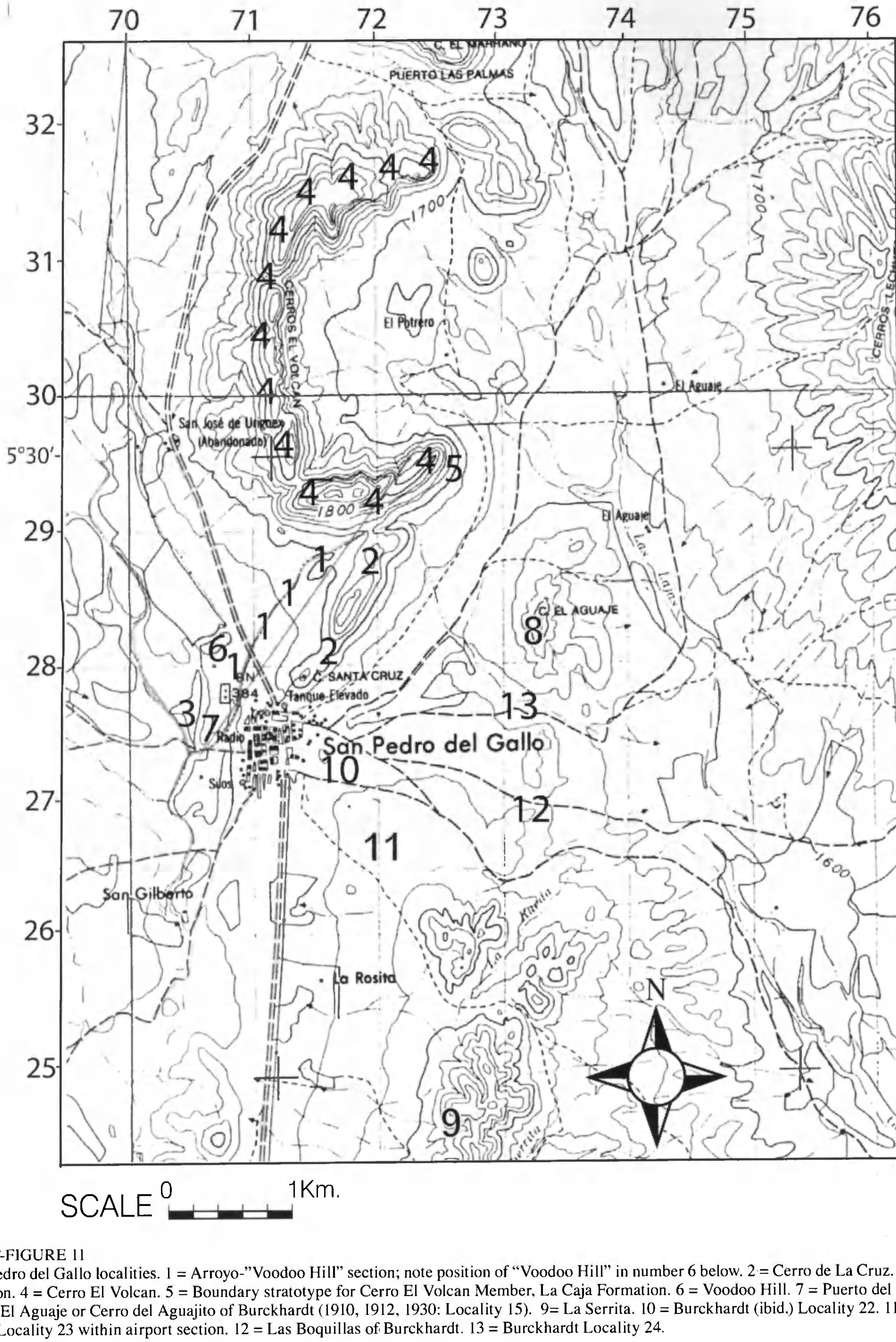
Imlay (1980) included the upper Tithonian in two ammonite assemblages: (1) a lower **Kossmatia-Durangites assemblage** and (2) an upper **Substeuroceras-Proniceras assemblage**. In Mexico and in California Imlay utilized the top of his **Substeuroceras-Proniceras assemblage** (=**Substeuroceras-Berriasella** complex of Jeletsky 1984, p. 99) to mark the top of the Tithonian. Moreover, he correlated strata bearing the **Substeuroceras-Proniceras assemblage** with the **Buchia sp. aff. B. okensis Zone** of Jones et al. (1969). According to Imlay and Jones (1970, p. B9; see also Imlay 1944a, p. 1017; 1944b, p. 1120; Jeletsky 1984, p. 99), strata overlying the **Substeuroceras-Proniceras assemblage** in Mexico include *Subthurmannia tenochi* (Felix) and *Spiticeras zirkeli* (Felix). In California, Imlay and Jones (1970, p. B12-B13) indicated that strata overlying the **Substeuroceras-Proniceras assemblage** are characterized by the presence of *Spiticeras (Negreliceras)*. These strata were correlated by Imlay and Jones with the lower two thirds of the **Buchia uncitoides**



TEXT-FIGURE 9
Correlation of lithostratigraphic units and chronostratigraphic units with paleobathymetry and paleobiogeographic position in selected San Pedro del Gallo Terrane remnants in Mexico and Cuba. Full explanation of annotations (1) to (31) shown on adjoining pages. From Pessagno and others (1999).

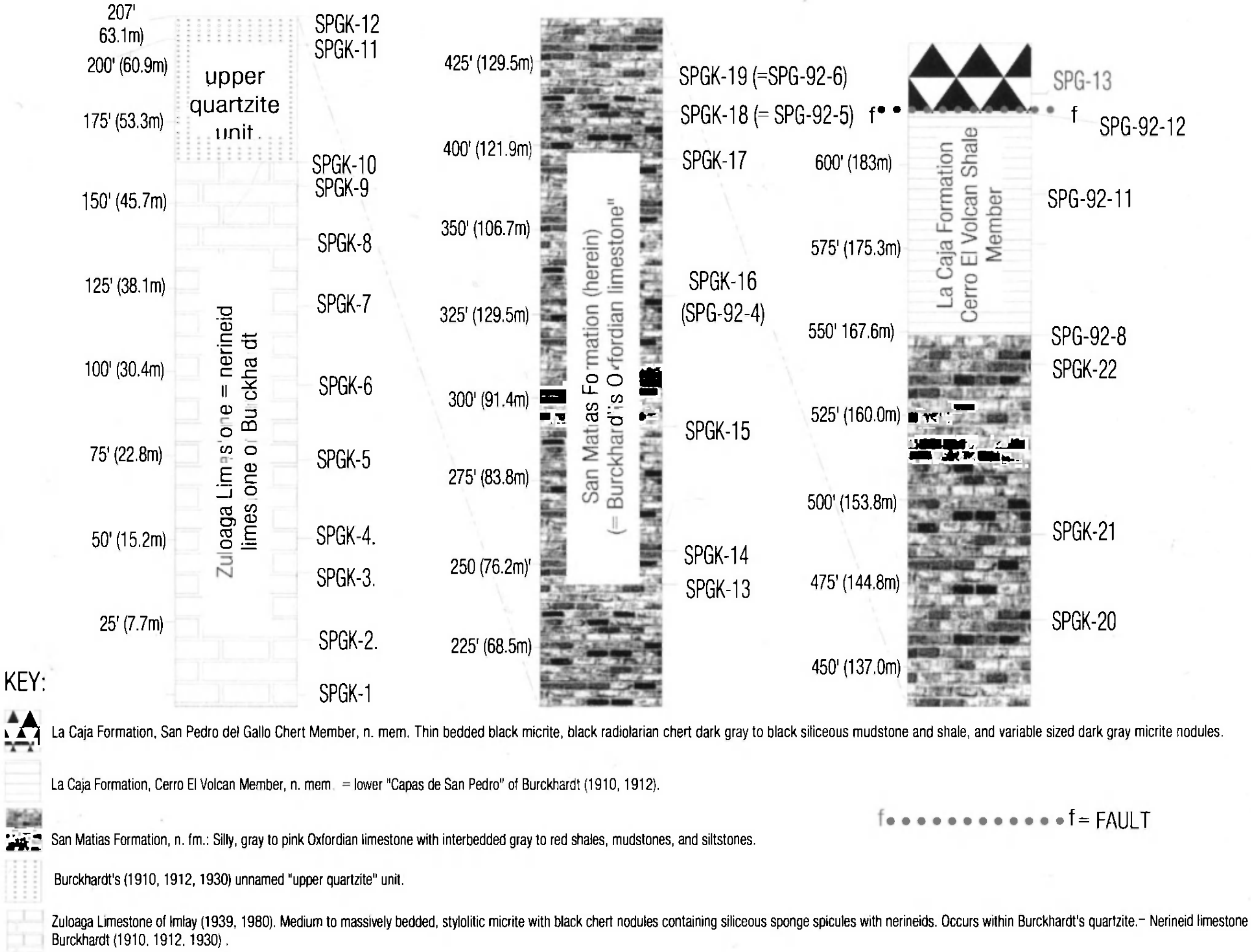


TEXT-FIGURE 10
Index map showing relative position of San Pedro del Gallo in the state of Durango, Mexico.



TEXT-FIGURE 11

San Pedro del Gallo localities. 1 = Arroyo-"Voodoo Hill" section; note position of "Voodoo Hill" in number 6 below. 2 = Cerro de La Cruz. 3 = Cerro Panteon. 4 = Cerro El Volcan. 5 = Boundary stratotype for Cerro El Volcan Member, La Caja Formation. 6 = Voodoo Hill. 7 = Puerto del Cielo. 8 = Cerro El Aguaje or Cerro del Aguajito of Burckhardt (1910, 1912, 1930: Locality 15). 9= La Serrita. 10 = Burckhardt (ibid.) Locality 22. 11 = Burckhardt Locality 23 within airport section. 12 = Las Boquillas of Burckhardt. 13 = Burckhardt Locality 24.

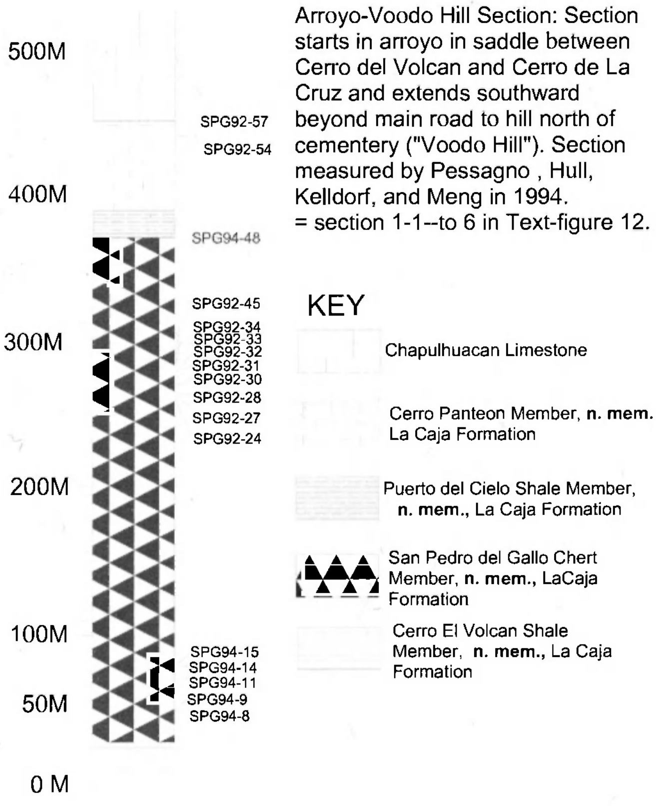


TEXT-FIGURE 12
San Pedro del Gallo. Section showing boundary stratotype for base of Cerro El Volcan Shale Member of the La Caja Formation at Cerro El Volcan with its contact with the underlying San Matias Formation.

Zone in the California Coast Ranges. It is now clear from our analysis of new ammonite and radiolarian biostratigraphic data from the Grindstone Creek section (northern California) that most, if not all, of the **Buchia sp. aff. B. okensis Zone** of Jones et al. (1969), is correlative with the uppermost Tithonian (See California Coast Ranges below herein).

Zeiss (1984, p. 104: Correlation Chart) disagreed with the correlations of Jones et al. (1969), Imlay (1980), and Jeletsky (1984). He correlated the North American **Substeuroceras-Proniceras assemblage** of Imlay (1980) and the equivalent **Substeuroceras-Berriasella complex** of Jeletsky (1984, p. 99) with the **Occitanica Zone** of the European upper Berriasian (e.g., Southern Spain, Southern France, south central Europe, Caucasus). He also correlated the **Buchia sp. aff. B. okensis Zone** of Jones et al. (1969) with the **Occitanica Zone**. Moreover, Zeiss correlated North American strata assignable to the **Buchia piochii Zone** of Jones et al. (1969) with the lower Berriasian **Euxinus Zone** of southern Europe and the Caucasus (Text-figure 1 herein).

Two factors have contributed to the incorrect correlation of uppermost Jurassic and lowermost Cretaceous strata in North America and the Caribbean: (1) a poor understanding of the ammonite faunal composition of the **Substeuroceras beds** and (2) the reliance on the European calpionellid zones of Le Hégarat and Remane (1968) and Remane (1969, 1978, 1985). These two factors are intimately entwined in the literature, but must be separated to allow accurate biostratigraphic and chronostratigraphic correlations between North America and Europe. Both Jeletsky (1984) and Zeiss (1984) lament the absence of *Durangites* in the **Substeuroceras beds** of Mexico. Zeiss (1984, p. 101) stated that Jeletzky alleged that the **Substeuroceras beds** of North America are coeval with the upper part of the **Transitorius Zone** (**Durangites Zone**) (See Text-figure 1). Zeiss stated that Jeletsky explained the absence of the *Durangites* in the **Substeuroceras beds** (=**Substeuroceras-Proniceras assemblage** of Imlay 1980) of Mexico by the cooling of the sea in this region whereas in Spain this taxon was present due to the presence of warmer waters. Moreover, Zeiss claimed that there was no reason for such a "cooling" in Mexico since Mexico and Spain are situated at approximately the same paleolatitudes. He concluded that the **Durangites/Kossmatia assemblage** of Mexico and the **Durangites Zone** of Southern Europe are of nearly the same age and, as a consequence, there was no need to unite this assemblage



TEXT-FIGURE 13
San Pedro del Gallo. Arroyo—"Voodoo Hill" section. Section links arroyo (1-1— in Text-figure 12) with "Voodoo Hill" (6 in Text-figure 12).

with that of the **Substeuroceras-Proniceras assemblage**. Finally, Zeiss (1984, p. 102) stated that the younger age of the **Substeuroceras beds** in Mexico is demonstrated by the calpionellid data presented by Cantu-Chapa (1967): "I have evaluated these calpionellids and placed them in the Lower Berriasian (Zone B of Mediterranean Europe and Zone C. This means the **Substeuroceras beds** correspond to the Lower Berriasian of Europe (Mediterranean realm)."

It is worth noting that *Durangites* Burckhardt (1910) was first described by Burckhardt from San Pedro del Gallo (Durango, Mexico). Burckhardt (1910, p. 318) indicated that *Durangites* is associated with *Buchia mosquensis* in the middle zone of his "Capas de San Pedro" (= La Caja Formation of Pessagno et al. 1999 and the San Pedro del Gallo Chert Member of the La Caja Formation herein). The association of *Durangites* with Boreal as well as Tethyan fossils has since been documented by a number of workers in Mexico and the Caribbean (Imlay 1939, 1980; Pessagno et al. 1999; Pszcolkowski 1999; Myczyński 1999). Pessagno et al. (1999) established that the San Pedro del Gallo remnant of the SPG originated at high Southern Boreal paleolatitudes during the middle Oxfordian. The Oxfordian to Tithonian part of this SPG succession is populated by a mixture of Tethyan and Boreal ammonites (e.g., *Amoeboceras, Idoceras, Durangites*), boreal bivalves (e.g., *Buchia concentrica, B. mosquensis, B. rugosa,* and *B. piochii*) as well as an abundance of *Parvicingula* and *Praeparvicingula* and rare pantanelliids among the Radiolaria. The megafossil and radiolarian assemblage coupled with preliminary paleomagnetic data indicate that this terrane remnant originated at Southern Boreal paleolatitudes (~ 40° N: Ogg in Pessagno et al. 1999) during the Oxfordian (Meng 1967; *see* Text-figures 7-8). The appearance of abundant calpionellids together with the presence of *Buchia* and the presence of common *Parvicingula* and *Praeparvicingula* in the upper part of the La Caja Formation demonstrate that the San Pedro del Gallo remnant had been transported to near the boundary (~30° N) between the Northern Tethyan Province and the Southern Boreal Province by the latest Tithonian (Late Jurassic) (Text-figures 7-8). The lack of Boreal elements such as *Buchia* in overlying Early Cretaceous strata suggests transport of the San Pedro del Gallo remnant to the Northern Tethyan Province (>22° to <30° N by the Berriasian. *Durangites* also appears in Southern Boreal or possibly Northern Tethyan strata in the Sierra de los Organos remnant of the San Pedro del Gallo terrane in Western Cuba (See Pessagno et al. 1999). Myczyński (1999, p. 77-92; Fig. 2) recorded *Durangites* in association with *Buchia* in the El Americano Member of the Guasasa Formation. Imlay (1939) recorded *Durangites* above the final occurrence of *Kossmatia* in association with *Substeuroceras* and tethyan ammonites in the upper Tithonian strata of the La Casita Formation at Sierra Jimulco (Cohuilatecano terrane of Pessagno et al. 1999). These and other data from North America and the Caribbean clearly indicate that *Durangites* was able to populate both the Tethyan and Boreal realms during the latest Jurassic. In Europe, *Durangites* appears to be strictly a Tethyan taxon. The data presented below will demonstrate that *Durangites* is associated with *Substeuroceras* both at the surface and in subsurface at a number of localities in Mexico. Moreover, it will be demonstrated that the calpionellid zones of Remane (1969, 1978, 1985) are diachronous and often coeval between North America and Europe and are totally unreliable for defining the Jurassic-Cretaceous boundary. The senior author first became aware of the problem with the calpionellids in 1984 when he noted that there was a major conflict between Bonet's (1956) calpionellid data and Imlay's ammonite data from the Sierra Cruillas (Tamaulipas, Mexico). Bonet (1956, p. 82, locs. 44, 45, 48) recorded Berriasian to Valanginian calpionellids from a horizon just below beds containing abundant ammonites assignable to Imlay's **Kossmatia-Durangites assemblage** (See Imlay 1980, p. 35: measured section at Loma Rinconada, Sierra Cruillas and Sierra Cruillas remnant of San Pedro del Gallo terrane herein). This sort of conflict between the ammonite and calpionellid biostratigraphic and chronostratigraphic data can be demonstrated at a number of localities. In spite of the efforts of co-author Cantu-Chapa (ibid.) to report anomalous calpionellid data in highest Jurassic and lowermost Cretaceous strata, most European ammonite and calpionellid workers have chosen to ignore the North American data. Adatte et al. (1994, p. 45) stated that "Most of the Mexican calpionellid materials studied by Bonet (1956) and by Trejo (1976, 1980) come from oil wells. Detailed surface sections have never been published and this might explain some of the discrepancies." The statement by Adatte et al. is both inaccurate and misleading. Cantu-Chapa (1967, p. 3-24) accurately documented the ammonite data and co-occurring calpionellids in a beautifully exposed surface section that encompasses the Jurassic-Cretaceous boundary at Mazatepec (Puebla, Mexico). Moreover, he noted (e.g., Table 1) that the calpionellid assemblage associated with **Parodontoceras aff. Callistoides Zone** (=upper part of **Substeuroceras-Proniceras assemblage** of Imlay 1980) included *Calpionella elliptica, C. alpina,* and *Tintinnopsella longa*. Similar relationships can be observed at San Pedro del Gallo (Durango, Puebla) and at Taman (San Louis Obispo). Moreover, it can be established from our studies in the Taman-Tamazunchale area that the base of Remane's **Zone A** (**Crassicollaria Zone**) occurs neither in the

TEXT-FIGURE 14A
Zuloaga Limestone on top of Cerro El Volcan north of San Pedro del Gallo Beds vertical to slightly overturned.

TEXT-FIGURE 14B
San Pedro del Gallo Chert Member in arroyo-"Voodoo hill" section. Note hammer for scale.

upper Tithonian as advocated by Geyssant (1997: *See* Text-figure 1 herein) nor at the base of the upper Tithonian as advocated by Pessagno et al. (1984, 1987), but actually in the lower Tithonian below the first occurrence of *Mazapilites*. These and other anomalies will be discussed in detail below.

It should be emphasized that all planktonic microfossils including the calpionellids have great biostratigraphic and chronostratigraphic potential. As aptly noted by Bralower et al. (1989, p. 155), the problem with the Le Hegarat and Remane (1969) calpionellid zonation is that some of the zonal and subzonal boundaries at the Jurassic-Cretaceous boundary are defined by relative abundance changes rather than first and last occurrences of taxa and, as a consequence, are difficult to define precisely

Biostratigraphic, chronostratigraphic, and lithostratigraphic data from San Pedro del Gallo terrane

The San Pedro del Gallo terrane (SPG) was first defined by Pessagno et al. (1993b) and described in more detail by Pessagno et al. (1999). It takes its name for the village of San Pedro del Gallo, Durango, Mexico (Text-figure 7-9, 10). This area was first studied in 1910 by the famous Swiss geologist, Charles Burckhardt. Burckhardt's studies formed the foundation for our investigations both in the San Pedro del Gallo and Mazapil remnants of the SPG and should be regarded as a template for all studies of Mesozoic strata in Mexico.

San Pedro del Gallo remnant, Durango, Mexico

As noted by Pessagno et al. (1999), Burckhardt's contributions to the geology of San Pedro del Gallo were five fold: (1) He accurately described the lithostratigraphy and established the superposition of Jurassic and Cretaceous strata by utilizing ammonite biostratigraphy and chronostratigraphy; (2) he monographed the rich megafossil assemblage (largely ammonites; Burckhardt 1912); (3) he made the first geologic map as well as the first topographic map of the area; (4) he interpreted the structure and produced numerous structural profiles; and (5) he assessed the mineral deposits of the area. Burckhardt's study was so thorough that few workers have been able to improve on it.

Imlay (1939) as well as Contreras-Montero et al. (1988) and Adatte et al. (1995) incorrectly correlated the informal unit which Burckhardt called the "Capas de San Pedro" with the La Casita Formation. Although these lithic units are approximately equivalent chronostratigraphically, it is clear from our examination of the La Casita in its type area (Sierra de Parras: Text-figure 8, Loc. 17) as well as in the Sierra Jimulco (Text-figure 8, Loc. 18) that the "Capas de San Pedro" are not correlative lithostratigraphically with the La Casita Formation (*See* Martin 1996; Pessagno et al. 1999). The La Casita Formation consists of gypsiferous gray to pinkish gray silty, calcareous to siliceous mudstone, silty micritic limestone, and siltstone deposited at inner neritic depths containing ammonites, brachiopods, bivalves, and a sparse, poorly diversified foraminiferal assemblage (five species, largely Textulariina: Senior author's observations). In contrast, Burckhardt's "Capas de San Pedro" consists of upper abyssal dark gray calcareous to siliceous mudstone with common black, thin-bedded radiolarian chert and common radiolarian-rich micrite nodules (See below). Although the "Capas de San Pedro" was informally named by Burckhardt, it is clearly genetically related to the La Caja Formation. We have observed black radiolarian chert in the La Caja Formation thus far at San

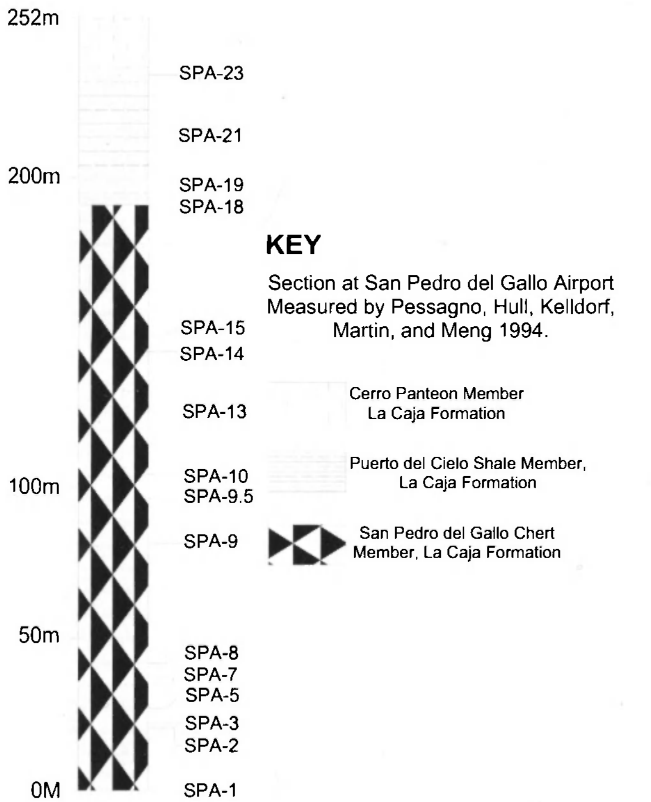
SPECIES/SAMPLES	SPG 94-8	SPG 94-9	SPG 94-11	SPG 94-14	SPG 94-15	SPG 94-34	SPG 92-24	SPG 92-27	SPG 92-28	SPG 92-30	SPG 92-31	SPG 92-32	SPG 92-33	SPG 92-34	SPG 92-45	SPG 94-48
Position in section: Meters.	45.8	49.4	59.8	73.9	74.48	157.7	264	267	267.7	271.4	275	279.1	284	284	323.4	373
Alievium spp.																R
Pantanellium ranchitoense		R				R		R		R		R	R		R	
Pantanellium whalenae		R								R	R	R	R	R	R	
Pantanellium spp.		R				R				R		A	R	R	R	
Vallupus hopsoni	R	R						R	R	A		R	R	A		
Vallupus nodosus															R	
Vallupus spp.		R											R	A		
Complexapora kozuri	R	R	R	A	R	R	R	R	R	A	A	R	A	R	C	R
Complexapora nova	R		R		R		R		A	R	R	R	R			
Complexapora spp.	A	A	R	A	A	R	R	R	R	R	A	A	R	R		
Loopus campbelii	C					R	R	R	R	R	R	R	R	R		R
Loopus primitivus	R	R		R	R	A	A	A	R	R	A	A	A	A	R	R
Loopus spp.	A	R		R	R	R	R	R	R	A	R	R	R	R		R
Archaeodictyomitra rigida			R					R				R			R	
Archaeodictyomitra shengi																R
Archaeodictyomitra spp								R		R					R	
Hsuum mclaughlini	R			R						R				R		
Hsuum spp.	R	R	R	R			R	A		A	R	R	R	R		
Caneta hsui	A	A	A	C	C	C	C	C	R	A	A	A	A	A	C	A
Caneta spp.	C	R	R		R	R		C	R	C	C	C	R	C	C	C
Mirifusus baileyi															R	
Mirifusus chenodes		R														
Mirifusus mediodilatatus		R														
Mita sixi					R				R	R			R	R		
Mita weddelliensis	R	R					R	C			R			R		
Mita spp.	R	A	R	A	R					A		R	A	A		R
Parvicingula alamoensis																R
Parvicingula corralensis		A	R			R					R	R				A
Parvicingula spp.	A	R	R	R	C	R	R	R	R	R	A	C	R	R	R	A
Praeparvicingula spp.	R	R	R	R	C	R	R	R	R	R	R	R	A	C	C	A
Ristola procera													R			
Novixitus spp.	R	A	R	R	R				R	R	R	R	R	R		
LA CAJA FORMATION	**San Pedro del Gallo Chert Member**															
BIOZONES	**Subzone 4 beta$_2$**															

TEXT-FIGURE 15
San Pedro del Gallo faunal and radiolarian biostratigraphic data from the arroyo—"Voodoo Hill" section (1-1-, 6 in Text-figure 12.

Pedro del Gallo, Cañon San Matias (Sierra Santa Rosa) near Mazapil, at its type locality in the Sierra de la Caja, in the Sierra de Catorce, and at other localities where the La Caja Formation has been reported (Imlay 1980; Pessagno et al. 1999. Text-figures 7-8 herein). Burckhardt frequently noted the presence of black chert in his accurate descriptions of measured sections that he made at these localities.

At San Pedro del Gallo Pessagno et al. (1999) divided the La Caja Formation (= "Capas de San Pedro" part; Burckhardt 1910) into four informal members (in ascending order): 1) the "lower shale member"; 2) the "chert member"; 3) the "upper shale member"; and 4) the "Cerro Panteon quarry unit 2" member. In this report these informal members are formally named (in ascending order) herein as follows: 1) The Cerro El Volcán Shale Member; 2) the San Pedro del Gallo Chert Member; 3) the Puerto del Cielo Shale Member; and 4) the Cerro Panteon Member.

1) The Cerro El Volcán Shale Member: This unit is equivalent to the "Capas de San Pedro inferior" of Burckhardt and "the lower shale member" of Pessagno et al. (1999). The Cerro El Volcán Shale Member consists of 52m (min.) of dark gray siliceous to calcareous mudstone with common dark gray, variably sized micrite nodules. Lenticular masses of thin-bedded, dark gray micrite are present locally. The bedded micrite and micrite nodules contain abundant calcified Radiolaria. In addition, this member contains common bivalves such *Buchia concentrica, B. rugosa,* and *B. mosquensis* as well as common ammonites such as *Idoceras* gr. *Durangense, I. tuttlei, I. lorioli, I. neohispanicium, I. angermanni, I. johnsoni, I. complanatum, I. boesei, I cragini, I disciforme,I. plicomphalum, I. mtuabile, I,* gp. *balderus, Sutneria* aff. *cyclodorsatus,* and *Glochiceras* gp. *fialar.* The Cerro El Volcán Shale Member is assignable to the late early Kimmeridgian to the late Kimmeridgian (*See* Burckhardt 1910; Imlay 1939; Pessagno et al. 1999, Meng 1997). It rests disconformably on the middle to early late Oxfordian red, siltstone, limestone and shale comprising the San Matias Formation, **n. fm.** (Text-figure 11. See Canyon San Matias, Sierra Santa Rosa herein). The undulating disconformable contact with the underlying San Matias Formation is exposed along the southeast side of Cerro El Volcán just east of adjacent Cerro de La Cruz (Burckhardt 1930. p. 62, figure 21; = Text-figure 12 herein). To the east of Cerro de La Cruz and along the southeast side of Cerro El Volcán, this unit is approximately 15m thick (Text-figure 13). Its upper contact with overlying San Pedro del Gallo Chert Member, **n. mem.**, is best exposed in a prominent ~ north-south arroyo that crosses the San Pedro del Gallo—Cinco de Mayo highway on the north side of town and trends toward the south side of Cerro



TEXT-FIGURE 16
Measured section of San Pedro del Gallo Chert Member of the La Caja Formation at San Pedro del Gallo airport.

El Volcan and, more or less, parallels the west side of Cerro de La Cruz (Text-figure12). The boundary stratotype for the base of the Cerro El Volcan Shale Member is designated as the southeast side of Cerro El Volcan (Text-figure 11. See Burckhardt 1930, p. 62, fig. 4). The boundary stratotype for the top of the unit occurs in the northern part of the prominent arroyo mentioned above (Text-figures 11, 14).

This unit is named for Cerro El Volcan (= Cerro del Volcan of Burckhardt (1910, 1912).

2) The San Pedro del Gallo Chert Member: The San Pedro del Gallo Chert Member includes the "middle zone" of the upper part of the Capas de San Pedro [beds with *Durangites*] of Burckhardt 1910 and the "chert member" of Pessagno et al.,1999). This unit includes ~ 343m of early late Tithonian dark gray siliceous mudstone interbedded with thin-bedded, black radiolarian chert, and minor dark gray, thin to medium bedded micrite that rest unconformably on the underlying Cerro El Volcan Shale Member (Text-figures 13, 14). Much of the lower Tithonian (e.g., **Mazapilites Zone** of Cantu-Chapa) appears to be missing at San Pedro del Gallo. It is not uncommon to find reworked lower Tithonian ammonites in the San Pedro del Gallo Chert Member. Occasional thin-layers of quartz-rich silty wacke often display graded bedding and represent turbidites.

The San Pedro del Gallo Chert Member contains common ammonites, abundant Radiolaria, abundant siliceous sponge spicules, common calpionellids, and common *Buchia*. Burckhardt (1910, p. 316-317) noted that his "middle zone" of the upper part of the Capas de San Pedro is richly fossiliferous and extends southwestward in a continuous band between Arroyo Aguajito toward Cerro de las Liebres (Text-figure 12). The assemblage described by Burckhardt from what is referred to herein as the San Pedro del Gallo Chert Member included eight new species of his new genus *Durangites* as well as three new species of the genus *Kossmatia* (*See* discussion of calpionellid data below). Imlay (1939: Table 8) recorded *Grayiceras mexicanus* Burckhardt, *Kossmatia interupta* Burckhardt, *K. pectinata* Burckhardt, *Durangites acanthicus* Burckhardt, *D. incertus* Burckhardt, *D. vulgaris* Burckhardt, *D. humbolti* Burckhardt, *D. nodulatus* Burckhardt, *D. latesellatus* Burckhardt, *D. densestriatus* Burckhardt, *D. fusicostatus* Burckhardt, *D. astillerensis* Imlay, and *Microacanthoceras* sp. cf. *M. microacanthum* (Oppel) from Burckhardt's (1910, Plate XLIX) Locality 23 situated about 0.6miles southeast of the village to the north of Cerro de Las Liebres (Text-figure 12). The Locality 23 ammonite assemblage occurs within the San Pedro del Gallo airport section (Text-figure 15 herein) and in the upper part of the San Pedro del Gallo Chert Member. This assemblage is clearly correlative with the **Kossmatia-Durangites assemblage** of Imlay (1980) and the **Proniceras and Kossmatia Zone** of Contreras-Montero et al. (1988). Burckhardt (1910, p. 318; 1912, p. 206, 221; 1930, p. 63, figure 21; see Imlay 1980, p. 34) also noted the presence of numerous *Buchia mosquensis* (von Busch) in what is referred to herein as the San Pedro del Gallo Chert Member. Moreover, according to Contreras-Montero et al. (1988, p. 21) *Buchia piochii* is also present in this unit. Unfortunately, these latter workers failed to cite the horizon where they recovered this taxon.

Radiolarian biostratigraphic data presented by Meng (1997) and supplemented by a re-analysis of the same samples by the senior author indicates the radiolarian assemblage from the San Pedro del Gallo Chert Member is assignable to **Zone 4**, upper part of **Subzone 4 beta**, (upper Tithonian) (See Text-figures 13, 15-17). The lack of *Perispyridium* is puzzling, but may be related to the lack of recovery of the more delicately preserved radiolarian tests from the chert samples using HF or to the distal backarc nature of the area. The presence of *Complexapora kozuri* Hull at SPG94-8 near the base of the San Pedro del Gallo Chert Member in the Arroyo-"Voodoo hill" section indicates that this horizon occurs within **Subzone 4 beta**, (Text-figures 13, 16). At Canyon San Matias near Mazapil, Zacatecas this taxon makes its first appearance within unit C of Burckhardt (1930); unit C, which is 5m thick, is characterized throughout by containing several species of *Kossmatia* (See Mazapil remnant of SPG terrane below). It should be also noted that in the Stanley Mountain remnant of the Coast Range ophiolite (California Coast Ranges) Hull (1997, p. 83: Text-figure 30) recorded *Complexapora kozuri* from sample SA43B 28m (volcanopelagic sequence) above the base of her **Subzone 4 beta** (= **Subzone 4 beta,** herein) to her **Subzone 4 alpha** (= **Subzone 4 alpha$_1$** herein). At Grindstone Creek (California Coast Ranges: See Grindstone Creek section below) *Complexapora kozuri* occurs throughout the **Buchia piochii Zone** and to near the top of **Subzone 4 alpha**, in strata which are assignable to the **Buchia sp. aff. okensis** Zone of Jones et al. (1969). This horizon (GR94-8: See Grindstone Creek section, California Coast Range below) is situated 59m below the base of the **Buchia uncitoides Zone** of Jones et al. (1969) and the base of radiolarian Zone 5, Subzone 5A of Pessagno (1977b).

The presence of *Neovallupus* sp.A in sample SPG-15A (1m from top of San Pedro del Gallo Chert Member) together with presence of *Pantanellium cantuchapai* and *Vallupus nodosus* in sample SPA-23 (top of Puerto del Cielo Shale Member) indicate

SPECIES/SAMPLES	SPA-1	SPA-2	SPA-3	SPA-5	SPA-7	SPA-8	SPA-9	SPA-9.5	SPA-10	SPA-13	SPA-14	SPA-15	SPA-18	SPA-19	SPA-21	SPA-23	SPG-13B	SPG-15A
Position in section: Meters.	0	20.7	22.1	26.9	37.8	41.3	80.6	95.3	103.1	124.2	142.4	148.2	190.8	196.9	213.6	233.5		
Bivallupus longoriai																		R
Neovallupus sp A																		R
Pantanellium cantuchapai	R		R			R										A		
Pantanellium meraceibaensis					C						R							
Pantanellium ranchitoense							R			R	R	R					R	
Pantanellium whalenae	R	R	R	R	C	R	R	R		R	R	R	R			R	R	R
Pantanellium spp.	R		R	R		R	C	R		R	C	A			R			R
Vallupus hopsoni	R	R		R	C	R		R			R	C	R			R	R	C
Vallupus laxus																		R
Vallupus nodosus																R		
Vallupus spp.	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Napora boneti					R													
Complexapora kozuri	R	C	R	C	R	R	A	C	R	C	R	R	R		R	C	R	R
Complexapora kiesslingi		R	R	R		R	R	R		R	R	R					R	C
Complexipora sp. A																C	C	
Complexapora spp.	C	C	C	C	C	C	C	C		C	C	C	C		C	C	C	C
Obesacapsula morroensis	R																	
Obesacapsula sp.aff. O. rotundata	C	C																
Obesacapsula spp.	C	C																
Loopus campbelli		C	C	R		R	R	R		R	R	R	R					R
Loopus primitivus	A	A	C	C	C	C	C	C		C	R	C	A	R	R	C	C	A
Loopus spp.	A	C	C	R			R	R		R	R	R	R			R	R	R
Archaeodictyomitra rigida			R				R			R	R				R		R	R
Archaeodictyomitra shengi	R		R					R										
Archaeodictyomitra spp			R		R							R					R	
Hsuum mclaughlini	R		R	R		R	R	R			R		C			R	C	R
Hsuum naturale		C		R	R							R						
Hsuum spp.	R	R	R	R	R	R	R	R	R	R	R	R	R		R	R	R	R
Caneta hsui	A	A	A	A	A	C	C	A		A	A	C	A		R	R	A	A
Caneta spp.	R	C	R	R	R	R	R	C		R	C	R	C				R	C
Mirifusus baileyi	R											R	R					
Mirifusus chenodes																R		
Mirifusus mediodilatatus	R				R								R					
Mita sixi	R		C	R	R						R	A	R			R	R	C
Mita weddelliensis		R		R		R		R				R					R	A
Mita spp.		R	R	R		R	R	R		R	R	R					R	C
Parvicingula alamoensis														R				
Parvicingula colemani																R		
Parvicingula corralensis							R				R					R		
Parvicingula excelsa									R									
Parvicingula jonesi											A							
Parvicingula turrita					R													
Parvicingula spp.	A	A	A	A	A	A	A	A		A	A	A	A		A	A	A	A
Praeparvicingula holdworthi		C	R			R												
Praeparvicingula spp.	A	A	A	A	A	A	A	A		A	A	A	A		A	A	A	A
Novixitus spp.		R	C	R	R	R	R	R		R	R	R	R				C	R
LA CAJA FORMATION	**San Pedro del Gallo Chert Member**													**Puerto del Cielo Shale Member**			**SPG Chert Member**	
BIOZONES	**SUBZONE 4 BETA$_2$**																	

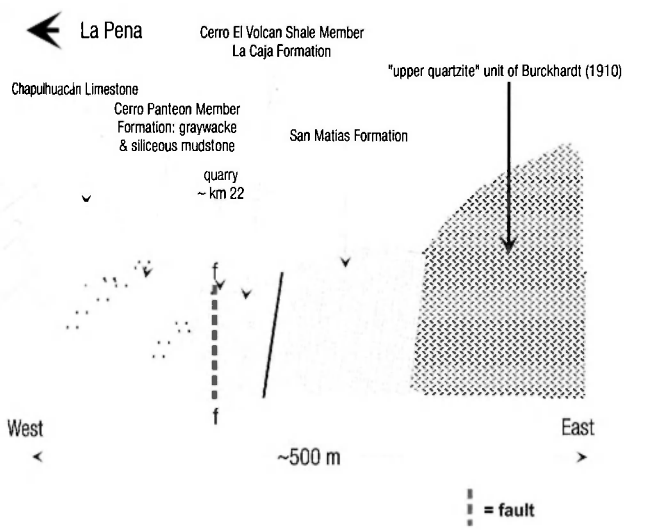
TEXT-FIGURE 17
San Pedro del Gallo airport section. Radiolarian faunal and biostratigraphic data from San Pedro del Gallo Chert and Puerto del Cielo Shale members of the La Caja Formation.

that this interval is assignable to the upper part of radiolarian biozones **Subzone 4 beta$_2$** (lower upper Tithonian. See also Taman-Tamazunchale area, Huayacocotla remnant of the SPG terrane below).

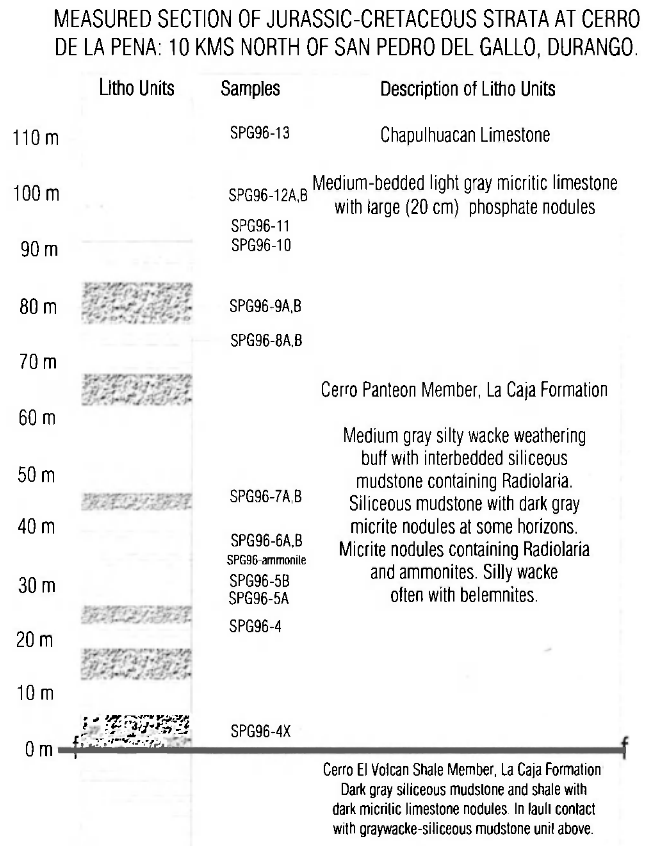
The San Pedro del Gallo Chert Member is exposed in its entirety in a prominent ~ north-south arroyo that crosses the San Pedro del Gallo—Cinco de Mayo highway on the north side of town and trends toward the south side of Cerro El Volcán and, more or less, parallels the west side of Cerro de La Cruz (See Arroyo-Voodoo Hill section in Text-figures 13, 16). In the measured section made along this arroyo the San Pedro del Gallo Chert Member is 343m thick. The arroyo-"Voodoo Hill" locality is designated the type locality.

The San Pedro del Gallo Chert Member is named for San Pedro del Gallo, Durango, Mexico.

3) The Puerto del Cielo Shale Member: The Puerto del Cielo Shale Member is equivalent to the "upper shale member" of Pessagno et al. (1999) and the "Zona superior" of Burckhardt (1910, 1912). This unit consists of 20 to 45m of dark gray siliceous mudstone and minor amounts of thin-bedded, often platey, dark gray micrite. The mudstone contains common dark gray



TEXT-FIGURE 18
La Pena profile. This locality is located 10km north of the village of San Pedro del Gallo, Durango, Mexico.

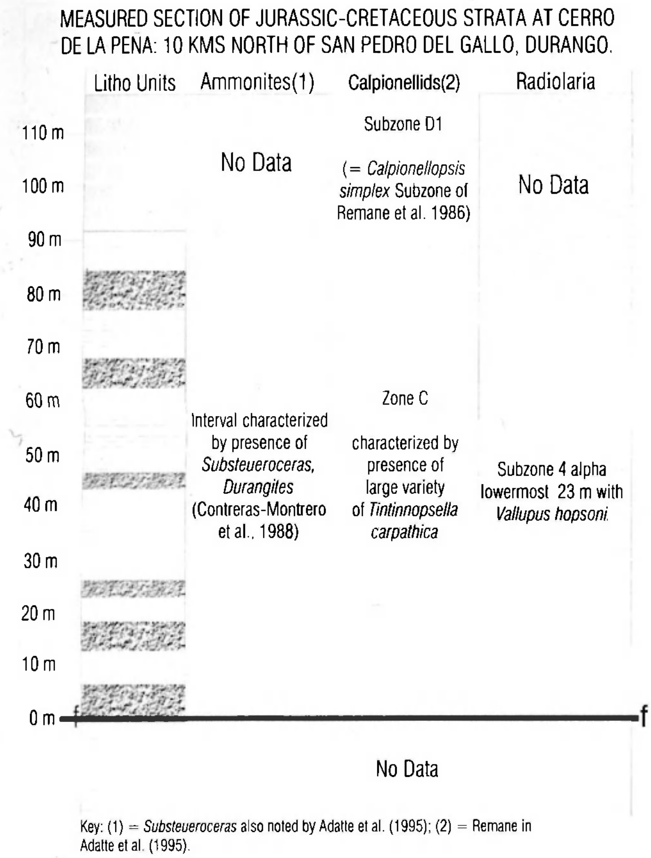


TEXT-FIGURE 19
Measured section of Cerro Panteon Member of the La Caja Formation at La Pena showing position of radiolarian samples and megafossils collected during the present investigation. La Pena is situated 10km north of San Pedro del Gallo, Durango, Mexico.

micrite nodules of variable size. Abundant Radiolaria and rare ammonites occur in the siliceous mudstone and in the micrite. Rare ammonites and abundant calpionellids occur in the micrite beds and nodules. Burckhardt (1910, p. 318) indicated that his "Zona superior" contained a sparse ammonite assemblage; he noted the presence of *Berriasella behrendensi* Burckhardt and *Hoplites* aff. *kollikeri* in these strata. However, according to Hillebrandt et al. (1992) Burckhardt's (1910, 1912) Locality 24 contains *Durangites, Kossmatia, Proniceras, Microacanthoceras,* and *Salinites grossicostatum*. Our field studies indicate that this horizon is within the Puerto del Cielo Shale Member.

Meng (1997) was able to recover well preserved Radiolaria from the Puerto del Cielo Shale Member at the San Pedro del Gallo airport section (Text-figures 16, 17). His radiolarian biostratigraphic data, supplemented by a re-examination of the same samples by the senior author, indicate that the Puerto del Cielo Shale Member is assignable to radiolarian **Subzone 4 beta$_2$** (Text-figures 15-17). The presence of *Pantanellium cantuchapai* and *Vallupus nodosus* in sample SPA-23 at the top of the Puerto del Cielo Shale Member indicates that this horizon is assignable to the top of **Subzone 4 beta$_2$** (Text-figure 17; see Cerro Panteon Member below). The upper Tithonian strata of the Puerto Cielo Shale Member rest conformably above the San Pedro del Gallo Chert Member and below the Cerro Panteon Member at the base of a hill to the west of San Pedro del Gallo known as Puerto del Cielo, along the runway at the San Pedro del Gallo Airport (immediately west of Las Boquillas), and to the west of the San Pedro del Gallo—Cinco de Mayo road in the prominent arroyo mentioned under the San Pedro del Gallo Chert Member above. At the airport runway the Puerto del Cielo Shale Member of the La Caja Formation is 45m thick; at Puerto del Cielo it is 65m thick. The east side of Puerto del Cielo is designated as the type locality.

4) Cerro Panteon Member: This unit was referred to by Burckhardt (1910, p. 318) as the "Capas limítrofes entre el Jurasico superior y el Cretaceo inferior". Imlay (1939) incorrectly correlated strata assignable herein to the Cerro Panteon Member and the Chapulhuacán Limestone with the inner neritic La Casita and Taraises formations (type area = Sierra de Parras, Text-figure 7: **Loc.** 3). Where the latter unit has been observed during the course of this study, it consists of rhythmically bedded chalky mudstone and interbedded medium gray, medium-bedded micritic limestone. Whereas the Taraises Formation contains a poorly diversified foraminiferal assemblage, brachiopods, echinoids, and ammonites, the San Pedro units contain common ammonites and foraminifera as well as abundant Radiolaria and calpionellids. Pessagno et al. (1999) informally referred the Cerro Panteon Member to "Cerro Panteon quarry unit 2". The Cerro Panteon Member of the La Caja Formation at San Pedro del Gallo consists of 77 to 93m of red, pink, and pinkish gray, and dark gray micritic limestone, calcareous siltstone, and calcareous mudstone with common ammonites, belemnites, calpionellids, and Radiolaria (reddish color probably result of hydrothermal alteration by Tertiary intrusives near the village of San Pedro del Gallo). Burckhardt (1910, p. 319-320) noted the presence of *Berriasella* sp. cf *B. calisto, B.* sp. cf. *B. obtusanodosa. B.* sp. cf. *B. calistoides,* and *Steueroceras* [=*Substeuroceras*] sp. cf. *S. permulticostatum* at Cerro Panteon (Text-figure 12). Moreover, Imlay (1939, Table 9) noted *Substeueroceras lamellicostatum* Burckhardt, *S. durangense* Burckhardt, "*Berriasella*" *storrsi* Stanton, *Berriasella tenuuicostata* Burckhardt, *Parodontoceras* cf. *calistoides* (Behrendensen), and *Proniceras* juv. aff. *pronum* at Burckhardt Locality 25 [base La Serrita] (1910, Plate XLIX). Contreras-Montero et al. (1988, p. 21, plates VII-VIII) illustrated *Durangites humbolti* (Burckhardt), *Durangites vulgaris*



TEXT-FIGURE 20
Ammonite, calpionellid, and radiolarian biostratigraphic data at La Pena. (1) = *Substeueroceras* also noted by Adatte et al. (1995); (2) = Calpionellids data from Remane in Adatte et al. (1995).

sp. juv. (Burckhardt) *Durangites* aff. *rarifurcatus* (Imlay), *Substeueroceras koeneni* (Steuer), *S. alticostatum* (Imlay), *Berriasella (B.)* aff. *subcallisto* (Toucas), *Berriasella* aff. *obcisa* (Oppel), and *Pseudosubplanites* aff. *grandis* (Mazenot) from La Serrita (Text-figure 12). The basal contact with the underlying Puerto del Cielo Shale Member is well exposed along the eastern flank of Cerro Panteon (e.g., at Puerto del Cielo) and the San Pedro del Gallo airport immediately west of Las Boquillas (Text-figure 12). At a low-lying hill ("Voodoo Hill") to the north of Cerro Panteon and the San Pedro del Gallo cemetery, the contact with the overlying Chapulhuacan Limestone is well exposed both on the south and north ends of "Voodoo Hill".

Cerro Panteon and the hill to the north of the cemetery ("Voodoo Hill") are designated as co-type localities. This member is named for Cerro Panteon.

At La Pena, 10km to the north San Pedro del Gallo, the Senior Author observed 92m of interbedded black siliceous shale, thin-bedded siltstone (wacke), and thin-bedded dark gray micrite containing belemnites, abundant Radiolaria, *Buchia*, and common ammonites (See Figures 18-21 herein). These strata are assigned herein to the Cerro Panteon Member of the La Caja Formation. The lower part of the Cerro Panteon Member at La Pena is in fault contact with the Kimmeridgian strata of the Cerro El Volcan Shale Member (Text-figures 18-19). Addate et al. (1995) as well as Contreras-Montero et al. (1988) incorrectly assigned this litho unit to the La Casita Formation and the overlying cream colored, very fine grained, medium bedded micritic limestone to the Taraises Formation. The latter unit is assigned to the Chapulhuacan Limestone herein. Ammonites as well as abundant calpionellids and Radiolaria were reported from this unit by Addate et al. (1995; *see* Addate et al. 1996). According to Addate et al. the ammonite assemblage includes the following taxa from the lower 13m of this section (Locs. Pg 1-5): *Phylloceras* sp., *Pterolytoceras* sp., *Vinalesites* sp., Himalayitidae gen. and sp. indet., *Substeuroceras durangense, S. kellumi, S. koeneni tabulalum, Schaireria* sp., *Spiticeras (Negreliceras) laeva,* and *Jabronella (Erdenella) laaria.* Moreover, they recorded *Himalayites* sp. "B" from their locality Pg. 19 approximately 60m above the base of the section and 5m below the contact between the Cerro Panteon Member and the overlying Chapulhuacan Limestone. Contreras-Montero et al. (1988, Plate IX) figured *Durangites* aff. *acanthicus* (Plate 9, figure 9), *Pseudoargentiniceras beneckei* (Jac) (Plate 9, figures 4, 5, 7), *Neocomites* aff. *praeneocomiensis* Burckhardt (Plate 9, figure 1) as well as belemnites from Cerro Panteon Member strata at La Pena.

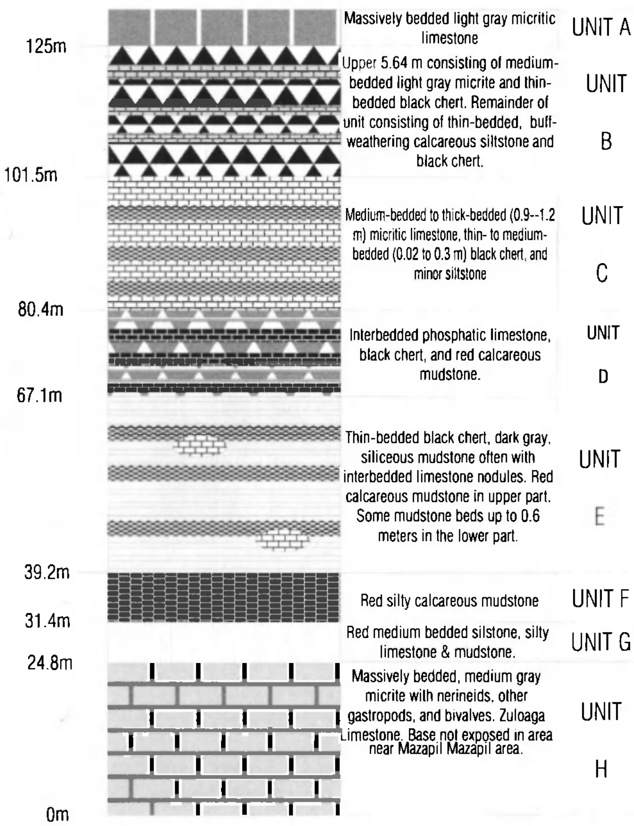
SPECIES/SAMPLES	SPG96-4X	SPG96-4	SPG96-5B	SPG96-6A	SPG96-9B
Position in section: Meters.	0	22.8	29.4	33.7	80.76
Vallupus hopsoni		A			
Vallupus spp.		A			
Complexapora kozuri		R	R	R	C
Complexapora kiesslingi		C	R		
Complexapora spp.		C			
Caneta hsui		C	C	C	
Caneta spp.		C			
Parvicingula bluefordae		R			
Parvicingula colemani	C				
Parvicingula cuyamaensis			R		
Parvicingula jonesi	C	C			
Parvicingula spp.	C	C	C	C	C
Ristola procera		R			
LA CAJA FORMATION	Cerro Panteon Member				
BIOZONES	Sz. 4 $alpha_1$		Sz. 4 $alpha_2$		

TEXT-FIGURE 21
Radiolarian assemblage and biozones for La Pena, 10k north of San Pedro del Gallo.

Text-figures 18-21 show the measured section of the succession at La Pena made by the senior author and Dr. Ignacio Pujana (University of Texas at Dallas) in 1996. The presence of *Vallupus hopsoni* at Locality SPA96-4 (Text-figures 20-21) 22.8m above the base of the measured section demonstrates that this interval is no higher than **Subzone 4 $alpha_1$** (Text-figure 4). Taxa such as *Pantanellium cantuchapai* Pessagno which make their final appearance at the top of **Subzone 4 beta**, are missing (See data from Puerto del Ceilo Member above). The presence of *Complexapora kozuri* at Locality SPG96-9B (10m below contact with the Chapulhuacan Limestone) indicates that all but the upper 10m of the Cerro Panteon Member are assignable to the upper Tithonian (**Subzone 4 $alpha_1$** and **Subzone 4 alpha,;** = **Subzone 4 alpha** of Pessagno et al. 1993, 1999). Accordingly, all but the uppermost part of the Cerro Panteon Member is included in the **Substeuroceras-Proniceras assemblage** of Imlay (1980) and to the **Substeueroceras and Microacanthoceras Subzone** of Contreras-Montero et al. (1988). Moreover, this interval can be equated to the **Buchia piochii Zone** and most of the **Buchia sp. aff. okensis** Zone (Jones et al. 1969: See Grindstone Creek, California Coast Ranges below). As will be seen in the discussion below, these data strongly conflict with the calpionellid data of Addate et al. (1995).

Chapulhuacan Limestone

Chapulhuacan Limestone (type area = Chapulhuacan, Hildago near Taman, San Luis Potosí: See Text-figure 8 and



TEXT-FIGURE 22
Description of lithostratigraphic units exposed in Mazapil remnant of San Pedro del Gallo terrane at Canyon San Matias, Zacatecas, Mexico.

Huayacocotla remnant of the San Pedro del Gallo terrane herein) consists of ~ 20m of medium to massively-bedded light gray to tan very aphanitic micrite with abundant calpionellids, common Radiolaria, and common ammonites. Some horizons (e.g., at La Pena) contain large (12cm) phosphate nodules.
Burckhardt (1910, p 322-323; 1930 [vol. L] p. 131) recovered numerous ammonites from the Chapulhuacan Limestone on the western slope of Cerro del Aguajito (northeast of San Pedro del Gallo and approximately 1km west of Cerro de la Cruz (Text-figure 12. See Burckhardt 1930, p. 129, Figure 36, Unit A.). This locality was examined by the senior author in 1990.

The rich fauna described by Burckhardt included *Spiticeras uhligi* Burckhardt, *S. binodum* Burckhardt, *S.* juv. aff. *scriptum* Strachey, *S. negreli* Toucas, *S. serpentinum* Burckhardt, *S. laeve* Burckhardt, *Berriasella neohispanica* Burckhardt, *B.* cf. *gracilis*, *Acanthodiscus transatlanticus* Burckhardt, *A. euthymiforms* Burckhardt, *Neocomites densestriatus* Burckhardt, and *N. praenecomiensis* Burckhardt. Burkhardt (1910, 1930) assigned these strata to the Berriasian.
Calpionellid data from San Pedro del Gallo

At San Pedro del Gallo calpionellids occur throughout the upper part of the San Pedro del Gallo Chert Member, all of the Puerto del Cielo Shale Member, all of the Cerro Panteon Member, and at least into the lower part of the Chapulhuacan Limestone.

In 1994 the senior author received a grant from the U. S. National Science Foundation to study the Jurassic-Cretaceous boundary problem in North America. Dr. Jurgen Remane (Institute of Geology, University of Neuchatel, Switzerland) was one of five collaborators who agreed to collect and/or examine samples collected in Mexico and California. A report was submitted to the senior author by Dr. Remane (August 24, 1995) detailing the results on his analysis of samples from Mexico and California. A copy of this report is included in the Appendix 2 herein.

Sample SPG94-48: Top of San Pedro del Gallo Chert Member immediately below contact with overlying Puerto del Cielo Shale Member (See Text-figures 13, 15). Remane (Report, 1995: See Appendix) recorded *Calpionellopsis oblonga*: upper Berriasian to lower Valanginian from this horizon and stressed that the typically Valanginian species *Calpionellites darderi* was never observed. Data presented above clearly indicates that the top of the San Pedro del Gallo Chert Member of the La Caja Formation occurs within the upper part of **Kossmatia-Durangites assemblage** of Imlay (1980) and the **Proniceras-Kossmatia Zone** of Contreras-Montero et al. (1988) (See the Imlay 1939 data from Burckhardt (1910, 1912 Locality 23). Moreover, it occurs within the upper part of radiolarian **Subzone 4 beta$_2$**. Both the ammonite and radiolarian biostratigraphic data indicate that the top of the San Pedro del Gallo Chert Member should be assigned to the upper Tithonian. The upper part of **Subzone 4 beta$_2$** and the early late Tithonian have been dated at 143.734Ma ± 0.060Ma [0.042%] at La Desirade (U-Pb date on zircon. See La Desirade herein). Moreover, the upper part of Subzone 5A and the upper Berriasian has been assigned a date of 137.1 +1.6/-0.6ma (U-Pb date on zircon. See Grindstone Creek herein and Bralower et al. (1990). Hence, it is clear that the calpionellid biostratigraphic and chronostratigraphic data also conflicts with the U-Pb geochronometric data.

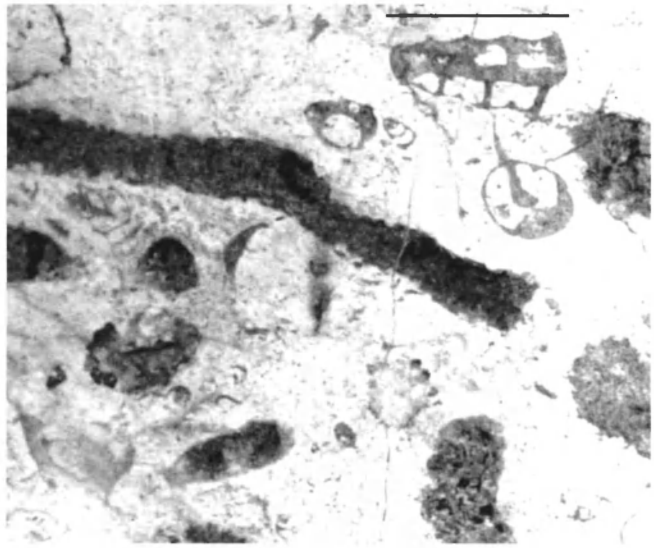
Samples SPG94-54, SPG94-55, SPG94-56 from Cerro Panteon Member of the La Caja Formation (Text-figure 13): Remane noted *Calpionella alpina* in these samples. The occurrence of this taxon together with *Calpionellopsis oblonga* in underlying SPG94-48 led him to favor a Berriasian age for these samples. The ammonite and radiolarian biostratigraphic data for the Cerro Panteon Member suggest that this unit is mostly assignable to the upper Tithonian (See Cerro Panteon Member at La Pena above).

SPG94-57, SPG94-58, SPG94-62, SPG94-64, SPG94-65, SPG94-66, SPG94-67 (Text-figure 16): Chapulhuacan Limestone. Remane observed *Calpionella alpina* in samples SPG94-57, 58, 62, 64, and 65; *Calpionellopsis oblonga* in samples SPG94-67 and SPG94-69; and *Calpionellopsis simplex* in samples SGP94-58, SPG94-66, and SPG94-67 and assigned these samples to Zone D (upper Berriasian).

SPG94-77, SPG94-78: Chapulhuacan Limestone at north end of Voodoo Hill (Text-figure 12). Sample SPG94-77 is immediately above contact with the underlying Cerro Panteon Member whereas SPG94-78 is 6m above the contact. Remane encountered *Calpionella alpina*, *Calpionellopsis oblonga*, and *Tintinnopsella carpathica* SPG94-77 and *Calpionellopsis simplex*, *Calpionellopsis oblonga*, and *Tintinnopsella carpathica* in SPG94-78 (upper Berriasian Zone D, its basal part (D 1) excluded).

PDC-13: Puerto del Cielo Shale Member of La Caja Formation: Immediately below contact with overlying Cerro Panteon Member at Puerto del Cielo (Text-figure 12). Remane identified *Calpionella elliptica* and *Calpionella alpina* (small form) at this

TEXT-FIGURE 23A
Photo of chert nodule in Zuloaga Limestone at Canyon San Matias, Sierra Santa Rosa, Mazapil remnant of San Pedro del Gallo terrane. Chert nodule to right of coin = ~ 8cm.



TEXT-FIGURE 23B
erineids and other molluscan fragments in Zuloaga Limestone at Canyon San Matias. Scale in upper right = 1.4cm.

locality. He assigned this horizon to Zone C or perhaps lower D1. The ammonite and radiolarian biostratigraphic and chronostratigraphic data clearly indicate that the Puerto del Cielo Shale Member is assignable to the upper Tithonian (See discussion above).

PDC-1, PDC-2, PDC-7: Cerro Panteon Member of La Caja Formation at Puerto del Cielo (Text-figure 12). Samples PDC-1 and PDC-2 occur at 15.4 and 12.6m respectively above the contact between the Cerro Panteon Member and the underlying Puerto del Cielo Shale Member. Sample PDC-7 occurs 6.8m above the same contact.

Remane recorded *Calpionellopsis simplex* from samples PDC-1 and PDC-2 and *Calpionella elliptica* from sample PDC-2. He indicated that the co-occurrence of the two latter taxa in PDC-2 demonstrates that this sample is assignable to Subzone D1 (upper Berriasian). Sample PDC-7 yielded *Calpionella elliptica*, *Calpionellopsis simplex*?, and *Tintinnopsella longa* indicating upper Zone C or ?lower D1.

Cerro Panteon Member of La Caja Formation and Chapulhuacan Limestone at La Pena: Text-figures 18-21 summarize radiolarian, ammonite, and calpionellid biostratigraphic data from Cerro de La Pena situated 10km north of San Pedro del Gallo on the San Pedro del Gallo-Cinco de Mayo road (Text-figures 10, 12). Ammonite and radiolarian biostratigraphic and chronostratigraphic data for this locality have been discussed under the Cerro Panteon Member above. As can be seen from an examination of Text-figure 20, Remane in Adatte et al. (1995, p. 52. Fig. 8) assigned all but the upper part of the Cerro Panteon Member at this locality to Zone C (Lower Cretaceous: middle Berriasian). The remainder of the Cerro Panteon Member and all of the overlying Chapulhuacan Limestone were assigned by Remane to Zone D, Subzone D1 (Lower Cretaceous: upper Berriasian). Both the radiolarian and ammonite biostratigraphic and chronostratigraphic data from the Cerro Panteon Member of the La Caja Formation at this locality and, indeed other localities in the vicinity of San Pedro del Gallo, indicate that this lithounit should be assigned to the Upper Jurassic (upper Tithonian) (See Cerro Panteon Member above). Although no ammonites have been found in the Chapulhuacan Limestone at La Pena, Burckhardt's (1910, 1930) data from this unit in the vicinity of San Pedro del Gallo favor its assignment to the Lower Cretaceous (lower Berriasian).

Remane's biostratigraphic and chronostratigraphic assignments for the San Pedro del Gallo Chert, Puerto del Cielo Shale, and Cerro Panteon members of the La Caja Formation defy the Principle of Superposition and are internally inconsistent. The superposition of these member units has been documented both by Burckhardt's investigations (1910, 1912, 1930) and those of the present study. It is puzzling to note that the top of the San Pedro del Gallo Chert Member (SPG94-48) contains calpionellids (*Calpionellopsis oblonga*: Zone D, Subzone D2-D3) that are younger than those occurring in the overlying Puerto del Cielo Shale and Cerro Panteon members in the Arroyo—"Voodoo Hill" section (Text-figures 12-13). The biostratigraphic data from the ammonites and Radiolaria show that the San Pedro del Gallo Chert Member, the Puerto del Cielo Shale Member, and all but the uppermost part of the Cerro Panteon Member are assignable to the upper Tithonian.

Mazapil Remnant at Canyon San Matias, Sierra Santa Rosa, Zacatecas, Mexico

The Mazapil Remnant (Text-figure 7, Loc. 5) of the San Pedro del Gallo terrane was first studied by Burckhardt (1906; 1930, p 50, fig. 13). His report not only dealt with the lithostratigraphy of Upper Jurassic and Lower Cretaceous rocks exposed at Canon San Matias in the Sierra Santa Rosa, but also with the rich

Litho Unit		Description	Age	Diagnostic Faunal Elements	Paleobathymetry	Faunal Realm/Province
Unnamed limestone		Medium bedded buff calcareous mudstone and micritic limestone. Micrite with common limonite nodules. Thickness (fide Burckhardt, 1930+ 50-70 m.	Valanginian	*Thurmannites* spp., *Asteria* aff. *psilostoma fide* Burckhardt (1930).	Upper Abyssal	Northern Tethyan Province
Chapulhuacan Limestone "UNIT A"		Massively bedded, very fine grained micritic limestone weathering to cream or buff color. Calpionellids. Radiolaria. Sparse ammonites. Thickness (fide Burckhardt 1930) = 15 m.	Berriasian ?	Calpionellids calcified Radiolaria		
La Caja Formation	"UNIT B"	Upper 5.64 m consisting of medium-bedded light gray micrite and thin-beddded black chert. Remainder of unit consisting of thin-bedded, buff-weathering calcareous siltstone and black chert (2). Abundant Radiolaria and ammonites. Thickness = 23.5 m	late Tithonian. upper part may be Berriasian	*Substeueosceras* spp. *Paradontoceras* aff. *callistoides*, *Durangites* sp.		
La Caja Formation	"UNIT C"	Medium-bedded to thick-bedded (0.9--1.2 m) micrite, thin to medium-bedded black chert, and minor siltstone Abundant Radiolaria and ammonites. Thickness = 21.1 m.	late Tithonian	*Kossmatia* spp. at base of Unit D. Radiolarian Subzones 4β, & $4\alpha_2$		
La Caja Formation	"UNIT D"	Interbedded phosphatic limestone, black chert and red calcareous mudstone. Abundant Radiolaria and ammonites. Thickness = 13.3 m	early Tithonian to early lateTithonian	*Hybonoticeras* spp., *Kossmatia* spp. + Subzone $4\beta_1$ & $4\beta_2$ Radiolaria.		
La Caja Formation	"UNIT E"	Thin-bedded black chert, dark gray, silicerous mudstone often with interbedded limestone nodules (up to ~ 4 m in maximum dimension). Red calcareous mudstone in upper part. Some mudstone beds up to 0.6 m in lower part. Abundant Radiolaria in all lithofacies. Abundant ammonites. Thickness = 27.9 m.	early late Kimmeridgian + hiatus early to late Tithonian	*Idoceras* spp, *Glochiceras* grp. *fialar*, *Buchia concentrica*, *Hyboniticeras*, and Zone 2α1, Zone 3, and Zone 4, Subzone4β Radiolaria.		Southern Boreal Province
San Matias Fm.	"UNIT F"	Red silty calcareous mudstone with 1.5 m dark gray micrite nodules in upper part. Common ammonites, bivalves. Common Radiolaria at top. Thickness = 7.8 m	late early Kimmeridgian at top	*Idoceras* spp. at top of 'UNIT F"	Outer Neritic	
San Matias Fm.	"UNIT G"	Red medium-bedded silty limestone and mudstone. Thickness = 6.6 m	middle Oxfordian	*Dichotomosphinctes*	Inner Neritic	
"UNIT H" Zuloaga Limestone		Massively bedded micritic limestone with nodules of black chert. Base not exposed.	middle Oxfordian or older	*Nerinea*, bivalves, corals, and sponge spicules *See* Burckhardt (1910, 1930)		

TEXT-FIGURE 24
Stratigraphic summary for Sierra Santa, Canyon San Matias near Mazapil, Zacatecas, Mexico. Martin (1996) interpreted the siltstone beds of Unit B to be turbidites. Graded bedding can be seen in many of the beds with fining in grain size occurring upward and chert pebble and skeletal conglomerates at base. This unit is genetically related to the Cerro Panteon Member of the La Caja Formation at San Pedro del Gallo. The siltstone turbidites may be a reflection of the Nevadan Orogeny in the distal backarc area of the Nevadan Island Arc.

ammonite faunas that occur in these strata. Subsequently, this succession was examined by Imlay (1939), Martin (1996), and by Pessagno et al. (1999). The Canyon San Matias succession is important because it contains abundant well-preserved ammonites, common *Buchia*, and abundant Radiolaria. The presence of numerous micrite nodules and layers throughout the succession offer great potential for collecting calcareous nannofossil (coccoliths and calpionellids) as well as organic microfossils (e.g., dinoflagellates, spore and pollen).

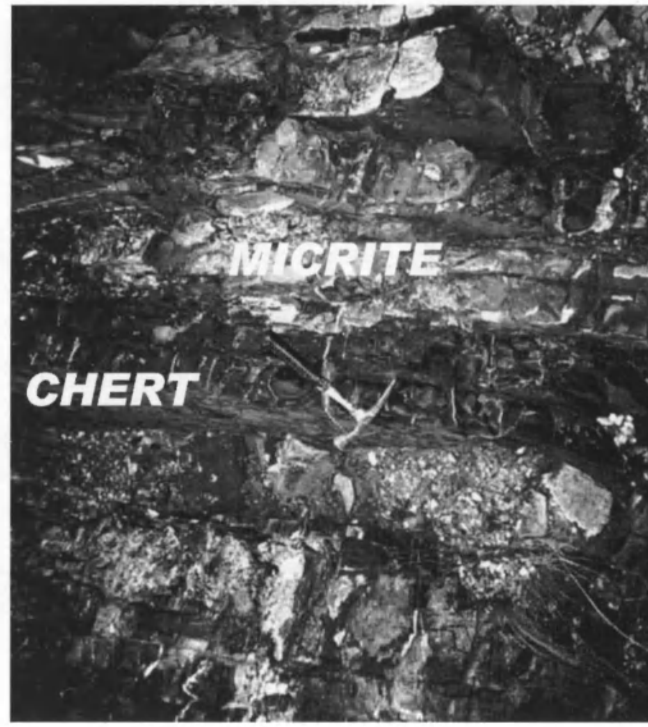
Text-figure 22 shows a measured section made of the Canyon San Matias succession made by the senior author, his students, and colleagues in 1994 and during subsequent visits in 1996 (See Pessagno et al. 1999; Pessagno and Martin 2003). As in the San Pedro del Gallo remnant, the base of the succession at Canyon San Matias is not exposed.

Zuloaga Limestone

The oldest unit exposed at this locality is the upper part of the Zuloaga Limestone (Unit H in Text-figure 22). The Zuloaga consists of massive to medium-bedded, often stylolitic medium-gray micritic limestone strata with nodules of black chert. Microfacies analyses of the Zuloaga at this locality indicate that the micrite contains encrusting coralline algae, nerineid gastropods, bivalves, foraminifera, and siliceous sponge spicules (Martin 1996, p. 67). According to Martin the faunal and floral data suggests that the Zuloaga Limestone at Canyon San Matias was deposited at inner neritic depths (<50m) on a carbonate bank free of wave energy. Martin's findings at Canyon San Matias are consistent with his data from the Zuloaga Limestone at its type locality in the Sierra Zuloaga. The age of the Zuloaga Limestone can only be established as middle Oxfordian or older via the superposition of overlying strata (Units G and F) containing middle Oxfordian ammonites. At San Pedro del Gallo (Durango) a middle Oxfordian ammonite was identified by co-author Cantu-Chapa from Burckhardt's (1910, 1912, 1930) "upper quartzite" unit.

San Matias Formation, n. fm.

Unit G and F are formally assigned to the **San Matias Formation (n. fm.,** herein). Unit G consists of medium bedded gray (weathering red) silty limestone and interbedded red silty

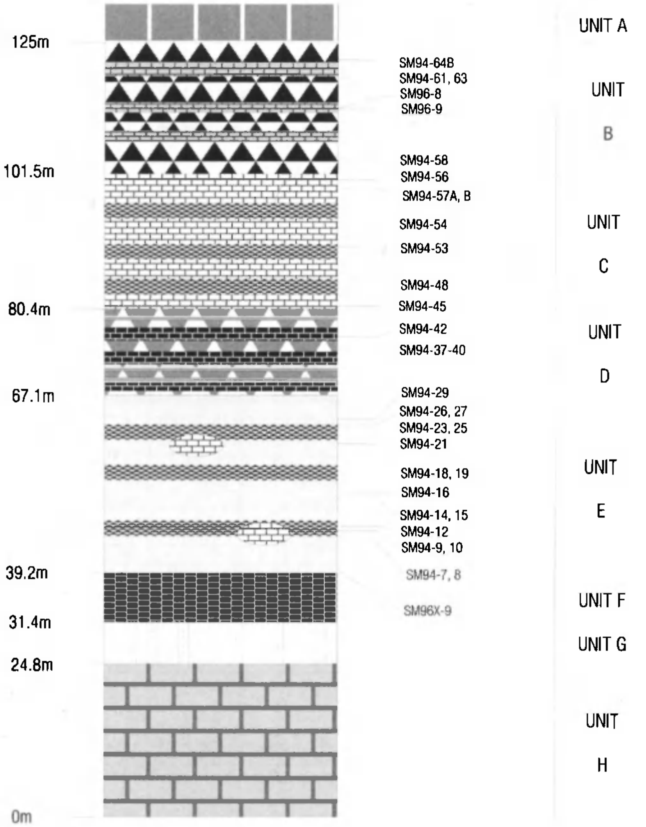


TEXT-FIGURES 25A, B
Photos of black chert and interbedded medium gray micrite. Canyon San Matias, Sierra Santa Rosa, Mazapil remnant of San Pedro del Gallo terrane. Note hammer for scale in 25B.

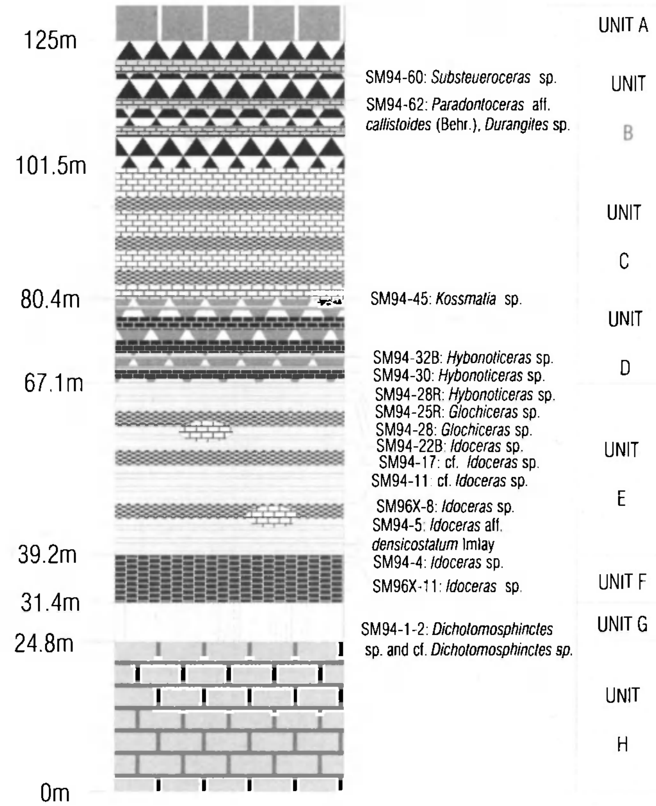
mudstone with common bivalves and ammonites. Unit F consists of medium bedded gray (weathering red) limestone with common to abundant ammonites and bivalves (Text-figures 22, 24). At Canyon San Matias the San Matias Formation is 14.4m thick (Text-figure 22). It conformably overlies the middle Oxfordian Zuloaga Limestone and disconformably underlies the upper lower Kimmeridgian strata of the La Caja Formation (See Unit E below and Text-figure 22). A specimen of *Idoceras* sp. was identified by co-author Cantu-Chapa from sample SM96X-11, 0.6m below the contact between the San Matias Formation and Unit E of the overlying La Caja Formation. The micrite nodule from which this ammonite was recovered also contains abundant Radiolaria. It is conceivable that the upper part of the San Matias Formation was reworked during the late early Kimmeridgian. Unit G of the San Matias Formation contains the middle Oxfordian ammonite *Dichotomosphinctes* (Text-figure 22, 29: Ammonite identifications by co-author Cantu-Chapa). Unit E of the overlying La Caja Formation contains *Buchia concentrica* and *Idoceras balderus, I. eomphaloides, I. humbolti, I. nesoaeum, I. santarosanum, I. sotelo, and I. zacatecanum* (See Burkhardt 1930, p. 50). Common Radiolaria are present in the upper part of Unit F. All of the Zuloaga Limestone, Unit G, and all but the upper part of Unit F were deposited at inner neritic depths. The sudden appearance of common Radiolaria in the upper part of Unit F reflects a rapid change in paleobathymetry from inner neritic depths to outer neritic depths (~ 200m) in the late Oxfordian (See Pessagno et al. 1999 and Pessagno and Martin 2003). Canyon San Matias in the Sierra Santa Rosa, Zacatecas is designated the type locality of the San Matias Formation. GPS Location: **N24°34'56.2"; W101°29'08.6"**. The San Matias Formation has also been recognized at Cerro El Vulcan near San Pedro del Gallo (See San Pedro del Gallo remnant above). At this latter locality it is 21m thick.

La Caja Formation

Units E, D, C, and B (lower Kimmeridgian to upper-most Tithonian/? lower Berriasian) are included in the La Caja Formation of Imlay (1938, 1939) (Text-fig. 22). All La Caja strata at Canyon San Matias are characterized by the presence of common to abundant beds of thin- to medium-bedded black, radiolarian chert identical to that in the San Pedro del Gallo Chert Member (herein). Black chert was noted by Burckhardt (1930) in his description of rocks now assigned to the La Caja Formation at its type locality in the Sierra de La Caja, Canyon San Matias, Sierra Zuloaga, and other localities in the west-



TEXT-FIGURE 26A
Distribution of radiolarian-bearing samples from lithostratigraphic units exposed in Mazapil remnant of San Pedro del Gallo terrane at Canyon San Matias, Zacatecas, Mexico.



TEXT-FIGURE 26B
Ammonites identified by Cantu Chapa from samples collected by Pessagno et al. (1999) from the Canyon San Matias section, Zacatecas, Mexico.

central Mexico. Curiously, the chert was not noted by Imlay (1938, 1939) in his description of the La Caja Formation at its type locality in the Sierra de La Caja (See Martin 1996; Pessagno et al. 1999). The black chert in the La Caja Formation at Canyon San Matias is interbedded with thin- to medium-bedded, dark gray micritic limestone and dark gray siliceous to calcareous mudstone commonly containing dark gray micritic limestone nodules which range in size from ~ 5cm to 2m in maximum dimension (Text-figure 25). Unit D, as noted by Burckhardt (1930: his units C, D, E), is unique in that it is characterized by the presence of beds of phosphate and phosphatic limestone. All La Caja strata contain a microfauna with profusely abundant Radiolaria, abundant siliceous sponge spicules, and rare benthonic foraminifera; the megafossil assemblage contains common to abundant ammonites. Deposition of La Caja strata at this locality during the Late Jurassic and Early Cretaceous (Berriasian) occurred at upper abyssal depths or, perhaps lower bathyal depths, above the ACD (compensation level of aragonite) and continued at these depths until the end of the Cretaceous (*See* Burckhardt 1930). Radiolarian chert consists of ~ fifty percent by volume of radiolarian tests and test fragments and hence, formed as a radiolarian ooze. The phosphate horizon occurring in unit D is both interesting and puzzling. Frequently, phosphate-rich sediments occur today along coast lines with narrow continental shelves and steep continental slopes at sites of upwelling of nutrient-rich waters. Whether this scenario could occur in the distal backarc setting characterizing all San Pedro del Gallo remnants is questionable. Phosphatic limestones and shales were recorded by Burckhardt (1930) in the Sierra Santa Rosa, Sierra de La Caja, and Sierra de Zuloaga (Text-figure 7: Locs. 5, 6, 8). They are not known from San Pedro del Gallo, Sierra Catorce, the Huayacocotla Anticlinorium, or from western Cuba (Text-figure 2: Locs. 12, 4, 3, 24). As suggested by Pessagno et al. (1999) an alternative to the upwelling model may be a large kill of fish and other organisms by a red tide—producing an abundance of phosphatized bones and other material at lower bathyal or upper abyssal depths (See also Cross and Pessagno 2006 for other alternative explanations).

The upper lower Kimmeridgian to lower upper Tithonian part of the La Caja Formation Unit E (Text-figures 22, 23-27) contains *Buchia*, Tethyan ammonites, abundant *Parvicingula/Praeparvicingula*, and poorly diversified pantanelliids indicative of Southern Boreal paleolatitudes. The remainder of Unit E and all of Units D, C, B, and A are assigned to the Northern Tethyan Province based on the presence of abundant, diversified pantanelliids, abundant to common *Parvicingula/Praeparvicingula*, and the presence of calpionellids (Units A and B: See Text-figures 5-6 herein). As noted by Pessagno et al. (1999), these data indicate that the Mazapil remnant of the SPG terrane was transported from Southern Boreal paleolatitudes (>30°N) to Northern Tethyan paleolatitudes (<30°N to >22°N) during the early Kimmeridgian to late Tithonian. It should be noted that Ogg's paleomagnetic data for the upper Tithonian at Canyon San Matias indicates 25°N/S.

SPECIES/SAMPLES	SM94-12B	SM94-14	SM94-15	SM94-16	SM94-18	SM94-19	SM94-21	SM94-25	SM94-26	SM94-27	SM94-29	SM94-37	SM94-38	SM94-39	SM94-40	SM94-45	SM94-48	SM94-53	SM94-54	SM94-56	SM94-57A	SM96-8	SM96-9	SM94-64
Position in section: Meters above base of Unit E, La Caja Fm.	7.9	11.7	12.3	13.4	16.7	16.47	21.9	24.5	25.7	26	29.5	35.9	37.3	37.5	37.6	41.4	45.3	55.6	57.3	64.1	59.5	74.5	73.9	81.8
Pantanellium cantuchapai					C		A	C				R		R										
Pantanellium heimi												R												
Pantanellium westermanni												R												
Pantanellium meraceibaensis	C	A		A	A	R		C						C										
Pantanellium whalenae	C														C									
Pantanellium spp.	C		R	A	A	R	R													C	A	C	A	C
Bivallupus longoriai					R																			
Vallupus hopsoni	R						C	R																
Vallupus nodosus																R								
Vallupus spp.																C								
Neovallupus spp.																C								
Acosta acer			R																					
Tripocyclia notablis					C																			
Orbiculiforma teres		R																						
Phantum inseperatum			R																					
Perispyyridium spp.	R	C		R			R				R													
Complexapora kozuri												A		R		R		R		R	A		R	
Complexapora kiesslingi																R								
Complexipora sp. A																R								
Complexapora spp.														R										
Obesacapsula sp.aff. O. rotundata		R	R							R														
Obesacapsula spp.		R	R	R			R																	
Spongocapsula palmerae			C									R	C											
Loopus primitivus	C	A	A	A		R	A	C				A	C·	A	R								C	R
Loopus spp.		C	C	C																				
Hsuum mclaughlini								R								R			C	R		R		
Hsuum naturale		R		R																	C			
Ristolla altissima																R		R		C				
Ristola procera								C	A	A							C		C					
Caneta hsui	C	C	C					C																
Caneta spp.	C	C	C					C		R														
Mirifusus mediodilatata																	R							
Mirifusus baileyi																	A							
Mirifusus spp.																	A		R					
Parvicingula alamoensis	A	A	A	C	C										R		R							
Parvicingula broqueta			R			R																		
Parvicingula colemani																C	R		R	R		C	R	
Parvicingula corralensis																								
Parvicingula excelsa						C							C	R		A			A			R		
Parvicingula gemmata																R								
Parvicingula gracila																			C					
Parvicingula jonesi						C										C	A		R	C	C	C	C	A
Parvicingula sanfillipoae														R				C						
Parvicingula spp.	A	A	A	C		A	R	A	A	A				A			A	C			A		A	A
Praeparvicingula holdworthi			C	R	C																			
Praeparvicingula(?) nebulosa			C																					
Praeparvicingula spp.	C			C						A		R		C			C	C			A			C
LA CAJA FORMATION	UNIT E											UNIT D *b				UNIT C						UNIT B		
BIOZONES	SUBZONE 4 BETA$_1$											SZ. 4 BETA$_2$					SUBZONE 4 ALPHA$_2$*							

TEXT-FIGURE 27

Faunal analysis of Tithonian radiolarian-bearing samples from the La Caja Formation at Canyon San Matias. *Subzone 4 alpha$_1$ not observed but probably present. Base of Unit D at 27.9 m. (SM94-28R: text-figure 7). Lower 1.9m of Unit E assignable to Subzone 2 alpha$_2$. (lower Kimmeridgian). Boundary between Subzone 2 alpha$_1$ and Subzone 2 alpha$_2$ occurs between 1.9m and 7.0m. SZ. 2 alpha$_2$.fauna occurs at 7.0m. Zone 3 not recorded to date but may occur in interval between 7.0m and 7.9m (base of Zone 4). recorded to date, but may occur in interval between 7.0m and 7.9m (base of Zone 4).

Discussion of radiolarian and ammonite biostratigraphic data and its chronostratigraphic significance

Text-figure 26 shows the distribution of Radiolarian-bearing samples within the La Caja Fomation. A faunal analysis of samples assignable to **Subzones 4 beta$_1$**, **4 beta$_2$**, and **4 alpha$_2$** is presented in Text-figure 27. Plates 3-6 provide scanning electron micrographs of Radiolaria recovered from the La Caja Formation at Canyon San Matias.

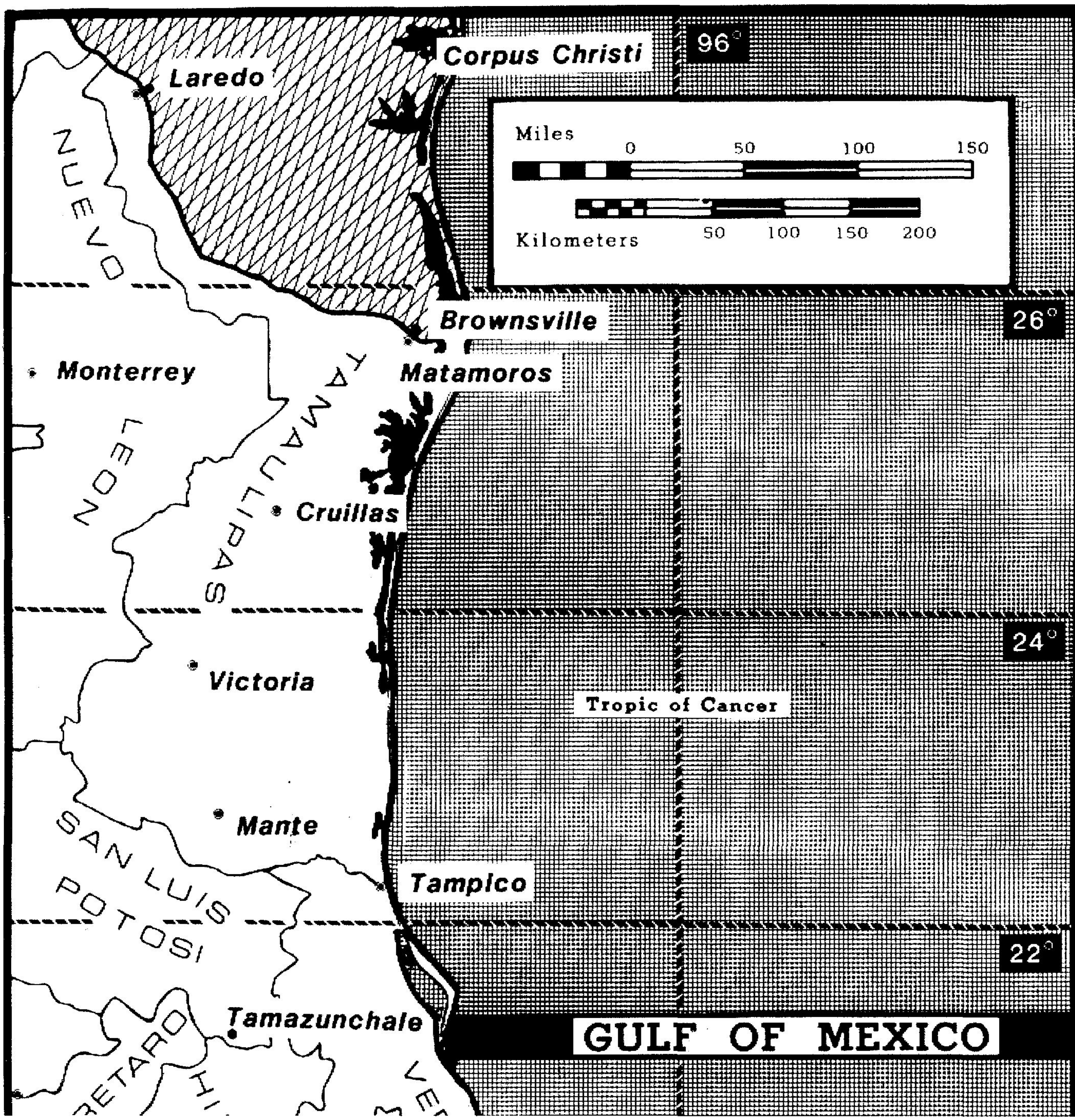
The lower 1.9m of the La Caja Formation unit E at Canyon San Matias contain a radiolarian assemblage assignable to the upper lower Kimmeridgian (**Zone 2, Subzone 2 alpha$_2$**). The boundary between **Subzone 2 alpha$_1$** and overlying **Subzone 2 alpha$_2$** occurs between 1.9m and 7.0m above the base of Unite E. Zone 3 Radiolaria have not been recorded to date, but may occur in the interval between 7.0m and 7.9m (Sample SM94-12 = base of **Subzone 4 beta$_1$** Text-figure 26). A major disconformity and an accompanying hiatus occurs between the base of the La Caja Formation (Unit E) and the underlying San Matias Formation (**n. fm.**, Units F and G; see above and Text-figure 22). Both the ammonite and radiolarian biostratigraphic data suggest that part of the upper Oxfordian and part of the lower Kimmeridgian are missing. This disconformity and hiatus reflect the opening of the Gulf of Mexico (*see* Pessagno and Martin 2003; Cross and Pessagno 2006). The presence of *Idoceras* sp. at SM94-22B reflects reworking associated with this unconformity (Text-figure 29). The interval from 7.9m (SM94-12B) to 37.3m (SM94-38) is assigned to **Subzone 4 beta$_1$** (upper lower Tithonian: *See* Text-figures 26-27) based on the presence of *Pantanellium cantuchapai, P. westermanni, P. whalenae, Vallupus hopsoni, Parvicingula alamoensis, P. broqueta, P. excelsa, P.(?) nebulosa, Praeparvicingula holdsworthi*, and *Perispyridium* spp. In the Huayacocotla remnant of the San Pedro del Gallo terrane *Pantanellium whalenae, P. westermanni* and *Vallupus hopsoni* make their first appearance at the base of **Subzone 4 beta$_1$** 6m below the contact between Mera Ceiba and the Barrio Guadalupe members of the Taman (*See* Pessagno et al. 1987a and Taman-Tamazunchale area, Huayacocotla remant of the SPG terrane below). Moreover, this horizon occurs 6m *below* the contact with the upper lower Tithonian **Mazapilites Zone** of Cantú-Chapa (1971).

Litho Unit	Description	Age	Diagnostic Faunal Elements	Paleobathymetry	Faunal Realm/Province
Chapulhuacan Limestone	Medium to massively bedded very fine-grained cream to light gray micrite with abundant Radiolaria, calpionellids, and rare ammonites. Micrite with black chert nodules and lenses. Thickness = ~ 30 m.	Berriasian to Valanginian.	*Subthurmannia* sp. *Neolissoceras* sp. *Spiticeras* sp. *Thurmanniceras* sp.	Abyssal	Central Tethyan Province
Pimienta Formation	Thin-bedded cream colored to light gray micrite interbedded with dark gray shale, common black radiolarian chert, and light green vitric tuff. Micrite with abundant Radiolaria and calpionellids together with rare ammonites and common sponge spicules. Thickness = ~ 200 m.	late Tithonian	*Paradontoceras* aff. *callistoides* *Durangites*, *Substeueroceras* + Subzone 4α Radiolaria at some localities to south		
Taman Formation T = 200-500 m. Barrio Guadalupe Member	Thin-bedded dark gray to medium gray micrite with thick interbedds of dark to medium gray shale. Shale layers with abundant micrite nodules. Micrite nodules and beds with abundant Subzone 4β Radiolaria siliceous sponge spicules and commonammonites.	late Tithonian	*Durangites*, *Kossmatia*, *Salinites grossicostatum* + very abundant Subzone 4β_2 Radiolaria.	Upper	Northern Tethyan Province
Mera Ceiba Member	Massively bedded dark gray to medium gray micrite interbedded with thin-bedded to medium bedded shale. Upper part of unit with numerous dark gray micrite nodules. Massive micrites and micrite nodules with abundant Radiolaria rare to common ammonites and common pectenacids (*Aulacomyella*). Hyaline calpionellids occur in basal Zone 4, Subzone 4β strata at same horizon as lower Tithonian ammonite *Mazapilites*.	early Kimmeridgian to early Tithonian	*Ataxioceras*, *Idoceras*, *"Glochiceras fialar"* *Mazapilites*, *Virgatosphinctes* + Radiolaria assignable to Subzone 2α_1, Zone 3, & Subzone 4β_1.		
				Outer Neritic	
Santiago Formation	Silty black shale, mudstone, micrte. Containing ammonites. Radiolaria occurring in upper-most part. Thickness = ~169 m.	early Callovian to late Oxfordian	*Reineckeia*, *Dichotomosphinctes*, *Discosphinctes*, *Ochetoceras*.	Inner Neritic	Southern Boreal Province
Tepexic Limestone	Calcarenite containing ammonites and bivalves. Thicknes = ~ 39 m.	late early Callovian	*Reineckeia*, *Neuqueniceras*		
Palo Blanco Formation	Organic rich black shale. Rare in surface outcrops. Present in subsurface.	late Bath.-e. Callov.	*Kepplerites*		
Cahuasas Formation	Continental red beds. Dominantly red shale, siltstone, sandstone, and conglomerate. Commonly cross-bedded. Overlies Lower Jurassic (Sinemurian) strata of Huayacocotla Group.The latter unit contains Sinemurian ammonites. Thickness ~ 40-1200 m. (1)	Bathonian to Bajocian.	Fossil plants.	NON MARINE	

TEXT-FIGURE 28
Stratigraphic summary for Taman-Tamazunchale area, Huayacocotla remnant (pt.), San Luis Potosi, Mexico. (1) In the subsurface the Cahuasas Formation is overlain by the marine (inner neritic) black shale of the Palo Blanco Formation (Cantú Chapa 1969, p. 5). The Palo Blanco Formation is important because it contains the first marine strata in the Gulf Mexico Province overlying Middle Jurassic continental red beds and because it contains the Boreal upper Bathonian to lower Callovian ammonite *Kepplerites*. In most surface sections the Palo Blanco is missing and the lower Callovian Tepexic Limestone overlies the Cahuasas.

Complexapora kozuri, the primary marker taxon for the base of **Subzone 4 beta$_2$**., makes its first appearance at locality SM94-39, 3.7m below the occurrence of a specimen of *Kossmatia* identified by co-author Cantú-Chapa at SM94-45(Unit D-C boundary: *See* Text-figs. 7, 21, 24, 26-29 herein). The phosphate-bearing interval represented by Unit D (Text-fig. 22) at Canyon San Matais corresponds to Units C, D, and E of Burckhardt (1910, p. 50, Fig. 13.). Burckhardt's Unit C, which is 5m thick, corresponds to the upper part of Unit D herein (cf. Text-figure 22). Burckhardt recorded *Steueroceras santarosanum* Burckhardt (1930) (= *Kossmatia flexicostata* (Aguira 1895) [See Verma and Westermann 1973, p. 221], *Kossmatia victoris*, and *Kossmatia zacatecana* from his Unit C. Sample SM94-45 from 41.4m contains *Neovallupus* sp. and *Vallupus nodosus* in association with *Kossmatia* and is assignable to the upper part of **Subzone 4 beta$_2$**. It is clear that the interval within **Subzone 4 beta$_2$** (SM94-39: 37.3m to SM94-45: 41.4m) marked by the first occurrence of *Complexapora kozuri* and the last appearance of *Neovallupus* sp. and *Vallupus nodosus* is assignable to the lower part of the upper Tithonian. As noted above, at San Pedro del Gallo, this interval contains *Kossmatia, Durangites*, and the first occurrence of *Buchia piochii*, the final occurrence of *Buchia mosquensis*. No Radiolaria were recovered from La Caja Formation Unit B above SM94-64 at 81.8m. *Complexapora kozuri* and other species characteristic **Subzone 4 alpha$_2$** persist as high as SM96-9 at 73.9m (*See* Text-figures 26-28 herein.). Additional species characteristic of the upper part of **Subzone 4 alpha$_2$** occur in sample SM94-64 at 81.8m. It should be noted that **Subzone 4 alpha$_1$**, though probably present, has not been observed to date in the La Caja Formation at Canyon San Matias.

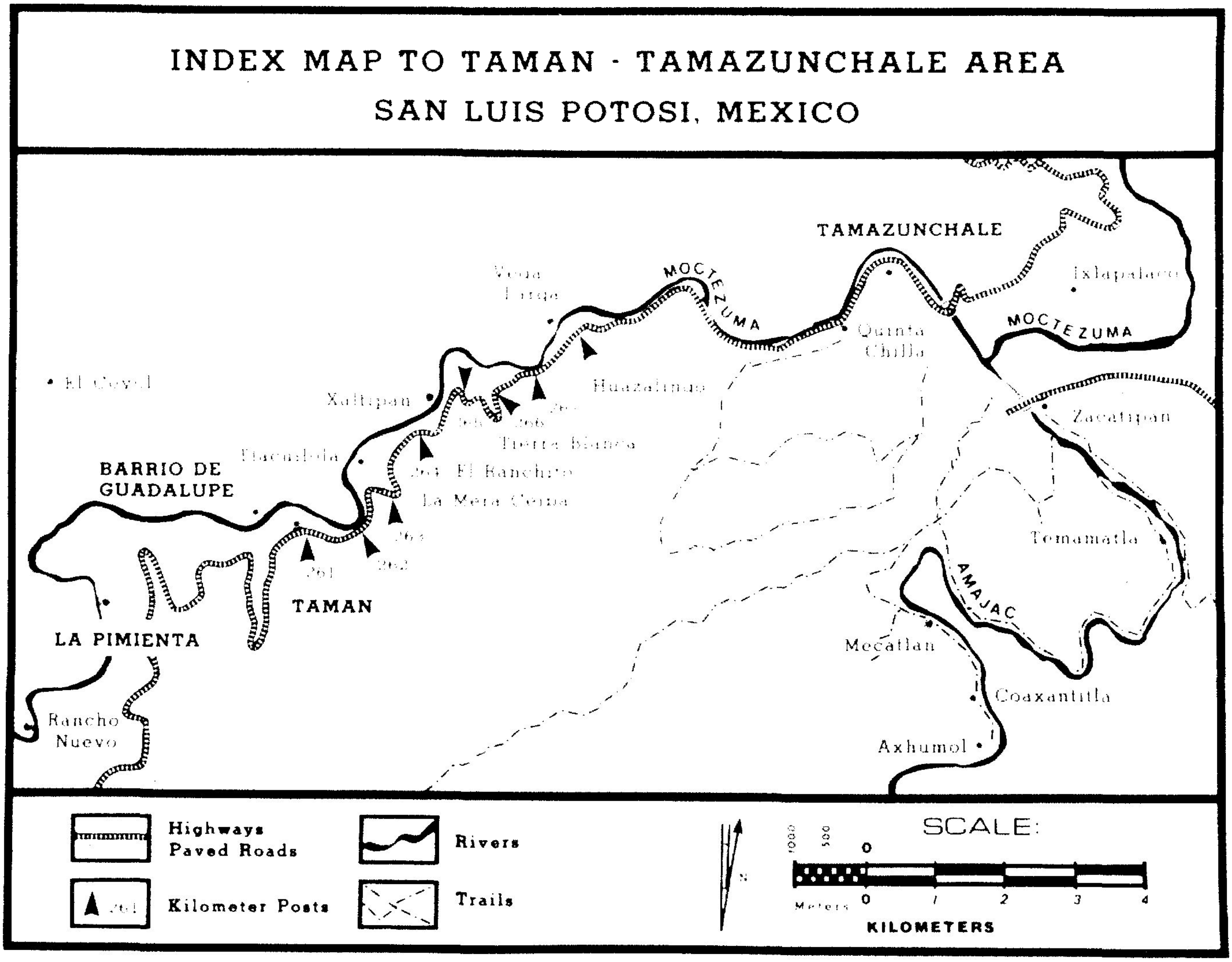
Ammonites recovered from the upper part of La Caja Formation Unit B and the upper part of radiolarian **Subzone 4 alpha$_2$** during the present study include *Parodontoceras* sp. aff. *P. callistoides* (Behr.) and *Durangites* sp. at SM94-62 at 76m and *Substeueroceras* sp. at SM94-60 (78.2m) (Identifications by co-author A. Cantú-Chapa). A specimen identified by co-author Cantú-Chapa as "cf. *Substeueroceras* sp." was recovered from float in the creek bed approximately 99m above the base of the La Caja Formation. A possible lower Berriasian ammonite was identified by A. Cantú-Chapa as "cf. *Protothummania* sp.) from sample SM96-2 in Unit B at 4.72m below the contact with Chapulhuacán Limestone (Unit A) and 81.08m above the base of the La Caja Formation. This ammonite occurs at essentially the same horizon as radiolarian sample SM94-64. The latter



TEXT-FIGURE 29
Regional index map for east-central and northeast Mexico from Pessagno et al. (1987a).

sample contains **Subzone 4 alpha$_2$** radiolarian assemblage with *Pantanellium whalenae* and *Loopus primitivus*. As will be seen in the discussion of radiolarian data from the California Coast Ranges *Loopus primitivus* has neither been observed in lower Berriasian strata assignable to the upper part of the **Buchia sp. aff. okensis Zone,** the overlying **Buchia uncitoides Zone,** nor to radiolarian **Zone 5, Subzone 5A**. Hence, it is suggested that the Tithonian-Berriasian boundary may occur at approximately 81m above the base of the La Caja Formation and 4.72m below the contact with the Chapulhuacán Limestone (Unit A). Additional samples are needed to resolve this problem. Remane (Report to Senior Author, Appendix 2 herein) identified *Calpionellopsis oblonga* in sample SM94-65 (his SM65) in the Chapulhuacán Limestone. He indicated that this taxon occurs in calpionellid Subzone D and in Zone E (upper Berriasian to lower Valanginian; probably upper Berriasian.

The Chapulhuacán Limestone (Unit A) consists of medium to massively bedded light gray (weathering buff to cream colored)



TEXT-FIGURE 30
Index map for Taman-Tamazunchale area, San Luis Potosí, Mexico from Pessagno et al. (1987). The majority of radiolarian samples were collected along Rt. 85 (Mexico, D. F.-Nuevo Laredo highway) in the canyon of the Río Moctezuma. These localities are referenced to kilometer posts along Route 85. Other samples localities are situated west of Barrio Guadalupe along the Río Moctezuma and along a road to the north.

very aphanitic micrite. Ammonites from the overlying Chapulhuacán Limestone (Unit A) were too poorly preserved to be identified. However, it is worth noting that at San Pedro del Gallo and at a number of localities in the subsurface of the Huayacocotla remnant, this unit contains lower Berriasian ammonites (*See* San Pedro del Gallo remnant above).

Huayacocotla remnant of the San Pedro del Gallo terrane

A detailed discussion of the stratigraphy of the Huayacocotla remnant was presented by Pessagno et al. (1999), by Pessagno and Martin (2003), and by Pessagno (2006) (See composite stratigraphic summary in Text-figure 8 herein). Pessagno et al. (1999) presented data to document the tectonic transport of the Huayacocotla remnant of the San Pedro del Gallo terrane from Southern Boreal paleolatitudes (40°N) during the late Bathonian/early Callovian to Northern Tethyan paleolatitudes during the late Oxfordian to early late Tithonian, and to Central Tethyan paleolatitudes by the late Tithonian (Text-figure 30). Only the stratigraphy of the Taman Formation and the overlying Pimienta Formation and Chapulhuacán Limestone is discussed in detail below.

Taman-Tamazunchale area, San Luis Potosí Taman Formation

The Taman Formation (Heim 1926, 1940) is well exposed at its type locality adjacent to the village of Taman (San Luis Potosí) along the Río Moctezuma (Text-figures 29-30 herein). Ammonites, ammonite aptychi, and the pectenacid *Aulacomyella* occur throughout the Taman Formation. Whereas *Aulacomyella* is common throughout the unit, ammonites are usually rare to common. The sparcity of ammonites reflects deposition at abyssal depths below the ACD. Radiolaria and siliceous sponge spicules are by far the most abundant fossils in the Taman Formation; they occur in both the bedded micrite and micrite nodules.

In this report the Taman Formation is divided into two new members: (1) The Mera Ceiba Member and (2) the Barrio Guadalupe Member. These new lithounits are equivalent to the

TABLE 1
Partial upper Tithonian (Upper Jurassic) sequence at Loma Rinconada, Sierra Cruillas, Tamaulipas, Mexico. Section measured and collected in June 1954 by William E. Humphrey, Raul Perez, and Teodoro Diaz. Ammonites identified by Ralph W. Imlay. Modified from Imlay (1980, p. 35).

Interval	Measured Interval	Thickness of Interval in Meters
12	Limestone, thin-bedded, tabular, laminated dark gray to black; lenses of black chert; intercalated gray shale. Contains *Microacanthoceras acanthellum* Imlay.	**13.0m**
11	Limestone, thin-bedded, laminated; intercalated gray shale. Contains *Corongoeras filicostatus* Imlay, *Metahaploceras*? and *Inoceramus*.	**5.5m**
10	Mostly covered. Some tuffaceous limestone. Contains *Kossmatia victoris Burckhardt*. Probable float also contains *Corongoeras*.	**8.5m**
9	Limestone, black, laminated, thin-bedded; lenses of black chert. Contains *Kossmatia victoris Burckhardt*. Float contains *Lytohoplites caribbeananus* Imlay and *Corongoeras filicostatus* Imlay.	**12m**
8	Tuff, sandy, thin-bedded, platy, laminated. Contains perisphinctid ammonites.	**5.5m**
7	Tuff, sandy, medium-bedded, siliceous.	**10m**
6	Limestone, dark-gray, thin-bedded, laminated, siliceous; limestone concretions and chert bands. Contains *Physodoceras* and *Metahoploceras*?. Float from probably the same unit contains *Durangites*, *Parodontoceras*?, and *Simonoceras*.	**6.0m**
5	Mostly covered.	**8.0m**
4	Limestone, siliceous, thin-bedded, shaley. Contains *Corongoceras*?	**7.0m**
3	Tuffs and black siliceous limestone	**18.0m**
2	Mostly covered.	**13.0m**
1	Limestone, gray to black, siliceous, banded, laminated, medium to thin-bedded; some tuffaceous shale. Contains *Microacanthoceras anthellum* Imlay and *Simoceras* (Virgatosimoceras). Float contains *Corongoceras filicostatum* Imlay.	**13.5m**

"lower massively bedded member" and the "upper thin-bedded member" of Pessagno et al. (1984, 1987a, b; 1999, Yang and Pessagno (1989), and Yang (1993). The two new members of the Taman Formation are described below.

Mera Ceiba Member of the Taman Formation (n. mem.)

The Mera Ceiba Member consists of medium to thick bedded, often highly petroliferous dark gray micrite with thin black shale and mudstone interbeds (Text-figure 31). The micrite weathers to light gray to often reddish gray color. Common limestone nodules ranging from 7cm to 0.6m occur in the upper half of the Mera Ceiba Member. The Mera Ceiba Member contains rare to common ammonites, common specimens of the pectenacid *Aulacomyella* and a rich microfauna which includes very abundant Radiolaria, abundant siliceous sponge spicules, and rare foraminifera (Textulariina). Rare calpionellids were observed by Longoria (in Pessagno et al. 1984) ~ 6m below the top of the unit. Because of the structural complexity of the area near Taman, the thickness of the Mera Ceiba Member is difficult to calculate. However, elsewhere in the Huayacocotla Anticlinorium the thickness of this unit ranges between 200 and 500m (Erben 1956).

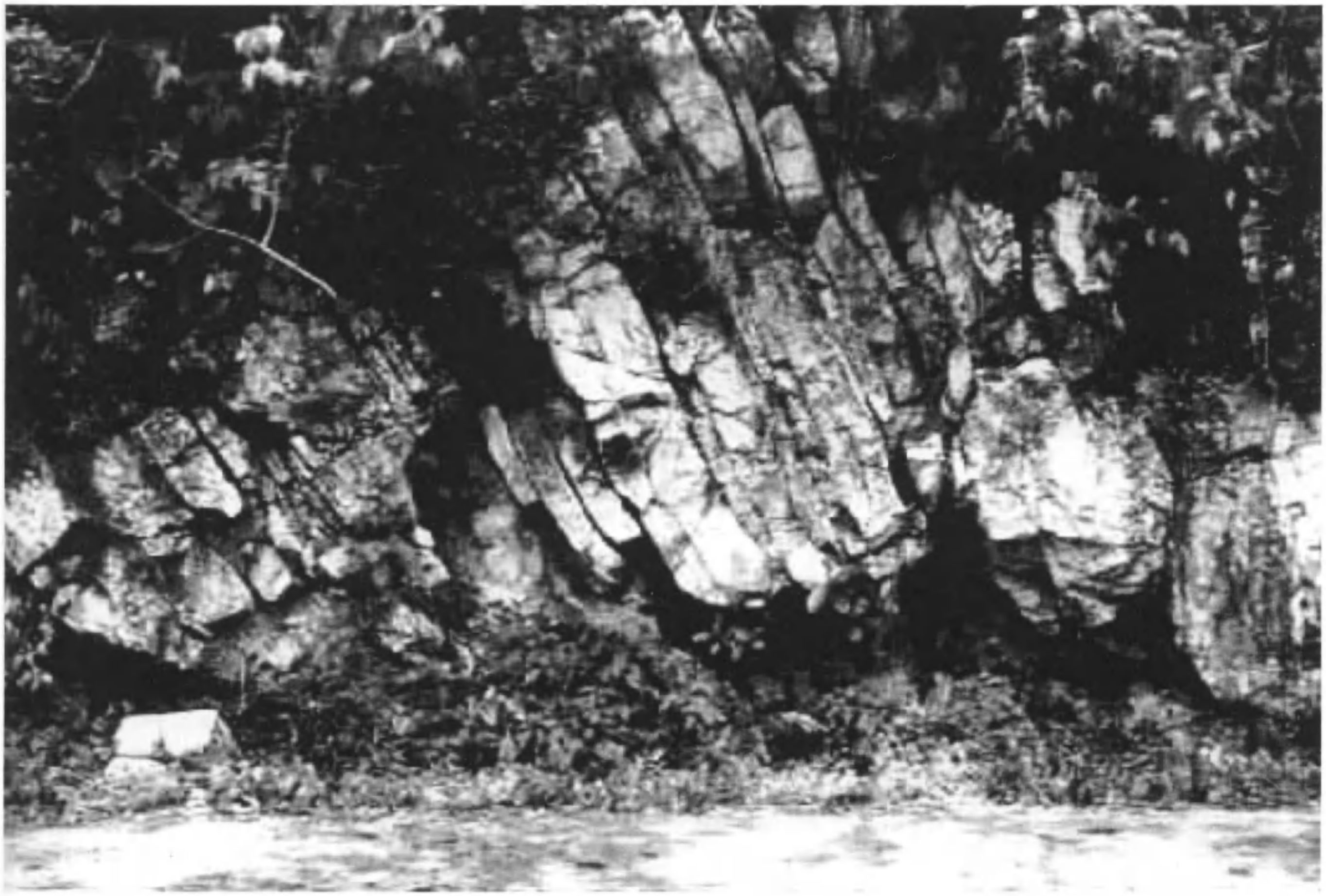
The contact between the base of the Taman Formation/base of Mera Ceiba Member and the underlying Santiago Formation is well exposed just east and downstream from the village of Taman on the north side of the Río Moctezuma. This exposure is designated the boundary stratotype for the base of the Taman Formation as well as the base of the Mera Ceiba Member. The Mera Ceiba Member can be recognized on the surface and in the subsurface along the entire Huayacocotla Anticlinorium. It corresponds to the Taman Formation of Cantú-Chapa (1971) and Imlay (1980).

This unit takes its name from Mera Ceiba just to the east of the village of Taman (Text-figure 30).

Barrio Guadalupe Member of the Taman Formation (n. mem.)

The Barrio Guadalupe Member of the Taman Formation consists of thin beds of dark gray to black micrite with thick interbeds of black shale, siltstone, and tuff (Text-figure 32). Small lenses of black chert occur occasionally in the upper half of this member. Common limestone (micrite) nodules, ranging in size from 7.6cm to 0.9m in diameter occur throughout the Barrio Guadalupe Member. The bedded micrite and nodules contain common ammonites, *Aulacomyella,* abundant Radiolaria, abundant sponge spicules, and common to abundant calpionellids. The Barrio Guadalupe Member is frequently characterized by the presence of olistostromal (submarine slump) masses indicative of deposition on a steep slope. At Barrio Guadalupe, the Barrio Guadalupe Member is a minimum of 150m in thickness (See Yang 1993). The Barrio Guadalupe Member is in fault contact with the overlying Pimienta Member locally in its type area.

At Taman the contact with the underlying Mera Ceiba Member can be recognized near the north end of the bridge over the Río Moctezuma between Taman and Barrio Guadalupe and just west



TEXT-FIGURE 31
Mera Ceiba Member of Taman Formation exposed west of Vega Larga on Rt. 85 (Mexico, D.F.-Nuevo Laredo highway) near Km 267 (San Luis Potosi, Mexico). Upper Jurassic (upper Kimmeridgian).

of Barrio Guadalupe (Cantu-Chapa ,1971, Af. 21; Pessagno et al. 1987a: Locs. MX 85-22, MX 85-23; MX 85-25; MX 85-26). At the latter locality the Barrio Guadalupe Member is infolded into the Mera Ceiba Member in a small, tight synclinal fold exposed in the bed of the Río Moctezuma near the foot trail on the north side of the river.

The exposure at the north end of the Rio Moctezuma bridge is designated the holoboundary stratotype for the Barrio Guadalupe Member and the exposure west of Barrio Guadalupe in the river bed is designated the paraboundary stratotype for the Barrio Guadalupe Member.

This member corresponds to the lower part of the Pimienta Formation of Cantu-Chapa (1971) and Imlay (1980) (See Pimienta Formation below). The Barrio Guadalupe Member can be recognized on the surface and in the subsurface along the east side of the Huayacocotla Anticlinorium from San Luis Potosi to Veracruz. At Taman the Barrio Guadalupe Member includes Cantu-Chapa's (1971) **Mazapilites** and **Saurites bituberculatum zones** and radiolarian **Subzones 4 beta$_1$ and 4 beta$_2$** herein.

The Barrio Guadalupe Member of the Taman Formation is named for Barrio Guadalupe immediately north of Taman (Text-figure 30).

Integration of ammonite and radiolarian biostratigraphic data from the Taman Formation in Taman-Tamazunchale area, San Luis Potosi, Mexico

The Mera Ceiba Member of the Taman Formation in its type area contains ammonites assigned by Cantu-Chapa (1971) to the **Ataxioceras Zone** (lower Kimmeridgian), the **Idoceras Zone** (uppermost lower Kimmeridgian), the **Glochiceras gp. fialar Zone** (upper Kimmeridigian), and the **Virgatosphinctes mexicanus-Aulacomyella neogeae Zone** (lower Tithonian). The Barrio Guadalupe Member of the Taman Formation (= Pimienta Formation [part] of Cantu-Chapa (1971) includes in ascending order the **Mazapilites Zone** and the **Saurites biturberculatum Zone** (See ammonites zones for Pimienta Formation sensu Pessagno et al. 1987a, below;Text-figure 33). The intervening **Kossmatia victoris-Pseudolissoceras zitteli Zone**, though probably present, has not been encountered to date in the Taman-Tamazunchale area. This zone has been recognized by Cantu-Chapa (1971) at Mazatepec and other localities to the south along the Huayacocotla Anticlinorium.

In Text-figures 4 and 33 the terms "primary marker taxa", "supplementary marker taxa", and "corporeal taxa" are used in the sense of Pessagno et al. (1984, p. 8, Text-figure 1. See Appendix 1 herein). As can be seen from an examination of Text-figure 34, a major decline in abundance and diversity occurs in

TEXT-FIGURE 32
Barrio Guadalupe Member of Taman Formation at Barrio Guadalupe on north side of Río Moctezuma opposite village of Taman.

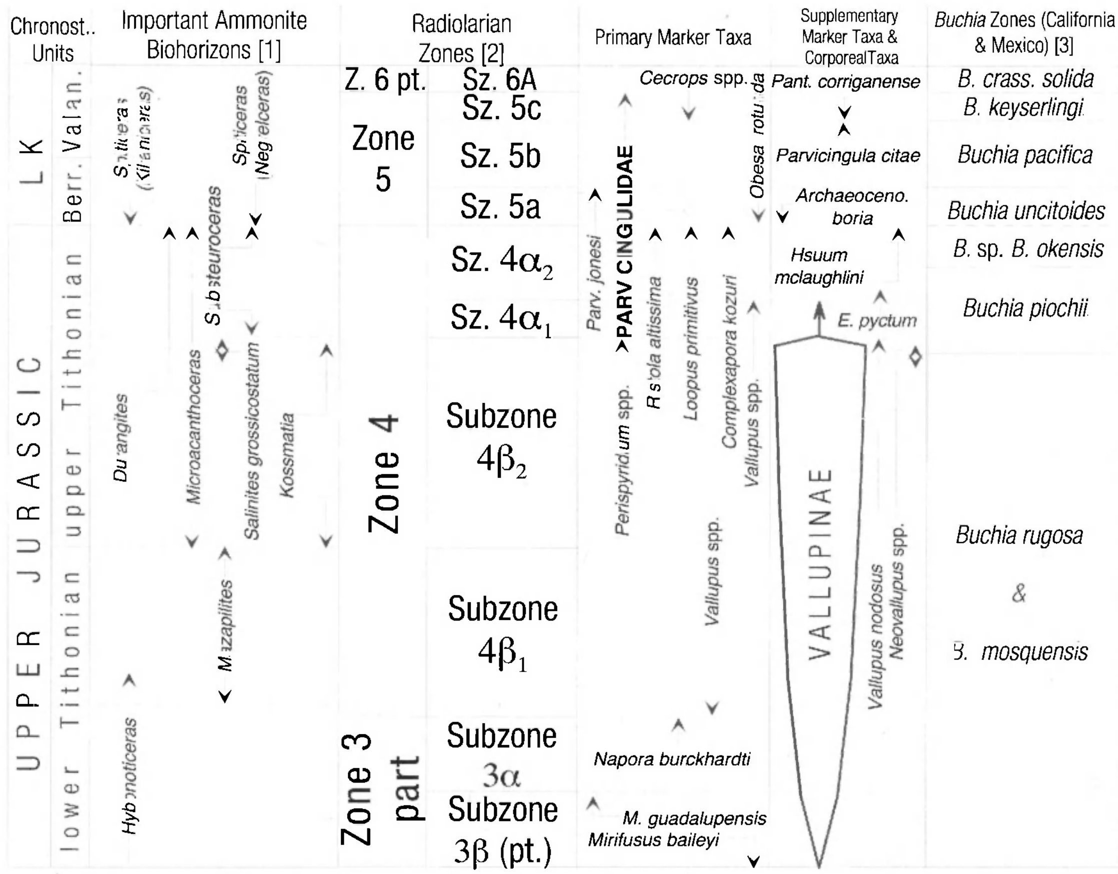
the pantanelliid Subfamily Vallupinae at the top of **Subzone 4 beta**, (See Pessagno et al. 1987a). Of particular importance is the final appearance of primary marker taxa *Perispyridium* Dumitrica at the top of **Subzone 4 beta**, (See also La Desirade herein).The base of radiolarian **Zone 4, Subzone 4 beta$_1$** occurs 6m below the base of the Barrio Guadalupe Member and the base of the **Mazapilites Zone** which marks the top of the lower Tithonian (Text-figure 33). In addition, it occurs at the same horizon where Longoria (in Pessagno et al. 1984, 1987) recovered *Crassicollaria* sp. As noted in the discussion of the ammonite, *Buchia*, and radiolarian biostratigraphic and chronostratigraphic data from San Pedro del Gallo, it is clear that the base of calpionellid **Zone A (Crassicollaria Zone**) is older in North America than it is in Europe (Text-figures 1, 34).

Studies by Pessagno et al. (1987a, b), Yang and Pessagno (1989), and Yang (1993) of the Upper Jurassic Radiolaria and associated ammonites indicate that *Neovallupus* first appears 63.7m above the base of the Barrio Guadalupe Member at MX85-23 near Barrio Guadalupe (Text-figure 32). The upper Tithonian ammonite, *Salinites grossicostatum*, was first identified by Professor Dr. Arnold Zeiss (Univ. Nurenberg -Erlangen, Germany *in* Pessagno et al. 1987a) at MX84-13 62m above the base of the Barrio Guadalupe Member of the Taman Formation to near the top of this unit. At Alamo Canyon in the Sierra Jimulco (Figure 9: Loc. 18 herein), Imlay (1939) recorded *Salinites grossicostum* from the upper part of the La Casita Formation. At this locality the La Casita Formation (71.9m) can be seen with both its lower contact with the La Gloria Formation and its upper contact with the Taraises Formation well exposed. Imlay indicated that the La Casita Formation is 71.9m (236f) thick. *Durangites*, the key zonal marker for the top of the upper Tithonian in Southern Europe, occurs with *Salinites grossicostatum* (Imlay) at a horizon 6.3m below the contact with the overlying Taraises Formation. At this locality as well as elsewhere in Mexico and Cuba, *Salinites grossicostatum* occurs above the final occurrence of *Kossmatia* (Imlay 1939, p. 7; Radiolaria 1976, p. 67-68). At 2m below the contact with the Taraises Formation *Durangites* and *S. grossicostatum* are missing in the faunal assemblage, but species of *Microacanthoceras* persist in association with *Substeueroceras* spp. and *Proniceras* spp. (*See* Collections K5 and K25 of Imlay 1939). *Salinites grossicostatum* has been reported associated with *Kossmatia* at San Pedro del Gallo (Hillebrandt et al. 1992) at Burckhardt Locality 23, Galeana, and other localities. The data from Barrio Guadalupe indicate that *Neovallupus* Yang and Pessagno has a range that corresponds closely to that of *S. grossicostatum*. At San Pedro del Gallo *Neovallupus* occurs no higher than the top of the San Pedro del Gallo Chert Member of the La Caja Formation in association with both *Kossmatia* and *Durangites*. It should be noted that Horizon M14 of Hillebrandt et al. (1992. = Locality 24 of Burckhardt 1910, 1912; see Text-figure 12) contains *Durangites, Kossmatia, Proniceras, Microacanthoceras*, and also *Salinites grossicostatum*. Locality 24 of Burckhardt occurs in the overlying Puerto del Cielo Shale Member of the La Caja Formation. At Canyon San Matias *Neovallupus* occurs with *Kossmatia* at locality SM 94-45 (See Text-figures 26-27). The interval with *Neovallupus* and *Kossmatia* corresponds to the **Suarites biturberculatum Zone** and possibly the upper part of the **Kossmatia victoris-Pseudolissosceras zitteli Zone** of Cantu-Chapa (1971). Moreover, this interval corresponds to the upper part of radiolarian **Subzone 4 beta$_2$**

Pimienta Formation (Emended herein)

The Pimienta Formation (Heim 1926, 1940) is named for the village of Pimienta, San Luis Potosi upstream and to the west of the village of Taman along the Río Moctezuma. Heim noted that the Pimienta Formation is typically exposed near the village of Pimienta and at Vega Larga (Text-figure 30). Unfortunately, field investigations by the senior author indicate that the exposure along the Río Moctezuma at Pimienta include strata that are included in the Lower Cretaceous (Barremian-Aptian) Ahuancatlalín Formation (See Bodenlos 1956), a unit which actually overlies the Chapulhuacan Limestone. Heim's exposure at Vega Larga occurs below the hanging bridge over the Río Moctezuma and includes strata that are consistent with the definition of the Pimienta Formation used herein and with that presented by Bodenlos (1956), Pessagno et al. (1984, 1987a, 1999, 2006), Pessagno and Yang (1989), and Yang (1993). By default, the Vega Larga locality is the type locality of the Pimienta Formation. In the Taman-Tamazunchale area near the village of Taman, the Pimienta Formation consists of approximately 200m of thin-bedded light to medium gray, often maroon weathering very fine grained micritic limestone alternating with black shale, black radiolarian chert, and occasional beds of yellowish-green vitric tuff. The Pimienta Formation differs from the underlying Barrio Guadalupe Member of the Taman Formation by possessing abundant thin beds of black radiolarian chert, occasional beds of light green vitric tuff, and thinner intervals of calcareous shale. Moreover, as noted by Pessagno et al. (1987a, p. 16), the Pimienta Formation lacks the abundant micritic limestone nodules characteristic of both members of the underlying Taman Formation. The Barrio Guadalupe Member of the Taman Formation was included by Cantu-Chapa (1971) in the Pimienta Formation. The Pimienta Formation as defined herein includes only the upper Pimienta of Cantu-Chapa and Imlay (1980). From the senior author's observations the Pimienta Formation both overlies the Taman Formation and underlies the Chapulhaucan Formation conformably in its type area.

As defined in the sense above, the Pimienta Formation encompasses **Parodontoceras aff. callistoides Zone** and possibly the upper part of the **Saurites biturberculatum Zone** of Cantu-Chapa (1971). Pessagno et al. (1987a) indicated that Cantu-Chapa's (1971) localities Af. 38 and Af. 39 contain ammonite assemblages assignable respectively to the **Parodontoceras aff. callistoides Zone** and the **Saurites biturberculatum Zone.** Moreover, they indicated that these localities occur in the "lower massively bedded member" (= Mera Ceiba Member herein) of the Taman Formation rather than in the "upper thin-bedded



TEXT-FIGURE 33
Correlation of important ammonite biohorizons with radiolarian and ammonite biozones of Pessagno et al. (1993 and herein), Cantu-Chapa (1971) and Imlay (1980).

member" (= Barrio Guadalupe Member herein) of the Taman Formation or in the Pimienta Formation. It is probable that this seemingly anomalous data resulted from the repetition of the upper Taman-Pimienta interval in a series of small anticlinal and synclinal folds that occur north and upstream from Barrio Guadalupe in the bed of the Río Moctezuma. Farther to the north and upstream from Barrio Guadalupe at localities Af. 37, 31, 30 Cantu-Chapa (1971) recovered ammonite faunas assignable to the **Parodontoceras aff. callistoides Zone** and to the Pimienta Formation s.s. Because the final appearance of *Salinites grossicostatum* occurs above the final appearance of *Kossmatia*, it is likely that the base of the **Saurites biturberculatum Zone** occurs in uppermost part of the Barrio Guadalupe Member of the Taman Formation and in the upper part of radiolarian **Subzone 4 beta**$_1$. *Salinites grossicostatum* has not been reported from the overlying Pimienta Formation in the Taman-Tamazunchale area. Farther to the south **Subzone 4 alpha**$_1$ Radiolaria were recovered by Pessagno et al. (1987a, p. 15, 35) from strata assignable to the "upper thin-bedded member" (= Barrio Guadalupe Member herein) of the Taman Formation (MX84-38A, 38B, 38C, 38D, 38E) exposed along the Río Texcapa adjacent to the power plant west of Huachinango, Puebla (Text-figure 30 herein). The radiolarian-bearing horizon occurs 61m above locality Af. 1 of Cantu-Chapa (1971). Ammonites recovered from Af. 1 were assigned to the **Saurites biturberculatum Zone** by Cantu-Chapa.

Pimienta strata in the area surrounding Taman contain *Calpionella elliptica*, *Tintonnopsella carpathica*, and *T. oblonga* (See Bodenlos 1956, p. 123). Although Radiolaria occur abundantly in both the micritic limestone and black chert, they are difficult to extract from these rocks. It is likely, however, that future workers may be able to extract calcified Radiolaria from the micrite using the acetic acid method of Kariminia (2006a) and from the chert using a more dilute solution of HF than that specified by Pessagno and Newport (1971).

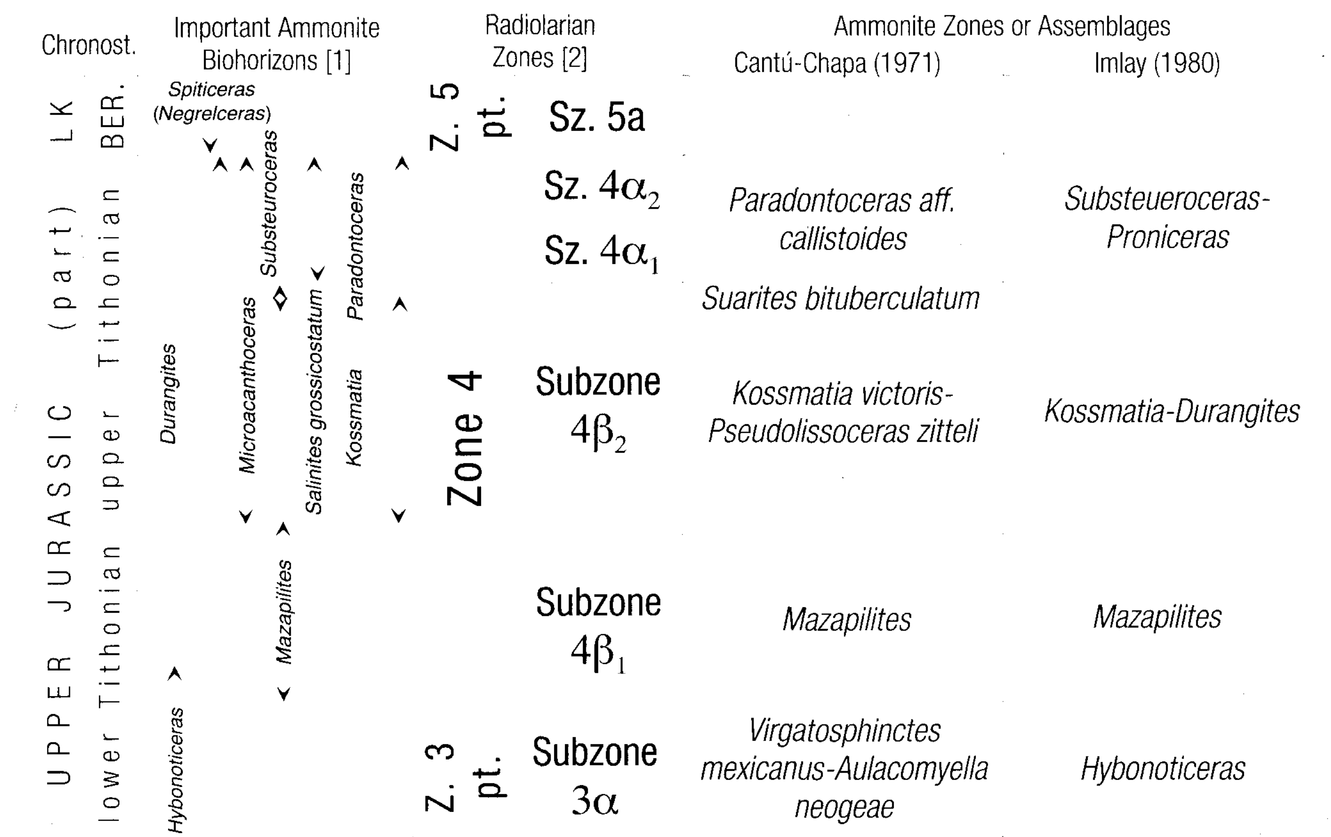
Pessagno et al. (1984, 1987a) incorrectly assigned the Pimienta Formation s.s. to the Berriasian based on the presence of the calpionellids cited above. However, it is now clear that the calpionellid biozones are diachronous and coeval between Europe and North America and that the Pimienta Formation should be assigned to the uppermost Tithonian.

Chapulhuacan Limestone

In its type area at Chapulhuacan, Hidalgo, Mexico the Chapulhuacan Limestone consists of medium to massively bedded, light gray to cream colored, white weathering micrite with beds, lenses, and nodules of black chert. Both the micrite and black chert contain abundant poorly preserved Radiolaria. No ammonites are reported from this unit in the Taman-Tamazunchale area.

Poza Rica District

Co-author Cantu-Chapa (1976, 1989, 1996, 1999) examined the Jurassic-Cretaceous boundary from over 1000 localities in the subsurface. In most cases he was able to relate his ammonite



TEXT-FIGURE 34
Correlation of important ammonite biohorizons with radiolarian and ammonite biozones of Pessagno et al. (1993 & herein), Cantú-Chapa (1971) and Imlay (1980).

biostratigraphic data to unpublished calpionellid biostratigraphic data generated by his colleague, the late Dr. Federico Bonet, when these workers both worked at the Petroleos Mexicanos Micropaleontology Laboratory. These subsurface data confirm the results of Cantú-Chapa's earlier study in 1967 from surface exposures at Mazatepec. In all cases, hyaline calpionellids such as *Calpionella elliptica* are associated with upper Tithonian ammonites and are longer ranging in North America than they are in Europe. Examples from Cantú-Chapa (1999) are presented below.

Northern Poza Rica district

In the Northern Poza Rica district south of Tampico (Text-figure 35) gamma rays were used by Cantú-Chapa (1999) for differentiating the boundary between the argillaceous and bentonitic strata of the Pimienta Formation from the micritic limestone of the overlying "lower Tamaulipas Formation" (= Chapulhuacán Limestone herein). At the Bejuco 6 well Cantú-Chapa (1999, p. 98, fig. 4) recovered a rich ammonite fauna from cores 7, 8, and 9 comprising the upper 20m of the Pimienta Formation. Ammonites from this 20m interval included *Salinites grossicostatum* (Imlay), *Proniceras victoris* Burckhardt, *P. subprunum* Burckhardt, *P. subtorrense* Cantú-Chapa, *P.* aff. *victoris* Burckhardt, *P.* aff. *subprunum* Burckhardt, *Durangites* aff. *vulgaris* Burckhardt, *Corongoceras* aff. *mendozanum* (Behrendsen), *Haploceras veracruzanum* Cantú-Chapa, *Durangites* sp., *Salinites inflatum* (Imlay), and *Salinites* sp. Moreover, Cantú-Chapa recovered the Berriasian ammonites *Subthurmania* sp., *Neolissoceras semisulcata* and *Berriasella (Berriasella)* aff. *jacobi* from the overlying "lower Tamaulipas Formation". No calpionellids were analyzed by Bonet from the Bejuco 6 well. However, gamma ray correlations from nearby wells supplied a datum for recognizing the contact between the Pimienta Formation and the overlying Chapulhuacán Limestone at adjacent well sites. Calpionellid biostratigraphic data from wells adjacent to the Bejuco 6 well and below the contact between the two formations are as follows:

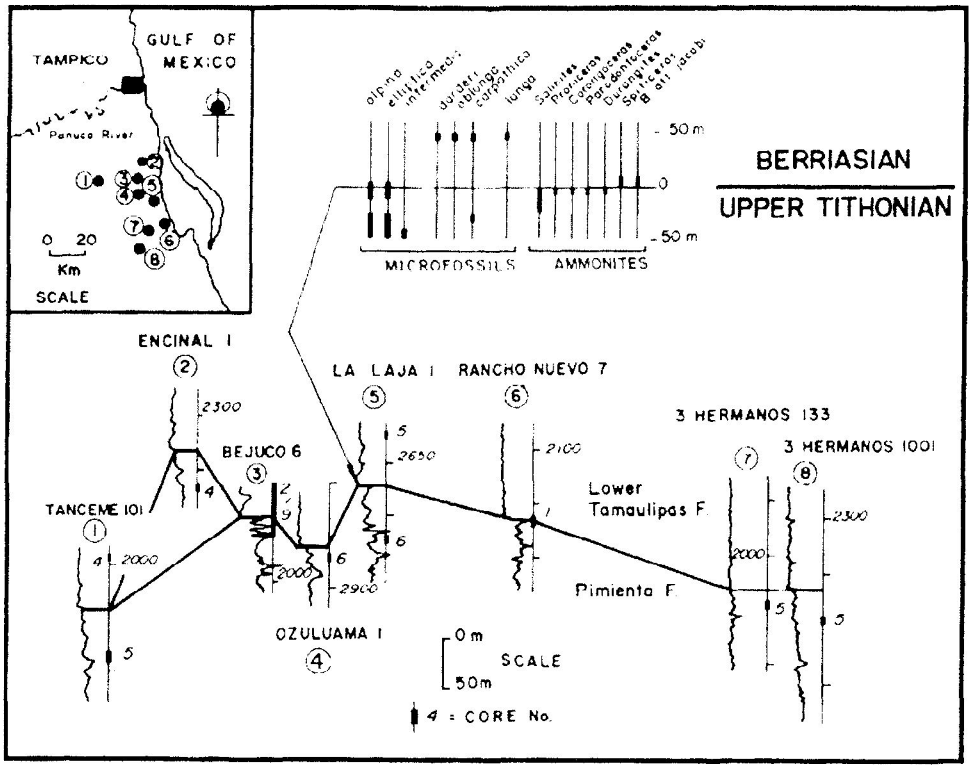
1) Tanceme 101 well, core 5: 2088-2090m: *Calpionella alpina, C. elliptica, Crassacollaria intermedia.*

2) Encinal well, core 4: 2366-2369m: *Calpionella alpina, C. elliptica.*

3) Ozuluama well-1, core 6: 2370-2372m: *Calpionella alpina, C. elliptica.*

4) La Laja well 1, core 6, :2722-2724m: *Calpionella alpina, C. elliptica.*

5) Rancho Nuevo 7 well, core 1: 2166-2169m: *Calpionella alpina, C. elliptica.*



TEXT-FIGURE 35
Jurassic-Cretaceous boundary in subsurface in Poza Rica field, Veracruz, Mexico. Top of Taman Formation referenced to gamma ray logs. Note distribution of calpionellids and ammonites.

6) 3 Hermanos 133 well, core 5: 2045-2047m: *Calpionella alpina, C. elliptica.*

7) 3 Hermanos 1003 well, core 5: 2392-2396m: *Calpionella alpina, C. elliptica.*

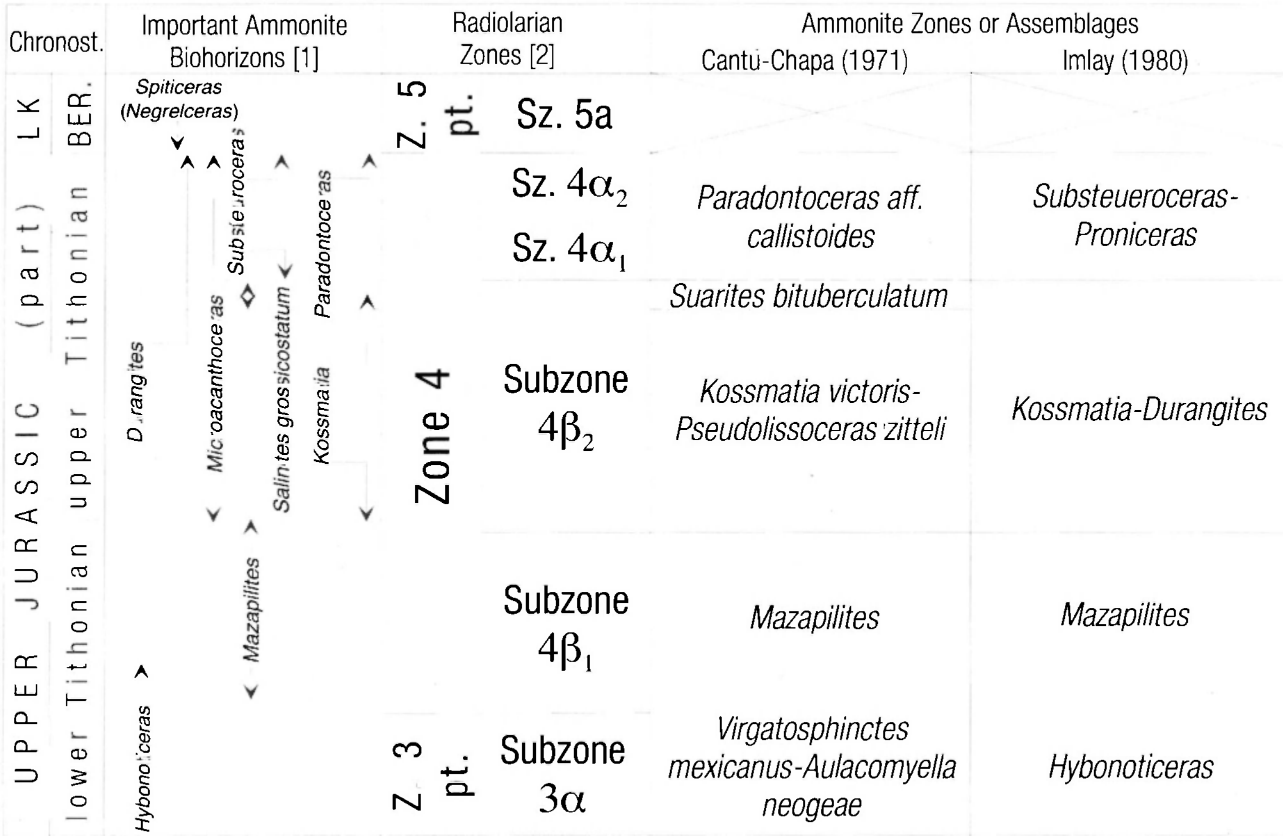
8) 3 Hermanos1001 well, core 5: 2392-2396m: *Calpionella alpina, C. elliptica.*
All of the calpionellid data cited above are from the Pimienta Formation (See Text-figure 35).

Southern Poza Rica district

In the Southern Poza Rica district Cantú-Chapa (1999) again used gamma ray curves to differentiate the Pimienta Formation from the overlying "lower Tamaulipas Formation". In this area the calpionellids occur in part of a ~70m thick interval in several wells (Mesagrande 2 well to the Zanzapote-1 well (See Text-figure 35). *Calpionella alpina, C. elliptica, Calpionellites neocomiensis, C. hispanica, Calpionellopsis oblonga, Tintinnopsella longa, T. carpathica,* and *T. cadischiana* appear simultaneously 25m below the top of the Pimienta Formation and continue throughout a 65m interval above the Pimienta-"lower Tamaulipas" contact. Cantú-Chapa (1999) indicated that *Salinites* was recovered from the Sultepec 1 well (core 2: 2159m) 25m below the top of the Pimienta Formation. *Durangites* and *Parodontoceras* occur in the upper 5m of the Pimienta Formation at the San Miguel del Rincon 3 well (core 3: 2940-2949m). No ammonites were recovered from the base of the "lower Tamaulipas Formation" (= Chapulhuacán Limestone herein).

Mazatepec, Puebla, Mexico

In 1967 Cantú-Chapa presented abundant evidence that demonstrated that allegedly Berriasian calpionellids occurred in association with upper Tithonian ammonites in the Pimienta Formation at Mazatepec, Puebla Mexico (Text-figures 36A, B). According to Cantú-Chapa the Pimienta Formation at Mazatepec includes in ascending order the **Kossmatia victoris-Pseudolissoceras zitteli Zone** (6m), the **Saurites bituberculatum Zone** (19m), and the **Parodontoceras aff. callistoides Zone** (48m). In this report the strata assigned to the **Kossmatia victoris-Pseudolissoceras zitteli Zone** are assigned to the Barrio Guadalupe Member of the Taman Formation in that they lack black radiolarian chert and include thin-bedded dark gray to black micritic limestone and interbedded dark gray to black yellow weathering shale (Observations of Senior Author 1981, 1983). The micrite contains abundant calcified Radiolaria. Cantú-Chapa (1967, p. 21) recorded *Pseudolissoceras zitteli* (Burckhardt), *Kossmatia victoris* Burckhardt, *K. subzacatecana* Cantú-Chapa, *Grayiceras*(?) *mexicanum* (Burckhardt), *Mazatepites arredondense* Cantú-Chapa, *Glochiceras* sp., *Aulacosphinctoides* sp., *Tithopeltoceras* sp., and *Inoceramus basei* Lecolle from this unit. No calpionellids were observed in strata assignable to this zone. The dark gray to black nature of these organic-rich strata makes it difficult to recognize calpionellids in thin-section. The overlying 48m of the succession are assigned to the Pimienta Formation s.s. in this report and to the **Parodontoceras aff. callistoides Zone** of Cantú-Chapa (1967, p. 10). The strata comprising the Pimienta Formation *s.s.* consist of medium to light gray, very aphanitic, thin-bedded micritic limestone interbedded with yellowish brown weathering black shale and



TEXT-FIGURE 34
Correlation of important ammonite biohorizons with radiolarian and ammonite biozones of Pessagno et al. (1993 & herein), Cantu-Chapa (1971) and Imlay (1980).

biostratigraphic data to unpublished calpionellid biostratigraphic data generated by his colleague, the late Dr. Federico Bonet, when these workers both worked at the Petroleos Mexicanos Micropaleontology Laboratory. These subsurface data confirm the results of Cantu-Chapa's earlier study in 1967 from surface exposures at Mazatepec. In all cases, hyaline calpionellids such as *Calpionella elliptica* are associated with upper Tithonian ammonites and are longer ranging in North America than they are in Europe. Examples from Cantu-Chapa (1999) are presented below.

Northern Poza Rica district

In the Northern Poza Rica district south of Tampico (Text-figure 35) gamma rays were used by Cantu-Chapa (1999) for differentiating the boundary between the argillaceous and bentonitic strata of the Pimienta Formation from the micritic limestone of the overlying "lower Tamaulipas Formation" (= Chapulhuacan Limestone herein). At the Bejuco 6 well Cantu-Chapa (1999, p. 98, fig. 4) recovered a rich ammonite fauna from cores 7, 8, and 9 comprising the upper 20m of the Pimienta Formation. Ammonites from this 20m interval included *Salinites grossicostatum* (Imlay), *Proniceras victoris* Burckhardt, *P. subprunum* Burckhardt, *P. subtorrense* Cantu-Chapa, *P.* aff. *victoris* Burckhardt, *P.* aff. *subprunum* Burckhardt, *Durangites* aff. *vulgaris* Burckhardt, *Corongoceras* aff. *mendozanum* (Behrendsen), *Haploceras veracruzanum* Cantu-Chapa, *Durangites* sp., *Salinites inflatum* (Imlay), and *Salinites* sp. Moreover, Cantu-Chapa recovered the Berriasian ammonites *Subthurmania* sp., *Neolissoceras semisulcata* and *Berriasella (Berriasella)* aff. *jacobi* from the overlying "lower Tamaulipas Formation". No calpionellids were analyzed by Bonet from the Bejuco 6 well. However, gamma ray correlations from nearby wells supplied a datum for recognizing the contact between the Pimienta Formation and the overlying Chapulhuacan Limestone at adjacent well sites. Calpionellid biostratigraphic data from wells adjacent to the Bejuco 6 well and below the contact between the two formations are as follows:

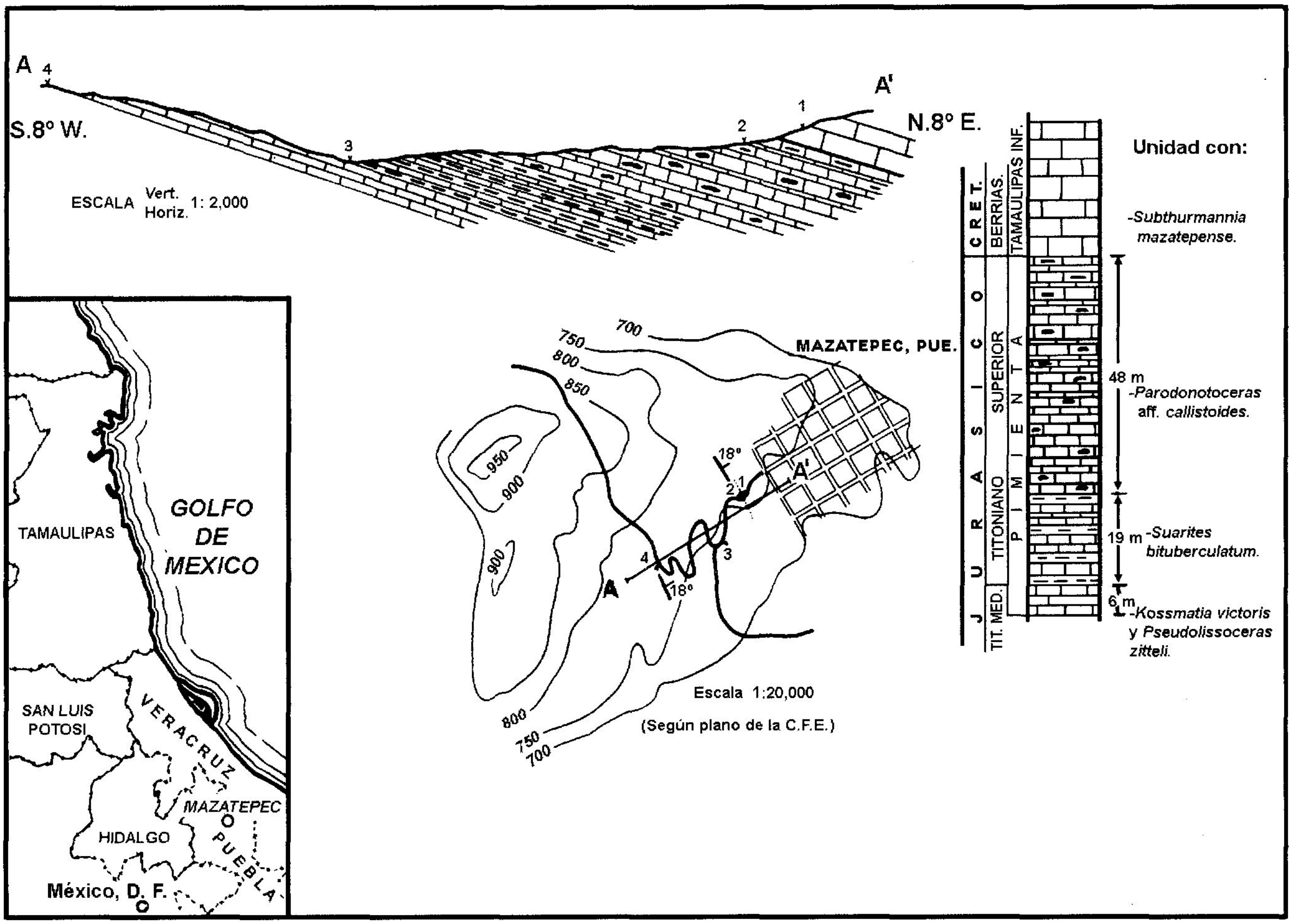
1) Tanceme 101 well, core 5: 2088-2090m: *Calpionella alpina, C. elliptica, Crassacollaria intermedia.*

2) Encinal well, core 4: 2366-2369m: *Calpionella alpina, C. elliptica.*

3) Ozuluama well-1, core 6: 2370-2372m: *Calpionella alpina, C. elliptica.*

4) La Laja well 1, core 6, :2722-2724m: *Calpionella alpina, C. elliptica.*

5) Rancho Nuevo 7 well, core 1: 2166-2169m: *Calpionella alpina, C. elliptica.*



TEXT-FIGURE 36A
Jurassic-Cretaceous boundary at Mazatepec, Puebla, Mexico. Modified from Cantú-Chapa (1967).

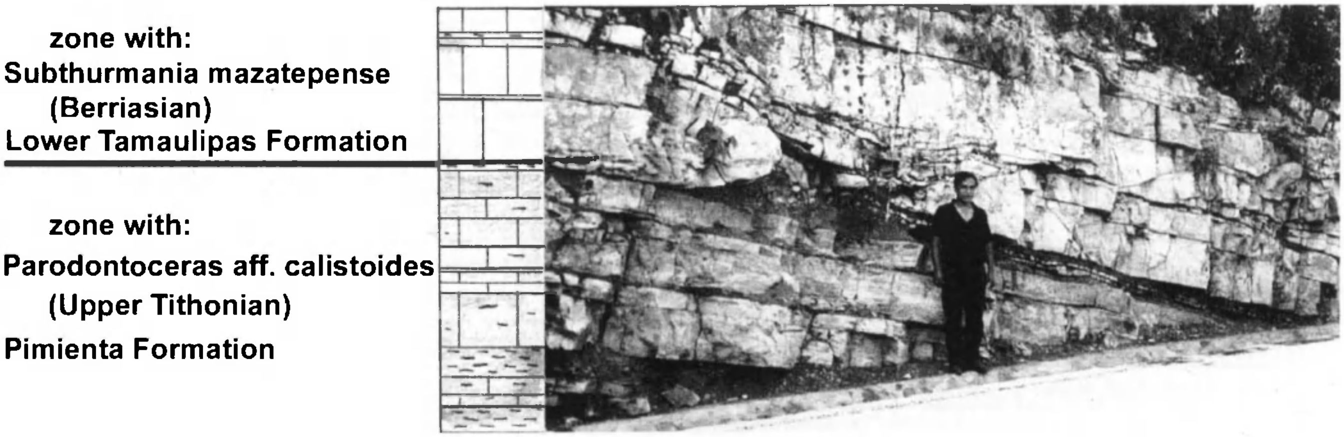
thin-beds and lenses of black radiolarian chert (independent observations by co-author Cantú-Chapa 1967 and senior author in 1981and 1983); all of the micrite contains abundant calcified Radiolaria. Ammonites occurring in this 48m interval comprising the **Parodontoceras aff. callistoides Zone** include *Parodontoceras* aff. *callistoides* (Behrendsen), *P.* sp., *Proniceras larense* Cantú-Chapa, *Protoacanthodiscus densicostatus* Cantú-Chapa, and *P.* sp. At San Pedro del Gallo, Mazapil (Canyon San Matias), and the Sierra Jimulco (Alamo Canyon), *Parodontoceras* occurs along with *Durangites* at the top of the upper Tithonian (See above). This horizon is correlative with the upper part of the **Substeueroceras-Proniceras assemblage** of Imlay (1980) and **Subzone 4 alpha$_2$** (See Text-figures 33-34 herein). Cantú-Chapa (1967, Table 1) recovered the following calcareous nannofossils from this 48m interval (identification by Leonel Salinas in Cantú-Chapa (1967): *Calpionella alpina*, *C. elliptica*, *Tintinnopsella longa*, *T. cadischiana*, and *Nannoconus steinmanni*.

Strata in the overlying **Subthurmannia mazatepecense Zone** are included in the "lower Tamaulipas" of Cantú-Chapa (1967) (=Chapulhuacán Limestone herein). The Chapulhuacán Limestone consists of medium to massively bedded, very aphanitic, light gray micrite (weathering cream to tan color) with nodules and lenses of black radiolarian chert. The micrite contains abundant calcified Radiolaria and was deposited at abyssal depths somewhat above the ACD. Cantú-Chapa (1967, Table 1) recorded the following ammonite taxa from the **Subthurmannia mazatepecense Zone**: *Subthurmannia dominguense* Cantú-Chapa, *S.* sp., *Groebericeras poblanense* Cantú-Chapa, *Berriasella* aff. *zacatecana* Imlay, *Taraisites* sp., and *Spiticeras* sp. Calcareous nannofossils that occur in these strata, include *Calpionella alpina* (Lorenz), *C. elliptica* (Cadisch), *Tintinnopsella longa* (Colom), *T. cadischiana* (Colom), *Calpionellites dadayi* (Knover), *C. neocomiensis* (Colom), *Nannoconus steinmanni* (Kamptner), and *Globochaete alpina* (Lombard).

The data presented for the Mazatepec area above again confirm the concurrence of allegedly Berriasian calpionellids such as *Calpionella elliptica* with upper Tithonian ammonites.

Cruillas remnant of the San Pedro del Gallo terrane

Strata correlative lithostratigraphically with the La Caja Formation s.l. and the Chapulhuacán Limestone s.s. crop out in the Sierra Cruillas ~ 200km south of the Texas border (Text-figure 29). Imlay (1980, p. 35) was the first to report Upper Jurassic ammonites correlative with his **Kossmatia-**



TEXT-FIGURE 36B
Photograph of outcrop showing contact between upper part of the La Pimienta Formation and overlying Chapulhuacan Limestone. Note that Chapulhuacan Limestone herein = the "Lower Tamaulipas" of Cantu-Chapa (1967) From Cantu-Chapa (1967).

Durangites assemblage (upper Tithonian) at Loma Rinconada (Sierra de La Virgen) about 5km southeast of the village of Cruillas (Tamaulipas). Imlay identified ammonites from the upper 120m of a succession measured and collected by Humphrey et al. (in Imlay 1980, p. 35) in 1954. It should be noted that the Loma Rinconada locality occurs near the religious shrine of the Virgin of Monserrat (GPS: **N24° 41'11.4". W098° 33' 35.2"**). The measured section of Humphrey et al. and the ammonite identifications subsequently made by Imlay and included in his 1980 report are presented in Table 1 below. From the detailed measured section presented by Imlay (1980: See Table 1 below) it is apparent that the thin-bedded radiolarian bearing dark gray micrite and black radiolarian chert are correlative with the La Caja Formation. The presence of tuff in this section is seemingly anomalous. However, the senior author has observed tuff interbedded with La Caja strata in the northern part of the San Pedro del Gallo remnant north of San Pedro del Gallo and south of Cinco de Mayo; in the Sierra Catorce remnant; and in the Huayacocotla remnant at Taman (See Pessagno et al. 1999). Moreover, the occurrence of tuff in the succession at Sierra Cruillas is predicted by the distal Nevadan backarc model proposed by Pessagno et al. (1999), Pessagno and Martin (2003), Cross and Pessagno (2006), and Pessagno (2006).

In 1981 abundant calcified Radiolaria were also observed by the senior author in samples from the Humphrey et al. collection shown to him by Dr. Ralph Imlay (Paleontology and Stratigraphy Branch, U. S. Geological Survey) in 1981. In 2000 the senior author observed abundant calcified Radiolaria in dark gray to black, laminated, thin-bedded (5 to 7cm.), silty micrite at the Loma Rinconada locality in the field. The presence of abundant specimens of *Parvicingula* Pessagno and *Praeparvicingula* Pessagno, Blome, and Hull in the radiolarian assemblage is important because it indicates that the Cruillas remnant of the San Pedro del Gallo terrane was situated at Northern Tethyan (22° to 29° north) or higher latitudes during the early late Tithonian. Imlay (1980, p. 34) and Pessagno et al. (1984, p. 3) noted that Bonet (1956, p. 82: locs. 44, 45, 48) recorded hyaline calpionellids from a horizon just below the strata containing *Kossmatia victoris* Burckhardt, *Durangites* Burckhardt, and other lower upper Tithonian ammonites (See Table 1). Calpionellid taxa recorded by Bonet included *Calpionella alpina* Lorenz, *C. elliptica* Cadisch, and *Tintinnoopsella oblonga* (Cadisch). According to Remane (1978, p. 166) the last two taxa are restricted to the Berriasian and the Berriasian-Valanginian respectively. This is the second instance in this report where allegedly Berriasian calipionellids have been associated with ammonites assignable to Imlay's lower upper Tithonian **Kossmatia-Durangites assemblage** (See San Pedro del Gallo remnant herein). No ammonites assignable to the **Substeueoceras-Proniceras assemblage** of Imlay (1980) have been reported from Loma Rinconada to date.

The overlying Chapulhuacan Limestone occurs approximately 100m above the base of the Humphrey et al. measured section (in Imlay 1980: Table I herein). The Chapulhuacan consists of very aphanitic cream to light gray medium to massively bedded micritic limestone with black chert nodules and lenses. Both the black micrite and chert contain abundant Radiolaria. No ammonites are reported from the Chapulhuacan at Loma Rinconada. The abundance of Radiolaria and lack of ammonites suggests that these strata were deposited below the ACD.

CORRELATION WITH AMMONITE "M" HORIZONS OF HILLEBRANDT ET AL. (1992): M10-M23

M10: Virgatosphinctes mexicanus—Aulacomyella neogeae Zone of **Cantu-Chapa (1971).**

At Taman, San Luis Potosi (See Text-figure 8 and Huayacocotla remnant of the San Pedro del Gallo terrane(SPG) herein), the top of this horizon occurs in the massive micritic limestone of the Mera Ceiba Member of the Taman Formation, immediately below the contact with the thin-bedded micrites of the Barrio Guadalupe Member of the Taman Formation (See Pessagno et al. 1987a). The basal part of the overlying Barrio Guadalupe Member is assignable to Cantu-Chapa's (1971) **Mazapilites Zone**. The base of radiolarian **Subzone 4 beta$_1$** occurs 6m below the contact between the Mera Ceiba and the Barrio Guadalupe members of the Taman in the upper part of the **Virgatosphinctes mexicanus—Aulacomyella neogeae Zone**. Barrio Guadalupe strata assignable to the **Mazapilites Zone** are also assignable to **Subzone 4 beta$_1$**.

As noted previously, Longoria in Pessagno et al. (1984, 1987a) found *Crassicollaria* sp. to occur ~ 6m below the base of the Barrio Guadalupe Member. Hence, the base of the **Crassicollaria**

TABLE 2
Lithounits at Alamo Creek, Stanley Mountain remnant Coast Range ophiolite, San Luis Obispo County California. See Text-figure 4.

Unit 5 (GVS) 15+m: Massively bedded graywacke.
Unit 4 (GVS) 14.99m+: Interbedded medium gray calcareous to siliceous mudstone and graywacke. Mudstone with common medium gray micrite nodules and thin beds of dark gray micrite. Micrite beds and nodules with abundant well-preserved calcified Radiolaria that can be extracted with the acetic acid method of Kariminia (2006a). Southern Boreal megafossil assemblage.
Unit 3 (GVS) 34.5m: Transitional interval between VP and GVS. Base of GVS and Unit 3 arbitrarily taken as the first graywacke bed. Unit 3 includes graywacke interbedded with black radiolarian chert and black cherty mudstone. Base of GVS occurs 129.4m above the VP-CRO contact. Top of Unit 3 at 159.9m above VP/CRO contact. ***Zone 4, Zone 4, Subzone 4 alpha$_2$*** (Upper Jurassic: upper Tithonian). Southern Boreal radiolarian and megafossil assemblage.
Covered interval. 83m.
Unit 2 (VP) 68m: Predominantly red to maroon tuffaceous chert and siliceous mudstone interbedded with thin-bedded light to medium gray, manganiferous micrite. Mudstone frequently containing common 5cm to 15cm light gray micrite nodules. Micrite nodules weathering to maroon color due to presence of manganese. Abundant Radiolaria occur in the chert, mudstone, and micrite. **Zone 3, Subzone 3 alpha** to **Zone 4, Subzone 4 alpha$_2$** (Upper Jurassic: lower Tithonian to upper Tithonian). Hiatus occurring between Units 1 and 2. Subzones 2 alpha$_1$, 2 alpha$_2$, and 3 beta missing (lower Kimmeridigian [part] to upper Kimmeridgian). **Zone 4, Subzone 4 alpha$_1$** (upper Tithonian) not observed. Northern Tethyan/Southern Boreal to Southern Boreal radiolarian assemblage.
Unit 1 (VP) 62m: Interbedded black, light green, and red tuffaceous chert, minor tuff breccia, and thin beds of medium gray micrite and occasional micrite nodules. Abundant Radiolaria occur in the chert, mudstone, and micrite **Zone 2, Subzone 2 gamma** to **Subzone 2 beta$_2$** (Upper Jurassic: middle Oxfordian to lower Kimmeridgian). Central Tethyan radiolarian assemblage.

Zone occurs in the lower Tithonian in North America as opposed to the lower part of the upper Tithonian in Europe (See Text-figure 1).

M11, M12, M13: MAZAPILTES

M11:**"Beds with *Waagenia [=Hybonoticeras]* and *Mazapilites*" at Toboso, Sierra de Symon (Burckhardt 1921; Imlay 1939, p. 10, bed 7.** Hillebrandt et al (p. 267) indicated that the forms that Burckhardt figured represented the microconchs of *Hybonoticeras hybonotum* (Oppel). This horizon was believed to represent the first occurrence of *Mazapilites*.

M12" Beds with *Mazapilites*". This horizon includes two slightly different faunas:

(1) M12a: Sierra de Symón, Toboso (Imlay 1939, p. 10, bed 8). Includes *Mazapilites symonensis* Burckhardt and three other species.

(2) M12b: Sierra de La Caja north of Mazapil (Burckhardt 1930, p. 52, Fig. 14, Bed G). This horizon includes *Mazapilites zitteli* and associated species (e.g., *Aspidoceras cyclotum, A. phosporiticum, A. cajaense).*

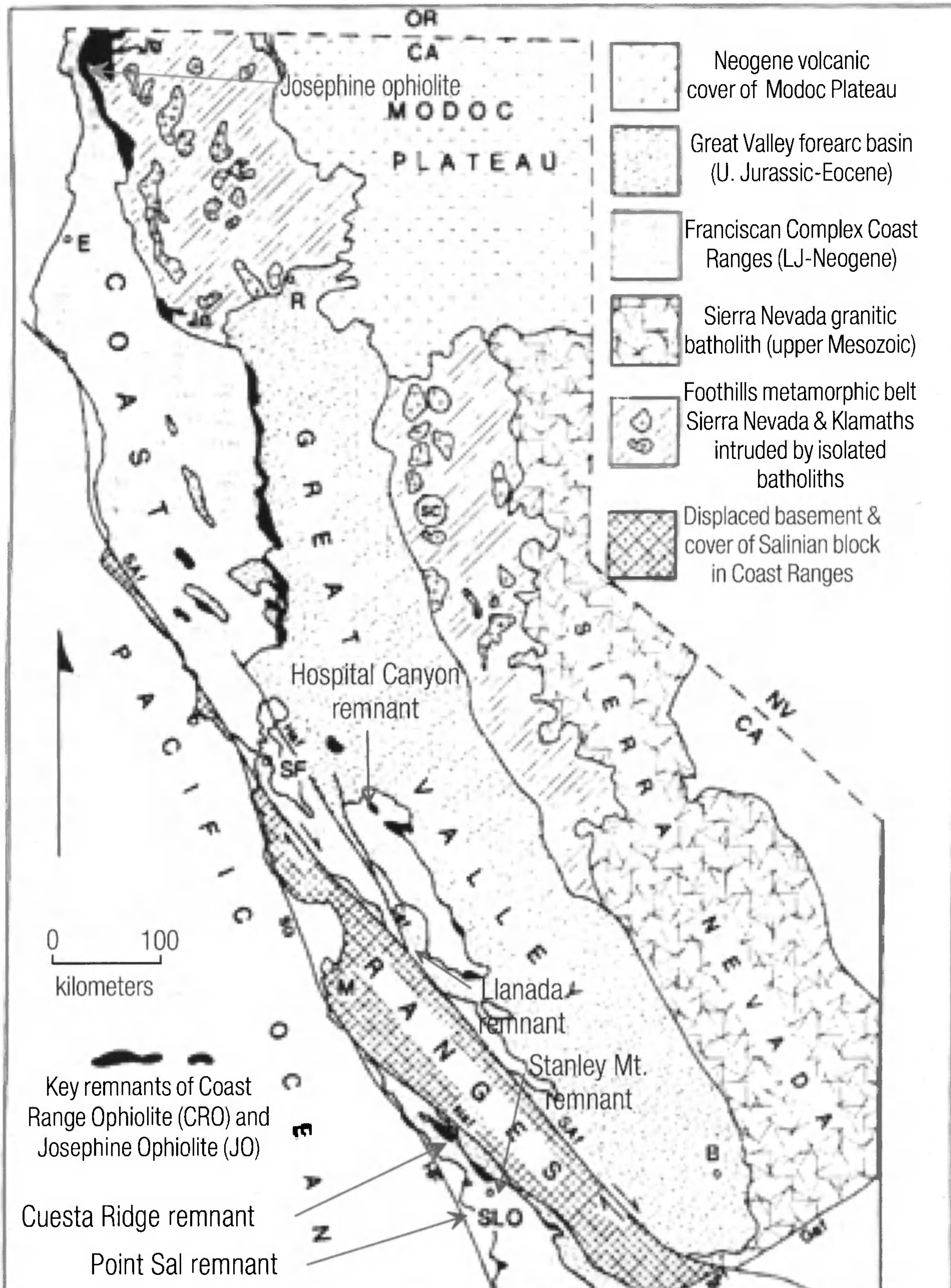
Hillebrandt et al. indicated that there is no clear evidence concerning the superposition of horizons 12a and 12b. However, it should be noted that Bed G of Burckhardt marks the beginning of the phosphate rich interval in the Sierra de La Caja (Units G-K of Burckhardt 1930, p. 52, fig. 14; see Mazapil remnant of SPG herein).

M13 "Virgatosphinctinae beds the Sierra Catorce of Verma and Westermann (1973)". Horizon M13 includes *Mazapilites mexicanus* (Aguilera) associated with *Pseudolissoceras zitteli, Torquatishinctes?, Pstosinus, Virgatosphinctes sanchezi,* and other species. Horizon M13 allegedly represents the highest occurrence of *Mazapilites*.

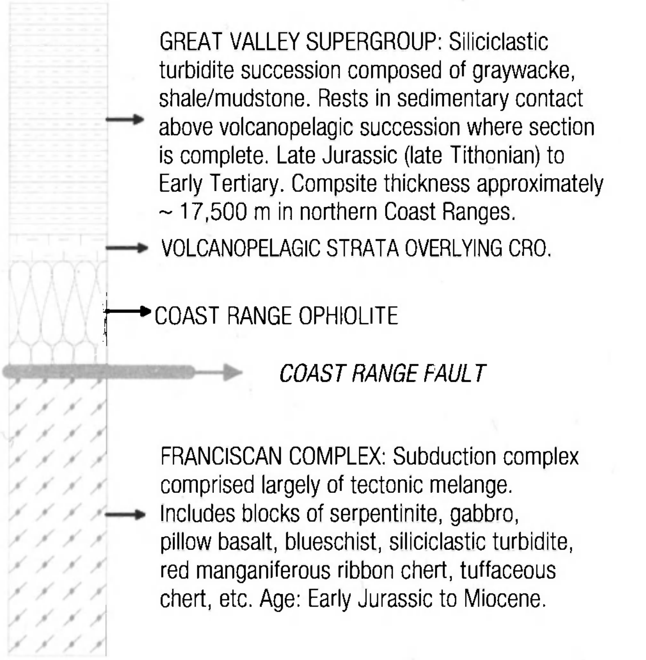
Near Canyon San Matias and Canyon Puerto Blanco Burckhardt (1930, Table 4) recovered *Mazapilites* at adjacent Canyon del Aire (See Text-figure 7, loc. 5 and Mazapil remnant of SPG herein). According to Burckhardt this horizon occurs just below the first phosphatic limestone. Our studies indicate that this horizon occurs 36.1m above the base of the measured section at Canyon San Matias and 34m above the base of La Caja Formation Unit E (See Text-figures 22, 26A-B, 27). *Hybonoticeras* sp. was identified by co-author Cantú-Chapa at this horizon in samples SM94-29R, SM94-30, and SM94-32B (See Text-figure 29A). Both samples SM94-30 and SM94-32B occur within the phosphatic limestone, black radiolarian chert, and calcareous mudstones of Unit D herein. The upper 5m of our La Caja Unit D (12.7m: SM94-28R [base] to SM94-44 [top]) includes Burckhardt's 5m thick Unit C. Burckhardt Unit C contains *Kossmatia victoris, K. zacatecana,* and *K. flexicostata.* Moreover, *Kossmatia* sp. was identified by co-author Cantú-Chapa from just above the top of our unit D and at the base of our overlying Unit C (See SM94-45: Text-figure 22, 26A-B, 27). Radiolarian biostratigraphic data indicate that samples SM94-22-SM94-32 (7.9m to 35.9m above the base of the La Caja Formation) are assignable to radiolarian **Subzone 4 beta$_1$**. Samples SM94-39-SM94-45 (36.5m to 41.4m above the base of the La Caja Formation) are assignable to **Subzone 4 beta$_2$**.

From the data cited above it is clear that the M11, M12, and M13 containing *Mazapilites* occur within **Subzone 4 beta$_1$**. At Taman, San Luis Potosí (Text-figure 7, loc. 3; text-figures 31-32) the base of **Subzone 4 beta$_1$** occurs 6m below the base of the **Mazapilites Zone** of Cantú-Chapa (1971) and the base of the Barrio Guadalupe Member of the Taman Formation in the upper part of the underlying Mera Ceiba Member. At Canyon San Matias the base of **Subzone beta$_1$** occurs 26.1m below the first occurrence of *Mazapilites* (See discussion above).

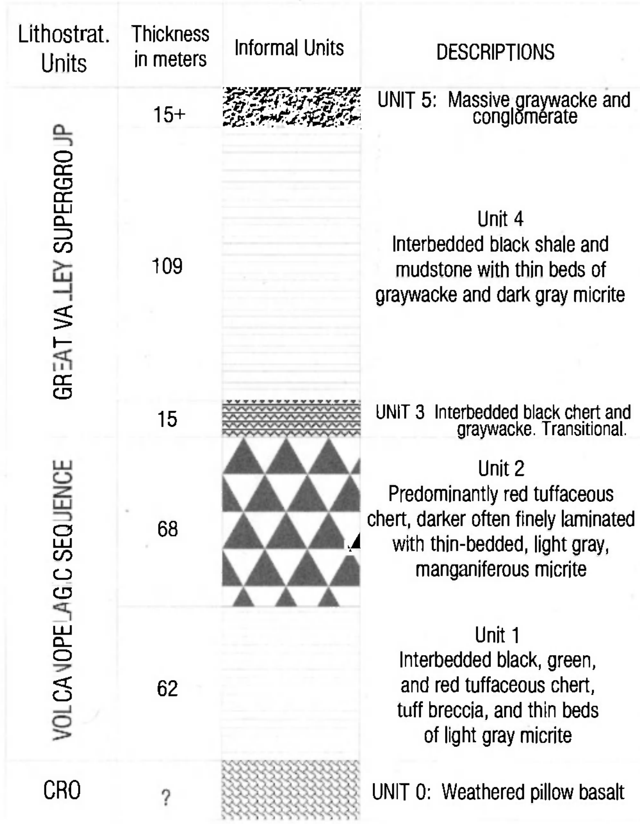
M14 "*Proniceras* beds" of Burckhardt (1930). Hillebrandt et al. indicate that this horizon can not be closely placed. They



TEXT-FIGURE 37
Index map showing important Coast Range ophiolite remnants, Josephine Ophiolite, the Franciscan Complex, the Great Valley forearc strata, the Foothills metamorphic belt (Sierra Nevada and Klamaths), Sierra Nevada batholith (granitic), etc. Modified from Dickinson, Hopson, and Saleeby (1996). For complete inventory of Coast Range ophiolite localities, see Hopson et al. (1981, Figure 14-1).



TEXT-FIGURE 38
Juxtaposition of Coast Range Ophiolite and younger rocks along Coast Range fault.



TEXT-FIGURE 39
Composite stratigraphic section, Stanley Mountain remnant, Coast Range ophiolite, San Luis Obispo Country, California.

indicate that it occurs above *Mazapilites* horizon 12a and below the beds with *Substeueroceras* (M19-M20).

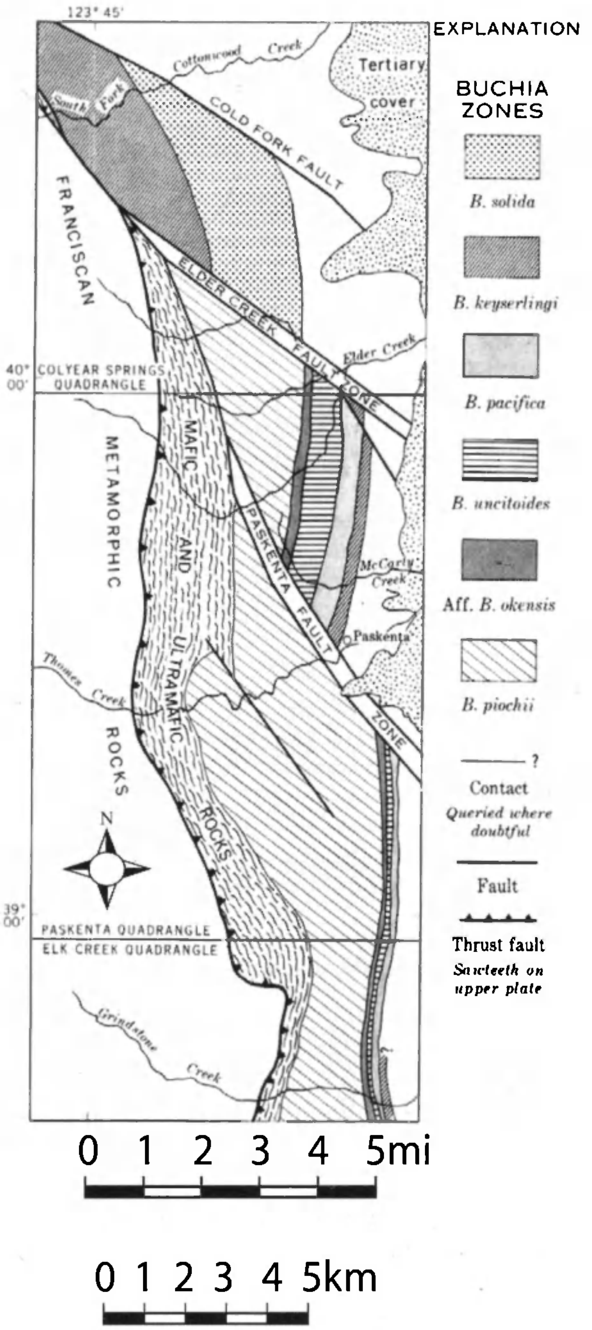
At San Pedro del Gallo Hillebrandt et al. indicated that their horizon M14 with *Proniceras* is present at Burckhardt's (1930) bed B (Note that bed B of Burckhardt 1930, p. 63, fig. 21= Loc. 22 of Burckhardt 1907, 1910: See Text-figure 12 herein). Data from the present study indicates that M14 occurs in the San Pedro del Gallo Chert and Puerto del Cielo members of the La Caja Formation and is assignable to the lower part of **Subzone 4 beta$_2$**. Our studies indicate that most of the lower Tithonian (e.g., beds with *Mazapilites*) is absent at San Pedro del Gallo.

M15 "*Durangites* beds" of Burckhardt (1912, 1930). This horizon primarily corresponds to Burckhardt's (1930, p. 63, Fig. 21, bed C) Locality 23 at San Pedro del Gallo (Text-figure 12). It has also been recognized in the Sierra Jimulco (Imlay 1939, p. 8, Fig. 21, bed 4, collections K2, K4); Sierra de Parras (Imlay 1939, Loc. 34); Cerro de La Cruz, near San Pedro del Gallo (Imlay 1939, p. 17); and at Galeana, Nuevo León (Cantú-Chapa 1968). Our investigations indicate that Locality 23 of Burckhardt occurs in the upper part of the San Pedro del Gallo Chert Member of the La Caja Formation. The fauna from this locality, as noted under the analysis of the stratigraphy of the La Caja Formation at San Pedro Gallo above, includes nine species of *Durangites* and several species of *Kossmatia*. Burckhardt (1910, p. 318; 1912, p. 206, 221; 1930, p. 63, fig. 21; see Imlay 1980, p. 34) also noted the presence of numerous *Buchia mosquensis* in what is referred to as the San Pedro del Gallo Chert Member herein. Hillebrandt et al. (p. 268) claimed that an "essentially similar" assemblage was recovered in Bed D of Burckhardt (1930, Fig. 21) at Burckhardt Locality 24 (Text-figure 12). Our analysis of the stratigraphy of the San Pedro del Gallo area indicates that Burckhardt's Locality 24 occurs in the Puerto del Cielo Shale Member of the La Caja Formation. The composite faunal list presented by Hillebrandt et al. includes both species of *Kossmatia, Proniceras, Microacanthoceras*, and *Durangites*. Moreover, they also noted the presence of *Salinites grossicostatum*.

Our data from San Pedro del Gallo indicate that the San Pedro del Gallo Chert Member of the La Caja Formation contains a radiolarian assemblage assignable to lower part of **Subzone 4 beta$_2$** (Loc. 23 of Burckhardt). The overlying Puerto del Cielo Shale Member contains a radiolarian assemblage assignable to the upper part of **Subzone 4 beta$_2$**.(Loc. 24 of Burckhardt). A discussion of the radiolarian assemblage recovered from these two lithounits is presented under the San Pedro del Gallo section above.

M16. "*Kossmatia* beds" of Burckhardt (1906, p. 50, Fig. 13, Bed C). Hillebrandt et al. indicate that horizon M16 occurs in the Sierra Santa Rosa at Canyon San Matias near Mazapil and also at Mazatepec, Puebla. Biostratigraphic data are presented from both of these localities in the sections above. It is clear from our data at Canyon San Matias that:

1) Unit C of Burckhardt is equivalent in part to Unit D herein. The upper part of our Unit D (SM94-39: F .5m to SM94-44: 40.8m above the base of the La Caja Formation) is included within radiolarian **Subzone 4 beta$_2$** and occurs within the upper 3.3m of Burckhardt's *Kossmatia*-bearing Unit C (5m). The base of our overlying Unit E (SM94-45: 41.4m) is assignable to Subzone 4 beta$_2$ (See Text-figures 22, 24, 26, 27 herein). Sample SM94-45 is significant because it contains the radiolarian



TEXT-FIGURE 40
Buchia zones in Great Valley Supergroup, Northern Coast Ranges. Note location of Grindstone Creek section in Elk Creek Quadrangle. From Jones et al. (1969).

Neovallupus as well as an ammonite identified by co-author Cantu-Chapa as *Kossmatia* sp.

2) The data from the Canyon San Matias succession as well as that from Taman, San Luis Potosi indicate that the range of *Neovallupus* corresponds closely with that of *Salinites grossicostatum* but concurs with that of *Kossmatia* (See Text-figures 33-34 herein). Composite data from this study indicate that *Neovallupus* occurs in the uppermost part of **Subzone 4 beta$_2$**.

3) These data suggest that horizon M16 overlaps the upper part of horizon M15.

M17. "*Saurites* beds" of Cantu-Chapa (1967, 1971, 1976). Our data from Taman indicate that the interval bearing *Neovallupus* and *Salinites grossicostatum* corresponds closely to the **Saurites bituberulatum Zone** of Cantu-Chapa (1971). This interval is assignable to the uppermost part of **Subzone 4 beta$_2$**. Moreover, it corresponds to the upper part of horizon M14 at San Pedro del Gallo (Puerto del Cielo Shale Member of the La Caja Formation at Burckhardt 1930, Fig. 21, bed D, Locality 24. See Text-figure 12 herein).

Hillebrandt et al. (1992) indicated that closest resemblance of the fauna of horizon M17 is to that of the fauna of the **Interspinosum Zone** of the Andes. Pujana's (1996) study of the radiolarian assemblage at Malm Quemado in the Neuquen Basin suggests that the **Interspinosum Zone** is equivalent to the upper part of **Subzone 4 beta$_2$** with associated *Neovallupus* and *Salinites grossicostatum* at Taman (See Correlation with Argentina below).

M18. *Corongoceras cordobai* Verma and Westermann. Hillebrandt et al. (1992) indicated that this horizon is probably below that with *Substeueroceras*. Because of the structural complexity of the area and occurrence of many of the ammonites from mine dump talus, the ammonite data from the El Verde Member of the La Caja Formation at Catorce is suspect and needs to be re-evaluated (See Verma and Westermann 1973, p. 125).

M19. "*Kossmatia exceptionalis* (Aguilera), Sierra Catorce, San Luis Potosi. Verma and Westermann (1973, p. 129) indicated that many of the fossils were collected from talus. As a consequence, mixing of faunal elements seem likely. *Kossmatia flexicostata, K. alamitosensis,* and *Substeueroceras catorcense* allegedly occur together in Verma and Westermann's section number 2.

M20. Principal *Substeueroceras* beds of San Pedro del Gallo (Burckhardt 1912, p. 207, loc. 25; 1930, p. 63, Fig. 21, bed E) and the Sierra Jimulco (Imlay 1939, p. 8, Fig. 3, bed 2, faunas K1, K5, K25) with *Substeueroceras kellumi* Imlay, *S. alticostatum, S. subquratum,* etc. Our studies of the San Pedro del Gallo area indicate that this horizon characterizes the Cerro Panteon Member of the La Caja Formation and contains a radiolarian assemblage assignable to **Subzones 4 alpha$_1$** and **4 alpha$_2$** (See San Pedro del Gallo remnant of SPG terrane herein.).

VIZCAINO PENINSULA, BAJA CALIF SUR

Subzone 4 alpha$_2$ Radiolaria were recorded by Davila-Alcocer (1986, p. 14) in two samples from the upper part of the volcanic member (base of exposure) of the Eugenia Formation at Arroyo La Amarguera, Vizcaino Peninsula, Baja California Sur. His lowermost sample contains *Mirifusus baileyi* Pessagno (pl. 9, fig. 12), *M. mediodilatata* (Rust) (pl. 9, fig. 2), *Ristola altissima* (Rust), *Praeparvicingula colemani* Pessagno and Blome (pl. 9, 17, 21), and *Parvicingula alamoenis* Hull (= *P.* sp. F of Davila-Alcocer 1986, pl. 9, fig. 3). Sample VO41 from approximately 40m above the base of the measured section contains *Eucyrtidiellum ptyctum* (Davila-Alcocer: pl. 9, fig. 3), and *Hsuum mclaughlini* Pessagno and Blome (= *Hsuum* sp. A, pl. 7, figs. 10, 15, 19) in direct association with *Buchia piochii* (identification by Dr. David L. Jones (U. S. Geological Survey, Menlo Park). Rangin (1976) identified *Buchia piochii, B. elderensis, Substeueroceras* sp. cf. *S. kellumi,* and *S.* sp. cf. *S. disputable* from the lowermost part of the Eugenia Formation at this locality. These data suggest that the lower part of **Subzone 4 alpha$_2$** is equivalent to the top

TABLE 3
Radiolarian assemblage at Llanada Locality LL94-4: **Subzone 4 alpha$_2$**: upper Tithonian. Sample collected by Pessagno, Meng, and Hopson in 1994 from north wall of Bitterwater Canyon: USGS Llanada Quadrangle (7.5"): T15S, R9E, NE1/4 of SW1/4, sec. 26

Complexapora kozuri Hull
Parvicingula sanfilippoae Hull
Parvicingula alamoensis Hull
Parvicingula sp. aff. *P. excelsa* (Pessagno and Blome)
Parvicingula spp.
Caneta hsui Pessagno
Mita sixi (Yang)
Podocapsa sp.

of the **Buchia piochii Zone** (sensu Jones et al. 1969). It should be noted that the Senior Author observed *Hsuum mclaughlini* at the top of the **Buchia piochii Zone** in a reexamination of residues and scanning electron micrographs from sample NSF 945 of Pessagno (1977a). Pessagno (1977a, text-figure 3B) recorded *Complexipora kozuri, Ristola procera* (Pessagno) and *Parvicingula turrita* (Rüst) from the same sample.

CALIFORNIA COAST RANGES

In the California Coast Ranges uppermost Jurassic to lowermost Cretaceous strata crop out discontinuously from Santa Barbara County to the south to Tehama County to the north in a bathyal to abyssal marine succession that overlies remnants of the Coast Range ophiolite (CRO) (See Hopson et al. 1981 and Text-figure 37-38 herein). The marine succession overlying the Jurassic oceanic crustal basement of the CRO includes in ascending order an Upper Jurassic volcanopelagic sedimentary sequence (VP) and a thick siliciclastic-turbidite succession comprising the Upper Jurassic to Middle Eocene Great Valley Supergroup (GVS). The CRO and its sedimentary cover are juxtaposed against the Jurassic-Tertiary Franciscan Complex (Text-figures 37-38) along the Coast Range fault (See Hopson et al. 1981; McLaughlin and Pessagno 1978; Pessagno et al. 2001). The reader is referred to Pessagno et al. (2001) for a more detailed discussion of the CRO, VP, and GVS.

Stanley Mountain remnant of Coast Range ophiolite, San Luis Obispo County, California

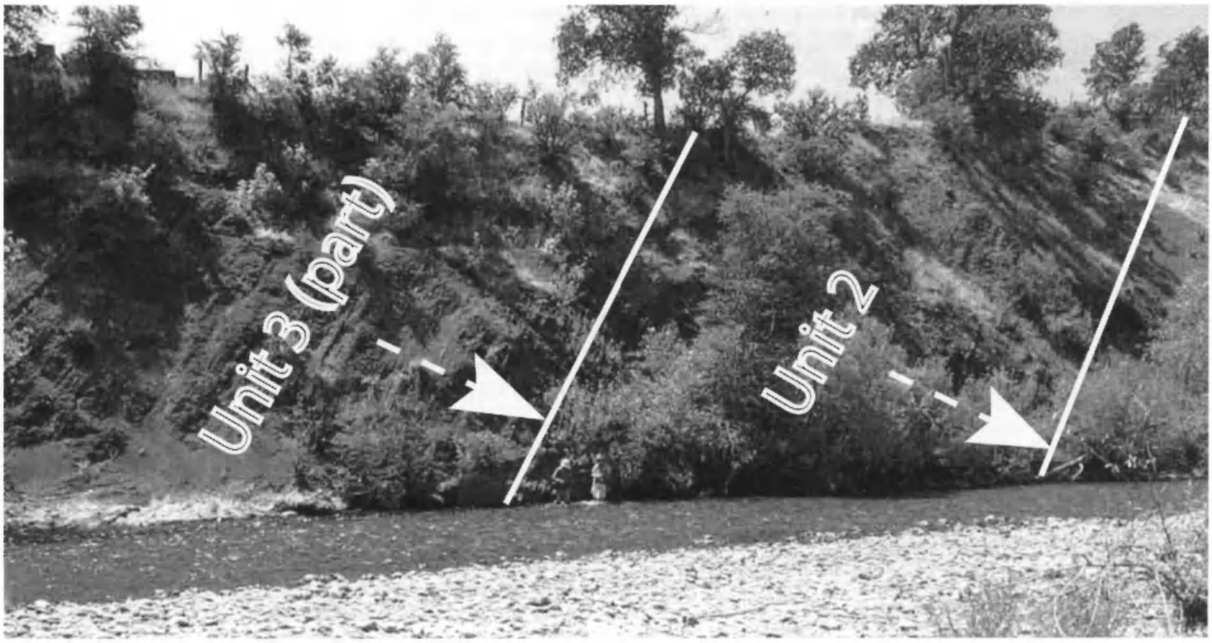
Extensive studies have been made of the volcanopelagic succession (VP) overlying the Coast Range ophiolite (CRO) at Stanley Mountain by Pessagno (1977a), Hopson et al. (1981), Pessagno et al. (1984), Hull et al. (1993), and Hull (1991, 1995, 1997). VP pelagic limestone (micrite) and radiolarian chert contain a rich Late Jurassic (middle Oxfordian to late Tithonian) radiolarian assemblage that has been described in detail by Hull (1995, 1997).

Investigations by Hull (1991, 1995, 1997) revealed that the VP succession cropping out along Alamo Creek is nearly complete. Hull's studies demonstrate that the composite VP sequence in three measured sections along Alamo Creek is 130m thick rather than 103m as indicated by Hopson et al. (1981) and by Pessagno et al. (1984, 1987a,b). Table 2 summarizes the lithostratigraphic, biostratigraphic, and paleolatitudinal attributes of this section based on Hull's investigations and the observations of the senior author. The paleolatitudinal data indicate that the Coast Range ophiolite and its cover of sediments was transported from Central Tethyan paleolatitudes to Southern Boreal latitudes during the Middle Jurassic (late Bathonian) to Late Jurassic (latest Tithonian) (See text figures 5-6. See Hopson et al. 1981, 1986, 1992, 1996; Hull et al. 1993; Hull 1995, 1997; Pessagno et al. 2001).

Hull (1997) included the interval in VP Unit 2 (Table 2) from 80m to 104m in **Subzone 4 beta** (= **Subzones 4 beta$_1$** and **4 beta$_2$** herein). Hull's abundant radiolarian biostratigraphic data indicate that *Complexapora kozuri* Hull, the primary marker taxon for the base of **Subzone 4 beta$_2$**, makes its first appearance in VP Unit 2 sample SA 43B from 98m above the CRO/VP contact (Table 2, Text-figures 4, 39 and Appendix 1 herein). Hence, this horizon represents the apparent base of **Subzone 4 beta$_2$** (lower upper Tithonian).

The interval from 80m to just below 98m may be assignable to either **Subzone 4 beta$_1$** (lower Tithonian) or **Subzone 4 beta$_2$** (lower upper Tithonian). *Vallupus hopsoni*, the primary marker taxon for the base of **Subzone 4 beta$_1$**, was recorded by Hull (1997) in VP Unit 2 sample SA 35 (80m) and VP Unit 2 sample SA 43B (98m). However, it should be noted that Pessagno et al. (1984, p. 23) also recorded this taxon at SA 39 (90m) and SA 40 (92.6m). The final appearance of primary marker taxon, *Perispyridium* sp., marks the top of **Subzone 4 beta$_2$**. (lower upper Tithonian). In the Alamo Creek section this horizon occurs at 102.5m (VP Unit 2 sample Stan 13B: See Hull 1997, p. 201-202). VP Unit 2 sample SM 50 from ~ 104m above the VP/CRO contact lacks *Perispyridium*. The interval between Stan 13B at 102.5m and SM 50 at 104m may be assignable to either **Subzone 4 alpha$_1$** or **Subzone 4 alpha$_2$**. The remainder of VP Unit 2 and all of GVS Unit 3 are assignable to **Subzone alpha$_2$** and lacks *Perispyridium* as well as *Vallupus*.

It should be noted that Hull's (1997, p. 200) description of locality SM 50 is contradictory: "SM 50. Unit 2, 37.5m below base of Section 2; 11.6 below top of overlying Unit 3. Approximately 104m above contact with basalts of ophiolite.—". Although sample SM 50 is situated 37.5m above the base of Section 2 and



TEXT-FIGURE 41
Great Valley Supergroup at Grindstone Creek. Co-authors Pessagno and Kariminia standing to right of boundary between "Units 2 and 3".

approximately 104m above the contact with the CRO, it is not 11.6m below the top of overlying Unit 3 (See Hull, p. 9, text-figure 7). The same sort of error occurs in Hull's descriptions of SM 51 and SM 53 (p. 200-201).

No radiolarian biostratigraphic data is presently available from GVS Units 3-4 (Table 2); all Radiolaria occurring in these intervals are replaced by calcite. However, the development of the acetic acid for the extraction of calcareous microfossils from limestone and chalk may be a powerful tool for radiolarian workers to use in future study (See Kariminia 2006a). It also should be noted that these strata contain *Buchia piochii* and should be assigned to the **Buchia piochii Zone** of Jones et al. (1969). As noted previously, *Buchia piochii* occurs in **Subzone 4 beta$_2$** strata at San Pedro del Gallo (Durango, Mexico: *See* San Pedro del Gallo Chert Member, La Caja Formation herein).

Llanada remnant of Coast Range ophiolite, San Benito County, California

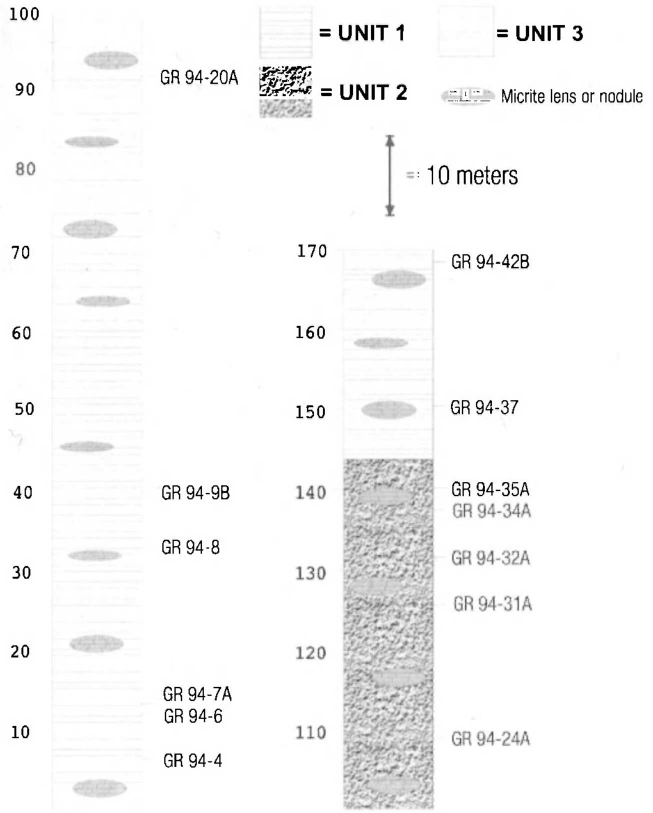
At Llanada (Text-figure 37) the VP includes 1245m of tuff breccia, volcaniclastic sandstone, and occasional beds of volcanic conglomerate (Hopson et al. 1981; Pessagno et al. 2001). Thin intervals of light green to medium gray tuffaceous chert occur within this dominantly proximal facies succession (*sensu* Pessagno et al. 2001). Lenticular masses of light green tuffaceous chert occur at the top of the VP. At VP locality SA 56, tuffaceous chert grades into the basal mudstone of the GVS (See Pessagno et al. 1984). Pessagno et al. (1984) recorded *Parvicingula colemani* Pessagno and Blome from SA 56 and *Parvicingula excelsa* Pessagno and Blome from SA 58. Table 3 shows radiolarian **Zone 4, Subzone 4 alpha**, radiolarian taxa identified by the senior author, from sample LL94-4, collected in 1994 near a porphyritic keratophyre sill near localities SA 56 and SA 58.

Great Valley Supergroup at Grindstone Creek, Glenn County, California

The nomenclatural history of the Great Valley Supergroup (GVS) is chaotic. It has been discussed by Jones et al. (1969) and will not be discussed in detail herein. Jones et al. discouraged the use of the terms ***"Knoxville, Paskenta, Shasta,*** and ***Chico"*** as used by numerous previous workers. Because these terms have been used in a lithostratigraphic, chronostratigraphic, and biostratigraphic sense by earlier stratigraphers, their meaning is ambiguous.

Although it is possible to define formational units in Upper Cretaceous GVS strata in the Northern California Coast Ranges (e.g., Kirby 1943a,b; Murphy et al. 1964; Pessagno 1976), the Upper Jurassic to Lower Cretaceous siliciclastic succession of the GVS in the Northern California Coast Ranges is difficult to subdivide into mappable lithostratigraphic units. As a consequence Jones et al. (1969), determined that the only mappable units in the Upper Jurassic (upper Tithonian) and Lower Cretaceous (lower Berriasian to upper Valanginian) are the *Buchia* zones. By mapping the *Buchia* zones and noting the offset of these zones, Jones et al. were able to recognize three major fault zones: the Paskenta Fault Zone, the Elder Creek Fault Zone, and the Cold Fork Fault Zone (Text-figure 40). Subsequently, these zones were used by Pessagno (1977b), Bralower (1993), and Bralower et al. (1989, 1990) as a framework for sampling for microfossils. In the present report we will focus primarily on the three lowermost of these zones: the **Buchia piochii Zone**, the **Buchia sp. aff. okensis Zone**, and the **Buchia uncitoides Zone**.

Jones et al. (1969, p. A6) noted that the *Buchia*-bearing succession at Grindstone Creek (Text-figure 40) is nearly 4268m thick. Most of this thickness is included in the *Buchia piochii* Zone. The overlying *B.* sp. aff. *okensis*, *B. uncitoides*, *B. pacifica* Zones, though well developed faunally, comprise only 335m to 365m of the overall succession (Jones et al. 1969, p. A6).



TEXT-FIGURE 42
Measured section of Great Valley Supergroup (GVS) at Grindstone Creek, Glenn County, California. GVS: Unit 1 = Dark gray siliceous mudstone with lenses and nodules of light to medium gray micrite. Unit 2 = Thin to thick bedded graywacke. Unit 3 = Same as Unit 1. Important horizons for reference in this section are both the base of Unit 2 and the top of Unit 2.

The Grindstone Creek succession is important because it includes the highest Jurassic (uppermost Tithonian) and the lowest Cretaceous (Berriasian) portions of the GVS. The sampled section is situated in the USGS Chrome Quadrangle (7.5'): T21N; R6W; Section 16 (GPS = N39°40'38.6". W122°31'52.9") just upstream from highway 306 bridge over Grindstone Creek. The GVS at Grindstone Creek can be divided into three informal lithostratigraphic units of local significance Text-figures 41-42):

Unit 1: Dark gray siliceous mudstone with lenses and nodules of light to medium gray micrite containing well preserved calcified Radiolaria. Base not exposed. Unit 1 includes the upper part of the **Buchia piochii Zone**, all of the **Buchia sp. aff. okensis Zone** and the lower part of the **Buchia uncitoides Zone** of Jones et al. (1969, p. A7).

Unit 2: Dark gray medium to thin-bedded graywacke and interbedded siliceous to calcareous mudstone, shale, and siltstone. Unit 2 includes the lower to middle part of the **Buchia uncitoides Zone** of Jones et al. (1969, p. A7); it can be subdivided into 2 subunits 2A and 2B (Text-figure 42). Unit 2A includes about 3.25m of thin-bedded graywacke interbedded with thicker intervals of dark gray mudstone. Unit 2B includes 43.3m of massive to medium bedded graywacke with thinner intervals of mudstone. The base of the **B. uncitoides Zone** occurs ~ 15m below the base Unit 2A (See Jones et al. 1969 and Pessagno (1977b, p. 11).

Unit 3: Dark gray siliceous to calcareous mudstone with abundant lenses and nodules of dark gray micrite containing abundant well preserved calcified Radiolaria (Text-figure 42). This unit includes the remainder of the **Buchia uncitoides Zone,** all of the **Buchia pacifica Zone**, and the lower part of the **Buchia keyserlingi Zone** of Jones et al (1969, p. A7).

The Grindstone Creek succession on the south side of Grindstone Creek was first sampled for Radiolaria by Pessagno (1977b) (See Text-figures 43-44). Samples collected from this succession were re-analyzed by Pessagno et al. (1984). In 1994 Pessagno and Meng re-sampled that part of the succession containing the **Buchia sp. aff. okensis Zone** and the overlying **Buchia uncitoides Zone** in more detail. Subsequently, it was discovered by the Senior Author in 1998 that an arroyo paralleling the south side of Grindstone Creek contains excellent exposures (~ 171m) of the **Buchia piochii Zone** and the **Buchia sp. aff. okensis Zone** (See Kariminia 2006b).

Text-figure 43 shows the distribution of radiolarian samples in the succession paralleling the south bank of Grindstone Creek. Important horizons for reference in this section are both the base of Unit 2 and the top of Unit 2. Text-figure 44 shows the Radiolaria recovered from these samples and their biostratigraphic assignment.

At Grindstone Creek the last occurrence of *Complexapora kozuri* is recorded from both the upper part of radiolarian **Zone 4, Subzone 4 alpha**, and the upper part of the **Buchia sp. aff. okensis Zone** in sample GRIN94-8 (117.4m below top of unit 2 and 52m below the base of the **Buchia uncitoides Zone**). The first observed occurrence of *Archaeocenosphaera boria*, a primary marker taxon marking the base of **Zone 5, Subzone 5A** is from sample GRIN 94-20A (60m above GRIN94-8). A specimen of *Spiticeras* s.s. was identified by co-author Cantu Chapa from sample (GR94-20A)

Based on last occurrence of primary marker taxon *Complexapora kozuri* (top **Zone 4, Subzone 4 alpha**,) and first occurrence of *Archaeocenosphaera boria*, the Jurassic-Cretaceous boundary occurs between GRIN94-8 and GR94-20A in the 60m interval between the last occurrence of *C. kozuri* and the first occurrence of the *A. boria* (uppermost **Buchia sp. aff okensis Zone** to lowermost **Buchia uncitoides Zone**).

Our radiolarian biostratigraphic data demonstrate that the radiolarian assemblage from the upper part of the **Buchia uncitoides Zone** of Jones et al. (1969) is assignable to radiolarian **Zone 5, Subzone 5A**. Sample G494-37 (Text-figures 42-43) contains *Pseudodictyomitra carpatica, Ristola cretacea*, and *Obesacapsula polyhedra*. These taxa are assigned to unitary associations (UAZ) 7-12, 12-17, and 13-17 of Baumgartner et al. (1995a, b). The concurrence of UAZ's suggest that sample Gr94-37 is probably correlative with the upper part of UA12. Baumgartner et al. assigned UA12 to the "early early late Tithonian". The calcareous nannoplankton, radiolarian, and ammonite biostratigraphic data indicate that UA12 of Baumgartner et al. is assignable to the upper Berriasian rather than to the lower upper Tithonian as indicated by Baumgartner et al.

Subsequent to the investigations of Pessagno (1977a, b) and Pessagno et al. (1984) Bralower et al. (1989) recovered a rich nannofossil assemblage from 150 samples collected from the *Buchia*-bearing beds at Grindstone Creek.

Bralower's (1990, p. 113, Fig. 6) lowermost sample, GC665, containing calcareous nannofossils occurs ~ 11.65m above

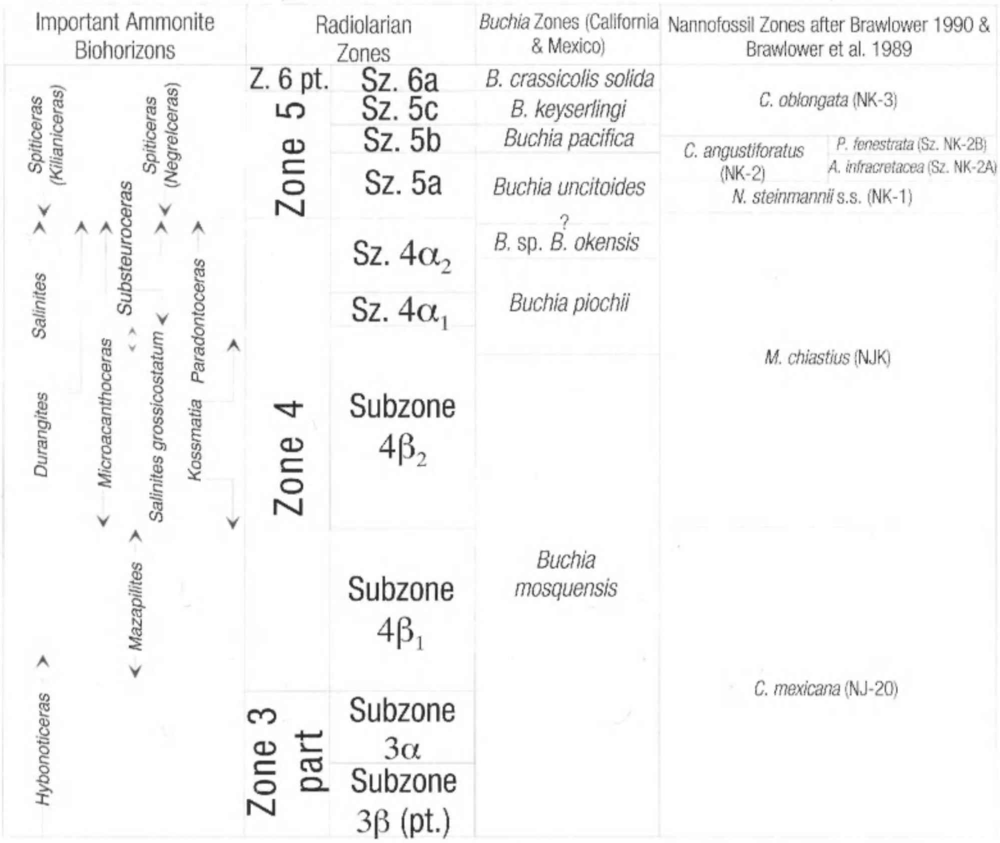
SPECIES/SAMPLES	GRIN94-4	GRIN94-6	GRIN94-7A	GRIN94-8	GRIN94-9B	GRIN94-20A	GRIN94-24	GRIN94-31A	GRIN94-32A	GRIN94-34A	GRIN94-35A	GRIN94-37	GRIN94-42B
Position in section: Meters.	6.7	12.19	13.56	33.07	40.09	92.53	109.6	126.06	131.55	137.95	140.39	150.45	169.35
Paronaella sp.													R
Cenodiscus sp.								R		C			
Archaeocenosphaera boria						A	A	A	A	A	A	R	A
Complexapora kozuri	A	A		A									
Archaeodictyomitra apiara												C	
Hsuum sp.					R						R		
Caneta boesii									C			C	A
Caneta hsui					R								
Caneta spp.													A
Mirifusus mediodilatatus												A	
Mirifusus spp.							R					C	
Parvicingula colemani			R										
Parvicingula jonesi			C	A				C	A	C	A	R	A
Parvicingula spp.	A	A							C	A	A		A
Ristola altissima				C									
Ristola sp. aff *R. altissima*									R				
Ristola cretacea												R	
Pseudodictyomitra carpatica											R	C	
Mita weddellensis												C	
Obesacapsulum polyedra								C				C	
Obesacapsulum sp. cf. *polyedra*												R	
Obesacapsula rotundata												R	
Obesacapsula verbum												C	
Obesacapsula spp.												A	
Great Valley Supergroup	**Unit 1 (part): *Buchia* sp. aff. *okensis--B.***						**Unit 2 *Buchia uncitoides Zone***						
BIOZONES	**Zone 4, Subzone 4 alpha$_2$**					**Zone 5, Subzone 5A**							
CHRONOSTRATIGRAPHIC ASSIGNMENT	**Upper Jurassic: upper Tithonian**					**Lower Cretaceous: lower Berriasian**							

TEXT-FIGURE 43
Illustration shows the radiolarian faunal assemblage at Grindstone Creek, Glenn County, California. Position of samples in measured section; biostratigraphic assignment of samples, and chronostratigraphic assignment of samples are noted.

the top of our Unit 2, 54.5m below the top of the **Buchia uncitoides Zone**, and approximately 5m above our sample Gr94-37 (Text-figures 43-44). According to Bralower his sample GC665 contains a lower Berriasian to lower upper Berriasian nannofossil assemblage with *Rotelapithus laffitei, Cretarhabdus sunirellus, Assipetra infracretacea,* and *Grantarhabus medii.* Bralower indicated that this assemblage is assignable to **Zone NK1** (**Nannoconus steinmanni steinmanni Zone** of Thierstein 1971; Bralower et al. 1989). Sample GC670.1 (82.5m from gauging station) contains *Cretarhabus angustiforatus*, the taxon which marks the base of **Zone NK2** (**C. angustiforatus Zone**). The remainder of the **Buchia uncitoides Zone** and all of the overlying **Buchia pacifica Zone** are included in **Zone NK2** (upper Berriasian).

No samples from the **Buchia sp. aff. okensis Zone** were collected by Bralower from the Grindstone Creek section. However, at McCarty Creek to the north (Text-figure 40) Bralower (1990, p. 117) assigned the strata of the **Buchia sp. aff okensis Zone** to the upper Berriasian and to nannofossil zone **NK2**. This biostratigraphic and chronostratigraphic assignment was based on the presence of *Microantholithus hoschulzii, M. obtusus, Rhagodiscus nebulosus, Diadorhombus rectus,* and *Percivalia fenestrate.* In contrast, Jones et al. (1969) assigned their **Buchia sp. aff. okensis Zone** to the upper Tithonian based on the presence of *Substeueroceras, Parodontoceras, Proniceras, Blandfordiceras, and Spiticeras* s.s. Pessagno (1977b, p. 59) questionably assigned radiolarian sample NSF 838 (upper **Buchia sp. aff. okensis Zone**) to his Zone 4 and to the upper Tithonian. This sample contained no diagnostic taxa other than *Parvicingula jonesi* which occurs in the upper Tithonian and throughout the Berriasian elsewhere. Curiously, at Grindstone Creek Bralower assigned the basal part of his fossiliferous section in the **Buchia uncitoides Zone** to **Zone NK1** (= **Nannoconus steinmanni steinmanni Zone**) (See discussion of Bralower sample GC665 above). For this reason it difficult to understand how nannofossil **Zone NK2** at McCarty Creek can occur in the **Buchia sp. aff. okensis Zone**. Our data indicate that the **Buchia sp. aff. okensis Zone** is mostly assignable to the upper Tithonian. By superposition zone **NK2** must be upper Berriasian. It is probable that the occurrence of **Zone NK2** nannofossils within alleged **Buchia sp. aff. okensis Zone** strata at McCarty Creek is due to unknown structural complications. Bralower et al. (1990, p. 70) correlate the base of **Zone NK1** with the base of the **Buchia uncitoides Zone**. However, no evidence from the California Coast Ranges is given to support this correlation. Radiolarian biostratigraphic data indicate that the upper part of the **Buchia sp. aff. okensis Zone** is assignable to **Subzone 4 alpha$_2$** (upper Tithonian). A 60m interval in which no Radiolaria were recovered separates the highest **Subzone 4 alpha$_2$** sample from the base of the overlying **Buchia uncitoides Zone** of Jones et al. (1969) and radiolarian **Subzone 5A** (lower Berriasian). At present, it cannot be determined whether this part of the **Buchia sp. aff. okensis Zone** is assignable to the upper Tithonian or the lower Berriasian (or both). It is likely that this interval may be correlative with nannofossil **Zone NJK** (**M. chiastius Zone**).

Jones et al. (1969) assigned the underlying **Buchia piochii Zone** to the upper Tithonian in California based on the presence of *Durangites*? and *Kossmatia.* As previously noted in the discussion of the San Pedro del Gallo area herein, Burckhardt



TEXT-FIGURE 44
Correlation of ammonite, Radiolaria, *Buchia*, and calcareous nannofossil zones. Ammonite biostratigraphic and chronostratigraphic data from Imlay (1980) and other sources. Radiolarian biostratigraphic and chronostratigraphic data from Pessagno (1977b), Pessagno et al. (1987a, b), Pessagno et al. (1993), and other sources. Buchiid biostratigraphic and chronostratigraphic data from Jones et al. (1969).

(1910) and Imlay (1939, Table 8) recorded species of *Kossmatia* as well as species of *Durangites* in the upper part of the San Pedro del Gallo Chert Member of the La Caja Formation. Burckhardt (1910) also noted the presence of numerous *Buchia mosquensis* (= his *"Aucella* d. gr. *Mosquensis* Kes. in Lahusen" within the unit that we now call the "San Pedro del Gallo Chert Member" (See Imlay 1980, p.34). Subsequently, *Buchia piochii* was noted by Contreras-Montero et al. (1988, p. 21) within these beds. In this report we assign the San Pedro del Gallo Chert Member to Radiolarian **Subzone 4 beta**, (lower upper Tithonian). As already noted, the upper part of the **Buchia piochii Zone** has been well calibrated biostratigraphically and chronostratigraphically from data from Baja California Sur (Vizcaino Peninsula) by Davila-Alcocer (1986) and Rangin (1976) (See Baja California Sur above).

In spite of the minor inconsistencies in correlation by Bralower (1990) and Bralower et al. (1990) noted above, the calcareous nannofossil data from highest Jurassic and lowest Cretaceous strata at Grindstone Creek are extremely useful. The nannofossils data not only can be integrated with that of the *Buchia*, ammonites, and Radiolaria, but it also can be related directly to U-Pb geochronometric dates resulting from the Bralower et al. 1990 study. At Grindstone Creek Bralower et al. recovered zircon from two tuff horizons in the Great Valley Supergroup (GVS):

Horizon A: Horizon A includes a 4cm greenish-brown weathered tuff in the upper part of the **Buchia uncitoides Zone** 16.5m below the base of the overlying **Buchia pacifica Zone** (*See* Bralower et al. 1990, p. 64-65). Moreover, this horizon occurs approximately 38m above sample GC665 which contains nannofossils assignable to **Zone NK1** (lower Berriasian to lower upper Berriasian). According to Bralower et al. (1990) a sample collected 1cm above Horizon A contains calcareous nannofossils assignable to **Zone NK2, Subzone 2A** (**Cretarhabdus angustiforatus Zone, Assipetra infracretacea Subzone**). This biostratigraphic assignment is suggested by the presence of *Cretarharbdus angustiforatus*, the taxon that marks both the base of **Zone NK2** and **Subzone 2A** (upper Berriasian). Taxa which make their first appearance in the upper Berriasian such as *Rhagodiscus nebulosus* occur several meters above Horizon A. The absence of *Percivalia fenestrata*, which defines the base of overlying **Subzone 2B** (**Percivalia fenestrata Zone**) indicates that Horizon A is assignable to the upper Berriasian.

Horizon B: This horizon is a 4cm bed of "coarsely crystalline" tuff that occurs 65m above Horizon A (*See* Bralower et al. 1990). Because *R. nebulosus* occurs 23m above Horizon B and *P. fenestrate* is still absent, Bralower et al. refer this horizon to the upper Berriasian and **Subzone 2A**.

Isotopic analyses of zircon from tuff in both Horizon A and Horizon B indicate an age (U-PB) of 137.1 +1.6/-0.6ma for the

TEXT-FIGURE 45
Index Map for Caribbean showing the island of La Desirade.

lower upper Berriasian. Since both dated horizons occur in **Subzone 2A**, it was first suggested that they were correlative with M-sequence **Polarity Zones M16 and M16n** at DSP Site 534. However, subsequent analysis of the calcareous nannofossil data from DSDP Site 389 changed this interpretation. Site 389 was drilled between M-sequence **Polarity Zones M15** and **M16**. Basal strata at Site 389 contain *R. nebulosus*. Hence, a correlation between the dated horizons at Grindstone Creek and magnetochrons 15-16 is favored (*See* Bralower et al. 1990; Pálfy et al. 2000, p. 941).

Bralower et al. (1990) interpolated the age of the Jurassic-Cretaceous boundary to be 141Ma. This age is also accepted by Palfy et al. (2000) and is compatible with our new date of 143.734Ma ± 0.06Ma for the lower upper Tithonian (upper **Subzone 4 beta**,) of La Desirade (See below).

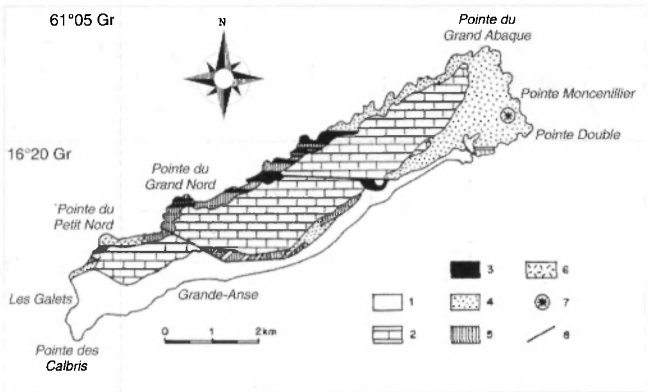
THE ANTILLEAN-CARIBBEAN REGION

The most significant exposures of upper Tithonian strata in the Antillean-Caribbean Region occur in La Desirade (Lesser Antilles) and in western Cuba (Greater Antilles). Both areas have a unique tectonic history. La Desirade occurs in the forearc area of the Lesser Antilles adjacent to the larger island of La Guadalupe (Text-figure 45). La Desirade, though part of the Lesser Antilles, has Late Jurassic (Tithonian) rocks in its basement complex which are more closely related to those of the Greater Antilles (e.g. Puerto Rico, Dominican Republic). The western part of Cuba includes remnants of the San Pedro del Gallo terrane and is not part of the Antillean volcanic arc complex (See Pessagno et al. 1999).

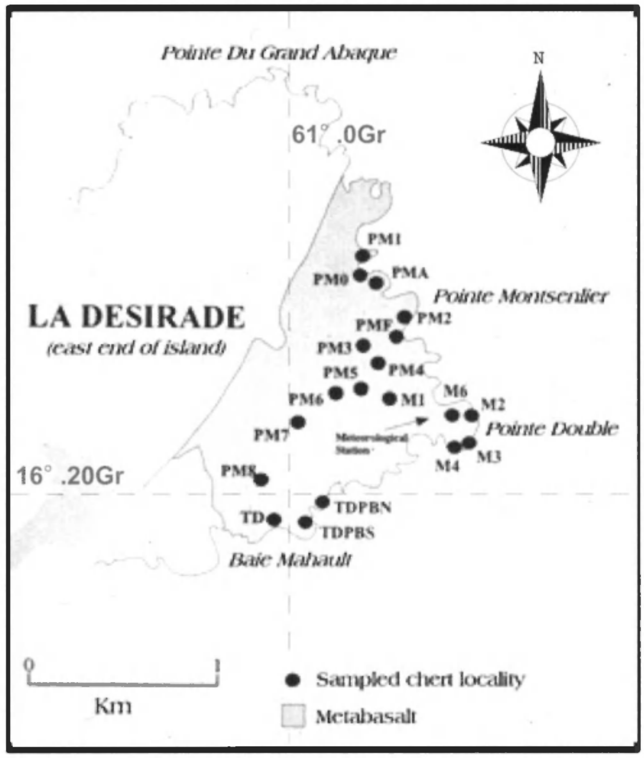
LA DESIRADE

Previous investigations by Mattinson et al. (1980) and Montgomery et al. (1992) established that the basement complex of La Desirade, the La Desirade igneous complex (LDIC), contains Late Jurassic (Tithonian) rocks. Subsequently, new and more accurate radiolarian biostratigraphic and chronostratigraphic data and U-Pb geochronometric data were presented by Mattinson et al. (2008). These new data can be used to constrain the placement of the Jurassic-Cretaceous boundary in the Western Hemisphere and elsewhere.

The island of La Desirade is a small island ($30km^2$) situated in the Lesser Antilles near the larger island of La Guadeloupe (Text-figure 45). The island is table-like in aspect with a maximum elevation of 275m. Pliocene limestone rests with angular unconformity above a Mesozoic basement complex. Mesozoic sedimentary and igneous rocks crop out extensively along the



TEXT-FIGURE 46
Geologic map of La Desirade.



TEXT-FIGURE 47A
Location of radiolarian localities on La Désirade.

shoreline (Text-figure 46). According to Maury et al. (1990, p. 146) the basement complex was originally considered to be Eocene to Early Miocene. Subsequently, geochronometric data from Fink et al. (1971), Mattinson et al. (1973, 1980), Dinkelman and Brown (1977), and Briden et al. (1979) indicated that the basement complex was of Mesozoic age.

Bouysse et al. (1983) divided the Mesozoic igneous basement of La Desirade into three major rock units (See Text-figure 46): (1) The central acid massif; (2) the northeast volcanic complex; and (3) the upper meta-andesite group. According to Mattinson et al. (2008) these units were originally ranked 1, 2, and 3 respectively in terms of their inferred age. Mattinson et al. (ibid.) re-named the first and third units the "Trondhjemite/Rhylitic Igneous Complex" and the "Diabasic/Metadiorite Dike Swarm" respectively in order to better characterize their rock assemblages. These authors retained the term "northeast volcanic complex" for the basaltic submarine lavas and associated rhyolitic eruptive rocks at Pointe de Grand Abique (Text-figure 46). The new terminology for the Bouysse et al. (1983) rock units presented by Mattinson et al. (2008) is used herein.

Origin of La Desirade Igneous Complex (LDIC)

According to Maury et al. (1990, p. 146) the LDIC extends along the La Désirade escarpment which forms the southern flank of the La Désirade trough. These workers noted that the escarpment is made up of "greenstones" along the scarp for over 50km. Bouysse et al. (1983) suggested that the La Désirade block had been uplifted 2000 to 4000m above the surrounding seafloor by the Miocene.

Many workers regard the northeast volcanic complex as an ophiolite complex (e.g., Dinkelman and Brown 1977; Fox and Heezen 1975; Briden et al. 1979; Mattinson et al. 1973, 1980; and Montgomery et al. 1992). Other workers such as Donnelly and Rodgers (1978), LeGuen de Kerneizon et al. (1979), Bouysse et al. (1983), and Donnelly et al. (1990, p. 353) discount an ophiolitic origin for the La Désirade basement complex largely based on geochemistry and the Bouysse et al. (1983) biostratigraphic and chronostratigraphic data. The advocates of a non-ophiolitic origin suggested that the La Désirade basement complex formed by island arc magmatic processes (See Mattinson et al. (2008) for a more detailed discussion). Whether the LDIC was of ophiolitic origin or island arc origin makes little difference in interpreting the isotopic age of the igneous section. As noted by Mattinson et a. (2008), even if a volcanic island origin is advocated, it is probable that these rocks were formed over a very limited time interval. Hence, the isotopic age of the igneous section is closely equivalent to the age of the radiolarian chert and pelagic limestone interbedded with and immediately overlying the volcanic section.

Red to reddish brown to occasionally black manganiferous chert and jasper lacking calcalkaline volcanic debris crops out at twenty localities on the eastern end of the La Désirade (Text-figures 47A-B) within the northeast volcanic complex (NVC). Usually, outcrops cover only a few square meters. Radiolarian chert can occur as an interpillow sedimentary rock or be interbedded with the pillow basalt. At Point Double tan pelagic limestone (micrite) and associated red chert wrap around basalt pillow structures in the area below the meteorological station (Text-figure 48). In addition, large, lenticular masses of radiolarian chert several meters in maximum dimensions occur along the shoreline in the same area (Text-figure 49). The radiolarian chert in the area surrounding the meteorological station produced the best preserved radiolarian assemblages (M series of Montgomery et al. (1992). Montgomery et al. (1992), Montgomery et al. (1994a,b), and Montgomery et al. (1994a,b) established that the manganiferous red chert that occurs in basement complexes at La Désirade, southwestern Puerto Rico, the Dominican Republic, and Cuba is clear indication that the Caribbean Plate originated in the Pacific rather than in the Atlantic. Red chert crops out around the Circum-Pacific margin from Baja California Sur to Indonesia and throughout the Alpine-Himalayan orogenic belt (e.g., Tibet, Iran, Turkey, Greece, Italy). Moreover, the Caribbean

SPECIES/SAMPLES	M3	M4	M6	TD	PM7	PF
Vallupus hopsoni		X	X	X	X	X
Neovallupus spp.			X			
Pantanellium cantuchapai				X		
Acanthocircus sp. cf. A dicranocanthos			X			
Acosta dura			X			
Archaeospongoprunum spp.			X			
Tritrabs ewingi			X			
Triactoma robusta				X		
Perispyridium spp.			X			
Eucyrtidiellum ptyctum			X			
Napora spp.			X	X		
Archaeodictyomitra sixi			X			
Hsuum mclaughlini			X	X		
Loopus primitivus			X			
Mirifusus baileyi			X	X		
Parvicingula holdsworthi	X	X	X	X		
Northeast Volcanic Complex	Red ribbon chert					

TEXT-FIGURE 47B
Upper Jurassic (upper Tithonian) Radiolaria occurring in northeast volcanic complex, La Desirade, Lesser Antilles. Localities M3, M4, M6, TD, and PM7 occur on northeast end of island (Figures 3-4). Locality PF occurs at southwest end of island 0.5 miles from Pointe Fregule. At this locality one thin bed of red to gray chert yielded Radiolaria.

TEXT-FIGURE 48
Tan pelagic limestone (micrite) and associated red chert wrap around pillow structures at area below meteorological station. Note hammer for scale.

red chert including that at La Desirade carries a Northern Tethyan radiolarian assemblage characterized by the presence of *Parvicingula/Praeparvicingula*. In contrast, to the north, Late Jurassic radiolarian faunas from DSDP Site 534 in the Blake-Bahama Basin contain lower latitude Central Tethyan radiolarian faunas (See Baumgartner 1984).

Biostratigraphy and Chronostratigraphy of interlava sedimentary strata

Previous studies of the La Desirade radiolarian assemblage by Schmidt-Effing in Bouysse et al.'s (1983) study, though perhaps state of the art for this point in time, are incorrect. These studies indicated that the LDIC is Early Cretaceous. Subsequent investigations by Montgomery et al. (1992) established that the LDIC is, in fact, Late Jurassic (Tithonian) in age. Montgomery et al. (1992 stated: "Unfortunately Schmidt-Effing's interpretation of the faunal assemblage is somewhat misleading. The figured taxa (Figure 4, 1-3 of Bouysse et al. [1983] include *Pantanellium riedeli* Pessagno, *Praeconocaryomma* sp., and *Paronaella diamphidia* Foreman. *Pantanellium riedeli* Pessagno is misidentified. The figured form possesses highly nodose pore frames and primary spines with deeply incised, mostly parallel-sided grooves. It appears to be representative of the *Pantanellium meraceibaense* Group of E. A. Pessagno and MacLeod (work of 1987; discussed by Pessagno [1987]. The form figured as *Praeconocaryomma* sp., though probably related to *Praeconocaryomma* should be assigned to *Praeconosphaera* Yang. The specimen referred to as *Paronaella diamphidia* Foreman is now placed by most workers in *Foremanella* Muzavor.

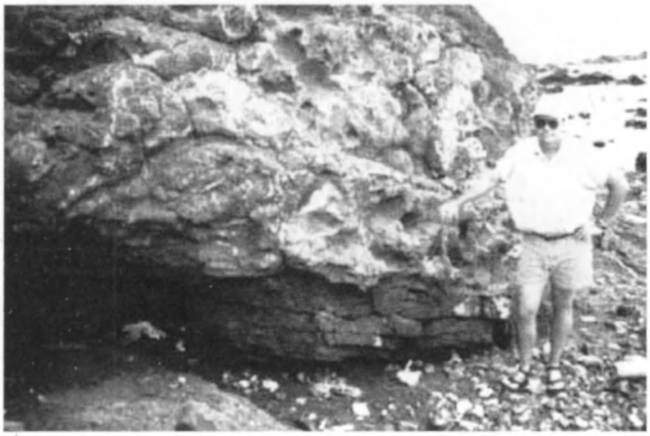
"We interpret the figured specimens of Bouysse et al. [1983] as being Jurassic (uppermost Callovian?; Oxfordian) to Lower Cretaceous (upper Valanginian/lower Hauterivian). Our data from east-central Mexico and from the Smith River Subterrane (northwest) California indicate the *Pantanellium meraceibaense* Group ranges from Superzone 1, Zone 1I (uppermost Callovian?; lower Oxfordian) to **Zone 5, Subzone 5C** (upper Valanginian/lower Hauterivian). Other taxa listed by Schmidt-Effing included *Thanarla pulchra* (Squinabol) and *Archaeospongoprunum tehamaensis* Pessagno. Both of these taxa are restricted to the Upper Cretaceous suggesting these specimens are misidentified. Except for the presence of *Parvicingula* Pessagno in the faunal list, other taxa listed are of no great significance.—". Pessagno (in Mattinson et al. 2008) re-analyzed the biostratigraphic and chronostratigraphic data presented by Montgomery et al. (1992). The discussion presented below is a minor revision of conclusions reached by Mattinson et al.

Text-figure 47A shows the position of six localities where radiolarian were successfully recovered from red manganiferous radiolarian chert by Montgomery et al. (1992) in the LDIC. Five of these localities occur on the northeast end of the island (M3, M4, M6, TD, PM7) and one (PF) occurs on the southwest end of the island. Locality M4 corresponds closely to the locality where Schmidt-Effing (in Bouysse et al, 1983) recovered alleged Hauterivian to Barremian Radiolaria. Text-figure 47B is a faunal chart showing radiolarian taxa occurring at these six localities. Plate 6 contains scanning electron micrographs of some of the more important elements occurring in the radiolarian assemblage. It should be noted that primary marker taxon *Vallupus hopsoni* (Text-figures 4, 33) occurs in five out of six LDIC localities (M4, M6, TD, PM7, PF). This taxon first appears at the base of **Zone 4 (Suhzone 4 beta$_1$:** upper lower Tithonian) and makes its final appearance just below the top of **Zone 4, Subzone 4 alpha$_1$** (upper Tithonian) (**See** San Pedro del Gallo area above and Text-figures 4, 43). The sixth locality, M3, though lacking *V. hopsoni*, contains *Praeparvicingula holdsworthi*. This taxon is restricted to **Zone 4 (Subzone 4 beta$_1$** to **Subzone 4 beta$_2$**: upper lower Tithonian to lower upper Tithonian) at Taman and San Pedro del Gallo. Significantly, the most fossiliferous sample , M6, contains *Neovallupus* sp. A. Radiolarian and ammonite biostratigraphic data from San Pedro del Gallo (Durango, Mexico), Canyon San Matias (near Mazapil, Zacatecas, Mexico), and Taman (San Luis Potosi, Mexico) indicate that:

(1) *Neovallupus* first appears at San Pedro del Gallo in upper Tithonian strata associated with the ammonites *Kossmatia* and *Durangites* (See San Pedro del Gallo remnant of San Pedro del Gallo terrane above);

(2) At Canyon San Matias near Mazapil *Neovallupus* occurs along with the last *Kossmatia;*

(3) At Taman *Neovallupus* is closely associated with the ammonite *Salinites grossicostatum* in an interval that



TEXT-FIGURE 49
Lenticular mass of red ribbon chert in pillow basalt below meteorological station at Pointe Double. Dr. Homer Montgomery (University of Texas at Dallas) standing by outcrop. Dr. Montgomery's knees in line with middle of chert lens.

corresponds to all but the upper part of Cantu-Chapa's (1971) **Saurites bituherculaltum Zone**;

(4) At San Pedro del Gallo *Neovallupus* occurs 1m below the contact between the San Pedro del Gallo Chert Member and the Puerto del Cielo Shale Member of the La Caja Formation. This horizon is approximately 2m below the contact between the Puerto del Cielo Shale Member and the overlying Cerro Panteon Member. The latter member contains the first specimens of the ammonite *Substeueroceras* and is assignable to Imlay's (1980) **Substeuroceras-Proniceras assemblage** (See discussions in the San Pedro del Gallo, Mazapil, and Huayacocotla remnants above).

(5) Finally, it should be noted that the specimens of *Neovallupus* figured from La Desirade and San Pedro del Gallo (Plate 1, figure 8 and Plate 7, figure 1 respectively) belong to the same yet unnamed species (*Neovallupus* sp. A herein). Accordingly, the presence of *Neovallupus* sp. A at both localities strengthens the correlation of the radiolarian bearing interval at La Desirade with the upper part of **Subzone 4 beta$_2$**. This horizon corresponds to the upper part of Imlay's (1980) **Kossmatia-Durangites assemblage**; at San Pedro del Gallo it occurs *above* the last occurrence of *Kossmatia* and 2m below the first occurrence of *Substeueroceras* and the base of the **Substeueroceras-Proniceras assemblage**.

New Ca-Tims zircon geochronometric data from central tronhjemtic/rhyolitic unit (CTRU)

Mattinson et al. (2008) presented new high precision, high-accuracy "CA-TMS" (Chemical Abrasion – Thermal Ionization mass Spectrometry) zircon ages for trondhjemitic basement from island of La Desirade. Details of the CA-TIMS technique may be found in Mattinson (2005), and a full discussion of the new La Desirade zircon ages is in Mattinson et al. 2008. Here we present a brief summary of that work. Three fractions of zircon were subjected to high-temperature annealing, then digested in a series of steps. For each fraction, the initial two steps evidently removed all parts of the zircon grains that had experienced any loss of radiogenic Pb. In each case, the remaining partial dissolution steps sampled "closed-system zircon", yielding a set of statistically identical ages (See Text-figures 50). The resulting age on the CTRU is 143.734Ma ± 0.060Ma [0.042%].

Geochronologic Summary

The combined biostratigraphic, chronostratigraphic and geochronometric data from La Desirade, San Pedro del Gallo (Durango, Mexico), Canyon San Matias near Mazapil (Zacatecas, Mexico) and the Taman-Tamazunchale area (San Luis Potosí, Mexico) indicate that the top of the lower part of the lower upper Tithonian is 143.734Ma ± 0.060Ma [0.042%]. This interval corresponds to the upper part of radiolarian biozone **Subzone 4 beta$_2$**, the upper part of Imlay's (1980) **Kossmatia-Durangites assemblage**, and the lowermost part of the **Buchia piochii Zone** of Jones et al. (1969). These data (see Text-figure 51) are compatible with the U-Pb age of 137.1 + 1.6/-0.6ma (Zircon from tuff) of Bralower et al. (1990) for the upper Berriasian part of the Great Valley Supergroup at Grindstone Creek (Glenn County, California).

Notes on Uppermost Jurassic and lowermost Cretaceous strata in western Cuba

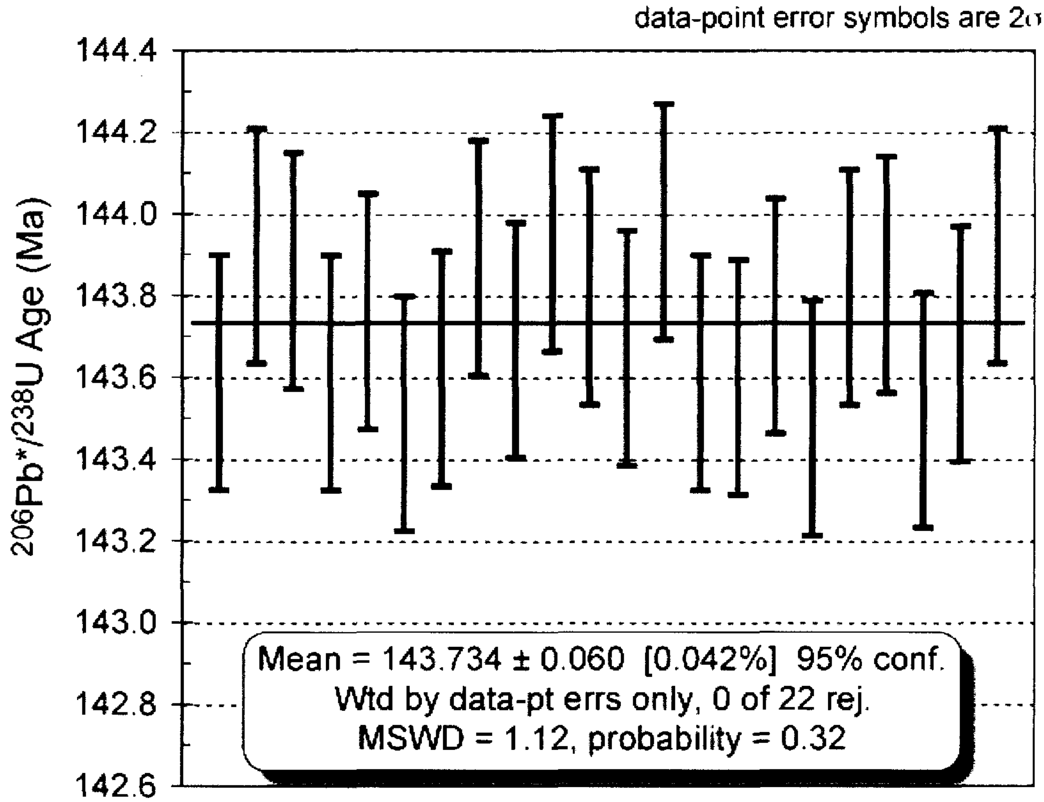
The Jurassic strata of western Cuba crop out in the Sierra del Rosario and the Sierra de Los Organos remnants of the San Pedro del Gallo terrane (SPG. See Pessagno et al. 1999). The presence of *Buchia*, tethyan ammonites, and *Parvicingula/Praeparvicingula* in highest Jurassic strata indicate that both SPG remnants were situated at Southern Boreal latitudes during the latest Jurassic (late Tithonian). Data from Baumgartner (1984) at DSDP Site 534 in the Blake-Bahama Basin to the north indicate that latest Jurassic and earliest Cretaceous strata contain a lower latitude Central Tethyan radiolarian assemblage. A tectonostratigraphic summary of the Cuban remnants of the SPG is given in Text-figure 8.

Imlay (1980, p. 35) stated that "The latest late Tithonian ammonite assemblage in the Gulf Region characterized by *Substeueroceras* and *Proniceras* is not known in Cuba." These studies also are confirmed by studies of the ammonite assemblage by Cantu Chapa (1971), Myczyński (1989, 1999), and Myczyński and Pszcolkowski (1994).

CORRELATION WITH ARGENTINA

Neuquen Basin

Investigations by Pujana (1991, 1999) of the radiolarian assemblage of the Vaca Muerta Formation in the Neuquen Basin established a strong link between the Argentine ammonite and radiolarian biostratigraphic data. Pujana's investigations indicate that at Bardas Blancas *Vallupus hopsoni, V. zeissi, Bivallupus longoriai, B. mexicanus, Mesovallupus guadalupensis,* and *Protovallupus* spp. first appear in the lower part of the **Pseudolissoceras zitteli Zone**. This assemblage is correlative with lower Tithonian radiolarian **Zone 4, Subzone 4 beta$_1$** herein (See Pujana 1999, p. 462, Fig. 4). Moreover, these investigations indicate that *Bivallupus patagoniensis, Protovallupus* sp, *Vallupupus japanicus, V. mendozaensis,* and *V.* sp. occur in an unzoned interval between the **Aulacosphinctoides proximus Zone** and the **Substeueroceras koeneni Zone**. Unfortunately, the radiolarian assemblage of the **Substeueroceras koeneni Zone** is at the moment unstudied. The presence of *Vallupus nodosus* in the vallupinid assemblage at Malin Quemado in strata assignable to the **Windhauseniceras interspinosum Zone** suggests that this horizon is correlative with the horizon



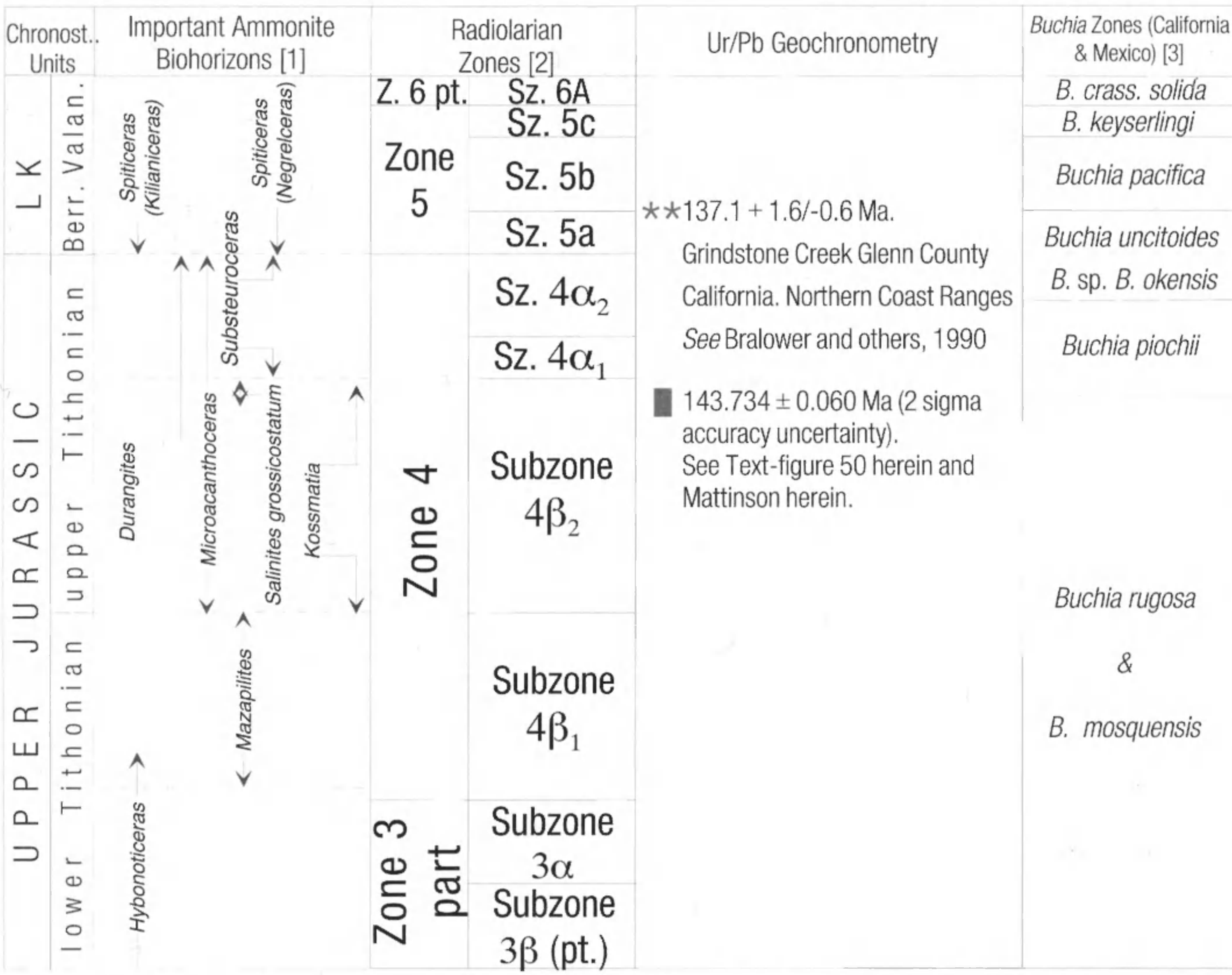
TEXT-FIGURE 50
Modified from Mattinson et al. (2008). 206Pb*/238U ages from 22 "closed-system" partial dissolution steps from three La Desirade trondhjemite zircon fractions.

characterized by the presence of *Neovallupus* and *Salinites grossicostatum* at Taman (See **Taman-Tamazunchale area, San Luis Potosí** above). *Vallupus nodosus* occurs 1m above the first occurrence of *Salinites grossicostatum* and *Neovallupus* in the Barrio Guadalupe Member of the Taman Formation at Barrio Guadalupe near Taman (See Text-figures 32, 34). At San Pedro del Gallo, Meng (1997) recovered *Vallupus nodosus* from 50m (SPG92-45: See Text-figure 15) below the top of the San Pedro del Gallo Chert Member to 2.6m (SPA94-23: See Text-figure 17) below the top of the overlying Puerto del Cielo Shale Member of the La Caja Formation. As noted previously, the contact between the Puerto del Cielo Shale Member and the overlying Cerro Panteon Member is equivalent to the boundary between radiolarian **Subzone 4 beta$_2$**.and **Subzone 4 alpha$_1$** as well as the boundary between Imlay's (1980) **Kossmatia-Durangites assemblage** and **Substeuroceras-Proniceras assemblage (=Substeueroceras-Berriasella** complex of Jeletsky 1984, p. 99). Moreover, *Vallupus nodosus* occurs near the top of **Subzone 4 beta$_2$** at Canyon San Matias near Mazapil (Zacatecas, Mexico: See Text-figure 27). These data indicate that the Argentine **Windhauseniceras interspinosum Zone** is correlative with the **Saurites bituberculaltum Zone** of Cantú-Chapa (1971) and the upper part of Imlay's (1980) **Durangites-Kossmatia assemblage**.

CORRELATION WITH THE ANTARCTIC PENINSULA

The Upper Jurassic of the Antarctic Peninsula contains both common ammonites and abundant, superbly preserved Radiolaria. The ammonite assemblage has been well documented by Whitman and Doyle (1989), Crane et al. (1993), and Kiessling et al. (1999). Pioneering studies by Kiessling and Scasso (1996), Kiessling (1999), and Kiessling et al. (1999) documented the presence of a high latitude Northern Austral Radiolaria assemblage. The studies of Kiessling (1999) and Kiessling et al. (1999) are immensely important because they demonstrate that radiolarian biohorizons can be correlated from the Southern Boreal Province to the North Austral Province. As a consequence, radiolarian biozones can be used as a framework to determine the chronostratigraphic position of ammonite biozones in these distant regions.

According to Kiessling et al. (1999, p. 688) the Antarctic Peninsula was part of a plate which was situated at higher latitudes during the Late Jurassic. These workers stated that this region was characterized by continuous magmatic activity from the Early Jurassic to the Miocene analogous to that of the southern-most Andes. Moreover, they stated that during the Jurassic Period the eastward subduction of the Pacific Phoenix Plate resulted in the formation of a calc-alkaline island arc complex – in part on continental crust basement. Volcaniclastic sediments comprising the Antarctic Peninsula Volcanic Group were deposited in the backarc and forearc. According to Kiessling et al. backarc volcaniclastics and anoxic radiolarian rich mudstone comprising the Antarctic Peninsula Volcanic Group unconformably overlie an older accretionary complex, the Trinity Peninsula Group. The radiolarian rich anoxic mudstone facies occurs in the Upper Jurassic Ameghino Formation (Medina and Ramos 1981; Medina et al 1983) and its chronostratigraphic equivalent in the forearc,



Text-figure 51: Relation of U-Pb geochronometry to ammonite, radiolarian, and *Buchia* biostratigraphic and chronostratigraphic data.

TEXT-FIGURE 51
Relation of U-Pb geochronometry to ammonite, radiolarian, and *Buchia* biostratigraphic and chronostratigraphic data.

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the Anchorage Formation. The anoxic radiolarian rich mudstone facies is characterized by containing numerous limestone nodules in both formational units. Whereas ammonites are common at widely separated horizons, Radiolaria by virtue of the occurrence in nodules, occur at nearly all horizons. Because the Ameghino Formation contains the most complete radiolarian and ammonite assemblage, only this unit will be discussed herein.

Radiolaria and ammonites were recovered at Graham Land at Longing Gap and at Livingston Island (Kiessling 1999; Kiessling et al. 1999: See Text-figure 52 herein). Text-figures 53-54 include columnar sections from Kiessling et al. showing samples collected in the Ameghino Formation at Longing Gap. These text-figure will serve as the basis of the discussion of the Tithonian to follow.

Six biohorizons allow us to recognize all of our North American Tithonian radiolarian biozones in the Antarctic Peninsula:

1. First occurrence of *Vallupus* spp. marking the base of **Zone 4** and **Subzone 4 beta$_1$**;

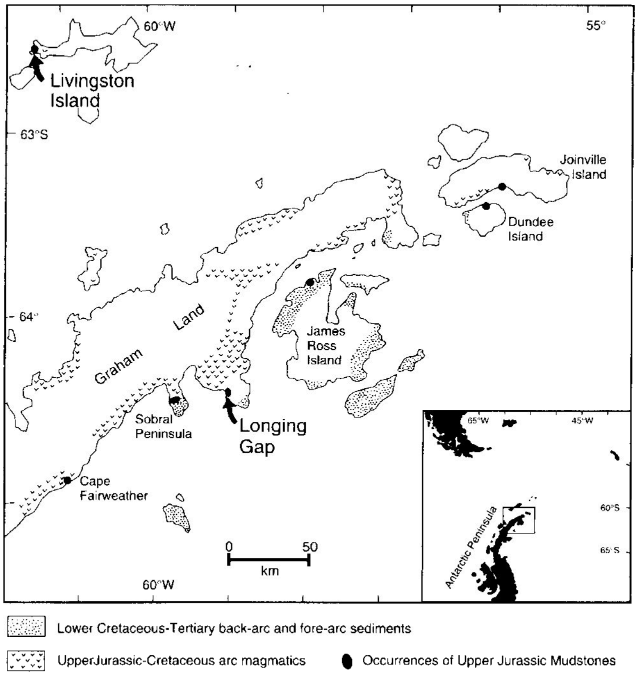
2. First occurrence of *Complexipora kozuri* (= *Zhamoidellum boehmi* of Kiessling 1999) marking the base of **Subzone 4 beta$_2$**;

3. First and last occurrence of *Neovallupus* spp;

4. Final appearance of *Perispyridium* spp. at the top of **Subzone 4 beta$_2$**;

5. Final appearance of *Vallupus* spp. at top of **Subzone 4 alpha$_1$**;

6. Final appearance of *Complexapora kozuri* Hull (=*Zhamoidellum boehmi* Kiessling 1999).



TEXT-FIGURE 52
Index and Geologic map of Antarctic Peninsula from Kiessling et al. (1999).

First Occurrence Or Vallupus SPP. (See Text- Figures 4. 33).

In the Longing Gap succession (Text-figures 53=54) *Vallupus hopsoni* first occurs in sample K20-1 (See Kiessling et al. 1999). Our data from east-central Mexico from the Huayacocotla remnant of the San Pedro del Gallo terrane (SPG) indicate that this biohorizon occurs in the upper part of the lower Tithonian (**Virgatosphinctes mexicanus-Aulacomyella neogeae Zone** of Cantú-Chapa 1971; see Taman-Tamazunchale area above). This horizon occurs 6m below the contact between the Mera Ceiba and Barrio Guadalupe members of the Taman Formation and the base of the **Mazapilites Zone** of Cantú-Chapa (1971). Kiessling et al. (1999, p. 700) indicated that "—The early Tithonian *Hybonoticeras hybonotum* zone is reached in concretion bed K18 as provided by characteristic *Taramelliceras* species.—".

First occurrence of Complexapora kozuri (Text-figures 4, 33).

Complexapora kozuri is the primary marker taxon for the base of our new **Subzone 4 beta$_2$**. At Canyon San Matias near Mazapil, Zacatecas Mexico this horizon occurs at the base of a 5m interval containing species of *Kossmatia* (See Burckhardt (1930) and detailed discussion under Mazapil remnant of the SPG terrane herein).

In the Longing Gap succession *Complexapora kozuri* (= *Zhamodellum boehmi* Kiessling 1999) first occurs at sample horizon LG1 (See Text-figure 53). Kiessling et al. (1999, p.698) identified the ammonite *Neochetoceras* (?) sp. from sample K27 (~ 5m above LG-1) (Text-figure 53). However, the presence of *Neovallupus modestus* at K27 is clear evidence that this horizon occurs in the upper part of **Subzone 4 beta$_2$** and in the lower part of the upper Tithonian (See discussion below).**3. First and last occurrence of Neovallupus spp (Text-figures 4, 33).**

Neovallupus is a corporeal taxon within the upper part of **Subzone 4 beta$_2$**. (See discussions under San Pedro del Gallo. Huayacocotla, and Mazapil remnants of the SPG above). In the Longing Gap section Kiessling (1999, p. 64, pl. 3) recovered *Neovallupus modestus* Yang and Pessagno from sample K27.

Final appearance of primary taxon Perispyridium.

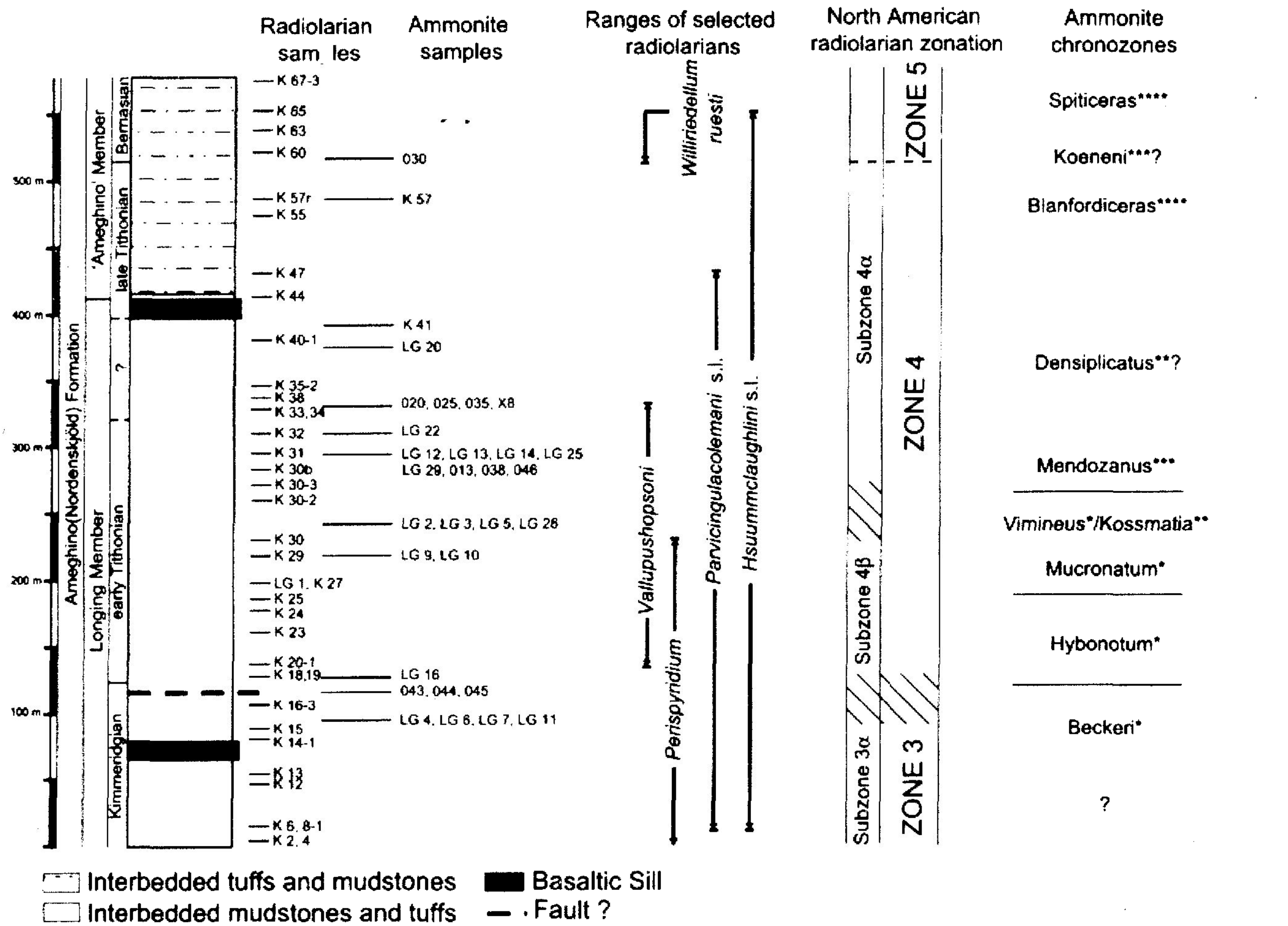
The final appearance of *Perispyridium* is used herein to mark the top of **Subzone 4 beta$_2$** and by Kiessling et al. (1999) to mark the top of **Subzone 4 beta** (*sensu* Pessagno et al. 1993). In the Longing Gap succession the final appearance of *Perispyridium* is at sample horizon K29 (See Text-figure 53). Kiessling et al. (1999, p. 700) stated that "In the middle part of the Longing Gap Member (K29, K30-1) the ammonites may correspond with the *Mucronatus* and *Vimeous* zones of Southern Germany. They are comparable with *Subplanitoides, Franconites,* and to the Pacfic genus *Kossmatia.*" At San Pedro del Gallo the top of **Subzone 4 beta$_2$** occurs at the top of the Puerto del Cielo Shale Member of the La Caja Formation immediately below the first occurrence of *Substeueroceras, Parodontoceras,* and *Berriasella* s.s. (See discussion above).

Final appearance of Vallupus spp. (Text-figures 4, 33)

Primary marker taxon *Vallupus* marks the top of new **Subzone 4 alpha$_1$**. **Subzone 4 alpha$_1$** can be recognized in Mexico at Cerro de La Peña 10km north of San Pedro del Gallo and along the Río Texcapa adjacent to the power plant (west of Huachinango, Puebla). Significantly, this zonal unit is also present at Longing Gap between sample horizons K29 (see above) and K33 (Kiessling et al. 1999, p. 702: Text-figure 53 herein). Samples K31-K32 contain a "—typical *Virgatosphinctes* fauna similar to that of the Argentine Neuquén Basin.—" and possibly is equivalent to the **Windhauseniceras interspinosum Zone** (See Kiessling et al. 1999, p. 700). Our analysis of Pujana's (1996) radiolarian biostratigraphic data from Argentina indicates that this ammonite biozone contains **Subzone 4 beta$_2$** rather than **Subzone 4 alpha$_1$** Radiolaria (See section on Argentina above). In Mexico, at the localities noted above, the La Peña locality contains *Substeueroceras, Durangites,* and other ammonite's characteristic of the Imlay's (1980) **Substeueroceras-Proniceras assemblage**. At the Rio Texcapa power plant locality the **Subzone 4 alpha$_1$** Radiolaria occur 61m above a horizon where Cantú-Chapa (1971) recovered ammonites assignable to his **Suarites bituberculatum Zone** (See Pessagno et al. 1984, 1987;.Yang and Pessagno 1989; Yang 1993).

Final appearance of Complexapora kozuri Hull (1997) (= Zhamoidellum boehmi Kiessling 1999). See text-figures 4, 33 herein.

Primary marker taxon *Complexapora kozuri* marks the top of **Subzone 4 alpha$_2$**. At Canyon San Matias this taxon makes its final observed appearance in samples SM96-9 73.9m above the base of the La Caja Formation (See Text-figures 26A, 27). At SM94-62, 76m above the base of the La Caja, ammonites collected by the senior author were identified by co-author Cantú-Chapa as *Parodontoceras* sp. aff. *P. callistoides* (Behr) and *Durangites* sp. (Text-figure 26B. See Mazapil remnant of SPG terrane herein). A possible lower Berriasian ammonite was identified by co-author Cantú-Chapa as cf. *Prothummania* sp. was recovered at 81m in sample SM96-2. At essentially the same horizon at SM94-64 **Subzone 4 alpha$_2$** Radiolaria including *Loopus primitivus, Parvicingula jonesi, Praeparvicingula holdsworthi,* and *Pantanellium whalenae* are also present. *Loopus primitivus*



TEXT-FIGURE 53
Columnar section showing Ameghino Formation at Longing Gap, Grahamn Island, Antarctic Peninsula. From Kiessling et al. (1999). Nodules bearing Radiolaria, ammonites, and other fossils prefixed by "K".

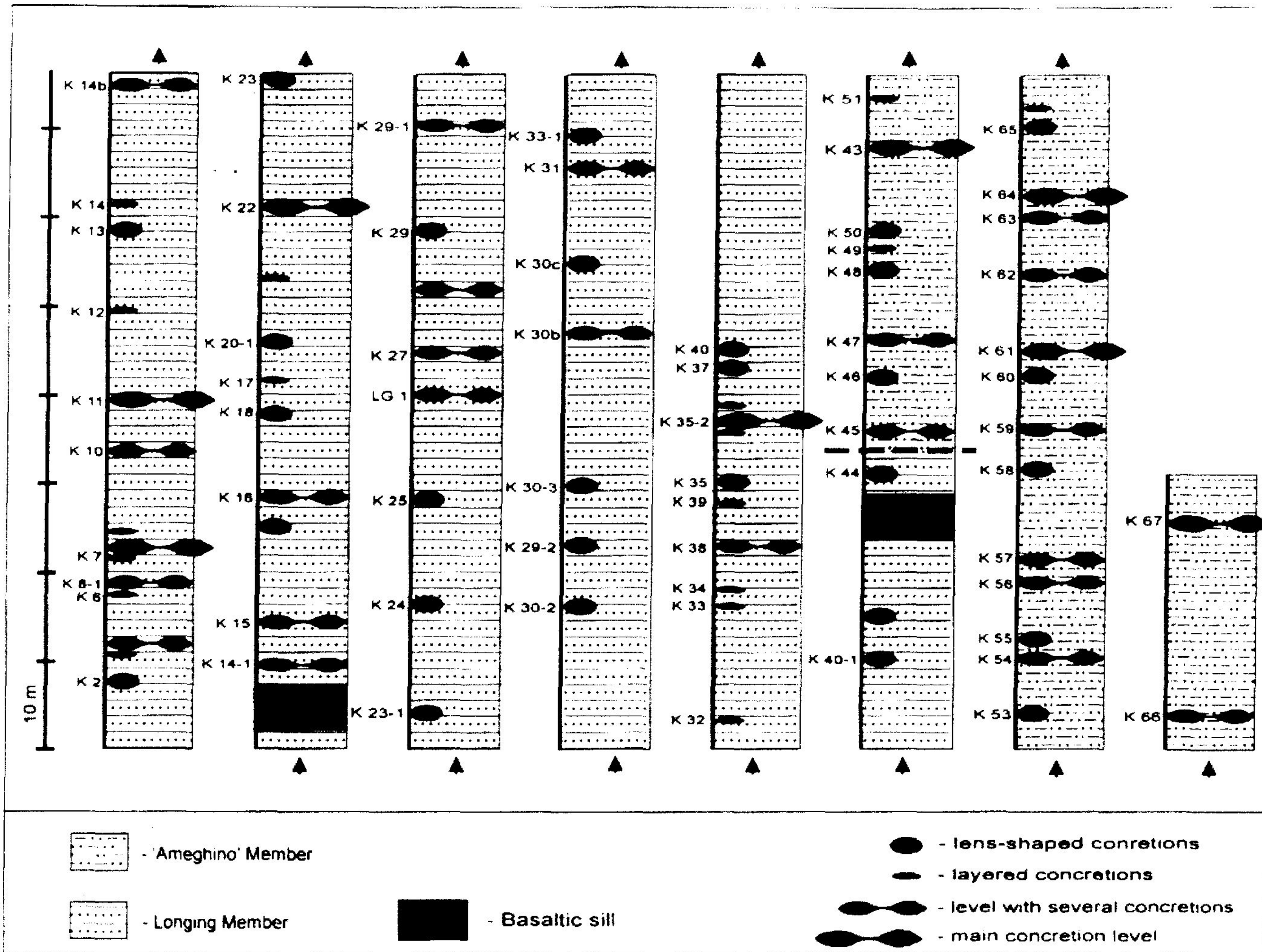
and *Praeparvicingula holdsworthi* are unknown from **Zone 5, Subzone 5A** (Berriasian) strata in the California Coast Ranges (See Grindstone Creek, California Coast Ranges herein).

In the Longing Gap succession Kiessling (1999) recorded the final occurrence of *Complexapora kozuri* at sample horizon K44. Moreover, Kiessling et al. (1999, p. 701) noted the presence of *Parvicingula colemani*, and *P. excelsa* in sample K44 and indicated that this sample is still assignable to **Subzone 4 alpha** (= **Subzone 4 alpha$_2$** herein) and to the upper Tithonian. At nodule horizon K57 Kiessling et al. (1999, p. 712) recovered the ammonite taxon *Blandfordiceras* cf. *weaveri* and indicated that this taxon is correlative with the upper Tithonian. According to these workers *Hsuum mclaughlini* occurs in sample K65. This taxon has not been observed above **Subzone 4 alpha$_2$** in our studies of North America Radiolaria. In the Huayacocotla remnant of the SPG terrane it has been observed in samples MX85-43 and MX84-38 from the area adjacent to the Rio Texcapa power plant near Huachinango, Puebla (See discussion above). Sample 85-43 occurs at the same horizon as locality Af. 1 (**Saurites bituberculatum Zone**) of Cantú-Chapa (1971). Sample MX84-38 occurs 63m above this horizon. The highest occurrence of *Hsuum mclaughlini* elsewhere in Mexico is at Canyon San Matias in our **Subzone 4 alpha$_2$** samples (Text-figure 27). Here it occurs in sample SM96-9, but not in overlying SM94-64 (See discussion above). In the Vizcaino Peninsula (Baja California Sur) *H. mclaughlini* occurs in association with other **Subzone 4 alpha$_2$** Radiolaria, *Buchia piochii* and *Substeueroceras* (See Davila-Alcocer 1986 and Vizcaino Peninsula above).In the California Coast Ranges the Senior Author observed *H. mclaughlini* at Grindstone Creek (Glenn County, California) in sample NSF 945 of Pessagno 1977a) at the top of the **Buchia piochii Zone**.

We correlate the interval in the Longing Gap section above K29 though K33-34 with **Subzone alpha$_1$** and the **Substeuerocas-Proniceras assemblage** of Imlay (1980). The interval above K33-K34 through K44, K47, and K65 is assignable to **Subzone 4 alpha$_2$** and to the upper part of Imlay's **Substeueroceras-Proniceras assemblage**.

PROBLEMS IN CORRELATIONS WITH RADIOLARIAN ZONATION OF BAUMGARTNER ET AL. (1995B) IN THE TITHONIAN AND BERRIASIAN

As noted by Kiessling (1999) and Kiessling et al. (1999), it is difficult to correlate the radiolarian zonation of Baumgartner et



TEXT-FIGURE 54
Detailed columnar section showing nodule-bear horizons at Longing Gap, Graham Island, Antarctic Peninsula. From Kiessling (1999, Text-figure 4).

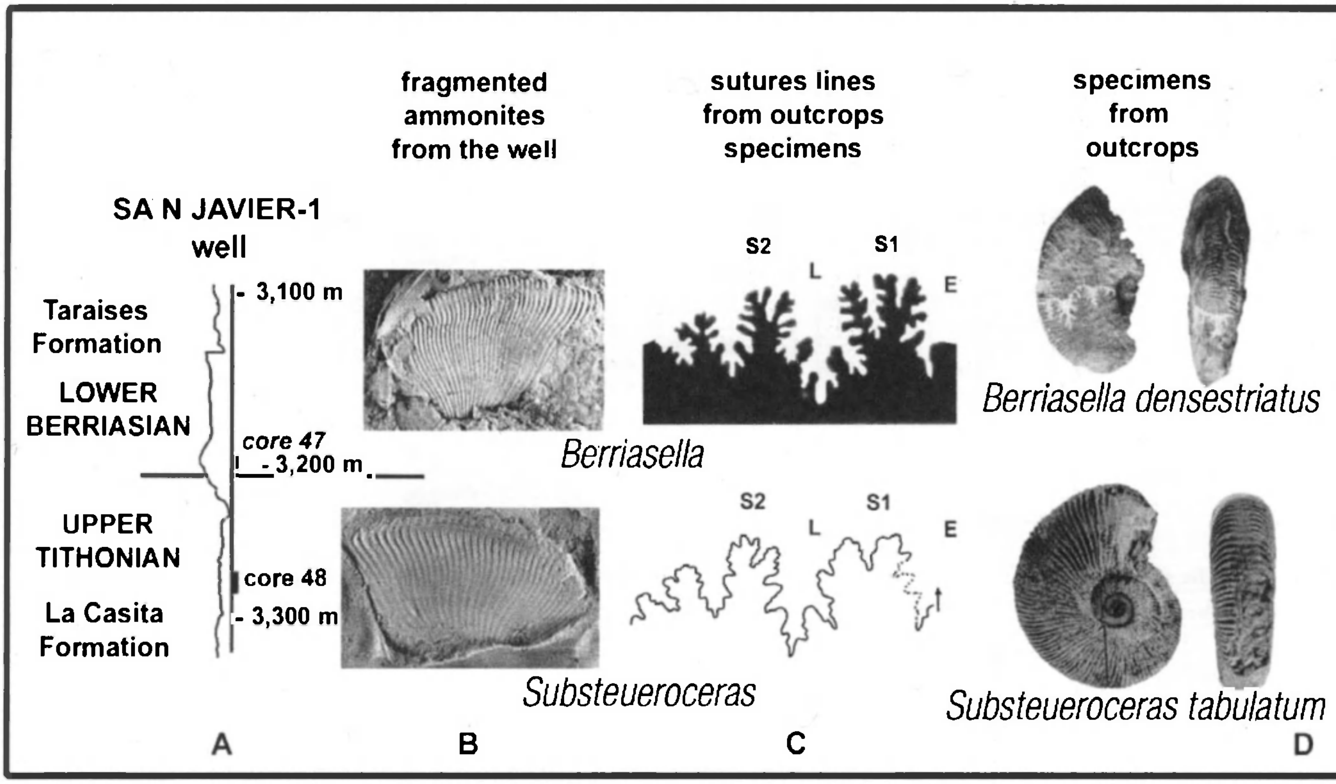
al. (1995a,b) with that proposed by Pessagno et al. (1987, 1993). The same problems occur with the emended and more detailed zonation for the middle Oxfordian to upper Tithonian proposed in the present report (See Text-figures 4, 33 and Appendix 1). These problems are caused by the Central Tethyan nature of the faunas studied by Baumgartner et al., by the over lumping of taxa, and by ignoring taxa (e.g., Pantanelliidae Pessagno and Blome, species of *Perispyridium*) which are used extensively in the Pessagno et al. zonation. These taxa do occur in tethyan ribbon chert successions and are frequently figured by workers from Japan and elsewhere.

Only a few biohorizons can be used to correlate the Baumgartner et al. (1995a, b) zonation with that proposed herein.

First occurrence of *Obesacapsula polyedra* (5565 of Baumgartner et al. 1995a: UAZ 13-17)

According to Baumgartner et al. *Obesacapsula polyhedra* makes its first appearance at the base of UAZ 13 ("late Tithonian"). In the California Coast Ranges this taxon first appears in sample Grin94-37 in the upper part of the **Buchia uncitoides Zone** and in the upper part of radiolarian **Subzone 5A**. In addition, this horizon occurs 5m below sample GC665 where Bralower et al. (1989) recovered a calcareous nannofossils assemblage assignable to nannofossils zone

NK1 (Nannoconus steinmanni s.s. Zone): upper Berriasian (See California Coast Ranges, Grindstone Creek herein). Moreover, Bralower et al. (1990) were able to obtain a U-Pb date of 137.1 +1.6/-0.6ma from zircon in a tuff horizon 38m above sample GC665 and 1cm below a horizon containing a **Zone NK2, Subzone 2A** nannofossil assemblage. Associated with *Obesacapsula polyedra* in our sample Grin94-37 are other UAZ species including *Ristola cretacea,* (3165) and *Pseudodictyomitra carpatica* (3293) which have UAZ ranges of 12-17 and 11-17 respectively. It also should be noted that an ammonite was identified as *Spiticeras* s.s. in sample Grin94-20 at the apparent base of **Subzone 5A**. There is virtually no evidence from our North American studies that *Obesacapsula polyedra, Ristola cretacea,* and *Pseudodictyomitra carpatica* occur in the Tithonian.



TEXT-FIGURE 55
Comparison of two fragmented ammonites from the San Javier-l well, Northern Mexico, and the relationships between the ventral ribbing and the suture lines of *Berriasella* and *Substeueroceras*.
A. SP well log; B. The fragmented berriasellids differ by their ribbing at the ventral region, and C. by the suture lines as shown in S1. D. Specimens from Mexican outcrops; modified from Cantu-Chapa (2006).
Plates 1-2: Radiolaria from the La Caja Formation, San Pedro del Gallo, Durango, Mexico.
Plates 3-6: Radiolaria recovered from units E, D, C, and B of the La Caja Formation in Mazapil remnant of San Pedro del Gallo terrane at Canyon San Matias, Zacatecas, Mexico.
del Gallo terrane.
Plate 7: Radiolaria from La Desirade.
Plate 8: Ammonites recovered from lithostratigraphic units exposed in Mazapil remnant of San Pedro del Gallo terrane at Canyon San Matias, Zacatecas, Mexico.

First occurrence of *Alievium helenae* (3228) of Baumgartner et al. (1995a,b): UAZ 11-22

The first appearance of *Alievium* is important because it also marks the first occurrence of an important Cretaceous family, the Pseudaulophacidae. Although we agree that this is an Upper Jurassic event, data from San Pedro del Gallo indicate that this event is a lower upper Tithonian event rather than an upper Kimmeridigian/ lower Tithonian event as suggested by Baumgartner et al. At San Pedro del Gallo *Alievium* occurs at locality SPG94-48 in **Subzone 4 beta**, close to the type locality of *Durangites* Burckhardt (1912) [See Text-figures 4, 15, 33. San Pedro del Gallo Chert Member of the La Caja Formation herein].

Final appearance of *Perispyridium "ordinarium* gr." (3108 of Baumgartner et al. 1995a: UAZ 5-11)

This event is important in the zonation used herein because *Perispyridium* spp. is a primary taxon for marking the top of **Subzone 4 beta**,. Abundant evidence from North America indicate that this is an upper Tithonian event occurring at the top of **Subzone 4 beta**, (See Huayacocotla Remnant of the SPG terrane, Taman-Tamazunchale area herein). Our data indicate the top of **Subzone 4 beta**, occurs in the lower upper Tithonian and corresponds to the boundary between the **Kossmatia-Durangites assemblage** and the **Substeueroceras-Proniceras assemblage of** Imlay (1980).

Final appearance of "*Pseudodictyomitra" primitiva* [= *Loopus primitivus* herein] (3189 of Baumgartner et al. 1995a: UAZ 7-12)

Based on the North American data the final appearance of *Loopus primitivus* occurs in the upper Tithonian at or near the top of **Subzone 4 alpha**,. To date, this horizon has not been recognized in the California Coast Ranges at Stanley Mountain, Grindstone Creek, and at other localities. In Mexico *Loopus primitivus* has been recognized only at Canyon San Matias (See Text-figures 15, 16, 27, 43 herein and Yang 1993). Matsuoka (1992) recorded this taxon above the last occurrence of *Vallupus* and concurring with the first occurrence of *Pseudodictyomitra carpatica* at ODP Site 801 (Sample 129, 20R-1, 7-9). Accordingly, the Jurassic-

Cretaceous boundary as presently drawn would occur between Sample 129, 20R-1: 7-9 and sample 129, 19R: CC.

Final appearance of ***Eucyrtidiellum ptyctum* (3017 of Baumgartner et al. 1995a: UAZ 5-11)**

In the revised zonation presented herein *Eucyrtidiellum ptyctum* is a corporeal taxon that makes its final appearance within **Subzone 4 alpha$_2$**. Data from Baja California Sur (Davila-Alconer 1986) indicate that this taxon occurs in **Subzone 4 alpha$_2$** and is associated with *Buchia piochii, B. elderensis,* and *Substeueroceras* spp. The megafossil assemblage is correlative with the **Buchia piochii Zone** (Jones et al. 1969) and the **Substeueroceras-Proniceras assemblage** of Imlay (1980) [upper Tithonian]. In contrast, Baumgartner et al. (1995a, b) indicated that *E. ptyctum* makes its final appearance in the lower Tithonian.

The failure to use the pantanelliid genus *Vallupus* in the Baumgartner et al. (1995a, b) zonation makes correlation with the Western Hemisphere (North America, Central America, South America, and the Antarctic Peninsula) difficult. However, Kiessling et al. (1999, p. 708) stated "The stratigraphic correlation of the correlation of the North American zones with the UAZ can be controlled by new data from Europe (Kiessling 1995; Chiari, et al. 1997, Zügel 1997). *V. hopsoni* was reported from UAZ 10 (Chiari, et al. 1997) to UAZ 12-13 (Zügel 1997, cf. Kiessling 1995, 1996). Two samples from the Southern Alps contain *Vallupus hopsoni* and lack *Perispyridium* and thus, can be assigned to the base of **Subzone 4 alpha (= Subzone 4 alpha$_1$)**". Kiessling et al. (1999) concluded that the range of *Vallupus hopsoni* in the Baumgartner et al. zonation is UAZ 10 to UAZ 12. The Mexican data from Taman (San Luis Potosí: Text-figures 31-32) indicates that *Vallupus* spp. first occurs in the uppermost part of the **Virgatosphinctes mexicanus-Aulacomyella neogeae Zone** (lower Tithonian) 6m below the contact with the **Mazapilites Zone** of Cantú-Chapa (1971). Hence, we place the base of UAZ 10 in the upper part of the lower Tithonian. The data presented above indicates that UAZ12 is correlative with the upper Tithonian **Subzone 4 alpha$_1$** and **Subzone 4 alpha$_2$**. The top of UAZ11 appears to be more or less equivalent to the top of **Subzone 4 beta$_2$** and, accordingly, to the top of the **Kossmatia-Durangites assemblage** of Imlay (1980). At La Désirade (Caribbean region: Lesser Antilles) the top of **Subzone 4 beta$_2$** is dated at 143.734ma ± 0.060ma [0,042] (U-Pb on zircon from trondhjemite. See La Désirade herein).

The first appearance of *Obesacapsula polyedra* (Event 1 above) seems to be the strongest link between the base of UAZ 12 and the upper part of **Subzone 5A**. The North American calcareous nannofossil, ammonite, and *Buchia* data from the Grindstone Creek section in the California Coast Ranges indicate that the base of UAZ 13 should be assigned to the upper Berriasian. As noted above, the first occurrence of *O. polyedra* can be related to the U-Pb date of 137.1 +1.6/-0.6ma (zircon from tuff). Pálfy et al. (2000, p. 941) suggest that the dated horizons represent CM16-CM15 magnetochrons within the upper Berriasian.

GEOCHRONOLOGY

Three horizons can be utilized for placing the Jurassic-Cretaceous boundary:

1. At the traditional horizon at the base of the Berriasian;

2. At the base of the **Substeueroceras-Proniceras assemblage** of Imlay and new radiolarian **Subzone 4 alpha$_1$**;

3. At the current base of the Valanginian stage.

As noted by Mattinson et. (2008, p. 187), the absolute age of the traditional Jurassic-Cretaceous boundary (1 above) is poorly constrained geochronometrically. These workers stated that "—Recent versions of the time scale place it at 144 ± 5 Ma (Palmer and Geissman 1999), or 142 +2.5/-1.8 Ma (Palfy et al. 2000), or 145.5 ± 4.0 Ma (Gradstein et al. (2004).—" The new accurate biostratigraphic data and U-Pb geochronometric data from La Désirade coupled with new and existing biostratigraphic U-Pb geochronometric data from Grindstone Creek in northern California allow us to provide a more accurate age for the traditional Jurassic-Cretaceous boundary (excludes calpionellid zones in its definition). This age agrees closely with that of Palfy et al. (2000). Moreover, it can be related to changes in the evolution of the ammonites that have been overlooked by European ammonite workers. Coauthor Cantú-Chapa (2006) carefully examined the relationship between ventral ribbing and suture lines of *Substeueroceras* and *Berriasella* of specimens from Northern Mexico at the conventional Jurassic-Cretaceous boundary. He determined that the two berriasellid genera differ by virtue of their ribbing and by their S1 sutures (See Text-figure 55 herein).

If alternative horizon 2 above is chosen, the new biostratigraphic and interrelated U-Pb geochronometric data from La Désirade (Mattinson et al. 2008; see La Désirade herein) can be utilized. At La Désirade we obtained a U-Pb date of 143.734ma ± 0.060Ma (0.042%) for the uppermost part of **Subzone beta$_2$**. Moreover, we have established that this horizon is correlative with the interval containing *Salinites grossicostatum* in Mexico and Cuba and occurs just below the base of Imlay's (1980) **Substeuerocas-Proniceras assemblage** at San Pedro del Gallo (Durango).

If alternative horizon 3 above (i.e. base of Valanginian) is chosen for the Jurassic-Cretaceous boundary, existing and new biostratigraphic, chronostratigraphic, and U-Pb data from Grindstone Creek in northern California can be utilized. Bralower et al. (1990) obtained U-PB of 137.1 +1.6/-0.6ma from zircon in two tuff horizons in the lower upper Berriasian. Both dated horizons occur in calcareous nannofossil **Subzone 2A** and in the upper part of radiolarian **Subzone 5A** herein.

SUMMARY AND CONCLUSIONS

1. Most system boundaries are characterized by marked faunal change. In the Mesozoic, for example, catastrophic change occurs at both the Triassic-Jurassic boundary and the Cretaceous-Tertiary boundaries. In stark contrast faunal and flora change at the Jurassic-Cretaceous boundary is almost imperceptible with the ammonites, Radiolaria, and other fossil groups. Because of this problem Newell (1966, p 71) went as far as to suggest that the Jurassic and Cretaceous be combined in a single supersystem.

2. The Berriasian stratotype at Berrias in Southern France has a "floating base". The basal strata of the stratotype lack ammonites; overlying strata are assignable to the **Euxinus Zone**.

3. After considerable debate as to what to call the terminal stage of the Jurassic (Portlandian, Volgian, Tithonian), the International Subcommision on Jurassic Stratigraphy (ISJS: September, 1990) selected the Tithonian. Unfortunately, when Oppel (1865, p. 535) established the Tithonian stage for marine strata in Southern Europe, he failed to select a stratotype.

4. Ammonite standard zones have traditionally been used to define stages. However, in the European type area correlation

between the Boreal and Tethyan realms is difficult because of ammonite provincialism.

5. In Western North America the gradual tectonic transport of geologic terranes northward or southward along megashears, analogous to the present-day San Andreas Fault system, has resulted faunas and floras that are transitional between the Tethyan and Boreal realms (e.g., Longoria 1984, 1985a, 1985b, 1986, 1987, 1994; Pessagno and Blome 1986; Pessagno et al. 1999). As a result of this gift from plate tectonics, there are a number of taxa among the ammonites, Radiolaria, calcareous nannoplankton, and other fossil groups that bridge faunal realm boundaries. Many of these same taxa (e.g., the ammonite *Durangites*) are restricted to the Tethyan or Boreal realms in Europe.

6. The lack of significant change in the ammonite assemblage at the Jurassic-Cretaceous boundary led ammonite biostratigraphers to utilize the base of **calpionellid Zone B** (Le Hégarat and Remane 1968) to mark the base of the Cretaceous (See Colloque sur la limite Jurassique-Cretacé de Lyon-Neuchâtel 1973; Geyssant 1997, p. 97). Our investigations clearly demonstrate that the calpionellid zones of Remane (1969, 1978, 1985) can not be used in correlation between Europe and North America. Moreover, their local use in Europe is highly suspect.

7. In east-central Mexico near Taman (San Luis Potosí) Pessagno et al. (1984, 1987a) used the base of the **Crassicollaria Zone (Zone A),** representing the first occurrence of hyaline calpionellids, to mark the base of the upper Tithonian . This unfortunate choice by Pessagno et al. resulted in including the **Virgatosphinctes mexicanus-Aulacomyella neogeae** and **Mazapilites zones** of Cantú-Chapa (1971) in the upper Tithonian. In addition, this decision resulted in placing the base of radiolarian Zone 4 in the upper Tithonian as well (See Huayacocotla remnant of the SPG terrane, Taman-Tamazunchale area herein). Given the fact that ammonite workers regard these ammonite zones as lower Tithonian, it is apparent that the base of the **Crassicollaria Zone (Zone A)** is diachronous between Europe and North America.

8. Cantú-Chapa (1967) was the first to demonstrate that allegedly Berriasian calpionellids occur along with upper Tithonian ammonites in the Pimienta Formation at Mazatepec, Puebla, Mexico (See Mazatepec, in Huayacocotla remnant of the SPG terrane herein). In a series of reports Cantú-Chapa (1976, 1982, 1989, 1992, 1999, 2006) presented subsurface data from a study of cores from over 1000 subsurface localities that indicated alleged Berriasian calpionellids are associated with upper Tithonian ammonites in the Pimienta Formation s.s (Re-defined herein) [See Huayacocotla remnant of the SPG terrane, Poza Rica district herein].

9. At Cerro de La Peña 10k north of San Pedro del Gallo Mexico (Text-figure 7) Remane in Addate et al. (1995, p. 52, fig. 8) assigned all of the Cerro Panteon Member of the La Caja Formation [= his La Casita Formation] to **calpionellid Zone C** (Lower Cretaceous: middle Berriasian) and to **Zone D, Subzone $\mathbf{D_1}$** (upper Berriasian) [See San Pedro del Gallo remnant of the SPG terrane herein]. Radiolarian biostratigraphic data from the Cerro de La Peña locality indicate that all but the uppermost part of the Cerro Panteon Member is assignable to **Subzone 4 $\mathbf{alpha_1}$** and **Subzone 4 $\mathbf{alpha_2}$** (upper Tithonian). Ammonites from this locality as well as those in Cerro Panteon strata near San Pedro del Gallo are assignable to the **Substeueroceras-Proniceras assemblage** of Imlay (1980) and to the **Parodontoceras aff. calistoides Zone** of Cantú-Chapa (1971) [See San Pedro del Gallo remnant of SPG terrane for more detailed discussion herein].

10. At San Pedro del Gallo Remane recorded *Calpionelopsis oblonga* (upper Berriasian to lower Valanginian) from sample SPG94-48 and stressed that the typically Valanginian species *Calpionella darderi* was absent (Report to senior author from Dr. J. Remane: August 24, 1994. Dr. Remane was one of several collaborators on a National Science Grant to study the Jurassic-Cretaceous boundary in North America. See Appendix 2 herein}. Sample SPG94-48 occurs in the uppermost part of the San Pedro del Gallo Chert Member of the La Caja Formation and is situated on the northwest side of the village. This horizon occurs in the upper part of the **Kossmatia-Durangites assemblage** of Imlay (1980) and the **Proniceras-Kossmatia Zone** of Contreras

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PLATE 1

All illustrations are scanning electron micrographs of Upper Jurassic (upper Tithonian) Radiolaria from the San Pedro del Gallo Chert Member of the La Caja Formation, San Pedro del Gallo, Durango, Mexico. Photos modified from those of Meng (1997).
Scale in upper right = number of μm cited for each illustration.

1,2 *Pantanellium cantuchapai* Pessagno and MacLeod. Locality SPA-23. Scales = 96 90μm respectively.

3,4,5 *Pantanellium whalenae* Pessagno and MacLeod. Figured specimens from localities SPG-13B. SPA-7, SPG94-9 respectively. Scales = 171, 120, 120μm respectively.

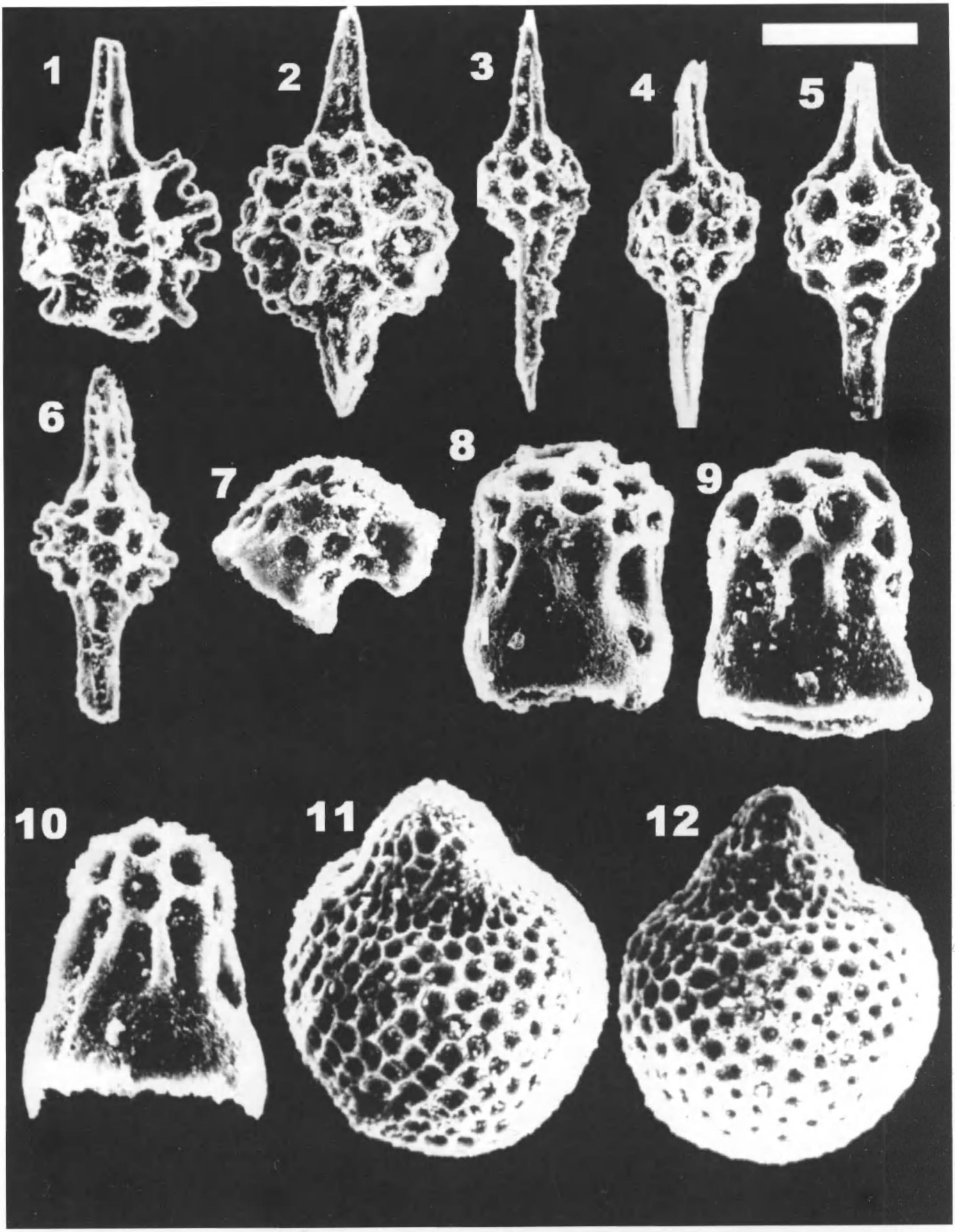
6 *Pantanellium meraceibaense* Pessagno and MacLeod. Figured specimen from SPA-7. Scale = 120μm.

7 *Bivallupus longoriai* Pessagno and MacLeod. Figured specimen from SPG-15A. Scale = 100μm.

8 *Neovallupus* sp. A Figured specimen from SPG-15A. Scale = 74μm.

9, 10 *Vallupus hopsoni* Pessagno and Blome. Figured specimens from localities SPG-15A and SPA-7 respectively. Scales = 71, 71μm respectively.

11, 12 *Complexipora kozuri* Hull. Figured specimens from localities SPA-18 and SPA-23 respectively. Scales = 60, 56μm respectively.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Montero et al. (1988) [See data from Imlay (1939) from Burckhardt (1910, 1912: Locality 23. Text-figure 12 herein]. Radiolaria from sample SPG94-48 are assigned to **Subzone 4 beta$_2$** (lower upper Tithonian. Text-figures 4, 32-33 herein).

11. At Loma Rinconada in the Sierra Cruillas (Text-figure 29) Bonet (1956, p. 82) recorded the following upper Berriasian to Valanginian species from his localities 44, 45, and 48: *Calpionella alpina, C. elliptica,* and *Calpionellopsis oblonga.* The calpionellid-bearing sample horizons occur below beds containing ammonites assignable to Imlay's (1980) lower upper Tithonian **Kossmatia-Durangites assemblage** (See Sierra Cruillas remnant of SPG terrane herein: Table 1). The 143.7ma date (zircon from trondhjemite basement) on upper **Subzone 4 beta$_2$** radiolarian bearing strata at La Désirade (West Indies: Lesser Antilles) and the 137.1ma (U-Pb date: Zircon from tuff) at Grindstone Creek (California Coast Ranges) on upper Subzone 5A faunas independently constrain the calpionellid faunas in Mexico (See La Désirade herein; Bralower et al. 1999; Pálfy et al. 2000).

12. It is apparent that the use of the Remane (1985) calpionellid zonation in the correlation of Upper Jurassic and Lower Cretaceous strata between Europe and North America has greatly hindered the resolution of the Jurassic-Cretaceous boundary problem. However, it is also important to emphasize that calpionellids like all planktonic microfossils, have great biostratigraphic and chronostratigraphic potential. It is unfortunate that the Remane (1985) zonation is based mostly on the abundance of taxa rather than the first and last occurrence of taxa or on unitary associations (Geux 1987).

13. At Taman (San Luis Potosí, Mexico) the base of **Zone 4, Subzone 4 beta$_1$** occurs in the uppermost part of the **Virgatosphinctes mexicana-Aulacomyella neogeae Zone** of Cantú-Chapa (1971) 6m below the contact with the **Mazapilites Zone**. It should be noted that in Argentina Pujana (1999) found a **Zone 4, Subzone 4 beta (= Subzone 4 beta$_1$** herein) in strata assignable to the lower Tithonian **Pseudolissoceras zitteli Zone**. On the basis of the ammonite data we assign this horizon to the lower upper Tithonian. The base of **Zone 4** can be recognized at Canyon San Matias (Zacatecas, Mexico), at Stanley Mountain (San Louis Obispo County, California), at Cuesta Ridge (San Luis Obispo County: Muñoz 1993), in the Neuquén Basin (Argentina. Pujana 1999), and in the Antarctic Peninsula (Kiessling 1999; Kiessling et al. 1999).

14. **Subzone 4 beta$_1$** (upper lower Tithonian) is missing at San Pedro del Gallo (Durango) due to a probable disconformity and hiatus. At Canyon San Matias (Zacatecas) this interval represents part of the phosphate-bearing interval noted by Burckhardt (1930) and by Cross and Pessagno (2006).

15. Subzone 4 beta$_2$ is marked at its base by the first occurrence of primary marker taxon *Complexipora kozuri* and at its top by the final occurrence of primary marker taxon *Perispyridium* spp. (Text-figures 4, 33). Corporeal taxon, *Neovallupus* occurs in the upper part of the subzone. The base of **Subzone 4 beta$_2$** is best documented by the first occurrence of *C. kozuri* at the beginning of the *Kossmatia* beds at Canyon San Matias near Mazapil (Zacatecas, Mexico. See Mazapil remnant of the SPG terrane above). At San Pedro del Gallo (Durango, Mexico) the base of **Subzone 4 beta$_2$** is not exposed. However, **Subzone 4 beta$_2$** strata contain species of *Kossmatia* and *Durangites* in the upper part of the San Pedro del Gallo Chert Member of the La Caja Formation near Burckhardt (1910, 1912) Locality 23 (See San Pedro del Gallo remnant of the SPG terrane and Text-figures 7, 12 herein). Corporeal taxon *Neovallupus* is best represented in the Barrio Guadalupe Member of the Taman Formation at Taman (San Luis Potosí, Mexico: Text-figures 7, 29, 30). Here, its range closely corresponds to that of *Salinites grossicostatum* in the lower part of the upper Tithonian (Text-figure 33). At Canyon San Matias *Neovallupus* occurs along with *Perispyridium* and *Kossmatia* near the top of **Subzone 4 beta$_2$** immediately above the interval with phosphatic limestone, radiolarian chert and shale (See Burckhardt 1930; Cross and Pessagno 2006). In the La Caja Formation at San Pedro del Gallo (Text-figure 7), *Neovallupus* occurs 1m below the top of the San Pedro del Gallo Chert member of the La Caja Formation and its contact with the overlying Puerto del Cielo Shale Member. This horizon is in the upper part of **Subzone 4 beta$_2$** and in the **Kossmatia-Durangites Zone** of Imlay (1980). At Graham Island (Longing Gap) in the Antarctic Peninsula Kiessling et al. (1999) recorded the presence of *Neovallupus* in

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PLATE 2

All illustrations are scanning electron micrographs of Upper Jurassic (upper Tithonian) Radiolaria from the San Pedro del Gallo Chert Member of the La Caja Formation, San Pedro del Gallo, Durango, Mexico. Photos modified from those of Meng (1997). Scale in upper right = number of µm cited for each illustration.

1, 2 *Mita weddelliensis* Kiessling. Figured specimens from localities SPG92-13B and SPA94-15. Scale = 42 and 60μm respectively.3, 4, 5 *Loopus campbelli* Yang. Figured specimens from localities SPG92-23, SPG94-48, SPG92-33 respectively. Scales = 100, 100, 100µm respectively.

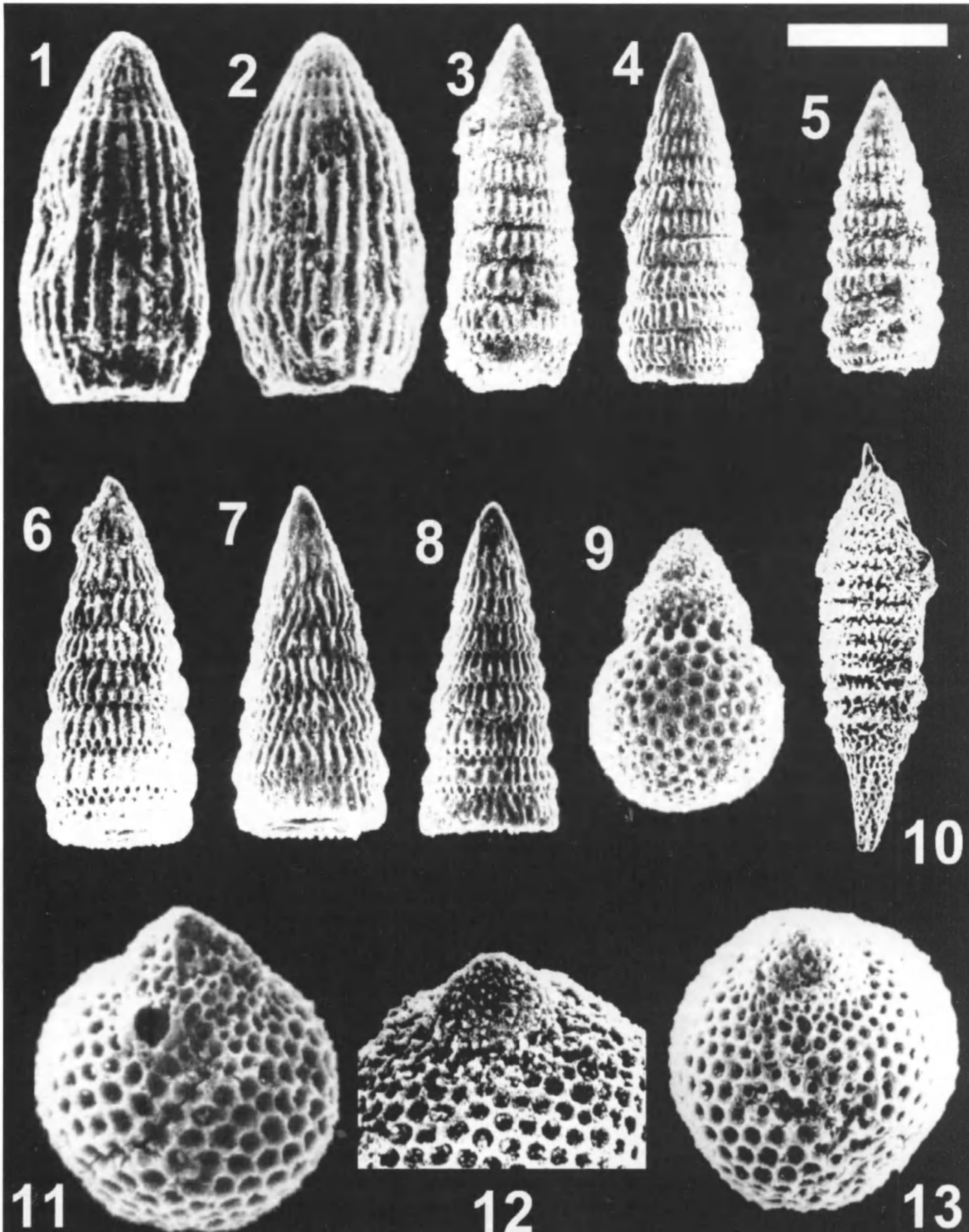
6,7,8, *Loopus primitivus* (Matsuoka and Yao). Specimens from locality SPG-15A, SPG-1, SPG-15A, SPG92-33. Scales = 72µm.

9 *Complexipora nova* Hull. Figured specimen from SPG-15A. Scale = 63µm.

10 *Parvicingula* sp. Figured specimen from SPA-1. Scales = 263, 143, 143µm respectively.

11 *Complexipora kozuri* Hull. Figured specimen from SPA-23. Scale = 100µm.

12,13 *Complexipora* sp. A Figured specimens from SPA-23. See illustrations of this form from Canyon San Matias (Plate 6, figure 10). Scales = 90, 63µm.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the Ameghino Formation in association with *Vallupus nodosus* and the ammonite *Subplaitoides* cf. *oppeli*.

16. The top of **Subzone 4 beta$_2$** can be best seen at San Pedro del Gallo at Cerro Panteon and the airport runway sections (Text-figures 12, 13, 16). Here the top of **Subzone 4 beta$_2$** occurs at the contact between the Puerto del Cielo Shale Member and the overlying Cerro Panteon Member of the La Caja Formation. Hillebrandt et al. (1992) noted that Locality 24 (Text-figure 12) of Burckhardt (1910, 1912) contains species of *Kossmatia, Proniceras, Microacanthoceras,* and *Durangites* as well as *Salinites grossicostatum*. Our analysis of the stratigraphy of the San Pedro del Gallo area indicates that Locality 24 of Burckhardt occurs in the Puerto del Cielo Shale Member of the La Caja Formation. The top of **Subzone 4 beta$_2$** can also be seen at Canyon San Matias and in the Taman-Tamazunchale area (See above). Moreover, this horizon can be recognized at Longing Gap (Graham Island) on the Antarctic Peninsula. At Longing Gap Kiessling et al. (1999, p. 700) determined that the top of **Subzone 4 beta (= Subzone 4 beta$_2$),** marked by primary marker taxon *Perispyridium*, occurs at Locality K29 in the middle of the Ameghino Formation. They noted that ammonites recovered at localities K29 and K30-1 included *Subplanitoides, Franconites,* and *Kossmatia*.

17. The base of **Subzone 4 alpha$_1$** occurs above the final appearance of primary marker taxon *Perispyridium* and supplementary marker taxa *Pantanellium cantuchapai* and *Vallupus nodosus*. The top of **Subzone 4 alpha$_1$** is defined by the final appearance of *Vallupus*. At San Pedro del Gallo the ~ base of and the top of **Subzone 4 alpha$_1$** occurs in the Cerro Panteon Member of the La Caja Formation at Cerro de La Peña 10k north of San Pedro del Gallo. The lower 13m of the Cerro Panteon Member at Cerro de La Peña contains *Substeueroceras, Spiticeras (Negreliceras), Phyloceras, Pteroolytoceras, Vinalesites, Jabronella (Erdenella),* and *Schaireria* (Addate et al. 1995). Our investigations indicate that the final appearance of *Vallupus*, marking the top of **Subzone 4 alpha$_1$** occurs at 23m (See Text-figures 12, 18-21). These studies show that the interval from 24m to 81m is assignable to **Subzone 4 alpha$_2$**. The presence of primary marker taxon *Complexapora kozuri at* 81m marks the apparent top of this biozone. Addate et al. noted the presence of *Himalayites* 5m below the contact between the Cerro Panteon Member (= their La Casita Formation) and the overlying Chapulhuacán Limestone. Contreras-Montero et al. (1988) figured *Durangites, Pseudoargentiniceras,* and *Neocomites* from the Cerro de La Peña locality. At the base of La Serrita near San Pedro del Gallo Imlay (1939, Table 9) recorded the following ammonite taxa from Burckhardt (1910, 1912) Locality 25: *Substeueroceras, Berriasella, Parodontoceras,* and *Proniceras* (See Text-figure 12). Contreras-Montero et al. (1988) recorded *Durangites, Substeueroceras, Berriasella,* and *Pseudosubplanites* from the same area. Elsewhere in Mexico **Subzone 4 alpha$_1$** can be recognized at the Rio Texcapa power plant near Huachinango, Puebla, 61m above a horizon where Cantú-Chapa (1971) recovered ammonites assignable to his **Suarites bituberculaltum Zone**. Here the top of **Subzone 4 alpha$_1$** occurs in the lower Pimienta Formation of Cantú-Chapa (1971) and Imlay (1980) [= Barrio Guadalupe Member of Taman Formation herein]. These data are compatible with those of Kiessling et al. (1999).

PLATE 3

All figures are scanning electron micrographs of Upper Jurassic (Kimmeridgian-Tithonian) Radiolaria from Canyon San Matias, Sierra Santa Rosa near Mazapil, Zacatecas, Mexico. Radiolaria extracted from black radiolarian chert. Scale at upper right = number of µm cited for each illustration.

1, 8 *Pantanellium cantuchapai* Pessagno and MacLeod. Sample locality SM94-14: Subzone 4 beta$_1$; lower Tithonian. Scales = 275, 271µm respectively.

2, 7 *Pantanellium meraceibaense* Pessagno and MacLeod. Sample locality SM94-14: Subzone 4 beta$_1$, lower Tithonian Scales = 299, 301µm respectively.

4 *Pantanellium ranchitoense* Pessagno and MacLeod. Sample locality SM94-16: Subzone 4 beta$_1$, Scale = 214µm.

5 *Teichertus* sp. Sample locality SM94-14: Subzone 4 beta$_1$, lower Tithonian;. Scale = 500 µm.

6 *Archaeocenosphaera* sp. A. Sample locality SM96X-9. Scale = 500µm.

9 *Higumastra* sp. Sample locality SM96X-9: basal La Caja Formation. Subzone 2 alpha$_2$, lower Kimmeridgian. Scale = 156µm.

10 *Praeconocaryomma* sp. SM96X-9: basal La Caja Formation. Subzone 2 alpha$_2$, lower Kimmeridgian. Scale = 500µm.

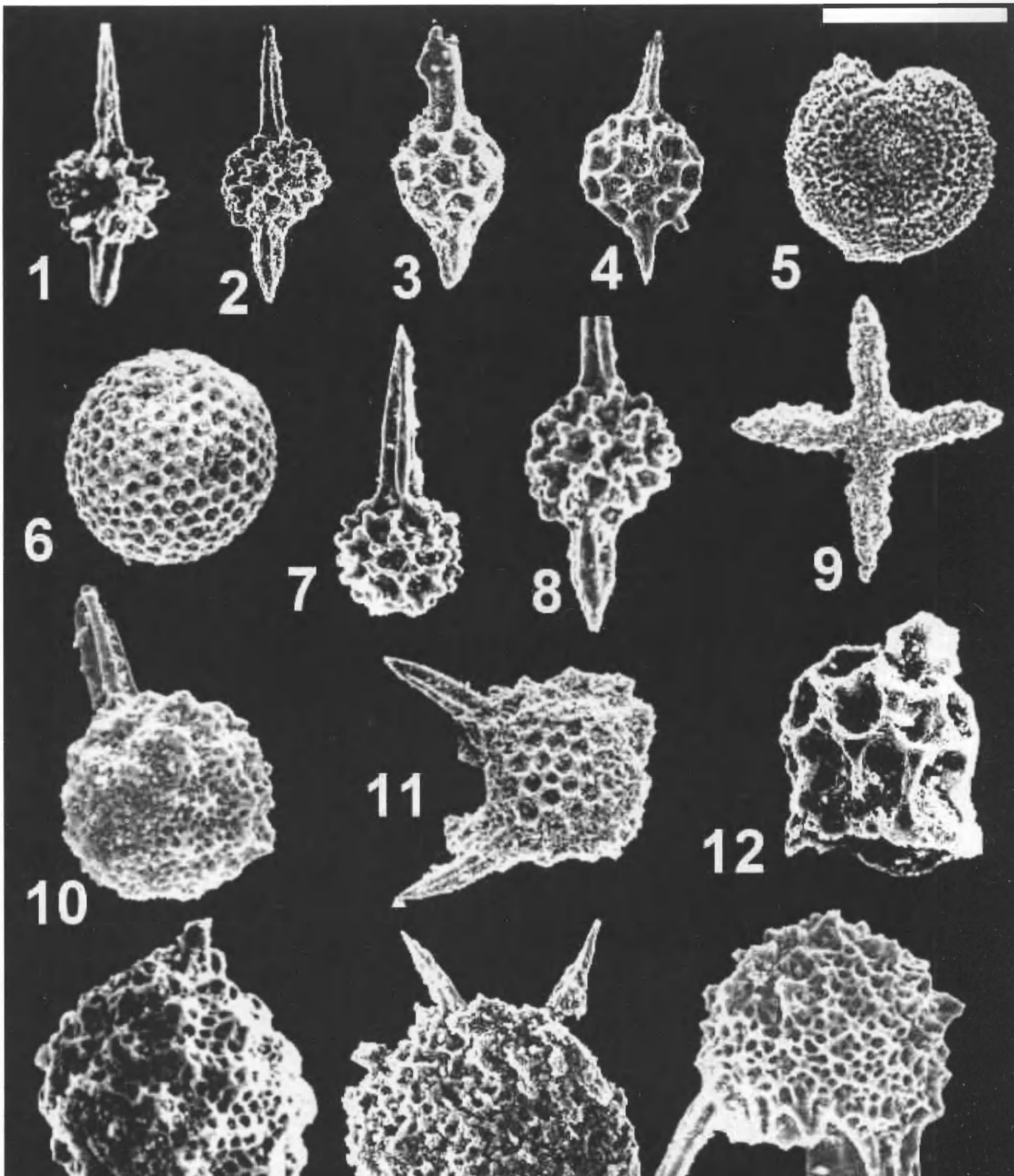
11 *Lanubus* sp. Sample locality SM96X-9: basal La Caja Formation. Subzone 2 alpha$_2$, lower Kimmeridgian. Scale = 150µm.

12 *Vallupus hopsoni* Pessagno and Blome. Sample locality SM94-16: Subzone 4 beta$_1$, lower Tithonian Scale = 100µm.

13 *Acaeniotyle* sp. A. Sample locality SM96X-9: basal La Caja Formation. Subzone 2 alpha$_2$, lower Kimmeridigian. Scale = 300µm.

14 *Bernoullius* sp. aff. *B. irwini* Pessagno, Blome, and Hull. Sample locality SM94-18: Subzone 4 beta$_1$, lower Tithonian. Scale = 333µm.

15 *Phantum inseperatum* Hull. SM94-15: Subzone 4 beta$_1$, lower Tithonian. Scale = 250µm.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18. The Mexican data from San Pedro del Gallo and Baja California Sur indicate that the **Buchia piochii Zone** (Jones et al. 1969) is correlative with **Subzone 4 beta$_2$** (lower upper Tithonian), **Subzone 4 alpha$_1$** (upper Tithonian), and the lower part of **Subzone 4 alpha$_2$** (upper Tithonian). The overlying **Buchia sp. aff. okensis Zone** of Jones et al. is included in the remainder of **Subzone 4 alpha$_2$** and possibly in the lowermost part of **Zone 5, Subzone 5A** (See below).

19. In the California Coast Ranges the top of **Subzone 4 alpha$_2$** is best represented in the strata of the Great Valley Supergroup at Grindstone Creek, Glenn County (Text-figure 43). Here, strata (Grin94-8) containing primary marker taxon *Complexapora kozuri* occur 60m below the base of overlying **Zone 5, Subzone 5A** (Grin94-20A) marked by the first occurrence of primary taxon *Archaeocenosphaera boria*. Sample Grin94-9B from 53m below Grin94-20A contains *Caneta hsui*. The presence of this taxon provides evidence that this horizon is still within the upper part of **Subzone 4 alpha$_2$**. The Jurassic-Cretaceous boundary, as presently defined, occurs somewhere in the interval between sample Grin94-8 (?Grin94-9B) and sample Grin94-20A (See Text-figure 43). This interval occurs in the upper part of the **Buchia sp. aff. okensis Zone** of Jones et al. (1969).

20. Combined biostratigraphic, chronostratigraphic, and geochronometric data from La Désirade (Lesser Antilles), Mexico (San Pedro del Gallo, Durango), Canyon San Matias (near Mazapil, Zacatecas), Taman (San Luis Potosí), indicate that the upper part of **Subzone 4 beta$_2$** (lower upper Tithonian) is 143.734ma ± 0.060ma (0.042%). This interval is equivalent to the upper part of the **Kossmatia-Durangites assemblage** of Imlay (1980) [See Text-figures 33, 34, 51].

21. In various reports Burckhardt (e.g., Burckhardt 1906, 1910, 1912, 1930) was the first to describe many lithostratigraphic units as well as their included fossils in the Jurassic and Cretaceous of Mexico. Burckhardt's descriptions of rock units were always accurate and, for the most part, still can be recognized by stratigraphers today. Burckhardt, however, never formalized the lithounits that he described in his numerous measured sections. Many of these units were subsequently formally named by Imlay (1939). Unfortunately, Imlay failed to note the presence of abundant black chert in the La Caja Formation at its type locality in the Sierra de La Caja (Zacatecas), at Canyon San Matias near Mazapil (Zacatecas), in the Sierra Zuloaga (Zacatecas), and at other localities (Text-figure 7). The presence of black chert is the "trademark" of the La Caja Formation. Our studies indicate that the black chert of this rock unit is a radiolarian chert composed of fifty percent (by volume) of radiolarian tests and originally formed as a radiolarian ooze. The failure to note chert by Imlay in his lithologic descriptions has led to the misidentification of the La Caja Formation throughout Mexico. As a consequence, the La Caja Formation has been frequently confused with the La Casita Formation (Imlay 1939). At San Pedro del Gallo our investigations demonstrate that Imlay (1939), Addate et al. (1995), and Contreras-Montero et al. (1988) included Burckhardt's (1910, 1912) "Capas de San Pedro" in the La Casita and the Taires formations. Our investigations, as well as those of Pessagno et al. (1999), clearly demonstrate that Burckhardt's "Capas de San Pedro" as well as his "Capas limítrofes entre el Jurásico superior y el Cretáceo inferior" should be included in the La Caja Formation.

22. In this report we have subdivided the La Caja Formation at San Pedro del Gallo into four new member units. These are in ascending order: (1) The Cerro El Volcan Shale Member; (2) the San Pedro del Gallo Chert Member; the Puerto del Cielo Shale

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PLATE 4

All figures are scanning electron micrographs of Upper Jurassic (Kimmeridgian-Tithonian) Radiolaria from the La Caja Formation, Canyon San Matias, Sierra Santa Rosa near Mazapil, Zacatecas, Mexico and from the Taman Formation, San Luis Postosí, Mexico. Radiolaria from La Caja Formation extracted from black radiolarian chert. Radiolaria from Taman Formation extracted from medium to dark gray micritic limestone. Scale at upper right = number of µm cited for each illustration.

1, 17 *Mirifusus quadalupensis* Pessagno. Figured specimens from locality MX96X-9: basal La Caja

2, 18 Formation. Subzone 2 alpha$_2$, upper part of lower Kimmeridgian Scales =429, 150, 300, 88µm respectively.

3, 4 *Parvicingula alamoensis* Hull. Sample localities SM94-15 and SM94-14 respectively: La Caja Formation; Subzone 4 beta$_1$, lower Tithonian. Scale = 30, 75µm respectively.

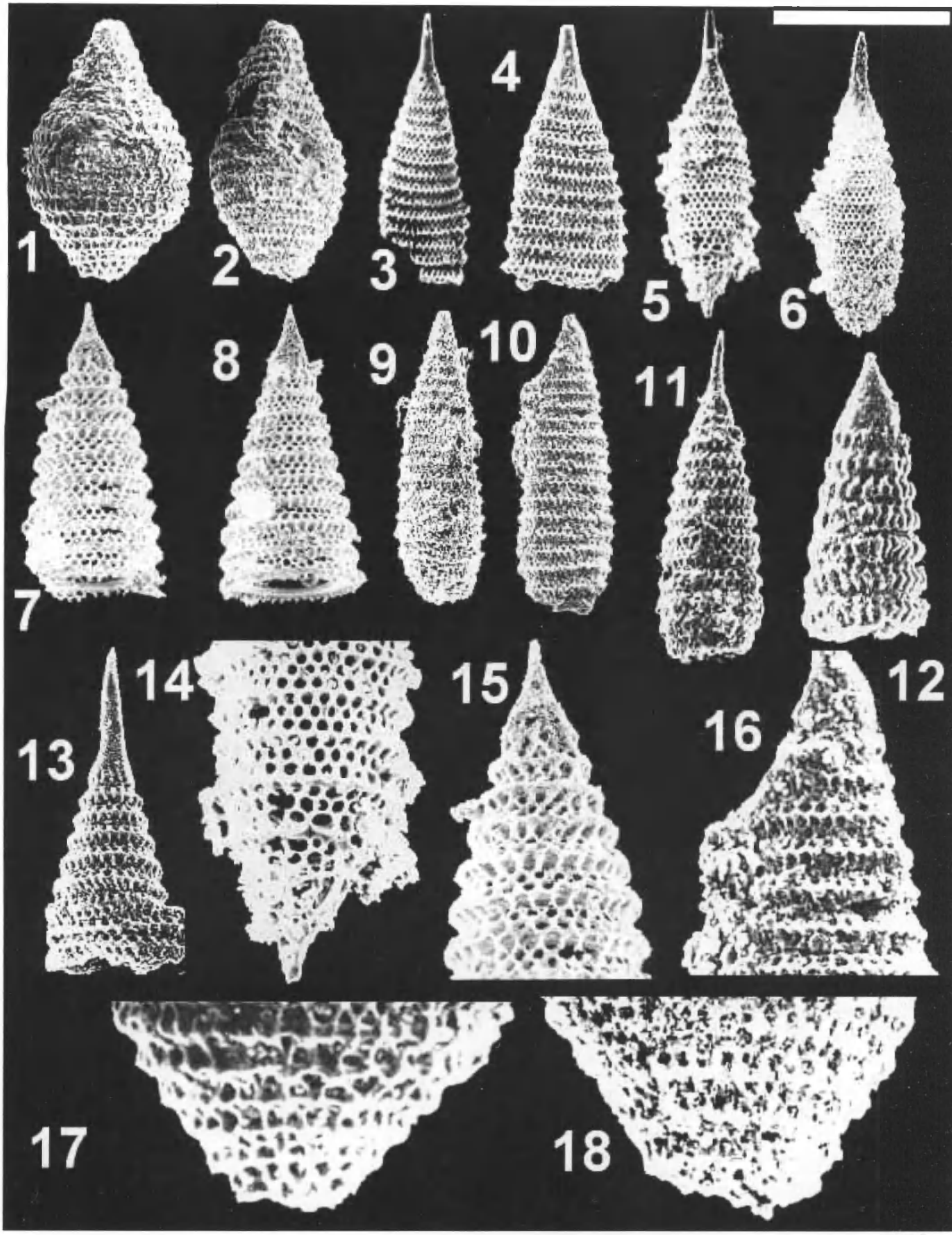
5, 6, 14 *Parvicingula* sp. A. MX82-15: Mera Ceiba Member of Taman Formation, Zone, Subzone 2 alpha$_2$ upper Kimmeridgian. Scales = 300, 90, 231µm respectively.

7, 8 *Parvicingula* sp. B. MX82-8: Barrio Guadalupe Member of Taman Formation, Zone 4, Subzone 4 beta$_1$, lower Tithonian. Scale = 231, 188µm respectively.

9, 10, 16 *Parvicingula* sp. C. MX96X-9: basal La Caja Formation. Subzone 2 alpha$_2$, lower Kimmeridgian. Scales = 300, 150µm respectively.

11, 13 *Praeparvicingula excelsa* Pessagno and Blome. Sample locality SM94-18 and SM94-14 respectively: Subzone 4 beta$_1$, lower Tithonian. Scales = 200, 375µm respectively.

12 *Loopus campbelli* Yang. Sample locality SM94-14: La Caja Formation. Subzone 4 beta$_1$, lower Tithonian. Scale = 150µm.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Member; and (4) the Cerro Panteon Member (See San Pedro del Gallo remnant of the SPG terrane herein). Each of these units corresponds to one of Burckhardt's informal units as well as those of Pessagno et al. (1999).

23. We have also formalized other units, where deemed important, at Canyon San Matias (Zacatecas) and at Taman (San Luis Potosí).

24. At Canyon San Matias reddish-gray weathering sandstone, siltstone, silty limestone, and shale which rest conformably above the Zuloaga Limestone and disconformably beneath the La Caja Formation are included in the San Matias Formation **n. fm.** (See Mazapil remnant of the SPG terrane herein). This unit can also be recognized at San Pedro del Gallo.

25. In the Taman-Tamazunchale area (Huayacocotla remnant of the SPG terrane) Pessagno et al. (1987a) noted that the Pimienta Formation as originally defined by Heim (1926, 1940) had cotype localities along the Rio Moctezuma.: (1) At the village of Pimienta and (2) at Vega Larga (Text-figure 30). Investigations by the senior author indicate that strata at the village of La Pimienta are actually assignable to the Lower Cretaceous (Barremian-Aptian) Ahuancatlín Formation (See Bodenlos 1956), a unit which overlies the Chapulhuacan Limestone. By default, Heim's Vega Larga locality (bed of Rio Moctezuma beneath hanging bridge at Vega Larga) becomes the type locality. As a consequence, the lower Pimienta of Cantú-Chapa (1971) and Imlay (1980), is included in the underlying Barrio Guadalupe Member of the Taman Formation. In the Taman-Tamazunchale area the Pimienta Formation s.s. consists of ~200m of thin-bedded light gray to medium gray often maroon weathering micrite alternating with thin intervals of black shale, black radiolarian chert, and occasional beds of yellowish green vitric tuff.

26. The Taman Formation of Heim (1926, 1940) is formally divided into two new members herein: a lower Mera Ceiba Member and an upper Barrio Guadalupe Member. The Mera Ceiba Member consists of massively bedded petroliferous dark to medium gray micrite and thin beds of shale. This unit contains common dark gray micrite nodules in its upper part. The Barrio Guadalupe Member consists of thin-bedded dark gray micrite with thick layers of shale and abundant dark gray micrite nodules. The Barrio Guadalupe Member differs from the overlying Pimienta Formation s.s. by lacking abundant black radiolarian chert, by having dark to medium gray micrites rather than light gray, very aphanitic micrite, and by lacking beds of green vitric tuff. Abundant calcified, pyritzed, and silicified Radiolaria occur both in the bedded micrites and the micrite nodules. Megafossils are rare at most horizons.

27 The radiolarian biozones developed here for the Tithonian offer a more accurate means of interrelating ammonite biozones between the Boreal, Tethyan, and Austral realms.

PLATE 5

All figures are scanning electron micrographs of Upper Jurassic (Kimmeridgian-Tithonian) Radiolaria from Canyon San Matias, Sierra Santa Rosa near Mazapil, Zacatecas, Mexico. Radiolaria extracted from black radiolarian chert from the La Caja Formation. Scale at upper right = number of µm cited for each illustration.

1 *Hsuum* sp. aff. *H. naturale* Hull. Sample locality SM94-14: Subzone 4 beta$_1$, lower Tithonian. Scale = 299µm.

2 *Pantanellium* sp. aff. *P. heimi* Pessagno and McLeod. Sample locality SM94-14: Subzone 4 beta$_1$, lower Tithonian. Scale = 250µm.

3, 13 *Hsuum* sp. A. Sample locality SM94-16: Subzone 4 beta$_1$, lower Tithonian. Scales = 200, 100µm respectively.

4 *Hsuum cuestaense* Pessagno. Sample locality SM96X-9: Basal La Caja Formation. Subzone 2 alpha$_2$, lower Kimmeridgian. Scale = 200µm.

5 *Hsuum* sp. B. Sample locality SM94-14: Basal La Caja Formation. Subzone 2 alpha$_2$, lower Kimmeridgian. Scale = 200 µm. 188µm.

6 *Pantanellium* sp. aff. *P. cantuchapai* Pessagno and McLeod. Sample locality SM94-14: Subzone 4 beta$_1$, lower Tithonian. Scale = 188µm.

7, 16 *Archaeodictyomitra rigida* Pessagno. Sample locality SM96X-9: Basal La Caja Formation. Subzone 2 alpha$_2$, lower Kimmeridgian. Scales = 194, 60µm.

8 *Caneta* sp. aff. *Caneta hsui* Pessagno. Sample locality SM94-14: Subzone 4beta$_1$, lower Tithonian. Scale = 88µm.

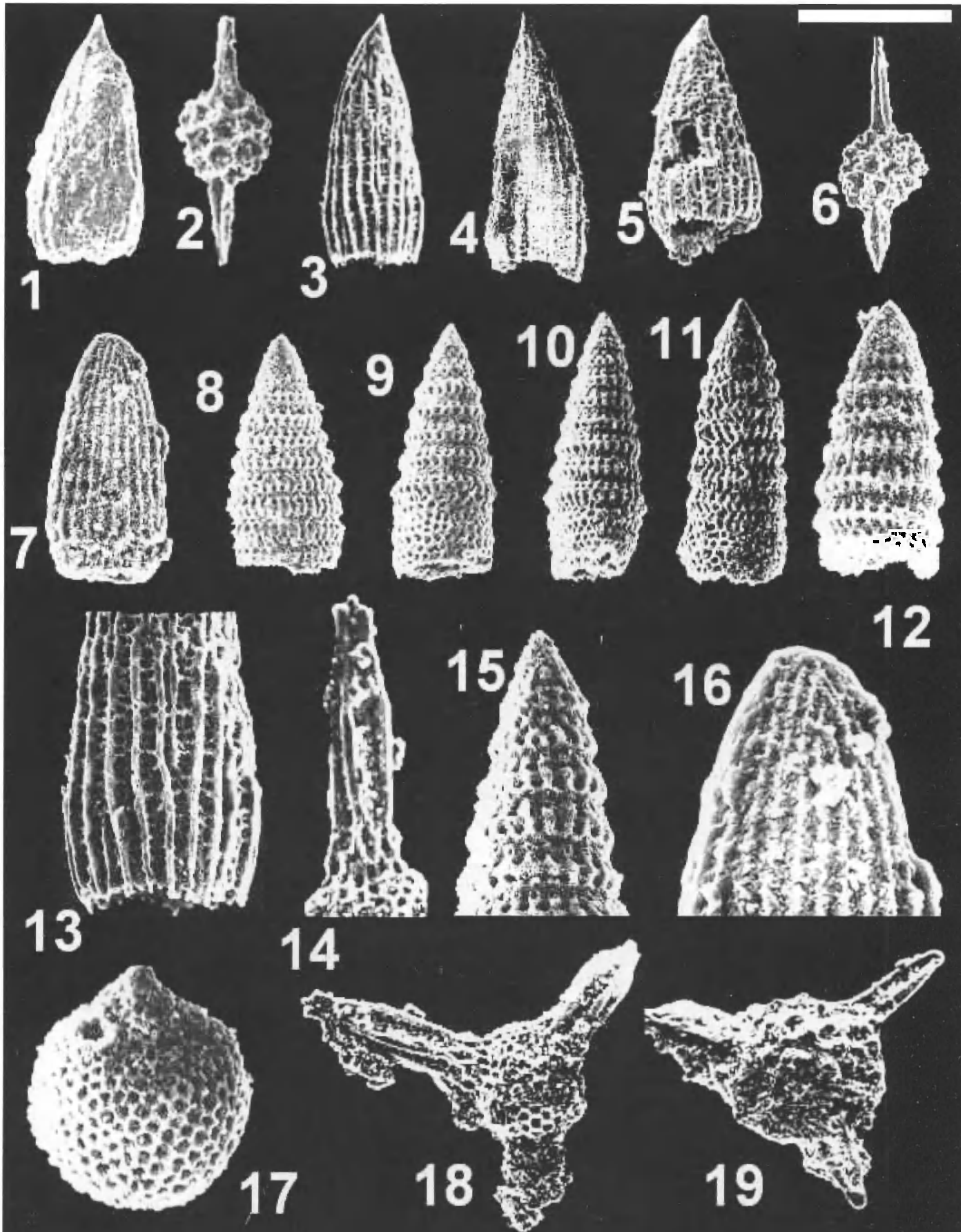
9, 15 *Praecaneta* sp. A. Sample locality SM94-14: Subzone 4beta$_1$, lower Tithonian. Scales = 10, 11188, 106, 158, 143µm respectively.

12 *Praecaneta* sp. cf. *P. decora* Pessagno and Whalen. locality SM96X-9: Basal La Caja Formation.Subzone 2 alpha$_2$, lower Kimmeridgian. Scale = 150µm.

14, 18 *Tripocyclia* sp. Sample locality SM94-18: Subzone 4beta$_1$, lower Tithonian. Scales = 77, 150µm respectively.

17 *Complexipora* sp. A. Sample locality SM94-45: Subzone 4 beta$_2$, upper Tithonian. Scale 100µm.

19 *Acastea* sp. aff. *A. remusa* Hull. Sample locality SM94-15: Subzone 4beta$_1$, lower Tithonian. Scale = 500µm.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28. The lack of faunal and floral change at the present Jurassic-Cretaceous boundary make it difficult to recognize in North America and elsewhere in the world. In North America the top of **Subzone 4 alpha$_2$** can be recognized in the California Coast Ranges at Stanley Mountain, Grindstone Creek, and at other localities. In Mexico it can be recognized at San Pedro del Gallo and possibly at Canyon San Matias. Primary marker taxon *Loopus primitivus* has been recognized at the top of **Subzone 4 alpha$_2$** at Canyon San Matias (See Text-figures 15, 16, 27, 43 herein and Yang 1993). Matsuoka (1992) recorded this taxon in **Subzone 4 alpha$_2$** strata above the last occurrence of *Vallupus* and concurring with the first occurrence of *Pseudodictyomitra carpatica* at ODP Site 801 (Sample 129, 20R-1. 7-9). Accordingly, the traditional Jurassic-Cretaceous boundary as presently drawn would occur between Sample 129, 20R-1: 7-9 and sample 129, 19R: CC.

Two other choices for placing the Jurassic-Cretaceous boundary are suggested:

1. Our studies of uppermost Jurassic and lowermost Cretaceous Radiolaria in the Western Hemisphere indicate that a second horizon to place the Jurassic-Cretaceous boundary is between radiolarian **Subzone 4 beta$_2$** and **Subzone 4 alpha$_1$**. This horizon can be recognized in Mexico (San Pedro del Gallo, Canyon San Matias) and even on the Antarctic Peninsula (Kiessling et al. 1999). A major decline occurs in the Pantanelliidae at the top of **Subzone 4 beta$_2$**. Numerous species among the Pantanelliinae as well as genera and species among Vallupinae become extinct at this horizon (See Pessagno et al. 1987a; Yang and Pessagno 1989. Text-figure 33 herein). Moreover, this zonal boundary corresponds to that between Imlay's **Kossmatia-Durangites assemblage** and **Substeueroceras-Proniceras assemblage**. Because of the U-Pb date of 143.734ma ± 0.060Ma (0.042%) on the upper part of **Subzone beta$_2$** in La Désirade, this candidate for the Jurassic-Cretaceous boundary is very promising. Pálfy et al. (1999) (Table 3, p. 931) place the base of the Tithonian at 150.5ma +3.1/-2.8ma. Accordingly, the length of the Tithonian would be only 6.7ma. The La Caja section at Mazapil as well as those in the Sierra Zuloaga (see Burckhardt 1930-1931) would make excellent sections to establish boundary stratotypes. These strata contain abundant ammonites, bivalves, Radiolaria, and calcareous nannoplankton.

2. Based on the data from North America a second favorable horizon to place the Jurassic-Cretaceous boundary would be between the Berriasian and Valanginian (see Wiedman 1980). This proposal is attractive because of the U-Pb date of 137.1 +1.6/-0.6ma for the upper Berriasian at Grindstone Creek in the California Coast Ranges (Bralower et al. 1990). The two tuff layers from which identical dates were obtained are from the upper part of the **Buchia uncitoides** and the lower part of the **Buchia pacifica Zone** of Jones et al. (1969). Moreover, Bralower et al. were able to assign the two tuff horizons to calcareous nannofossil biozoes **Zone NK2, Subzone 2A (Cretarhabdus angustiforatus Zone, Assipetra infracretacea Subzone)** [upper Berriasian]. Our radiolarian biostratigraphic data from the Grindstone Creek succession indicate that the lower tuff horizon is assignable to the upper part of **Subzone 5A** (upper **Buchia uncitoides Zone**) and upper tuff horizon is assignable to the lower part of **Subzone 5B** (lower **Buchia pacifica Zone).** The Grindstone Creek section in Northern California would be an excellent section to establish a boundary stratotype.

29. The choices cited above for placing the Jurassic-Cretaceous boundary should be considered by both the International Subcommission on Jurassic Stratigraphy and the International Subcommission on Cretaceous Stratigraphy.

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PLATE 6

All figures are scanning electron micrographs of Upper Jurassic (Tithonian) Radiolaria from Canyon San Matias, Sierra Santa Rosa near Mazpil, Zacatecas, Mexico. Scale at upper right = number of μm cited for each illustration.

1-2 *Praeparvicingula colemani* Pessagno and Blome. Sample SM94-18. Subzone 4 beta1, lower Tithonian. Scale = 200µm.

3 *Praeparvicingula holdsworthi* Yang. Sample 94-18. Subzone 4 beta1, lower Tithonian. Scale = 250µm. scale

4 *Praeparvicingula* sp. Sample SM-94-18. Scale = 162 4 beta1, lower Tithonian. Scale = 162µm.

5, 7, 8 *Parvicingula gemmata* (Hull). The presence of a broken narrow tube on the final postabdominal segment indicates that this species should re-assigned from the genus *Praeparvicingula* to the genus *Parvicingula*. In the California Coast Ranges Hull (1993???) indicated that this species occurs in the upper part of Subzone 4 beta (=4 beta$_2$) and in the lower part of Subzone 4 alpha (= 4 alpha$_2$ herein). Sample SM94-45, 4 beta$_2$, upper Tithonian. Scales = 200, 54, 54µm respectively.

6 *Neovallupus* sp. Sample SM94-45, Subzone 4 beta$_2$, upper Tithonian. Scale = 60µm.

9 *Vallupus* sp. Sample SM94-45, Subzone 4 beta$_2$, upper Tithonian. Scale = 15µm.

11 *Complexipora kozuri* Hull. Sample SM94-45, Subzone 4 beta$_2$, upper Tithonian. Scale = 100µm.

10, 12 *Complexipora* sp. A. Specimens from SM 94-45: Subzone 4 beta$_2$, upper Tithonian. Scale = 100 and 150µm respectively.

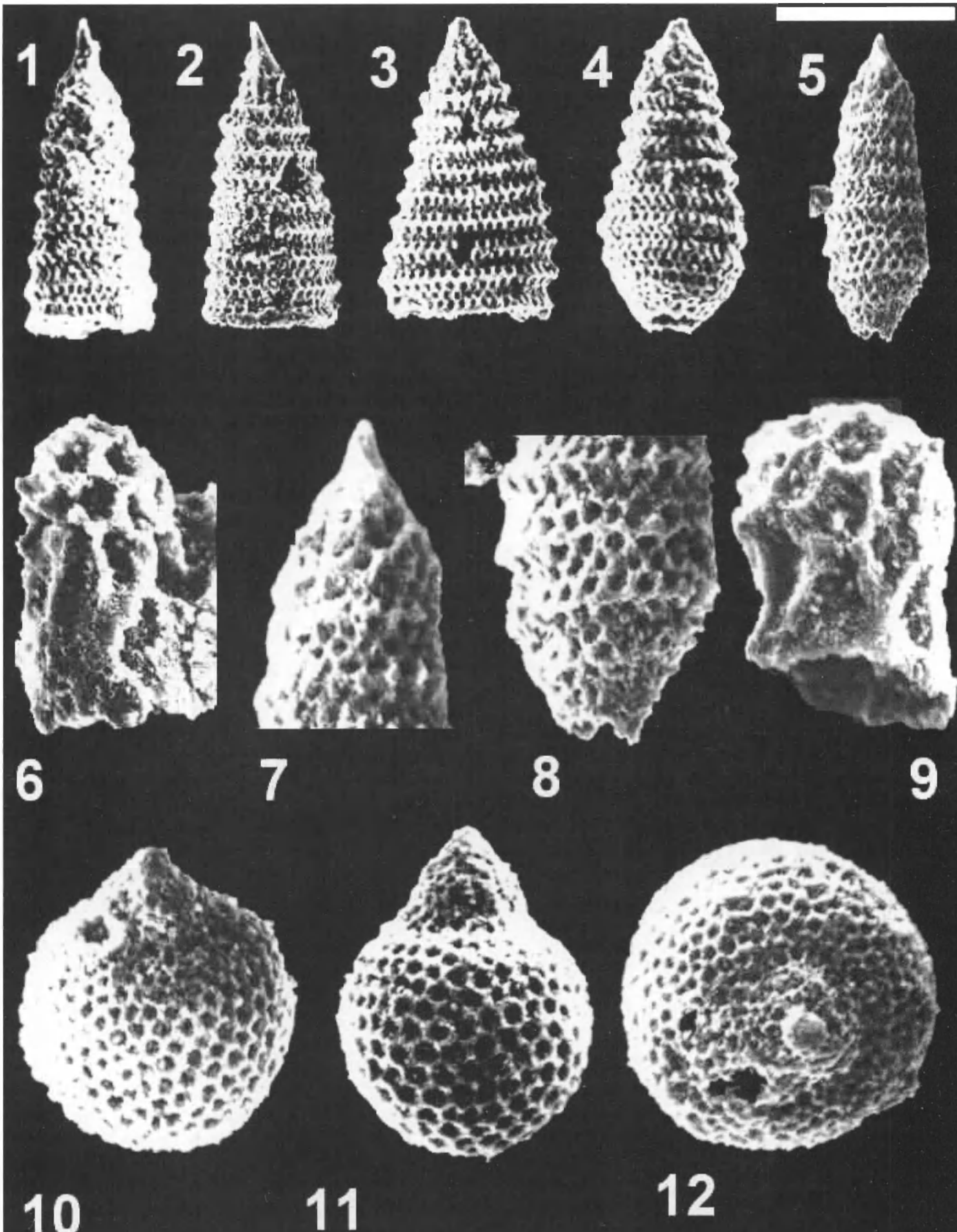
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PLATE 7

All illustrations are scanning electron micrographs of Upper Jurassic (upper Tithonian) Radiolaria from the island of La Désirade, Lesser Antilles. Scale in upper right = number ofμm cited for each illustration.

1 *Neovallupus* sp. A. Specimen from locality M6: Red manganiferous chert occurring as lens within pillow basalt. Scale = 340µm.

2 *Vallupus hopsoni* Pessagno and Bloe. Specimen from locality TD. Scale = 100µm.

3 *Pantanellium cantuchapai* Pessagno and MacLeod. Specimen from locality TD. Red manganiferous ribbon chert. Scale = 240µm.

4 *Eucyrtidiellum pustulatum* Baumgartner. Specimen from locality M6: Red manganiferouschert. Scale = 89.4µm.

5 *Eucyrtidiellum pyctum* Reidel and Sanfilippo. Specimen from locality M6: Red manganiferouschert. Scale = 113µm.

6,7,8,9 *Praeparvicingula holdsworti* (Yang). Specimens from localities TD, TD, M6, and M3 respectively. Red manganiferous chert. Scales = 171, 142, 110, 126µm respectively.

10 *Perispyridium* sp. Specimen from locality M6. Red manganiferous chert. Scale = 180µm.

11 *Loopus primitivus* (Matusuoka and Yao). Specimen from locally TD: Red manganiferous chert. Scale = 100µm.

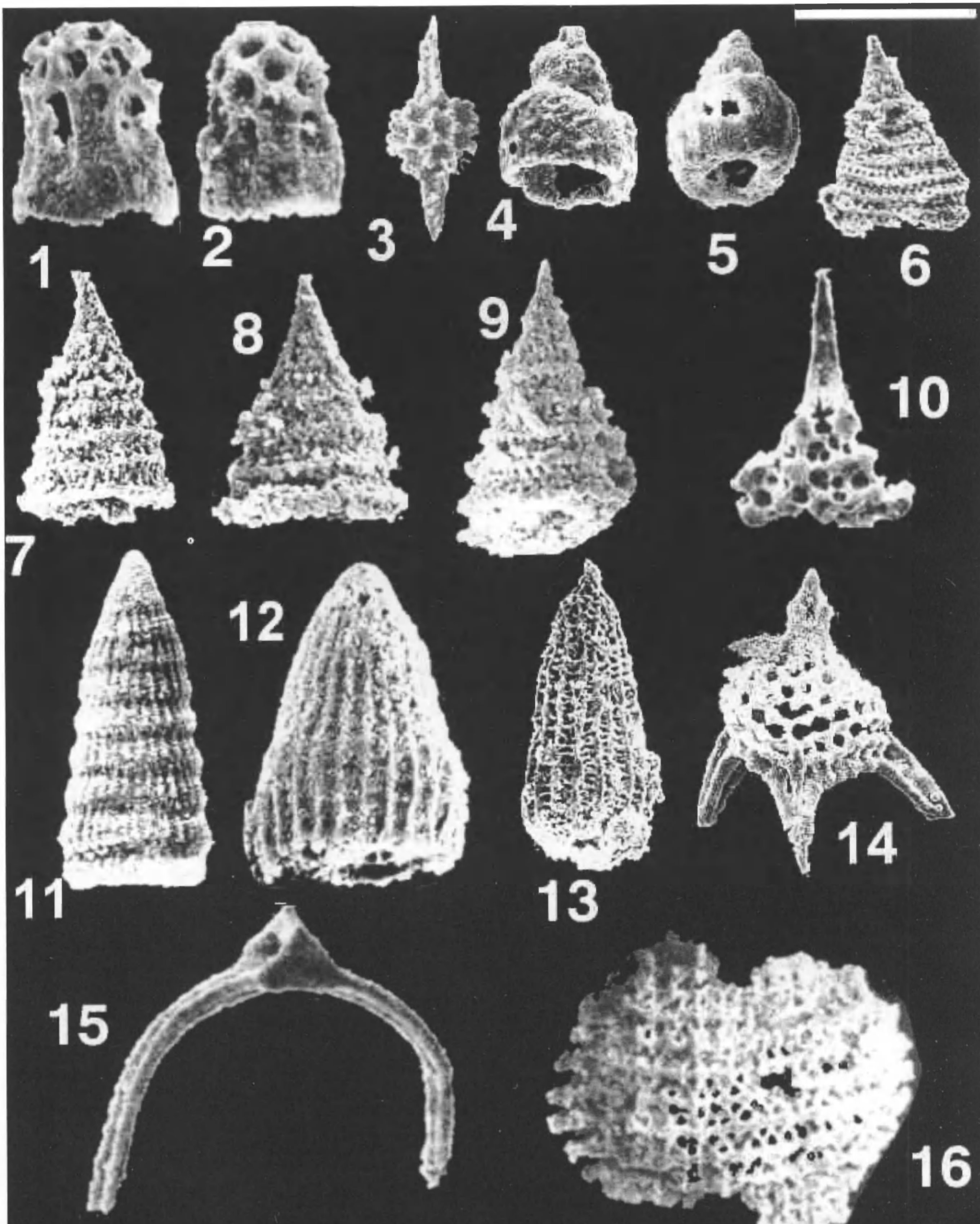
12 *Mita sixi* (Yang). Specimen from locality M6: Red manganiferous ribbon chert. Scale = 71µm.

13 *Hsuum mclaughlini* Pessagno and Blome. Specimen from locality TD: Red manganiferous chert. Scale = 22µm.

14 *Napora* sp. Specimen from locality M6: red manganiferous chert. Scale = 227µm.

15 *Acanthocircus* sp. Specimen from red manganiferous chert at locality 6. Scale = 59µm.

15 *Mirifusus* sp. cf. *Mirifusus baileyi* Pessagno. Specimen from red manganiferous chert at locality TD. Scale = 200µm.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APPENDIX 1

Emendation of radiolarian zonation presented for Middle Jurassic (Bathonian-Callovian) and Upper Jurassic (Oxfordian to Tithonian), Pessagno et al. 1993.

In this report two new subzones are added to **Zone 2** and four new subzones are added to **Zone 4** (See Text-figure 18). The terms ***primary marker taxa***, ***secondary marker taxa***, and ***corporeal taxa*** used in Text-figure 18 are used in the sense of Pessagno et al. (1984, p. 8). These workers stated: "Taxa that are used as the primary means of defining a zonal unit in this report are referred to as "primary marker taxa". Primary marker taxa are selected because they are distinctive in character, because they have sturdy tests that are likely to be preserved in a variety of rock types, and preferably because they have been observed in more than two localities in the Boreal and Tethyan realms. Taxa used as a secondary means of defining a zonal unit are referred to as "supplementary marker taxa". Generally, speaking these are not as distinctive or have been observed at fewer localities. However, in the absence of the primary marker taxa they can be used with a lower level of confidence in helping to delimit a given zonal unit. Other taxa that make their first or last appearance within the body of a zonal unit are referred to as "corporeal taxa" [from *corporeal* (adj.) = of the body]. It should be emphasized that the formal definition of a given zone herein is based on the primary marker taxa and not on the supplementary marker taxa.—".

All zonal units other than the new units shown below follow the definition presented by Pessagno et al. (1993).

New Zonal Units (See Text-figures 4, 33)

Subzone 2 **beta** of Pessagno et al. (1993) is subdivided into two new subzones **Subzone 2 beta$_1$** and **Subzone 2 beta$_2$**; moreover,

Subzone 2 alpha of Pessagno et al. (1993) is subdivided into two new subzones: **Subzone 2 alpha$_1$** and **Subzone 2 alpha$_2$.** Zone 2 follows the definition presented in Pessagno et al. (1993) although its chronostratigraphic calibration has changed slightly. Zone 4 of Pessagno et al. (1993) is now subdivided into four new subzones. In this report **Subzone 4 beta** of Pessagno et al. (1993) is subdivided into **Subzone 4 beta$_1$** and **Subzone 4 beta$_2$** whereas **Subzone 4 alpha** of Pessagno et al. (1993) is subdivided into **Subzone 4 alpha$_1$** and **4 alpha$_2$**.

Definition of Subzone 2 beta$_1$*: *Protovallupus* spp. – *Parvicingula s.s. interval subzone.

Top: Occurs immediately below the first occurrence of *Parvicingula* s.s.

Base: Occurs immediately above the first occurrence of *Protovallupus* spp.

Supplementary Marker Taxa and Corporeal Taxa: None.

Type of Zone: Interval zone sensu International Stratigraphic Guide (International Subcommission on Stratigraphic Classification, 1994, p. 59-60)

Chronostratigraphic calibration: The top of **Subzone 2 beta$_1$** can be best seen in east-central Mexico near Taman, (San Louis Obispo: Text-figures 28, 29). Here, a radiolarian assemblage from samples MX 82-3, MX 82-6, and MX84-48. lack *Parvicingula* s.s. and contain only *Praeparvicingula*. Moreover, Samples MX82-3 and MX84-48 contain *Protovallupus* spp. (See Pessagno et al., 1987a). It can be established that the top of **Subzone 2 beta$_1$** is assignable to either the upper part of the lower Kimmeridgian or to the lower part of the lower Kimmeridigian. (See discussion of **Subzone 2 alpha$_2$** below). The lower part of **Subzone 2 beta$_2$** occurs near the base of the Taman Formation. Associated ammonites are assignable to Cantú-Chapa's lower Kimmeridgian **Ataxioceras Zone** (See discussion below).

Definition of Subzone2 beta$_2$*: *Xiphostylus-Protovallupus interval subzone.

Top: Occurs immediately below the first occurrence of *Protovallupus*.

Base: Occurs immediately above the final occurrence of *Xiphostylus*.

Supplementary Marker Taxa and Corporeal Taxa: First occurrence of *Hsuum cuestaense* occurs in lower part of zonal unit. Final occurrence of *Praeconocaryomma immodica* group occurs in middle of zonal unit.

Type of Zone: Interval zone sensu International Stratigraphic Guide (International Subcommission on Stratigraphic Classification, 1994, p. 59-60)

Chronostratigraphic calibration: The top of the zonal unit occurs immediately below the first occurrence of lower Kimmeridgian ammonites in the Mera Ceiba Member of the Taman Formation near Taman (San Louis Obispo: Text-figures 28, 29). Cantú-Chapa (1971) assigned this horizon to his lower **Ataxioceras Zone** at Taman (San Louis Obispo: Text-figures 28, 29 herein). Pessagno et al. (1993, p. 101) established that the base of their **Subzone 2 beta (=Subzone 2 beta$_2$** herein) occurs in the middle Oxfordian or, possibly in the lower part of the upper Oxfordian. This conclusion was based on the fact that *Xiphostylus* occurred along with specimens of *Mirifusus* that possessed 2 rows of pore frames between 2 given circumferential ridges in the lower part of the Galice Formation s.l. The lower part of the Galice Formation s.l. in the Smith River subterrane (Western Klamath terrane) contains *Buchia concentrica* (middle middle Oxfordian to upper Kimmeridigian).

Occurrence: California Coast Ranges at Stanly Mountain, Point Sal, Cuesta Ridge, and other localities.

Definition of Subzone 2 alpha$_1$ Loopus-Mirifusus baileyi Subzone.

Top: Occurs immediately below the first occurrence of primary marker taxa *Mirifusus baileyi* and *Caneta hsui*.

Base: Occurs immediately above the first occurrence of *Loopus*.

Supplementary marker taxa and corporeal taxa: None.

Type of Zone: Interval zone sensu International Stratigraphic Guide (International Subcommission on Stratigraphic Classification, 1994, p. 59-60).

Chronostratigraphic calibration: At Canyon San Matias *Loopus primitivus* marks the base of **Subzone 2 alpha$_2$** and occurs in samples SM94-9 and SM94-10, 7m above the base of the La Caja Formation. This horizon marks the base of **Subzone 2 alpha$_1$** and occurs well within the **Idoceras Zone** of Cantú-Chapa (1971) and beds with *Idoceras* of Burckhardt (1930). There is little question that base of this zonal unit is assignable to the upper part of the lower Kimmeridgian. Pessagno et al. (1987b) noted that "In the California Coast Ranges near Paskenta (Tehama Co.; locality 22, Hopson and others, 1981), **Subzone 2 alpha** [= **Subzone 2 alpha$_1$** herein] Radiolaria are associated with *Buchia rugosa* (Fischer) and forms transitional to *Buchia rugosa* (Sowerby). Jones (1975, p. 330) and Imlay (1980) favor a late Kimmeridgian (sensu gallico) for the *Buchia* assemblage.—"

Occurrence: West-central Mexico at Canyon San Matias near Mazapil (Zacatecas). East-central Mexico near Taman (San Luis Obispo). California Coast Ranges at Point Sal, Santa Barbara County and other localities.

***Definition of Subzone 2 alpha$_2$. Parvicingula* s.s.-*Loopus* interval subzone.**

Top: Occurs immediately below the first occurrence of *Loopus*.
Base: Occurs immediately above the first occurrence of *Parvicingula* s.s. (sensu Pessagno et al., 1993).

Supplementary Marker Taxa and Corporeal Taxa: None.

Type of Zone: Interval zone sensu International Stratigraphic Guide (International Subcommission on Stratigraphic Classification, 1994, p. 59-60)

Chronostratigraphic calibration: In this study **Subzone 2 alpha$_2$** can best be observed at Canyon San Matias near Mazapil (Zacatecas, Mexico) in an interval 1.9meters above the base of the La Caja Formation (Unit E: Samples SM96X-8 and SM96X-9). The radiolarian assemblage at this horizon is characterized by the presence of *Parvicingula* s.s., *Mirifusus mediodilatatus, M. guadalupensis, Spongocapsula palmerae, Lanubus* spp., *Pantanellium merceibaense,* and *Ristola altissima*. Associated ammonites in the lower 3m of the La Caja Formation contain *Idoceras* spp. and *Idoceras* sp. aff. *I. densicostatum* (identifications by co-author Cantú-Chapa). This interval occurs within the lower part of the 12m interval termed "beds with *Idoceras*" by Burckhardt (1930, p. 50, figure 13). Species of *Buchia* and *Idoceras* recovered by Burckhardt from this 12m interval include *Buchia concentrica, Idoceras zacatecanum, I. humboldti, I. neogaeuni, I. soteloi, I. balderus, I. santarosanum, I. figueroae, I. viverosi,* and *I. subdedalus.* These beds are equivalent to Cantú-Chapa's (1971, p. 26) ***Idoceras Zone***. Moreover, at San Pedro del Gallo sample SPG92-23 (= Burckhardt (1910) Locality 14: Landfill quarry northwest of the town) a limestone concretion from the Cerro Vulcan Member of the La Caja Formation contained both an ammonite and abundant Radiolaria. The ammonite was identified by co-author Cantú-Chapa as *Idoceras* gr. *durangense* Burckhardt. Examination of the radiolarian assemblage indicated that it contained *Parvicingula* s. s., but lacked *Loopus*.

At Taman (San Louis Obispo) a radiolarian assemblage from samples MX 82-3 and MX 82-6 lack *Parvicingula* s.s. and contain only *Praeparvicingula*. These samples are assignable to the lower-most part of the **Idoceras Zone** and to the underlying **Ataxioceras Zone** (lower Kimmeridgian). Moreover, they are assignable to radiolarian biozone **Subzone Subzone 2 beta$_1$**. At Taman the basal part of the Taman Formation (Mera Ceiba Member herein) was assigned by Cantú-Chapa to the **Ataxioceras Zone.**

Occurrence: West-central Mexico at Canyon San Matias near Mazapil (Zacatecas). North-central Mexico (Durango) at San Pedro del Gallo. East-central Mexico near Taman (San Luis Obispo).

Emendation of base of Zone 3/Subzone 3 beta: *Caneta hsui* is elevated from a supplementary marker taxon to a primary marker taxon for marking the base of Zone 3. This taxon can be recognized both in the Northern and Southern Hemisphere (See Kiessling 1999a, 1999b). In contrast, primary marker taxon, *Mirifusus baileyi*, and, indeed, all species of *Mirifusus* seem to be absent as far as can be determined in the Southern Hemisphere. Pessagno et al. (1993, p. 101) state:

"In east-central Mexico (San Luis Potosi) the base of Zone 3 can be observed in the type area of the Taman Formation near Tamazunchale (Pessagno et al. 1987a, b). Here, it occurs about 40m (131 f) below the first occurrence of the calpionellid *Crassicollaria intermedia* (see above). Furthermore, it occurs either within the uppermost part of the *Glochiceras* gp. *fialar* Zone (uppermost upper Kimmeridgian sensu gallico) or the lowermost part of the *Virgatosphinctes mexicanus-Aulacomyella neogeae* Zone (lowermost Tithonian; Radiolaria, 1971).—".

***Definition of Zone 4*: See definition of base of Subzone 4 beta$_1$ and top of Subzone 4 alpha$_2$ below.**

***Definition of Subzone 4 beta$_1$*: *Vallupus* spp.- *Complexapora kozuri* interval subzone.**

Top: Occurs immediately below the first occurrence of *Complexapora kozuri*.

Base: At the first occurrence of *Vallupus* spp. and immediately above the final occurrence of *Napora burckhardti* which marks the top of **Zone 3, Subzone 3 alpha**.

Supplementary marker taxa and corporeal taxa: None.
Type of Zone: Interval zone sensu International Stratigraphic Guide (International Subcommission on Stratigraphic Classification, 1994, p. 59-60).

Chronostratigraphic calibration: At Taman-Tamazunchale (San Luis Potosí) the base of **Zone 4/Subzone 4 beta$_1$** occurs 6m below the contact between the Mera Ceiba Member of the Taman Formation and the overlying Barrio Guadalupe Member of the Taman Formation. As noted under the Huayacocotla remnant of the San Pedro del Gallo terrane and by Pessagno et al. (1987a), the base of **Zone 4/Subzone 4 beta$_1$** also corresponds closely with the first evolutionary appearance of hyaline calcareous calpionellids (i.e., *Crassacollaria intermedia*) within the Mera Ceiba Member of the Taman Formation. Moreover, the base of this subzone occurs in the lower Tithonian **Virgatosphinctes mexicanus-Aulacomyella neogeae Zone** of Cantú-Chapa (1971) and 6m below the base of Cantú-Chapa's lower Tithonian **Mazapilites Zone** (Barrio Guadalupe Member). It should be noted that Pessagno et al. (1987a) included part of the **Virgatosphinctes mexicanus-Aulacomyella neogeae Zone** and all of the **Mazapilites Zone** of Cantú-Chapa in the upper Tithonian. This invalid chronostratigraphic interpretation was based on the presence of *Crassicollaria intermedia* within the upper part Mera Ceiba Member.

***Definition of Subzone 4 beta$_2$*: *Perispyridium* spp. – *Complexapora kozuri* interval subzone.**

Top: The final appearance of *Perispyridium.*

Base: The first appearance of *Complexapora kozuri*
Supplementary marker taxa and corporeal taxa: Supplementary marker taxa include the final appearance of *Pantanellium cantuchapai* and *Vallupus nodosus* at the top of the zonal unit. The corporeal taxon *Neovallupus* makes its first appearance and final appearance in the upper part of the zone. The range of *Neovallupus* corresponds closely to that of the ammonite *Salinites grossicostatum* in the Mexican successions.

Type of Zone: Interval zone sensu International Stratigraphic Guide (International Subcommission on Stratigraphic Classification, 1994, p. 59-60).

Chronostratigraphic calibration: The top of **Subzone 4 beta$_1$** and the base of **Subzone 4 beta$_2$** can best be calibrated chronostratrigraphically at Canyon San Matias near Mazapil, Zacatecas, Mexico. At this locality (See Mazapil remnant of San Pedro del Gallo terrane above) the primary marker taxon for the base of **Subzone 4 beta$_2$**, *Complexapora kozuri,* occurs within the 5m interval where Burckhardt recovered five species of *Kossmatia* (See Burckhardt, 1930). The top of **Subzone 4 beta$_2$** is best documented at San Pedro del Gallo (Durango Mexico: See San Pedro del Gallo remnant of San Pedro del Gallo terrane herein). The presence of primary taxon *Neovallupus* at the top of the San Pedro del Gallo Chert Member of the La Caja Formation together with the presence *Pantanellium cantuchapai* and *Vallupus nodosus* in sample SPA-23 at the top of Puerto del Cielo Shale Member indicate that this interval is assignable to the upper part of **Subzone 4 beta$_2$**. (upper Tithonian) and Imlay's (1980) **Kossmatia-Durangites assemblage**. At Cerro Panteon, to the south-southeast of San Pedro del Gallo, the overlying Cerro Panteon Member contains common specimens of *Substeueroceras* spp.

Occurrence: West central and east central Mexico. California Coast Ranges at Stanley Mountain. La Désirade (Lesser Antilles: See above). Argentina. Antarctica (See above). *Perispyridium* sames to be rarer in basins (e.g., Solenhoffen basin, distal back arc basins). Whether this is due to differences in salinity or to an increase in turbidity still needs to be determined.

Definition of Subzone 4 alpha$_1$: Perispyridium-Vallupus interval subzone.

Base: Immediately above the final occurrence of *Perispyridium.*

Top: Immediately below final appearance of *Vallupus.*

Supplementary Marker Taxa and Corporeal Taxa: None.

Type of Zone: Interval zone sensu International Stratigraphic Guide (International Subcommission on Stratigraphic Classification, 1994, p. 59-60).

Chronostratigraphic calibration: At San Pedro del Gallo (Durango, Mexico: See San Pedro del Gallo remnant of San Pedro del Gallo terrane above) The base of this zonal unit occurs above the first occurrence of the ammonite *Substeueroceras* in the lower part of the Cerro Panteon Member of the La Caja Formation. This subzone can be best observed at Cerro de La Peña situated 10 k north of San Pedro del Gallo on the San Pedro del Gallo-Cinco de Mayo road (Text-figure 12). Within the Huayacocotla remnant of the San Pedro del Gallo terrane Pessagno et al. (1987a) recovered radiolaria from this zonal unit within the Barrio Guadalupe Member of the Taman Formation at locality MX 84-38 (samples A-E) adjacent to the Rio Tezcapa Power Plant (Puebla, Mexico: *See* Cantú-Chapa, 1971, fig. 1, area 7, loc. Af.-1 and text figure 29 herein).

Occurrence: Upper part of Halfa Formation of Oman; east-central and west central Mexico (see above).

***Definition Subzone 4 alpha$_2$: Vallupus-Complexapora kozuri* Subzone**

Base: Immediately above the final occurrence of *Vallupus.*

Top: Marked by final occurrence of primary marker taxa *Complexapora kozuri, Loopus primitivus* and *Ristola altissima.*

Supplementary Marker Taxa and Corporeal Taxa: Corporeal taxon *Eucyrtidiellum ptyctum* makes its final appearance in the lower part of this subzone and corporeal taxon *Hsuum mclaughlini* makes its final appearance below the top of this subzone. See discussion of correlation with the upper Tithonian of Antarctica herein.

Type of Zone: Interval zone sensu International Stratigraphic Guide (International Subcommission on Stratigraphic Classification, 1994, p. 59-60).

Chronostratigraphic calibration: The base of this zonal unit occurs above the first occurrence of *Substeueroceras* at San Pedro del Gallo. The top of this subzone corresponds closely to the top of Imlay's (1980) **Substeueroceras-Proniceras assemblage** at San Pedro del Gallo and in Grindstone Creek in the California Coast Ranges (See discussions herein).

Occurrence: East-central and West Central Mexico. Baja California Sur. California Coast Ranges at Stanley Mountain, Grindstone Creek. Antarctic Peninsula at Graham Island (Longing Gap).

APPENDIX 2

Remane, personal communication, 1995:

> Anyway, let's come to the results which I have obtained so far. In a general way, calpionellids, if they are present (which is not always the case) are mostly rare and often not very well preserved. New thin sections are being made in order to have more material for a precise age assignment. I indicate the ages in terms of my calpionelled zonation, as it used in all my publications.
>
> **GRIN 94**
> Apparently no calpionellids. I have not yet systematically scanned thin sections line by line, but even in looking very carefully, no section was discovered which might be a calpionellid.
>
> **PDC**
> PDC 1, 2, 7 + 13 have provided diagnostic species (see below), whereas in PDC 10, 12, and 23 the presence of calpionellids is not absolutely certain, in any case they are too rare to allow a determination of the age. The other samples are of intermediate quality.
> **PDC 1 and 2** contain both *Calpionellopsis simplex*, indicating Zone D (Calpionellopsis) = upper Berriasian (Boissieri Zone in terms of Mediterranean ammonite zones). The co-occurrence of *Calpionella elliptica* and *Calpionellopsis simplex* in **PDC 2** allows to narrow down the age of this sample to the lower part of Subzone D1.
>
> **PDC 7** has yielded *Calpionella elliptica*, this species ranges from uppermost B through Zone C into lower D 1, *Calpionellopsis simplex*? And *Tintinnopsella longa*, indicating upper Zone C or ? lower D1.
>
> **PDC 13** yielded *Calpionella elliptica*; indicating Zone C (or perhaps lower D1) which agrees well with the other ages.
>
> *Calpionells alpina,* represented by small forms occurring in the entire Berriaasian was observed in PDC 1, 2, 3, 7, 13, 18, 25, and 30, thus excluding a Tithonian or Valanginian age for these samples which cannot be dated with greater precision for the moment being.
>
> **SM**
> Only SM yielded some calpionellids, among them *Calpionellopsis olonga*, ranging from Subzone D 2 into Zone E. An early Valanginian age cannot be excluded, but late Berriasian seems more probable to me.
>
> **SPA**
> Apparently no calpionellids.
>
> **SPG**
> More or less diagnostic species have been found in series SPG 48 to 69 and SPG 70 to 78. SPG 48 to 69: *Calpionellopsis oblonga*, indicating upper Berriasian to lower Valanginian, has been encountered in SPG 48, 67 and 69. It has to be stressed that the typically Valanginian *Calpionelliyes darderi* was never observed.

The presence of *Calpionella alpina* in SPG 54, 55, 56, 57, 58, 62, 64, and 65 speaks in favour of a Berriasian age of the whole succession. Zone D is confirmed by the presence of *Calpionellopsis simplex* in SPG 58, 66 and 67.

The presence of *Calpionellopsis* across the whole interval allows an attribution to the upper Berriasian Zone D, as there are no positive arguments for Zone E (absence of *Calpionellites darderi*). It is nevertheless a bit frustrating that the available data do not allow a subdivision of the series.

SPG 72 to 78: Only two samples have so far yielded diagnostic species.

SPG 77: *Calpionella alpina, Calpionellopsis oblonga, Tintinnopsella carpathica*

SPG 78: *Calpionellopsis simplex, Calpionellopsis oblonga, Tintinnopsella carpatzhica.*

Again we are in the late Berriasian Zone D, its basal part (D1) excluded.

STAN
Apparently no calpionellids.

CONTENTS Volume 6 Number 3 2009

BIOSTRATIGRAPHY