2

Tectonostratigraphic Evidence for the Origin of the Gulf of Mexico

Emile A. Pessagno, Jr.

Department of Geosciences, The University of Texas at Dallas, Richardson, Texas, U.S.A.

Christopher Martin

Consultant, Colorado Geological Survey, Denver, Colorado, U.S.A.

ABSTRACT

Tectonostratigraphic data derived from ongoing biostratigraphic, chronostratigraphic, paleobathymetric, paleobiogeographic, and lithostratigraphic investigations in west-central and east-central Mexico suggest that the Gulf of Mexico formed in two phases:

Phase 1: Rifting and subsequent sea-floor spreading during the Late Jurassic (middle Oxfordian). All but the southwestern portion of the Gulf of Mexico formed during Phase 1.

Phase 2: Northwest-to-southeast tectonic transport of allochthonous San Pedro del Gallo terrane remnants along the west side of Walper Megashear during the Middle Jurassic to Early Cretaceous.

Where the stratigraphic successions are complete, megafossil data indicates that the San Pedro del Gallo terrane was situated at Southern Boreal paleolatitudes (>30° N) in the Nevadan back arc domain during the Middle Jurassic (late Bathonian to early Callovian) and was subsequently carried to lower paleolatitudes during the Late Jurassic and Early Cretaceous. For example, in the Huayacocotla remnant, the Boreal ammonite *Kepplerites* was recovered in the subsurface from the Palo Blanco Formation by Cantú-Chapa. In North America, *Kepplerites* is known from the Izee terrane (east-central Oregon), Western Interior (Montana and Saskatchewan), and northward to southern Alaska. Radiolarian, calpionellid, ammonite, and bivalve faunal data indicate that the Huayacocotla remnant had been transported to Northern Tethyan paleolatitudes (23° N to 29° N) during the Kimmeridgian and Tithonian and to Central Tethyan paleolatitudes (<23° N) by the beginning of the Early Cretaceous.

INTRODUCTION

As noted by many workers, Mexico is a key component in all plate tectonic reconstructions dealing with the break up of Pangea and the subsequent formation of the Gulf of Mexico, the Caribbean, and the North Atlantic. The obvious overlap position of Mexico and South America in Atlantic reconstructions requires moving much of the Mesozoic succession of Mexico away from its present-day position. As a consequence, most plate-tectonic reconstructions of the Atlantic, Gulf of Mexico, and Caribbean regions invoke megashears as mechanisms to transport Mexican crustal blocks to explain the overlap

46

position of Mexico in the reconstruction of Pangea (Figure 1, Inset A).

To accommodate the removal of Mexico, Longoria (1994) utilized four northwest-to-southeast-trending megashears: (1) the Texas Megashear, (2) the Walper Megashear, (3) the Cserna Megashear, and (4) the Sierra Madre del Sur Megashear (Figures 1 and 2). The Walper Megashear of Longoria (1985a, b, 1986, 1987, 1994 = Sonora-Mohave Megashear (part) of Sedlock et al., 1993) (Figure 1, Inset B) is the best substantiated of these four megashears. Pessagno et al. (1993b, 1999) presented new tectonostratigraphic data that both substantiated the presence of the Walper Megashear and established that terranes to the west of the Walper Megashear (e.g., San Pedro del Gallo terrane [SPG], Parral terrane [PAR]) had been transported tectonically from northwest to southeast and from high latitudes to lower latitudes.

In previous reports by Pessagno et al. (1984, 1987, 1999) it was suggested that the Gulf of Mexico formed during the Middle Jurassic (late Bathonian or early Callovian). This hypothesis is supported by the fact that the oldest marine strata in the Sierra Madre Oriental that unconformably overlie the Middle Jurassic red beds of the Cahuasas Formation are of this age (tectonostratigraphic data from the Huayacocotla remnant of the San Pedro del Gallo terrane [Figures 1–3]). However, given that all remnants of the SPG were at higher latitudes (Boreal realm: 30° to 40° N) during the late Bathonian to Oxfordian interval, it is likely that this hypothesis is incorrect (Figure 2). In this report, evidence is presented to substantiate an Oxfordian origin for the Gulf of Mexico.

IMPORTANCE OF FAUNAL AND FLORAL DATA IN PALEOGEOGRAPHIC RECONSTRUCTIONS

Mexico west of Longoria's (1985a, b, 1986, 1987, 1994) Walper Megashear consists of suspect terranes or displaced terranes (Pessagno et al., 1999). Previous studies by Taylor et al. (1984), Pessagno and Blome (1986), Pessagno et al. (1986, 1993a, b, 1999), and Montgomery et al. (1992, 1994a, b) have established the importance of faunal and floral data in paleogeographic reconstructions in North America as well as in the Caribbean. Recognition of displaced tectonostratigraphic terranes depends primarily on paleolatitudinal data derived from paleontology and paleomagnetism, but it can be based on lithostratigraphic and geochemical data (Figures 5 and 6; Cross, 2001). Faunal and floral data can be used to constrain existing paleomagnetic data and, in some cases, also

can help determine whether tectonostratigraphic terranes originated in the Northern or Southern Hemisphere or in the Eastern or Western Pacific (Pessagno et al., 1999, 2000). Faunal data from a variety of sources suggest either northwest-to-southeast movement or southeast-to-northwest movement along other possible megashears (Figure. 1). Burckhardt (1927, 1930) was the first to record the presence of a Middle Jurassic (Bajocian to Callovian) ammonite assemblage in the states of Oaxaca and Guerrero, which strongly resembled the Argentinean assemblage that he previously described (Burckhardt, 1903). Subsequently, Arkell (1956), Imlay (1980), Sandoval and Westermann (1988), Sandoval et al. (1990), and von Hillebrandt et al. (1992) noted the strong Andean affiliation of the Middle Jurassic ammonite assemblage of Oaxaca and Guerrero. That no Middle Jurassic ammonite faunas with strong Andean affiliation are known from elsewhere in Mexico and North America suggests that the Middle Jurassic (Bajocian to Callovian) succession in these states has undergone southeast-to-northwest tectonic transport along a more outboard megashear paralleling the Walper Megashear (i.e., the Cserna Megashear of Longoria, 1994; Figures 1 and 2).

Radiolarian Paleolatitudinal Model

The senior author's analyses of radiolarian faunal data from North America and elsewhere in the world indicate that Radiolaria can be utilized in paleobiogeographic investigations and to monitor the tectonic transport of terranes both in the Northern and Southern Hemispheres (Figure 5). Much of the circum-Pacific margin is a collage of tectonostratigraphic terranes. Many of these terranes have been displaced paleolatitudinally hundreds or, in some cases, possibly thousands of kilometers (e.g., Wrangellia terrane of Jones et al., 1977). Circum-Pacific Jurassic paleogeography, as a result, is difficult to discuss in simplistic terms. Displaced terrane remnants may be likened to blocks of ice in an ice flow where some blocks rotate and move in the direction of the flow and others rotate in place.

In the Northern Hemisphere, Pessagno and Blome (1986) and Pessagno et al. (1986, 1987, 1993a, b, 1999) divided the Tethyan Realm into a Central Tethyan Province, characterized by a radiolarian assemblage with high pantanelliid abundance and diversity and the absence of *Parvicingula/Praeparvicingula,* and into a Northern Tethyan Province with high pantanelliid abundance and diversity and common *Parvicingula/Praeparvicingula* (Figure 5). The Boreal Realm

was subdivided into a Southern Boreal Province and a Northern Boreal Province. 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*; the Northern Boreal radiolarian assemblage is distinguished by abundant *Parvicingula/Praeparvicingula* and by its total lack of pantanelliids. In Figure 5, the boundary between the Tethyan Realm and the Boreal Realm is placed at ~30° N; the boundary between the Central Tethyan Province and the Northern Tethyan Province is established by associated paleomagnetic data at ~22° N (Pessagno et al., 1987, 1999; Yeh and Cheng, 1996). Pessagno and Blome (1986) originally proposed that the model for the Southern Hemisphere is the mirror image of that in the Northern Hemisphere. Subsequently, new data from the Southern Hemisphere has substantiated this model: Argentina (Pessagno et al., 1991; Pujana, 1989, 1991, 1993, 1996), New Zealand (Aita and Grant-Mackie, 1992), Antarctica (Kiessling, 1995; Kiessling and Scasso, 1996; Kiessling, 1999), and the Sula Islands (Pessagno and Hull, 2002).

PALEOLATITUDINAL RECONSTRUCTIONS USING MULTIPLE CRITERIA

Although radiolarian paleobiogeographic reconstructions are useful and can stand alone, they are far more effective when combined with information derived from paleomagnetism, analysis of the total faunal and floral assemblage, and other criteria having paleolatitudinal or paleolongitudinal significance (Figure 6). The thesis stressed not only in previous reports (Pessagno and Blome, 1986; Pessagno et al., 1986, 1987, 1993a, b, 1999) but also herein, is that paleogeographic reconstructions should use all available criteria and should not focus on any one facet (e.g., analysis of the ammonite assemblage alone). Nevertheless, even in eugeoclinal terranes, where other fossils are absent, it is often possible to determine the relative paleolatitudinal position of a given terrane from the study of the radiolarian assemblage alone. Conversely, in successions where megafossils are present and the Radiolaria remain unstudied, it is possible to predict the character of the radiolarian assemblage from that of the paleogeographic character of the megafossil assemblage. This was, in fact, the case in our initial studies of the San Pedro del Gallo area by Pessagno et al. (1993b). Because there was a mixture of Boreal ammonites such as *Amoeboceras* sp. cf. *alterans* (von Busch) (Burck-

hardt, 1930; Imlay, 1980) and *Buchia* associated with Tethyan ammonites, the senior author was able to predict that the radiolarian assemblage, if present in these strata, would be assignable to the Southern Boreal Province (Meng, 1997).

CRITICISM OF PESSAGNO AND BLOME (1986) MODEL BY HAGSTRUM AND MURCHEY (1996)

Hagstrum and Murchey (1996), in a report entitled "Paleomagnetism of Jurassic radiolarian chert above the Coast Range Ophiolite at Stanley Mountain, California and implications for its paleogeographic origins," challenged the validity of the methodology of Pessagno and Blome (1986) and Pessagno et al. (1987, 1993a). In spite of such criticism, we are appreciative of the paleomagnetic data that these authors obtained from the upper part of the volcanopelagic succession at Stanley Mountain (i.e., 32° ± 8°). This paleomagnetic data supports the previous conclusions of Pessagno et al. (1984) and Hopson et al. (1996) that this Coast Range ophiolite remnant and its overlying sedimentary cover was at mid to high latitudes (Southern Boreal Province) by Tithonian times. As noted in the rebuttal by Hull et al. (1997), Hagstrum and Murchey's interpretation of the paleogeographic model presented by Pessagno and Blome (1986), and Pessagno et al. (1986) is inaccurate. The following points 1 through 4 merit discussion herein. Refer to Hull et al. (1997) for a more in-depth discussion.

1) Distribution of Praeparvicingula and Parvicingula Cannot be Linked to Environment of Deposition Based on Rock Type

The distribution of *Praeparvicingula* and *Parvicingula* (the horned parvicingulids of Hagstrum and Murchey) cannot be linked to the environment of deposition based on rock type as suggested by these authors.

Hagstrum and Murchey (1996, p. 650) followed Baumgartner (1987) in stating that "In general, horned parvicingulids occur in hemipelagic rocks such as tuffaceous mudstone or graywacke mudstone, and siltstone (Baumgartner (1987)." This statement is totally erroneous. It infers that "horned parvicingulids" only occur in coastal environments. *Parvicingula* and *Praeparvicingula* not only occur in hemipelagic strata, but they also occur in pelagic strata such as red manganiferous ribbon cherts at a number of localities throughout the world (some of which occur in Hagstrum and Murchey's own
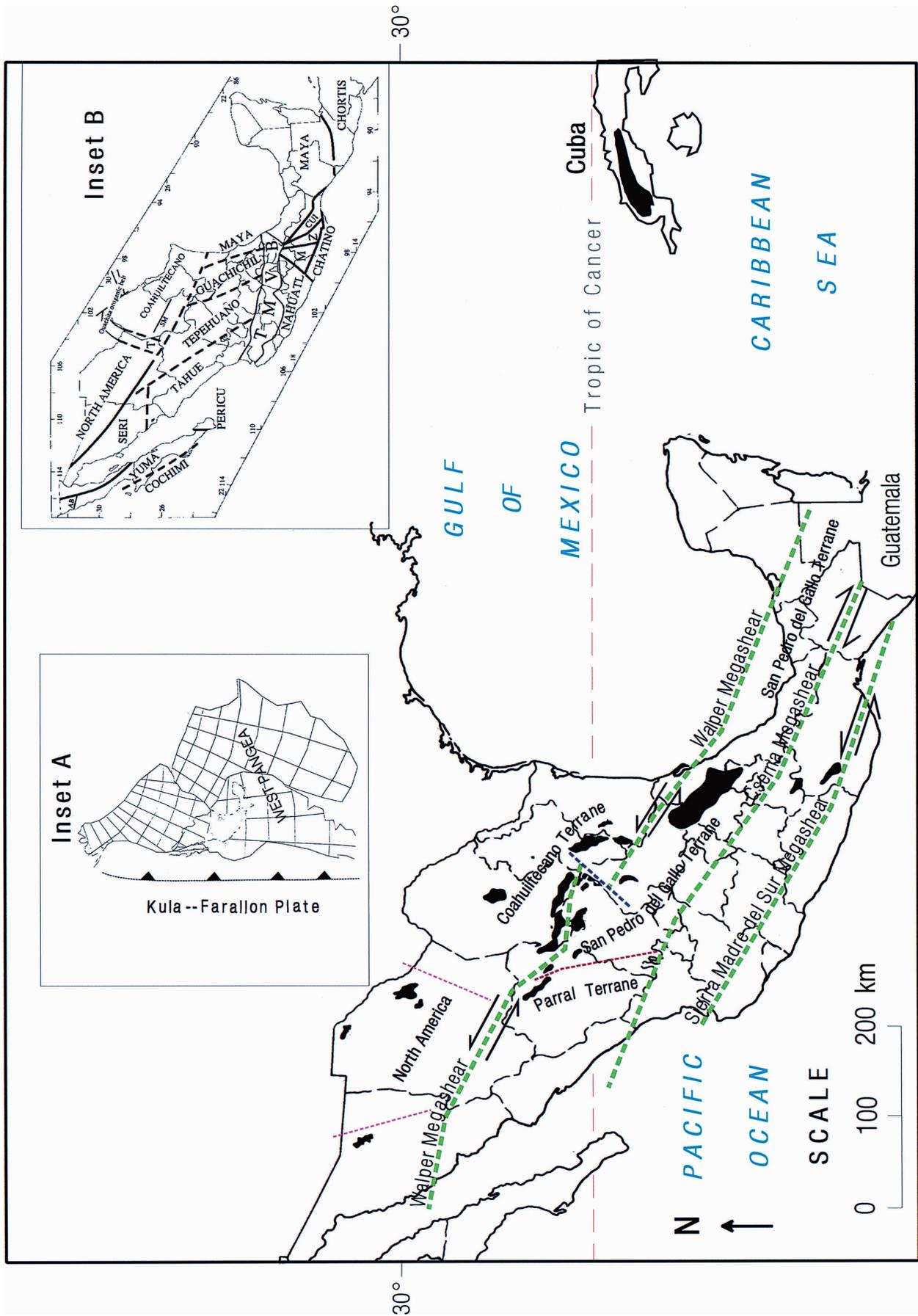
backyard in the California Coast Ranges). Examples of such occurrences are as follows:

a. Thousands of meters of Upper Jurassic oceanic plateau-type basalt interbedded with red manganiferous ribbon chert in the Franciscan Complex at Wilbur Springs and Stoneyford (Localities 17, and 18 of Hopson et al., 1981).
b. Red ribbon cherts throughout the Greater Antilles in the Caribbean (e.g., volcanic member of ophiolite complex in La Désirade; ophiolite remnants in Bermeja Complex of southwestern Puerto Rico; and ophiolite remnants in the Duarte Complex of the Dominican Republic (Montgomery et al., 1992, 1994a, b).
c. Subduction complex in the Philippines (Yeh and Cheng, 1996).

Red ribbon cherts from all of these localities contain *Parvicingula* and *Praeparvicingula* and clearly lack any sort of terrestrial input. Obviously, these taxa flourished in a wide range of sedimentary environments, ranging from open ocean beyond the reach of terrigenous or volcanic input (red ribbon cherts and also some pelagic limestone such as that occurring in the pillow lava at La Désirade) to open ocean downwind from an island arc (e.g., tuffaceous chert above Coast Range Ophiolite at Point Sal, Santa Barbara County, California) to back-arc, interarc, and forearc environments (e.g., ''chert member'' of La Caja Formation at San Pedro del Gallo [back arc]; Rogue Formation, Klamath Mountains, Southwestern Oregon [interarc]; and Snowshoe Formation, Izee terrane, east-central Oregon [back arc; Pessagno and Blome, 1986].

2) Distribution of Pantanelliids as a Criterion Still Useful, Although it Must be Used With Caution

As noted by Pessagno et al. (1986, p. 8), the abundance and diversity of pantanelliids in radiolarian chert and siliceous mudstone is controlled by diagenesis. However, it is also influenced by the method of extracting the microfossils from rock samples using hydrofluoric acid (Blome and Reed, 1993). The fragile nature of many pantanelliid taxa prevents them from being preserved in sedimentary strata that were metamorphosed or underwent lithification subsequent to deposition. Crushing and stretching of specimens extracted from radiolarian chert and shale is common and usually results in the total destruction of all fragile Radiolaria. Only Radiolaria with thick-walled, sturdy tests are preserved (e.g., *Parvicingula, Praeparvicingula, Mirifusus, Archaeocenosphaera*), although these forms often may be quite abundant. The best recovery of well-preserved pantanelliids and, indeed, all Radiolaria occurring in Mesozoic strata, comes from limestone. Radiolarian diversity is at least three times greater in limestone strata than it is in adjacent chert or mudstone layers. This is in part a result of two factors: (1) the use of the hydrofluoric acid (HF) technique (Pessagno and Newport, 1972) to extract the Radiolaria from siliceous strata and the use of hydrochloric acid (HCl) to extract Radiolaria from limestone, and (2) the early lithification of limestone strata at the time of deposition, as opposed to the postdepositional lithification of the chert. Blome and Reed (1993) demonstrated that the use of the HF technique invariably results in the destruction of Radiolaria with more fragile tests (e.g., most pantanelliids). The most dramatic example exemplifying the early lithification of limestone close to the time of deposition comes from Pessagno et al.'s (1993a) study of the volcanopelagic succession overlying the Josephine Ophiolite (Smith River Subterrane, Klamath Mountains, northwestern California). At this locality (Middle Fork of Smith River), volcanopelagic strata consisting of dark gray to greenish gray tuffaceous chert and light gray pelagic limestone overlie the Josephine Ophiolite and underlie the flysch of the Galice Formation. Identical radiolarian chert occurs in the volcanic member of the Josephine Ophiolite. In the interval that incudes the volcanic member of the Josephine Ophiolite and the overlying volcanopelagic strata, the limestone strata produced approximately three times more radiolarian taxa than did the chert strata. Moreover, approximately four times more pantanelliid taxa occur in limestone strata than they do in

Figure 1. Map showing distribution of terranes referred to in text. Distribution of megashears largely follows that of Longoria (1994). Offset of Walper Megashear differs based on reanalysis 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% 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). Modified from Pessagno et al. (1999).
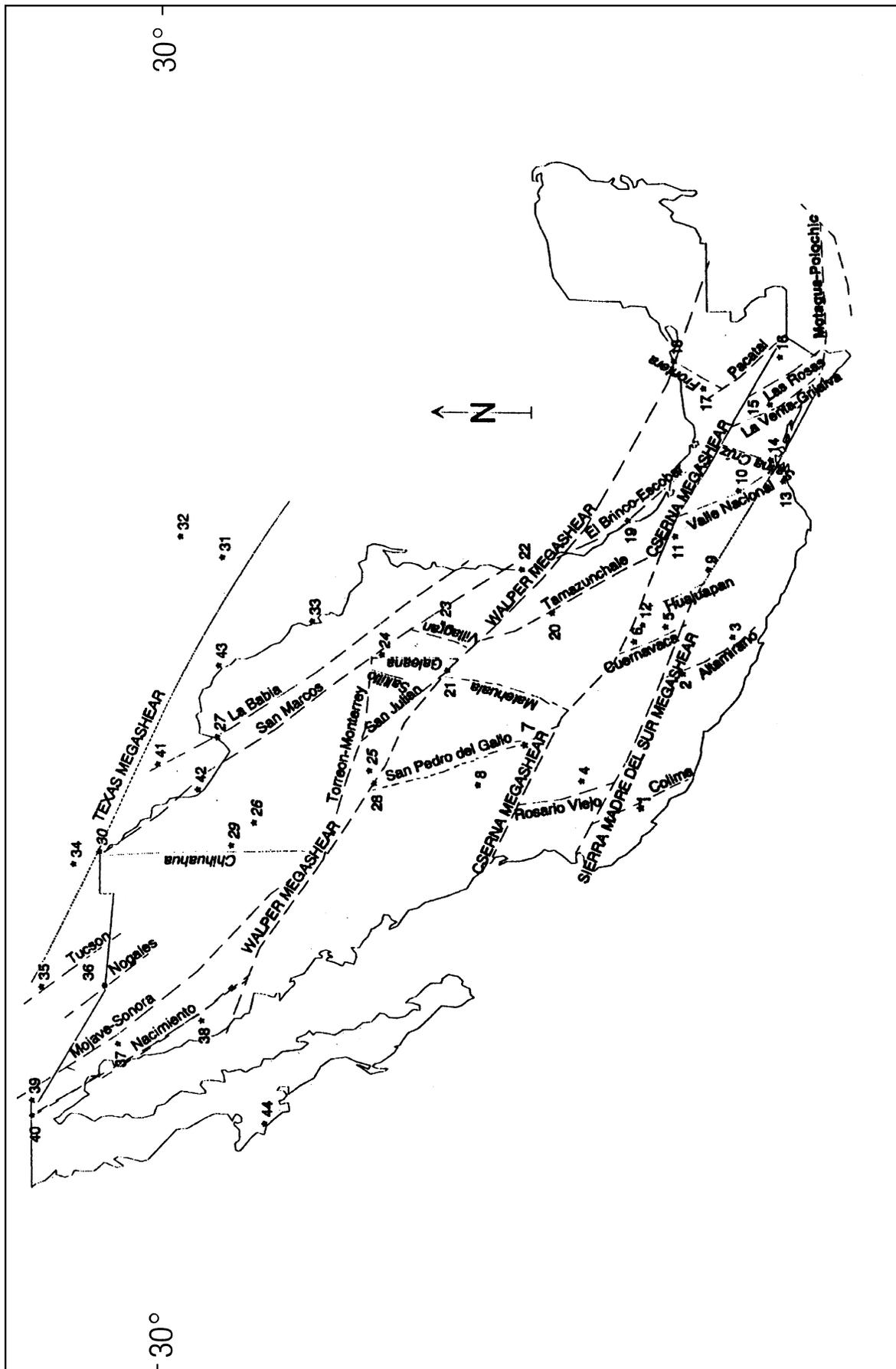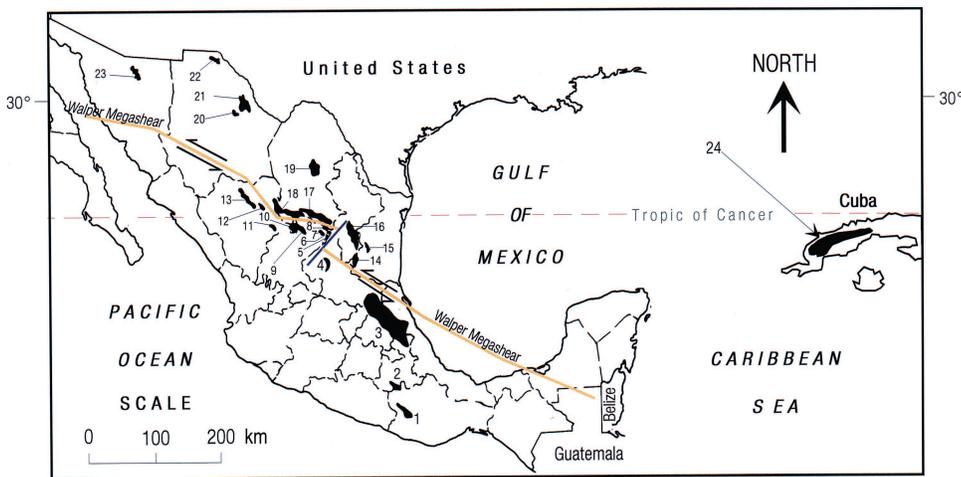
Figure 3. Index map showing important Jurassic localities in Mexico and Cuba. The most important localities for this report are 3–18 and 24. Key to localities: (1) Tlaxiaco: Sierra Madre del Sur, Oaxaca. (2) Pletalcingo: Sierra Madre del Sur, Puebla. (3) Huaya-cocotla Anticlinorium: Taman-Tamazunchale, San Luis Potosí; Huayacocotla, Veracruz; Huachinango, Puebla. (4) Sierra Catorce, San Luis Potosí. (5) Sierra Santa Rosa, Zacatecas. (6) Sierra de la Caja, Zacatecas. (7) Sierra Candelaria, 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, Coahuila. (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). From Pessagno et al. (1999).

rassic and Early Cretaceous; and by Pessagno et al. (1993a) for the Smith River subterrane during the Middle and Late Jurassic. In all of these examples, Radiolaria were extracted from either bedded limestone or from limestone nodules using hydrochloric acid; they were exposed to no higher than prehnite-pumpellyite to greenschist metamorphism; and they were well-preserved. In the Izee terrane, for example, well-preserved, abundant, and diversified pantanelliids associated with Tethyan mega-fossils characterize the Late Triassic (Karnian-Norian) Rail Cabin Formation, the Early Jurassic Nicely Formation (late Pliensbachian), the Early Jurassic Hyde Formation (early to middle Toarcian), and the Early Jurassic part of the Warm Springs Member of the Snowshoe Formation (middle to late Toarcian). Moreover, such an assem-

chert strata. Other examples of this sort are cited in studies by Blome and Reed (1993) and Hull (1995).

Although cases undoubtedly exist in which pantanelliids cannot be used in paleogeographic reconstructions because of the factors noted above, it is important to point out that this group of radiolarians has been successfully utilized to establish paleolatitudes by Pessagno and Blome (1986) for the Izee terrane (east-central Oregon) during the Late Triassic, Early Jurassic, and Middle Jurassic; by Pessagno et al. (1984, 1987) for the Huayacocotla remnant of the San Pedro del Gallo terrane during the Late Ju-

blage also characterizes the Aalenian, early Bajocian, and late Bajocian (Middle Jurassic) parts of the Snowshoe Formation (Warm Springs Member to lower part of the South Fork Member). However, as noted by Pessagno and Blome (1986), pantanelliid diversity and abundance drop dramatically in the late Bathonian part of the South Fork Member of the Snowshoe Formation and in the early Callovian Lonesome Formation. The great drop in diversity and abundance of pantanelliids can be directly related to the first occurrence of Boreal ammonites such as *Kepplerites* and *Pseudocardoceras* in the upper part of the South

Figure 2. Map of Mexico showing lineaments, fault sets, and domains of fault system in the Mesozoic sedimentary cover. From Longoria (1994, p. 85). Numbers indicate names of towns for geographic reference of areas where ground regional geologic verification was undertaken: (1) Comima; (2) Huetamo; (3) Chipancingo; (4) Guadalajara; (5) Cuernavaca; (6) Toluca; (7) Aguascalientes; (8) Lobatos; (9) Huajuapan; (10) Valle; (11) Orizaba; (12) Districto Federal; (13) Salina Cruz; (14) Juchitan; (15) Tuxtla Gutierrez; (16) Comitan; (17) Villa Hormosa; (18) Frontera; (19) Veracruz; (20) Tamazunchale; (21) Matehuala; (22) Tampico; (23) Ciudad Victoria; (24) Monterrey; (25) Torreon; (26) Delicias; (27) Boquillas; (28) San Pedro del Gallo; (29) Chihuahua; (30) El Paso; (31) San Antonio; (32) Austin; (33) Laredo; (34) Las Cruces; (35) Tucson; (36) Nogales; (37) Caborca; (38) Hermosillo; (39) Yuma; (40) Mexicali; (41) Alpine; (42) Presidio; (43) Del Rio; (44) San Hipolito.

Fork Member (Pessagno and Blome, 1986; Pessagno et al., 1986).

Hull et al. (1997, p. 1634–1635) stated, "Thus facing both successes and questions about pantanelliids, we agree that much remains to be solved concerning the paleoceanographic and/or paleolatitudinal preferences of this group of radiolarians. It must be remembered that the recovery of pantanelliids and, indeed, all radiolarians, is greatly influenced by the care taken in sample processing. The recovery of abundant pantanelliids in the Oxfordian and Kimmeridgian parts of other CRO [Coastal Range Ophiolite] remnants could also be influenced by other factors, such as preferred high fertility upwelling areas. Although Hagstrum and Murchey selectively point to pantanelliids as favoring high-fertility upwelling areas, it could be equally expected that parvicingulids flourished in such areas, subject, however, to different water temperature (paleolatitude) controls. The published literature notably lacks any reference to the comparative preference of pantanelliids over parvicingulids for high fertility upwelling areas.

"Regarding this link between high fertility and radiolarian assemblages, we also question Hagstrum and Murchey's use (their Figure 8) of Lisitizin's 1972 map, showing spatial distribution of the annual production of silica by marine organisms in the world ocean, for the purpose of advancing their thesis that 'the tuffaceous Stanley Mountain cherts (CRO [Coast Range ophiolite]) were likely deposited at ∼30° N within a high productivity zone near the western margin of North America'. This map for the modern ocean illustrates silica production predominantly for diatoms near continental coastlines. Diatoms are chief silica producer in modern oceans and are responsible for the greater than seventy percent of the total marine silica (Kennett, 1982); silica production from radiolarians ranks a distant second among siliceous plankton, and presumably, silicoflagellates and siliceous sponge spicules contribute silica as well. Moreover, it is well known that radiolarians generally are not as abundant in nearshore waters of modern oceans (Kennett, 1982) as diatoms in such settings, particularly in eastern boundary regions. We believe that the high production of biogenic silica in the coastal regions bordering North America during the Recent (Hagstrum and Murchey, Figure 8) reflects diatom production and therefore, once again, provides no clue to the geographic distribution of Stanley Mountain radiolarians in the Late Jurassic ocean.

3) Use of Multiple Criteria Rather Than Solely the Presence of Pantenelliids and Praeparvicingula and Parvicingula

Pessagno and Blome (1986) and Pessagno et al. (1986, 1987, 1989, 1993b) stressed the use of multiple criteria (Refer to the previous section titled Paleolatitudinal Reconstructions using Multiple Criteria) rather than solely the presence of pantanelliids and *Praeparvicingula* and *Parvicingula,* as incorrectly indicated by Hagstrum and Murchey.

As noted by Hull et al. (1997), in their discussion of the paleogeographic foundation for the Pessagno and Blome model, Hagstrum and Murchey neglect to mention that the model's realms and provinces are, by definition (Pessagno and Blome, 1986), always constructed on multiple criteria. This thesis subsequently was stressed repeatedly in a series of reports by Pessagno et al. (1986, 1987, 1993a, 1993b).

4) Pessagno and Blome Model Not Dependent on Paleomagnetic Data from Stanley Mountain

The Pessagno and Blome model is not dependent on paleomagnetic data from Stanley Mountain, as indicated by these authors. Hagstrum and Murchey (p. 650) indicate that the model presented by Pessagno and Blome (1986) incorporates little quantitative paleolatitudinal control. Moreover, their suggestion that placement of the Central Tethyan–Northern Tethyan boundary at 22° N was based on the Stanley Mountain paleomagnetic data (i.e., 14° ± 7° N/S presented by McWilliams and Howell (1982). This statement is totally erroneous. The province boundary was tentatively placed at 22° N because of the presence of Central Tethyan Berriasian faunas occurring at 20° N at DSDP (Deep Sea Drilling Project) Site 534 (Blake Bahama Basin: Baumgartner, 1984; Ogg, 1983; Pessagno et al., 1987, p. 7). In addition, this placement is now supported by new data from the Philippines (Yeh and Cheng, 1996). Quantitative data was also cited by Hopson et al. (1996) for the Llanada and Point Sal remnants of the CRO [Coast Range ophiolite] and by Pessagno et al. (1993b) for west-central Mexico. There is little question that more paleomagnetic data is needed by workers in futures studies; however, it should be pointed out that quantitative paleomagnetic data for the Phanerozoic is completely dependent on biostratigraphically derived chronostratigraphic data. The Phanerozoic chronostratigraphic scale is based on fossil biozones. Moreover, the geochronologic scale (geologic time scale) is derived from the integration of

biostratigraphic and chronostratigraphic data with geochronometric data (e.g., U/Pb dates).

COMPARISON OF TERRANES TO EAST AND WEST OF WALPER MEGASHEAR

San Pedro del Gallo Terrane

The downfall of many Mexican tectonostratigraphic studies in recent years has been the failure of workers to familiarize themselves with problems of nomenclature surrounding Mexican lithostratigraphic units and failure to examine these units in the field at their type localities. Investigations by Pessagno et al. (1984, 1987, 1993b, 1999) revealed major discrepancies between the description of rock units in the literature and our observations in the field (Refer to the discussion of stratigraphy of San Pedro del Gallo remnant of SPG terrane in the next paragraph).

New Jurassic and Early Cretaceous stratigraphic data (Martin, 1996; Meng, 1997; Pessagno et al., 1999) from terranes (e.g., San Pedro del Gallo (SPG): Pessagno et al., 1993b, 1999, 2000; Parral: Campa, 1983) in Central Mexico situated southwest of the Walper Megashear demonstrate similar records of paleobathymetry and tectonic transport (Figures 3 and 4). Each remnant of the SPG terrane shows the same paleobathymetric fingerprint (Figure 4): (1) marine deposition at inner neritic depths during the Callovian to early Oxfordian (Middle to Late Jurassic); (2) marine deposition at outer neritic depths during the late Oxfordian (Late Jurassic); (3) sudden deepening to bathyal or upper abyssal depths (ACD [aragonite compensation level]) from the early Kimmeridgian (Late Jurassic) until the end of the Cretaceous. Moreover, although they vary in detail, each remnant of the SPG terrane that has been examined in the mosaic of suspect terranes 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 (Pessagno et al., 1999; Figure 4). For example, the paleolatitudinal signature of the San Pedro del Gallo remnant of the SPG terrane (Durango) supplied by faunal data (Radiolaria and megafossils) and preliminary paleomagnetic data indicates that this terrane was transported tectonically from higher paleolatitudes (Southern Boreal Province: ~40° N) during the Late Jurassic (Oxfordian) to lower paleolatitudes (Tethyan Realm: Northern Tethyan Province) by the Early Cretaceous (Berriasian).

The Jurassic and Lower Cretaceous successions at Mazapil (Zacatecas), Sierra de la Caja (Zacatecas), Sierra de Zuloaga and adjacent Sierra de Sombretillo (Zacatecas), Symon (Durango), and Sierra de Catorce (San Luis Potosí) all are related genetically to that at San Pedro del Gallo. These successions represent dismembered remnants of the SPG terrane. Faunal data (Radiolaria and megafossils) from the Mazapil succession (Sierra Santa Rosa) indicate that this remnant of the SPG was situated at Southern Boreal paleolatitudes (>30° N) during the Oxfordian and Kimmeridgian and at Northern Tethyan paleolatitudes (22 to 29° N) during the Tithonian and Berriasian (Pessagno et al., 1999). Preliminary paleomagnetic data from the upper Tithonian to Berriasian part of the Mazapil succession indicates that this remnant was located ~25° N (Ogg in Pessagno et al., 1999). Farther to the southeast (San Luis Potosí, Hidalgo, Veracruz, and Puebla) in the Huayacocotla segment of the Sierra Madre Oriental, previous investigations indicate tectonic transport from Southern Boreal paleolatitudes (>30° N) during the Callovian to Northern Tethyan paleolatitudes (22 to 29° N) during the Kimmeridgian and Tithonian and to Central Tethyan paleolatitudes (<22° N) during the latest Tithonian (Late Jurassic) and the Berriasian (Early Cretaceous) (Pessagno et al., 1984, 1987, 1993a, b, 1995, 1999).

STRATIGRAPHIC SUMMARIES OF SELECTED SAN PEDRO DE GALLO TERRANE REMNANTS

Pessagno et al. (1999) presented a detailed analysis of a number of San Pedro del Gallo terrane remnants, both in Mexico and western Cuba. A summary of this analysis is presented in Figure 4. In this report, the stratigraphy of three SPG remnants will be discussed: (1) The San Pedro del Gallo remnant (Figure 3: Locality 12); (2) the Mazapil remnant (Figure 3: Locality 5); and (3) the Huayacocotla remnant (Figure 3: Locality 3). The stratigraphy of these remnants strongly contrasts with that of the Coahuiltecano terrane (emended Pessagno et al., 1999) to the east the Walper Megashear (Pessagno et al., 1999).

San Pedro del Gallo Remnant

Figure 3 shows the position of the San Pedro del Gallo terrane (Locality 12) to the west of the Walper Megashear. Figure 7 shows a space shuttle image of the western front of the Sierra Madre Oriental

KEY	MID. JURASSIC				UPPER JURASSIC							LK		Chronostrat. Units
	BATHON.	CALLOVIAN			OXFORDIAN			KIMMER.		TITHONIAN		Berias.	VALAN.	
	low.	up.	low.	mid.	up.	low.	mid.	up.	low.	up.	lower	upper		

Representative Mexican San Pedro del Gallo Terrane remnants

San Pedro del Gallo

- Lithostratigraphic Units: Zuloaga Lms. (1) — (2) — (3) — (4) — La Caja Fm. (5) — (6) — La Caja Formation (7) — Chapulhuacan Limestone (8)
- Paleobathymetry (200 m, 1000 m, 3000 m): inner neritic; abyssal; upper
- Paleobiogeography: (9) Southern Boreal Province NT (10)

Sierra Santa Rosa

- Lithostratigraphic Units: Zuloaga Limestone (11) — (12) — La Caja Fm. (13) — HIATUS — La Caja Formation (14) — Chapulhuacan Limestone 15
- Paleobathymetry: inner neritic (16); abyssal; upper
- Paleobiogeography: Southern Boreal Province Northern Tethyan Province

Sierra Catorce

- Lithostratigraphic Units: Cahuasas Fm. (17) Continental red beds HIATUS — Zuloaga Limestone — HIATUS — La Caja Fm. (18) — HIATUS — El Verde Member (18) — La Caja Formation (19)
- Paleobathymetry: HIATUS; inner neritic; abyssal; upper
- Paleobiogeography: Southern Boreal Province Northern Tethyan Province

Huayacocotla Remnant Taman–Tamazunchale

- Lithostratigraphic Units: Cahuasas Fm. (20) Continental red beds — Tepexic Lms. (21) — Santiago Formation (22) — Taman Formation (23) "lower, massive limestone member" / "upper thin-bedded limestone member" — Pimienta Fm. (24) — Chapulhuacan Limestone
- Paleobathymetry: HIATUS; inner neritic; abyssal; upper
- Paleobiogeography: Southern Boreal Province (25) N. Tethyan Province (26) C. Tethyan Prov.

Cuban SPG remnants — Cordillera de Guaniguanico — S.del Rosario S. de los Organos

- Lithostratigraphic Units: San Cayetano Formation (part) (27) HIATUS — Francisco Formation — HIATUS — Jagua Fm. — HIATUS — S. Vicente Mem. (28) — Artemisia Formation (part) — La Zarga Member / Sumidiro Member — Guasasa Formation (part) — El Americano Member — Tumba. & Tumbitas Mem.
- Paleobathymetry: Continental red beds HIATUS; inner neritic ?; abyssal; upper (29)
- Paleobiogeography: Southern Boreal Province (30) Northern Tethyan Province (31)

Base not exposed ?

Figure 4. Correlation of lithostratigraphic and chronostratigraphic units with paleobathymetry and paleobiogeographic position in selected San Pedro del Gallo (SPG) terrane remnants in Mexico and Cuba. Full explanation of annotations (1) to (31) is shown on adjoining pages. **(1)** ''Lower quartzite unit'' of Burckhardt (1910). Unfossiliferous, massively bedded, white to pink sandstone. **(2)** ''Upper quartzite unit'' of Burckhardt (1910). Unfossiliferous, massively bedded sandstone, overlies Burckhardt's ''nerineid limestone'' (equivalent to Zuloaga Limestone of Imlay, 1938). **(3)** Unnamed pink, silty limestone, mudstone, and siltstone. Contains *Buchia,* common ammonites, and Radiolaria (upper part only). Chronostratigraphically significant megafossils include the ammonites *Dichotomosphinctes and Discosphinctes* and the *Buchia concentrica* (middle to upper Oxfordian). **(4)** Lower Kimmeridgian *Ataxicoceras* Zone and probably part of *Idoceras* Zone (ammonites) are missing. Upper part of the upper Oxfordian probably is missing. Regional unconformity present in much of western North America. Corresponds approximately to onset of deposition of flysch during the middle Oxfordian in the Klamath Mountains of northwestern California and southwestern Oregon (Galice Formation) and in the Sierra Nevada (Mariposa Formation, Monte del Oro Formation). See Pessagno et al. (1993a). Possibly reflecting pre-Nevadan orogenic pulse in back-arc domain. **(5)** ''Lower shale member'' of La Caja Formation, lower part of ''Capas de San Pedro'' of Burckhardt (1910). Dark-gray calcareous to siliceous mudstone with micrite nodules containing abundant Radiolaria, common ammonites, and *Buchia.* Basal strata are assignable to *Idoceras* Zone (upper half of lower Kimmeridgian) and radiolarian Subzone 2 alpha-1 (Meng, 1997). **(6)** Regional unconformity in western North America recognizable in Nevadan back-arc terranes (e.g., all San Pedro del Gallo remnants in Mexico and in Cuba) and in Nevadan fore-arc terranes (e.g., volcanopelagic [VP] strata overlying Stanley Mountain remnant of Coast Range Ophiolite, San Luis Obispo County, California, and Point Sal remnant of Coast Range Ophiolite, Santa Barbara County, California). See Hull (1991, 1995), Hull et al. (1993); Hopson et al., (1996). **(7)** Includes upper part of ''Capas de San Pedro'' of Burckhardt (1910) and ''chert,'' ''upper shale,'' and ''Cerro Panteon quarry unit 2'' members of La Caja Formation herein. Note that the La Caja Formation at San Pedro del Gallo was miscorrelated lithostratigraphically by Imlay (1939) with his La Casita Formation. All members of the La Caja Formation at San Pedro del Gallo contain abundant Radiolaria. Sudden influx of silty wacke at Cerro Panteon and at La Peña (10 km north of San Pedro del Gallo) reflects onset of Nevadan orogeny. Contact of Great Valley Supergroup (flysch) and underlying VP sequence at Stanley Mountain above Stanley Mountain remnant of Coast Range Ophiolite occurs in the lower part of Subzone 4 alpha (uppermost upper Tithonian). At San Pedro del Gallo, equivalent strata contain the ammonite *Durangites* and *Buchia piochii*. **(8)** Unnamed thin-bedded, tan to pink mudstone and micrite with common ammonites and calcified Radiolaria. These strata overlie the massive- to medium-bedded tan micrites of the Chapulhuacan Formation (type area in Taman-Tamazunchale area to southeast. Imlay (1937) miscorrelated these strata with the shallow neritic Taraises Formation (type area, Sierra de Parras). **(9)** Paleomagnetic data (''upper quartzite unit'') from Ogg indicates a paleolatitude of ~40° N or S of Jurassic paleoequator (Pessagno, 1995). Presence of the Boreal megafossils *Buchia concentrica* and *Amoeboceras* sp. in overlying Oxfordian strata associated with Tethyan ammonites such as *Dichotomospinctes* indicate Southern Boreal Realm. Overlying La Caja Formation with *Buchia concentrica, B. rugosa, B. mosquensis,* and *B. piochii* is associated with Southern Boreal radiolarian assemblage characterized by high diversity and abundance of *Parvicingula* and *Praeparvicingula.* Upper part of La Caja Formation with *Buchia* is associated with *Parvicingula/Praeparvicingula* and abundant calpionellids (Tethyan: See Pessagno et al., 1996). Late Tithonian portion of the La Caja Formation formed at the approximate boundary between the Boreal Realm and Tethyan Realm. **(10)** Abundant calpionellids, together with lack of *Buchia* and presence of only Tethyan ammonites, suggests Northern Tethyan Province (Meng, 1997). **(11)** Units G and F of Figure 13. **(12)** Regional unconformity noted in annotation (4) above. **(13)** Unit E (part). The discovery of the lower Kimmeridgian ammonite *Idoceras* in a limestone nodule 1.5 m below contact between units E and F indicates that the uppermost part of unit F is lower Kimmeridgian (identification by Dr. Cantú-Chapa, Instituto Politecnico Nacional, Mexico); the middle Oxfordian ammonite, *Dichotomosphinctes* was recovered 7 m below this horizon (identification by Dr. Cantú-Chapa, Instituto Politecnico Nacional, Mexico). **(14)** Units E (pt) comprise B of Figure 13. Note that silty wacke occurs in the upper part of Unit B in lower Subzone 4 alpha. This horizon occurs below the final occurrence of *Durangites* and *Substeueroceras* (identification by Dr. Cantú-Chapa, Instituto Politecnico Nacional, Mexico). **(15)** Unnamed limonitic mudstone and limestone of Burckhardt (1930; Burckhardt's unit B). **(16)** Change from inner neritic to outer neritic occurs in upper part of unit F (Figure 13). Martin (1996) noted the first occurrence of common Radiolaria in upper unit F. This horizon also may correspond to the regional unconformity noted in annotation (12) above. **(17)** Called La Joya Formation by Imlay (1980). Lower Jurassic strata below this unit contain ammonites and probably are equivalent to the Huayacocotla Group (see Imlay, 1980). **(18)** El Pastor Member of La Caja Formation (Verma and Westermann, 1973), with massively bedded medium-gray micrite with thin beds of black radiolarian chert and wacke. Wacke often contains displaced shallow neritic megafossils. Overlying El Verde member consists of thin-bedded, dark-gray micrite and black radiolarian chert together with wacke. Graded bedding and displaced shallow-water fossils are noted in wacke. **(19)** Incorrectly correlated with shallow neritic La Taires Formation by Verma and Westermann (1973). **(20)** Overlies Huayacocotla Group in Huayacocotla remnant. **(21)** Cantú-Chapa (1969) recovered the Boreal ammonite *Kepplerites* in the subsurface of the Huayacocotla remnant from the shallow neritic Palo Blanco Formation. This ammonite is common in terranes in the Sierra Nevada, in the Izee Terrane of east-central Oregon, and in western terranes north to Alaska. It is indicative of the uppermost Bathonian or lower Callovian (Imlay, 1980). In the surface, the Cahuasas Formation is overlain by the Tepexic calcarenite. **(22)** All but the uppermost part of the Santiago Formation contains an inner neritic molluscan assemblage. Common Radiolaria (including *Praeparvicingula*) first occur near the top of the unit (Pessagno et al., 1987). **(23)** Taman Formation, characterized by abundant Radiolaria, common

(cont.) pectenacids, and rare ammonites. The rarity of ammonites suggests deposition in the upper abyssal depth zone just below the depth of composition (CCD) of aragonite. See Pessagno et al. (1987). Co-occurring throughout the Taman Formation, in the area south of Taman (e.g., near Huauchinango Puebla), are discontinuous masses of inner neritic calcarenite (San Andres Member, Cantú-Chapa, 1969, 1971; Imlay, 1980) that represent either shallow neritic carbonate sedimentation on sea mounts or turbidites. The definition of Taman Formation follows that of Pessagno et al. (1987). **(24)** The Pimienta Formation differs from the Taman Formation by consisting of light- to medium-gray, thin-bedded micrite interbedded with black radiolarian chert and occasional layers of green vitric tuff. **(25)** See annotation (21) above. Taman Formation with a rich Northern Tethyan radiolarian assemblage, including *Parvicingula* and *Praeparvicingula* and abundant diversified pantanelliids associated with Tethyan ammonites and calpionellids (Tithonian). (See Pessagno et al., 1987). **(26)** Pimienta Formation and overlying Chapulhuacan Limestone with abundant calpionellids, Tethyan ammonites, and lacking *Parvicingula/Praeparvicingula.* Central Tethyan Province. **(27)** Data from Imlay (1980), Haczewski (1976), Lewis and Draper (1990), and Myczynski and Pszczólkowski (1994). Imlay indicates that marine bivalves of probable Middle Jurassic age occur in the upper part of this unit. **(28)** San Vincente Member (Myczynski, 1994) is anomalous and appears to be an analog of the San Andres Member of the Taman Formation in the Huayacocotla remnant. See annotation (23) above. **(29)** Radiolarian-rich strata comprising all of the Artemisa Formation and most of Guasasa Formation (except for San Vincente, see above) were deposited at upper abyssal depths either above or slightly above the CCD of aragonite. **(30)** The presence of *Parvicingula/Praeparvicingula* in the radiolarian assemblage associated with Tethyan ammonites and *Buchia* (Myczynski, 1994) indicates that the Cuban SPG remnants were at Southern Boreal paleolatitudes. **(31)** Northern Tethyan paleolatitudes are indicated by same association as in annotation (30) but with common to abundant calpionellids (Myczynski and Pszczólkowski, 1994). Modified from Pessagno et al. (1999).

(right). The boundary between Coahuiltecano terrane (emended Pessagno et al., 1999) and displaced terranes to the west occur immediately west of mountain front along the Walper Megashear.

The stratigraphic analysis of the San Pedro del Gallo remnant which follows is based on investigations by Pessagno et al., 1993b, 1999), Martin (1996), and Meng (1997), as well as previous observations by Burckhardt (1910, 1912, 1930) and Imlay (1939). For many years, lithostratigraphic units in the San Pedro del Gallo succession have been miscorrelated with those in the Coahuiltecano terrane (Sedlock et al., 1993; emended Pessagno et al., 1999) to the east of the Walper Megashear (Figure 1).

Figure 5. Paleolatitudinal model based on distribution of selected Radiolaria from the Jurassic and Lower Cretaceous.

Examination of the type Zuloaga Limestone in the Sierra Sombretillo (Zacatecas: Martin, 1996; Pessagno et al., 1999) established that Burckhardt's ''nerineid limestone'' at San Pedro del Gallo is its lithostratigraphic equivalent. At San Pedro del Gallo, the Zuloaga Limestone (Figures 4 and 8–11) occurs as a tongue in Burckhardt's (1910) quartzite unit. Unfortunately, Imlay, whose correlations were normally very accurate, incorrectly correlated Burckhardt's quartzite unit with the La Gloria Formation (type locality = Sierra La Gloria, ~50 km east-southeast of Parras [Figure 3: Locality 17], Imlay, 1936) in the Coahuiltecano terrane.

The base of the succession at San Pedro del Gallo is not exposed. No age-diagnostic fossils have been recovered from the Zuloaga Limestone or the lower quartzite. Recently, a middle Oxfordian ammonite (under study by Dr. A. Cantú-Chapa, Instituto Politecnico Nacional, Mexico; Figure 10) was recovered from the upper quartzite unit at Kelldorf Locality LM3 (GPS = N25° 39′ 19″; W104° 16′ 34″). Strata at locality LM3 crop out just to the east of La Peña and 10 km north of San Pedro del Gallo along the main road. This ammonite represents the first ammonite ever found in Burckhardt's upper quartzite unit. Our field data indicate that the ammonite horizon (LM3) occurs 10.6 m below the contact between the upper quartzite unit and the overlying pink siltstone, silty mudstone, and silty limestone unit (Figure 8).

Martin's (1996, p 105) microfacies analysis of the Zuloaga Limestone indicates that it consists of bioturbated micrite (''lime mudstone'') and peloidal
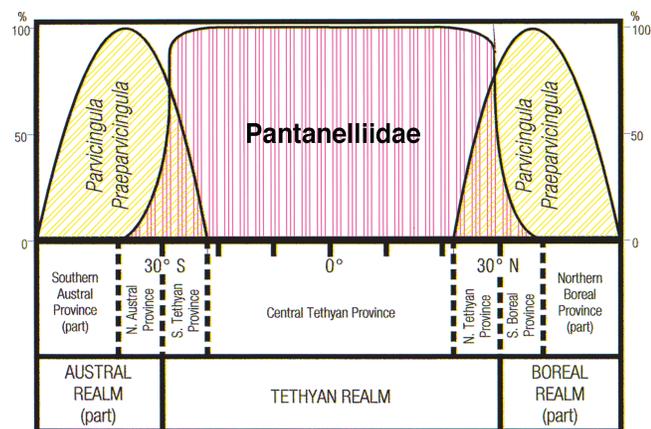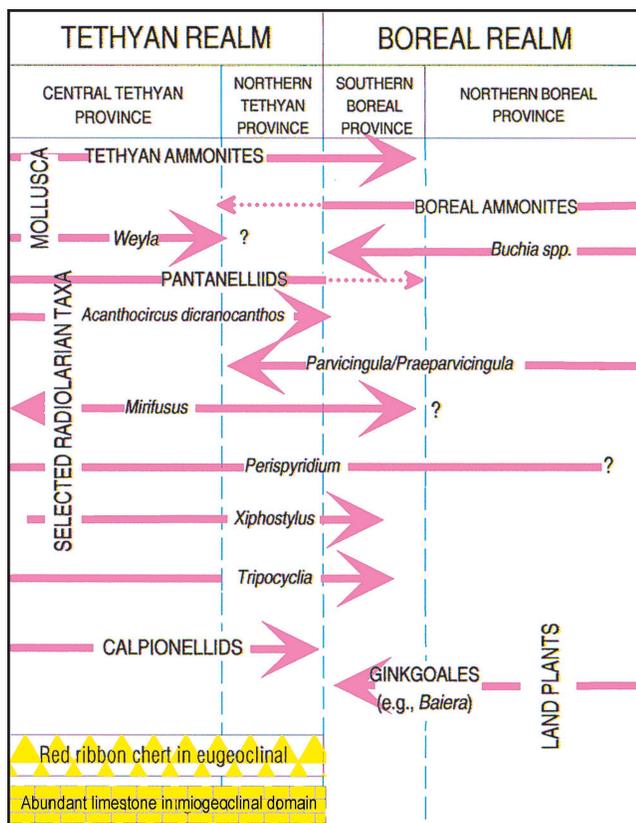
Figure 6. Multiple criteria for use in paleobiogeographic reconstructions in the Northern Hemisphere.

well-sorted nature of the quartz sand and micrite peloids suggests that the upper quartzite unit may have been deposited at even shallower inner neritic depths near a shoreline where sediments would be subjected to higher wave energy.

The upper quartzite unit (Figures 4 and 8) is overlain by a unit consisting of pink siltstone, mudstone, and silty limestone with middle and upper Oxfordian ammonites, brachiopod shell fragments, *Buchia concentrica,* common nodosarids (benthonic foraminifera), and miliolids (benthonic foraminifera) (Pessagno's observations and those of Martin, 1996). Martin noted that the calcareous siltstone is slightly laminated and contains 10 to 35% angular to subangular, well-sorted quartz grains. The upper part of this unnamed Oxfordian unit contains common Radiolaria.

Figure 7. Space shuttle image showing the western front of the Sierra Madre Oriental (right). The boundary between Coahuiltecana terrane (emended herein) and displaced terranes to the west occurs immediately west of the mountain front along the Walper Megashear.

lime grainstone with black chert nodules and numerous styolites. The faunal assemblage of the Zuloaga Limestone is characteristic of inner neritic depths. It contains nerineids, other gastropods, rare corals, echinoid fragments, and rare benthonic Foraminiferida (Miliolina and Textulariina) (Martin, 1996). The presence of miliolids in the Zuloaga Limestone indicates that it was deposited at depths no greater than 100 m. Martin noted that most of the allochems are well-sorted peloids. He noted that many of the peloids have poorly defined rims, which may indicate that they were formed by the rolling action of near-shore waves. Moreover, he suggested that the bioturbated micrite was deposited on a gently sloping carbonate bank in an area that was isolated from the winnowing action of wave energy.

The "upper quartzite unit" consists of thick-bedded, well-sorted quartz arenite with symmetrical ripple marks, trough cross-beds (Martin, 1996, p. 105), and occasional large gastropods. Martin indicated that the uppermost beds of this unit are peloid lime grainstone similar to those occurring within the Zuloaga Limestone tongue. Moreover, according to Martin, the

Litho unit	Description	Age	Diagnostic faunal elements	Paleobathymetry	Faunal realm/province
Chapulhuacan Limestone	Medium-to massive-bedded light-gray to tan, very aphanitic micrite with abundant calpionellids, common Radiolaria, and rare ammonites. Some horizons with phosphate nodules.	Berriasian	Abundant calpionellids[1]	Abyssal	N. Tethyan Province
"Cerro Panteon quarry unit 2 member"	Red, pink, and pinkish-gray limestone, calcareous siltstone (wacke), and calceous mudstone with common ammonites, common belemnites, Buchia, common Radiolaria, and abundant calpionellids. Thickness = 6 to 77 m.	late Tithonian	Durangites, Substeueroceras, belemnites, Buchia piochii + abundant calpionellids, abundant Radiolaria (Subzone 4a).	Abyssal	Southern Boreal Province
"upper shale member"	Dark-gray siliceous mudstone, minor thin-bedded, dark-gray micrite and dark-gray micrite nodules. Rare ammonites. Buchia rugosa and B. mosquensis. Common calpionellids. Thickness = 36 m.	late Tithonian	Durangites + Buchia rugosa, B. mosquensis + Subzone 4a Radiolaria	Abyssal	Southern Boreal Province
"chert member"	Dark-gray siliceous mudstone interbedded with black, thin-bedded radiolarian chert and minor dark-gray micrite. Common ammonites and Buchia + abundant Radiolaria. Common calpionellids. Thickness = ~316 m.	late early Tithonian to late Tithonian	Buchia rugosa, B. mosquensis + Kossmatia, Durangites + Subzone 4b Radiolaria. See Meng (1997).	Upper	Southern Boreal Province
"lower shale member"	Dark-gray siliceous to calcareous mudstone with common dark-gray micrite nodules throughout. Lenticular masses of thin-bedded, dark-gray micrite present locally. Micrite nodules and bedded limestone with abundant Radiolaria, rare to common ammonites, and Buchia. Rests unconformably on Oxfordian strata below. Thickness = 52 m (minimum).	early Kimmeridgian to early late Kimmeridigan	Buchia concentrica, B. rogusa, and B. mosquensis in same bed with Glochiceras gp.fialar sensu Burckhardt Idoceras spp. Subzone 2a1 Radiolaria.	Upper	Southern Boreal Province
unnamed red siltstone, limestone, and shale	Interbedded red silty limestone, silty mudstone, and siltstone containing Buchia and common ammonites. Radiolaria first occurring in upper part. Thickness = 21.2 m.	middle Oxfordian to late Oxfordian	Discosphinctes, Buchia concentrica, Dichotomosphinctes.	Outer Neritic	Southern Boreal Province
"upper quartzite unit"	Massively bedded white to red sandstone. Cross-beds and symmetrical ripple marks. See Martin (1996). Paleomagnetic data = 40° N/S. Thickness = 3.3 m.		No fossils.	Inner Neritic	Southern Boreal Province
Zuloaga Limestone	Massively bedded micritic limestone with nodules of black chert.	middle Oxfordian or older	Nerinea, bivalves, corals, and sponge spicules. See Burckhardt (1910, 1930)	Inner Neritic	Southern Boreal Province
"lower quartzite unit"	Massively bedded red and white fine-grained sandstone. Base not exposed.		No fossils		

La Caja Formation (comprising "Cerro Panteon quarry unit 2 member", "upper shale member", "chert member", and "lower shale member")

Figure 8. Stratigraphic summary for San Pedro del Gallo, Durango, Mexico. Note that numerous calpionellids were identified by Dr. Jurgen Remane (University of Neuchâtel, Switzerland) during a study of the Jurassic-Cretaceous boundary at San Pedro del Gallo. Remane's data clearly show that calpionellid taxa-range zones (e.g., C. elliptica) are longer ranging at San Pedro del Gallo than in Europe. Moreover, investigations by Cantú-Chapa (1989) of 35 well sites situated in a 1300 km² area in the Huayacocotla remnant substantiate the same occurrence of allegedly Berriasian calpionellids well below the final occurrence of Durangites.

Figure 9. Zuloaga Limestone at Cerro Volcan, San Pedro del Gallo, Durango, Mexico. A tongue of Zuloaga Limestone (Figure 12) is exposed at the top of Cerro Volcan ~10 km north-northeast of the village of San Pedro del Gallo, Durango, Mexico. It is a medium- to massively bedded gray micritic limestone with nerineids and other gastropods, containing no age-diagnostic fossils. For location, see Figure 3: Locality 12. Late Jurassic: middle Oxfordian or older; the base is not exposed in this area.

Figure 10. Close-up view of the Zuloaga Limestone at Cerro Volcan, shown in Figure 9.

Figure 11. Upper Jurassic (middle Oxfordian) ammonite occurring in Burckhardt's (1910) upper quartzite unit at Cerro Volcan, San Pedro del Gallo, Durango. This ammonite occurs stratigraphically above the Zuloaga Limestone shown in Figures 9 and 10.

The sudden occurrence of the Radiolaria in this part of the succession reflects a rapid shift in paleobathymetry from inner neritic to outer neritic depths during the late Oxfordian (Figure 4).

Imlay (1939) correlated the informal unit, which Burckhardt called the ''Capas de San Pedro,'' with the La Casita Formation (Figures 4 and 8). Although these lithic units are approximately equivalent chronostratigraphically, it is clear from our examination of La Casita strata in its type area (Sierra de Parras: Figure 2, Locality 17), as well as in the Sierra Jimulco (Figure 2, Locality 18), that the Capas de San Pedro are not correlative lithostratigraphically with the La Casita Formation (Martin, 1996). 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 in its upper part and common radiolarian-rich micrite nodules in its lower part. Field investigations by Pessagno et al. (1999) clearly indicate that Burckhardt's Capas de San Pedro are genetically related to and lithostratigraphically correlative with the La Caja Formation of Imlay (1939). We have observed black radiolarian chert in the La Caja Formation thus far at Cañon San Matias and Cañon Puerto Blanco (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). Curiously, in spite of thin-bedded black radiolarian chert lithofacies being the trademark of the La Caja Formation, all other workers except Burckhardt failed to observe it.

The La Caja Formation (= Capas de San Pedro part of Burckhardt, 1910) was divided by Pessagno et al. (1999) 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.

1) ''lower shale member''

The lower shale member consists of 52 m (minimum) of dark gray siliceous to calcareous mudstone with common dark gray micrite nodules. Lenticular masses of thin-bedded, dark gray micrite are present locally. The bedded micrite and micrite nodules contain abundant Radiolaria, rare to common ammonites, and *Buchia* (Figure 8). This unit is assignable to late early Kimmeridgian to early late Kimmeridgian. It rests unconformably on the middle to early late Oxfordian strata of the unnamed red, siltstone, limestone, and shale unit (Figures 4 and 8).

2) chert member

This member includes ∼316 m of early to late Tithonian dark gray siliceous mudstone interbedded with thin-bedded, black radiolarian chert, and minor dark gray micrite that rests disconformably on the underlying shale member. Occasional thin-layers of quartz-rich silty wacke often display graded bedding and represent turbidites. This unit contains common ammonites, abundant Radiolaria, abundant siliceous sponge spicules, common calpionellids, and common *Buchia* (Figure 8).

3) upper shale member (= top of Burckhardt's Capas de San Pedro)

The upper shale member consists of 36 m of dark gray siliceous mudstone and minor amounts of thin-bedded dark gray micrite. The mudstone contains common micrite limestone nodules. Abundant Radiolaria and rare ammonites as well as common *Buchia* occur in the siliceous mudstone and in the bedded micrite and micrite nodules. The late Tithonian strata of the upper shale member rest conformably above the chert member and below Cerro Panteon quarry unit 2 (Figure 8).

4) Cerro Panteon quarry unit 2 member

This member of the La Caja Formation at San Pedro del Gallo consists of 6 to 77 m of red, pink, and pinkish gray micritic limestone, calcareous siltstone, and calcareous mudstone, with common ammonites, belemnites, calpionellids, and Radiolaria (reddish color probably is the result of hydrothermal alteration by Tertiary intrusives). At La Peña, 10 km to the north of San Pedro del Gallo, the Senior author observed 92 m of interbedded black siliceous shale, thin-bedded siltstone (wacke), and thin-bedded dark gray micrite containing belemnites, abundant Radiolaria, *Buchia,* and common ammonites. Abundant calpionellids were reported from this unit by Addate et al. (1995). Contreras-Montero et al. (1988) recorded abundant ammonites (including *Durangites* Burckhardt) and *Buchia piochii* as well as abundant Radiolaria and belemnites from this locality.

Imlay (1939) correlated strata assignable to Cerro Panteon quarry unit 2 member and the Chapulhuacán Limestone (Figures 4 and 8) with the inner neritic Taraises Formation (type area = Sierra de Parras, Figure 3: Locality 17). 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 (Figure 8).

The Chapulhuacán Limestone (type area = Chapulhuacán, Hidalgo near Taman-Tamazunchale, San Luis Potosí: Figure 2: Locality 3) consists of ∼20 m of medium to massively bedded light gray to tan very

aphanitic micrite with abundant calpionellids, common Radiolaria, and rare ammonites assignable to the Berriasian. Some horizons contain large phosphate nodules (12 cm).

The La Caja Formation, as well as the Chapulhuacán Limestone, contains abundant Radiolaria and siliceous sponge spicules, rare benthonic foraminifera, and common ammonites (Figures 4 and 8). Deposition took place at upper abyssal depths somewhat above the ACD (compensation level of aragonite) during early Kimmeridgian to Berriasian times and continued at these depths through the Late Cretaceous (Burckhardt, 1930). The radiolarian cherts usually contain nearly 50% radiolarian tests. As a result, it is likely that they formed as radiolarian ooze.

The Oxfordian to upper Tithonian part of the succession is characterized by containing a mixture of Tethyan and Boreal ammonites (e.g., *Amoeboceras, Idoceras, Durangites*), common *Buchia* (e.g., *Buchia concentrica, B. mosquensis, B. rugosa*) 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, 1995) during the Oxfordian (*See* Figures 5 and 6). The appearance of abundant calpionellids coupled with the presence of *Buchia* and the presence of common *Parvicingula* and *Praeparvicingula* in the Cerro Panteon quarry unit 2 member of the La Caja Formation demonstrate that the San Pedro del Gallo remnant had been transported to close to the boundary (~30° N) between the Northern Tethyan Province and the Southern Boreal Province by the latest Tithonian (Late Jurassic) (Figures 4–6). The lack of Boreal elements such as *Buchia* in overlying Early Cretaceous strata may suggest transport of the San Pedro del Gallo remnant to the Northern Tethyan Province (>22° to <30° N by the Berriasian. Based on Ogg's paleomagnetic data and the faunal data cited above, Meng (1997) estimated the rate of movement of the San Pedro del Gallo remnant along the Walper Megashear to be 4.9 cm/yr.

(2) The Mazapil remnant

The Mazapil remnant of the SPG terrane was examined at Cañon San Matias in the Sierra Santa Rosa (Figure 3: Locality 5). As in the case of the San Pedro del Gallo remnant, the base of the succession at Cañon San Matias is not exposed. The oldest unit exposed at this locality is the Zuloaga Limestone (Unit H in Figures 12 and 13). The Zuloaga consists of massive to medium-bedded, styolitic, medium-gray micritic limestone strata with nodules of black chert (Figure 12). Microfacies analysis of the Zuloaga at this locality by Martin (1996) indicates that the micrite contains encrusting coralline algae, nerineid gastropods, bivalves, foraminifera, and siliceous sponge spicules (Martin, 1996, p. 67). The faunal and floral data suggest that the Zuloaga Limestone at Cañon San Matias was deposited at inner neritic depths (<50 m) on a carbonate bank free of wave energy. The age of the Zuloaga can only be established as middle Oxfordian or older via the superposition of overlying strata (Units G and F) containing middle Oxfordian ammonites (Figure 9).

Unnamed units G and F consist of pink, silty mudstone, micritic limestone, and siltstone rich in bivalves and with common ammonites. 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 (~200 m) in the late Oxfordian.

Units E, D, C, and B (lower Kimmeridgian to Berriasian) are included in the La Caja Formation of Imlay (1938, 1939; Figure 13). All La Caja units at Cañon 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 chert member of Burckhardt's (1910) Capas de San Pedro'' (Figures 8, 13–15). The chert 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. Unit D, as noted by Burckhardt (1930) is unique in that it is characterized by the presence of beds of phosphate and phosphatic limestone (Cross 1999, 2001). All La Caja strata are characterized by containing a microfauna with abundant Radiolaria, abundant siliceous sponge spicules, and rare benthonic foraminifera and a megafossil assemblage with common to abundant ammonites and common *Buchia*. 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: presence of common to abundant ammonites) and continued at these depths until the end of the Cretaceous (Burckhardt, 1930; Figure 4). The radiolarian chert consists

Figure 12. Zuloaga Limestone at Cañon San Matias (Mazapil area), Sierra Santa Rosa, Zacatecas, Mexico.

of ∼50% by volume of radiolarian tests and test fragments; hence, it is likely that it formed as a radiolarian ooze. The origin of the phosphate unit (Unit D) has been discussed in detail by Cross (1999, 2001) and will not be elaborated on in detail here. Cross recognized five major phosphate horizons at Mazapil (Cañon San Matias and Cañon Puerto Blanco) assignable to three phosphatic ''realms.'' Cross (2001) determined that Unit D Mazapil displays geochemical signatures resulting in the identification of three phases or pulses of phosphatic limestone turbidite activity. He proposes that the following factors limit the initiation and subsequent termination of phosphate deposition within the San Pedro del Gallo terrane back-arc basin:

1) Paleogeographic configuration of continental masses;
2) Resulting paleocurrent configurations and the point that these currents encounter the zone of photosynthesis (abiotic) together with the effects of nutrient-rich upwelling waters (biotic).

Cross (2001) established through petrologic and scanning electron microprobe analyses that mafic and heavy minerals characteristic of andesite island-arc volcanism have been concentrated in the neritic and bathyal PR-zones from the Mazapil and Iturbide remnants but are lacking in the deep-water phosphorites (PR-3) from both remnants. It is likely that phosphate deposition in the San Pedro del Gallo basin was influenced by the opening up of the Gulf of Mexico and the resulting connection of the narrow, nutrient-rich Tethyan North Atlantic–Mediterranean seaway with the Pacific.

The phosphate event is recognizable in a number of San Pedro del Gallo remnants. Phosphatic limestones and shales were recorded by Burckhardt (1930) in the Sierra Santa Rosa, Sierra de La Caja, and Sierra de Zuloaga (Figure 2.: Localities 5, 6, and 8). They are not known from San Pedro del Gallo, Sierra Catorce, the Huayacocotla Anticlinorium, or from western Cuba (Figure 2: Localities 12, 4, 3, and 24).

The upper Oxfordian to lower upper Tithonian part of the La Caja Unit E (Figures 4 and 9) 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 assignable 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: Figure 4). These data indicate that the Mazapil remnant of the SPG terrane has been transported from Southern Boreal paleolatitudes (>30°N) to Northern Tethyan paleolatitudes (<30°N to >22°N) during the early Kimmeridgian to late Tithonian interval. Ogg's preliminary paleomagnetic data for the late Tithonian indicates 25°N/S at Mazapil strongly supports the faunal data.

3. Huayacocotla Remnant (Figures 4 and 16)

The Mesozoic succession (Figure 16) begins in this area with the deposition of the Lower Jurassic (Sinemurian to lower Pliensbachian) Huayacocotla Formation, which consists of black shale, mudstone, and graywacke. A rich ammonite assemblage occurs in the lower and middle parts of the unit (Figure 4) (Burckhardt, 1930; Erben, 1956; Imlay, 1980). Bivalves and land plants have been recorded from the upper part.

The Huayacocotla Formation overlies the Mississippian to Lower Permian strata of the Guacamaya Formation with marked hiatus associated with an

Litho Unit	Description	Age	Diagnostic faunal elements	Paleobathymetry	Faunal realm/province
Unnamed limestone Unit [1]	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).	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	Abyssal	Northern Tethyan Province
"UNIT B"	Upper 5.64 m consisting of medium-bedded light-gray micrite and thin-bedded 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.	Upper	Northern Tethyan Province
"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. Boundary between Subzone 4β and 4α in upper part of Unit B.	Upper	Northern Tethyan Province
"UNIT D"	Interbedded phosphatic limestone, black chert, and red calcareous mudstone. Abundant Radiolaria and ammonites. Thickness = 13.3 m.	lateTithonian	Hybonoticeras spp., Kossmatia spp. +Subzone 4β Radiolaria.	Upper	Northern Tethyan Province
"UNIT E"	Thin-bedded black chert, dark-gray siliceous 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, Hybonoticeras, and Zone 2α1, Zone 3, and Zone 4, Subzone 4β Radiolaria.	Upper	Northern Tethyan Province
"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	Northern Tethyan Province
"UNIT G"	Red medium-bedded silty limestone and mudstone. Thickness = 6.6 m.	middle Oxfordian	Dichotomosphinctes	Inner Neritic	Southern Boreal Province
"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).	Inner Neritic	Southern Boreal Province

La Caja Formation

Figure 13. Stratigraphic summary for Sierra Santa Rosa, Cañon San Matias, near Mazapil, Zacatecas, Mexico. [1]"Unit B" of Burckhardt (1930). [2]Martin (1996) interpreted the siltstone beds at this horizon as 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 the base. From Pessagno et al. (1999).

Figure 14. Thin-bedded black radiolarian chert in La Caja Formation at Cañon San Matias, Sierra Santa Rosa (Mazapil area), Zacatecas. Chert is interbedded with dark-gray, thin-bedded micrite weathering tan.

angular unconformity. According to Nestell (1979), the Guacamaya Formation contains fusulinids with South American affinities. This likewise seems to be true of fusulinids occurring in the Guacamaya Formation at Peregrina Cañon near Ciudad Victoria (Tamaulipas). The thickness of the unit varies from 560 to 1200 m.

As far as can be determined, all references to the presence of the Upper Triassic Huizachal Formation (continental red beds) in this area are erroneous. The Huizachal has largely been confused with the Middle Jurassic Cahuasas Formation, which also consists of continental red beds (cf. Imlay, 1980).

The Cahuasas Formation consists of 40 to 1200 m of red arkosic sandstone, conglomerate, and shale that rest with angular unconformity on the Huaya-cocotla Formation (Imlay, 1980, p. 49). Imlay indicates that the Cahuasas must be older than Callovian because where it crops out on the surface, it lies disconformably below marine beds of early to middle Callovian age. In the subsurface, however, it underlies latest Bathonian to early Callovian marine shale of the Palo Blanco Formation (see further discussion of the Palo Blanco Formation in the following paragraph). Imlay also indicates that the Cahuasas must be younger than Toarcian (Early Jurassic) in that it passes downward into plant-bearing beds that are early Middle Jurassic.

The Cahuasas Formation is overlain disconformably in surface outcrops by the inner neritic early Callovian Tepexic Limestone. The Tepexic is a calcarenite containing common to abundant *Liogryphaea-nebrascaensis* and ammonites such as *Neuquenisceras neogaeum* and *Reineckeia* (Cantú-Chapa, 1969, p. 19; Imlay, 1980, p. 50). In the subsurface and at some surface localities, an inner-neritic, black-shale unit, the Palo Blanco Formation (Cantú-Chapa, 1969, p. 5; Imlay, 1980, p. 49), underlies the Tepexic Limestone and rests disconformably on the Cahuasas. The Palo Blanco Formation contains the late Bathonian to early Callovian ammonite *Kepplerites* (Cantú-Chapa, 1969, p. 5; Imlay, 1980).

The Tepexic Limestone is overlain conformably by silty black shale, siltstone, and silty micritic limestone constituting the Santiago Formation (middle Callovian to upper Oxfordian). The lower and middle


Figure 15. Medium- to thin-bedded chert in La Caja Formation, Cañon San Matias, Sierra Santa Rosa (Mazapil area), Zacatecas.

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 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.	Abyssal	Central Tethyan Province
Taman Formation T = 200–500 m. "upper thin-bedded limestone member"	Thin-bedded dark-gray to medium-gray micrite with thick interbeds 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 common ammonites.	late Tithonian	Durangites, Kossmatia, Salinites grossicostatum + very abundant Subzone 4β Radiolaria.	Upper	Northern Tethyan Province
Taman Formation "lower massively bedded limestone 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 2α1, Zone 3, and Subzone 4β.	Upper	Northern Tethyan Province
Santiago Formation	Silty black shale, mudstone, micrite. Containing ammonites. Radiolaria occurring in uppermost part. Thickness = ~169 m.	early Callovian to late Oxfordian	Reineckeia, Dichotomosphinctes, Discosphinctes, Ochetoceras.	Outer Neritic	Northern Tethyan Province
Tepexic Limestone	Calcarenite containing ammonites and bivalves. Thickness = ~ 39 m.	late early Callovian	Reineckeia, Neuqueniceras.	Inner Neritic	Southern Boreal Province
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	Southern Boreal Province

Figure 16. Stratigraphic summary for Taman–Tamazunchale area, Huayacocotla remnant (part), San Luis Potosí, 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 of 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. From Pessagno et al. (1999).

Figure 17. Massively bedded, medium-gray micritic limestone containing abundant Radiolaria and rare ammonites interbedded with thin layers of black shale. Zone 2, Subzone 2 alpha. Upper Jurassic: upper Kimmeridgian. ''Lower massively bedded member'' of Taman Formation exposed on Mexican Route 85 (Nuevo Laredo–Mexico, D.F. highway) at locality MX 82-16 (km 267.3) of Pessagno et al. (1987), in the Taman-Tamazunchale area (San Luis Potosí) in Huayacocotla Anticlinorium. **For location, see** Figure 3: Locality 3.
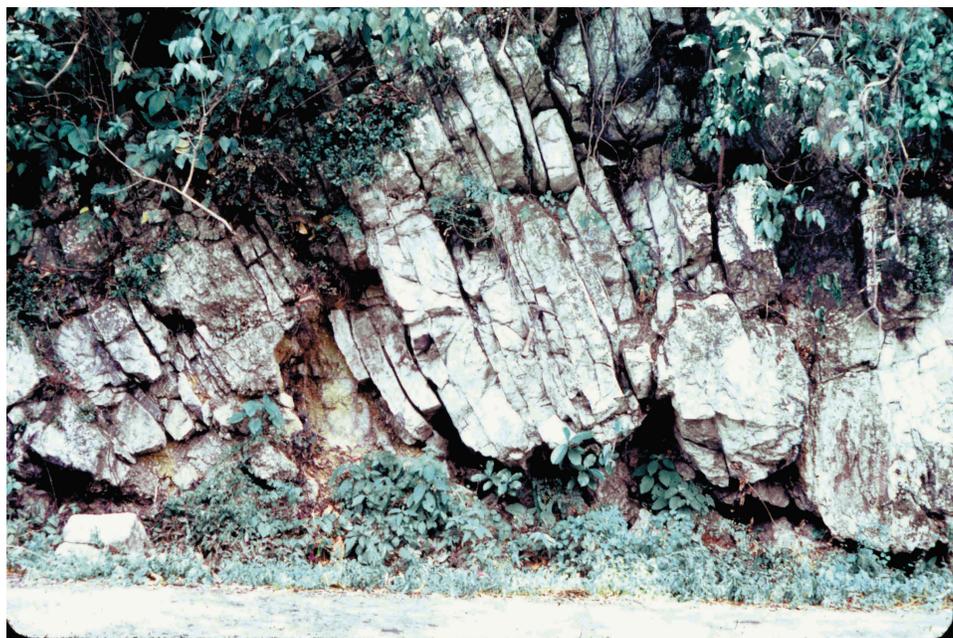
parts of the Santiago contain bivalves (e.g., small *Ostrea*, senior author's observations) and ammonites; microfacies analysis by Longoria (1984) indicates that most of this unit was deposited at inner-neritic depths. The uppermost (upper Oxfordian) part of the Santiago Formation (e.g., at Taman, San Luis Potosí) contains common Radiolaria as well as ammonites (Pessagno et al., 1987). These Santiago strata reflect the same sudden change in water depths from inner neritic to outermost neritic during the late Oxfordian that was noted in the San Pedro del Gallo and Mazapil remnants. The Santiago Formation is overlain conformably by the Taman Formation (*sensu* Pessagno et al., 1984, 1987).

The Taman Formation (thickness = ∼30–60 m) consists of two informal units (Figures 16, 17, and 18): (1) a massively bedded to medium-bedded micritic limestone member (lower Kimmeridgian to upper Tithonian) and (2) a thin-bedded micritic limestone member (upper Tithonian) (Pessagno et al. 1984, 1987). Both members of the Taman Formation contain profusely abundant Radiolaria, rare foraminifera (chiefly Textulariina), common siliceous sponge spicules, ammonite aptychi, and occasional ammonites. The abundance of Radiolaria, together with the sparse benthonic foraminiferal assemblage and the rarity of ammonites (aragonite), suggests that Taman strata were deposited at upper abyssal depths at or somewhat below the ACD (aragonite compensation level) (see microfacies analysis in Longoria, 1984).

The Taman is overlain conformably by the latest Tithonian (Late Jurassic) to Berriasian (Early Cretaceous) Pimienta Formation (*sensu* Pessagno et al., 1984, 1987) and overlain conformably by the Berriasian to Valanginian Chapulhuacán Limestone). The Pimienta Formation includes 200–400 m of light-gray, thin-bedded micritic limestone with thick shale intervals, thin-bedded black radiolarian chert, and

Figure 18. Medium-bedded to thin-bedded dark-gray micrite weathering buff with thick intervals of black mudstone and shale containing dark-gray micrite nodules. Bedded micrite and micrite nodules contain abundant Radiolaria and common ammonites. ''Upper thin-bedded member of Taman Formation'' of Pessagno et al. (1987) north of Río Moctezuma and Barrio de Guadalupe near Taman.

light-green vitric tuff; it contains abundant Radiolaria, calpionellids, siliceous sponge spicules, and common ammonites (Figure 16). Pimienta deposition likewise took place at upper abyssal depths somewhat above the ACD.

The Chapulhuacán Limestone consists of about 30 m of medium to massively bedded, very fine-grained, cream to light-gray micrite with frequent nodules of black chert. This unit contains abundant Radiolaria, calpionellids, nannoconids, and planktonic foraminifera, as well as rare ammonites at most localities (senior author's observations as well as those of Longoria, 1984, p. 69). Chapulhuacán strata were also deposited at upper abyssal depths somewhat above the ACD. Deposition continued at these depths during the remainder of the Cretaceous.

The upper Bathonian (Middle Jurassic) to upper Oxfordian (Upper Jurassic) part of the succession contains Boreal megafossils such as the ammonite *Kepplerites* in the Palo Blanco Formation (Cantú-Chapa, 1969, p. 5; Imlay, 1980, p. 50). Elsewhere in western North America, this ammonite is known from Middle Jurassic strata from the upper Bathonian part of the Snowshoe Formation, Izee terrane (east-central Oregon), and from Boreal Middle Jurassic strata as far north as Alaska (Imlay, 1980; Pessagno and Blome, 1986; Pessagno et al., 1986, 1987).

The lower Kimmeridgian to upper Tithonian (Upper Jurassic) part of the succession (Taman Formation, *sensu* Pessagno et al., 1984, 1987) contains a rich Northern Tethyan Radiolarian assemblage characterized by the abundance and diversity of pantanelliids and by the presence of common to abundant *Parvicingula* and *Praeparvicingula*. Calpionellids (Tethyan) occur in the upper Tithonian part of the Taman Formation. Moreover, the megafossil assemblage is Tethyan in aspect (Figures 4 and 16) (Imlay, 1980; Cantú-Chapa, 1989). The Pimienta Formation, as well as the overlying Chapulhuacán Limestone, is characterized by a Tethyan ammonite assemblage and by a microfossil assemblage, including abundant calpionellids and nannoconids lacking *Parvicingula/Praeparvicingula*. This association of faunal elements is indicative of the Central Tethyan Provinces (Figures 5 and 6).

These data indicate that the Huayacocotla remnant of the SPG terrane underwent tectonic transport from Southern Boreal paleolatitudes (>30° N) during the late Bathonian (Middle Jurassic) to Northern Tethyan paleolatitudes by the early Kimmeridgian (Late Jurassic) to Central Tethyan paleolatitudes (<22° N) during the Berriasian (Early Cretaceous).

COMPARISON OF PALEOBATHYMETRY OF SAN PEDRO DEL GALLO TERRANE TO THAT OF COUILTECANO TERRANE

As noted by Pessagno et al. (1999), the paleobathymetric fingerprint of the San Pedro del Gallo terrane differs markedly from that occurring to the east-northeast of the Walper Megashear in the Coahuiltecano terrane (COAH)(emended, Pessagno et al., 1999). In the Coahuiltecano terrane (e.g., Peregrina Cañon near Ciudad Victoria, Tamaulipas), no Mesozoic marine deposits older than late Oxfordian occur. The paleobathymetric fingerprint of this terrane was (1) inner neritic during the late Oxfordian (Late Jurassic) to about the Barremian (Early Cretaceous) and (2) bathyal to abyssal during the remainder of the Cretaceous (Aptian to Maastrichtian).

Figure 19 shows a comparison of the composite paleobathymetry of the SPG terrane and the COAH terrane along opposing sides of the Walper Megashear. As can be seen from this illustration, the paleobathymetric signature of the COAH is totally different from that of the SPG. The COAH paleobathymetric signature can be substantiated by examining the succession exposed at Peregrina Cañon and elsewhere along the eastern front of the Sierra Madre Oriental (e.g., Longoria, 1984). Moreover, it can be documented by examining published well records from the Tampico Embayment area presented by Burckhardt (1930), Muir (1936), Imlay (1980), López-Ramos (1985), and numerous other workers. Burckhardt (1903, p. 95) reported inner-neritic megafossils (including *Ostrea* and hydrocorals) in upper Tithonian oolitic limestone from a depth of 986–1029 m in well Chocoy No. 2, ∼50 km northwest of Tampico. Inner-neritic strata continue upward into the Berriasian and Valanginian (lower part of Tamaulipas Formation).

Near Panuco Well Panuco No. 82 to the southwest of Tampico, the succession includes Upper Jurassic (lower Tithonian) black carbonaceous limestones and shales with *Aptychus*, pectenacid *Aulacomyella*, and ammonites like *Mazaplites zitteli* Burckhardt. These strata lithologically appear to be similar to those of the Taman Formation and the La Caja Formation. *Ostrea*, bryozoans, and the remains of conifers occur at two horizons. These may represent inner-neritic forms that have been displaced by turbidity currents to bathyal or abyssal depths (cf. Mazapil area: Martin, 1996; Cross, 1999, 2001).

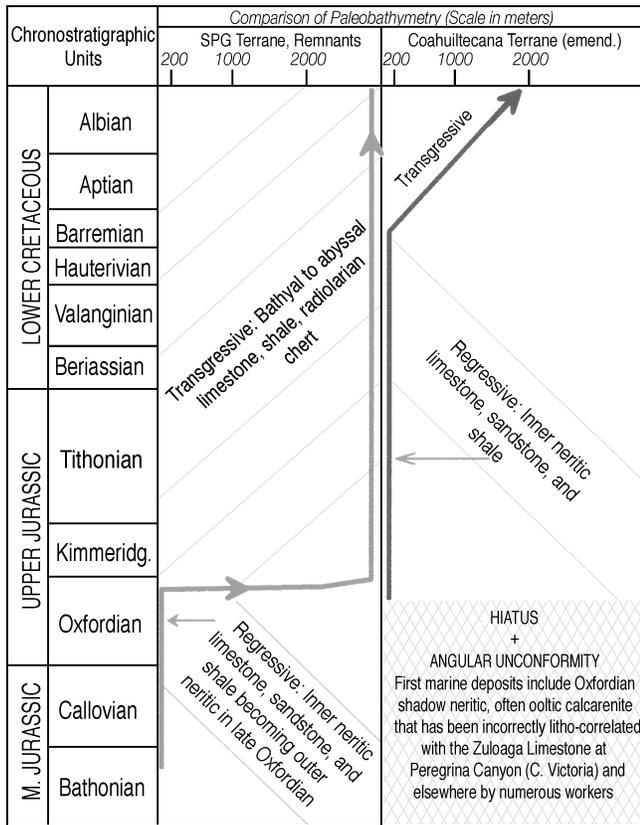By Late Cretaceous times, the paleobathymetric record of the Mexican SPG terrane remnants and

Figure 19. Comparison of paleobathymetry on adjoining sides of the Walper Megashear and the approximate latitude of Ciudad Victoria, Tamaulipas, Mexico.

COAH terrane remnants become similar. Both terranes show a similar lithostratigraphic record during the remainder of the Late Cretaceous. At this point in time (about the Albian/Cenomanian) it would appear that terrane amalgamation had occurred and movement along the Walper Megashear had ceased.

Anomalies to the scenario described above are inner-neritic platform deposits (e.g., El Abra Limestone: Rudistid reef complex in Sierra del Abra, west of Tampico) that formed during the Albian to Turonian interval (Murray, 1961). These strata (rudistid and miliolid limestones) were probably deposited on seamounts at inner-neritic depths and relate to remnant horst and graben topography resulting from previous rifting.

CONCLUSIONS

The paleogeographic framework resulting from our studies of the San Pedro del Gallo terrane, the Coahuiltecano terrane, and the Walper Megashear can be used to determine the origin of the Gulf of

Mexico. With this paleogeographic framework in mind, it is apparent that no marine deposition occurred in the Gulf of Mexico until the late Oxfordian. In the Coahuiltecano terrane at Peregrina Cañon near Ciudad Victoria, massively bedded medium-gray calcarenite with molluscan fragments and oolitic limestone (50–85 m) overlie the Lower to Middle Jurassic continental red beds of the La Joya Formation with angular unconformity. These strata frequently have been assigned to the Zuloaga Limestone in eastern Mexico (e.g., Diaz, 1956). However, they are totally unlike the Zuloaga Limestone where we have observed it—at its type locality in the Sierra Sombretillo, Mazapil (Sierra Santa Rosa), and San Pedro del Gallo. West of the Walper Megashear the Zuloaga Limestone is dominantly micritic with an abundance of black chert nodules and styolites. Microfossils that the senior author has observed in thin sections of the limestone and as free HF acid residues from the chert nodules are more recrystallized than those in the overlying strata. The preservation of the microfossils, taken together with the occurrence of numerous
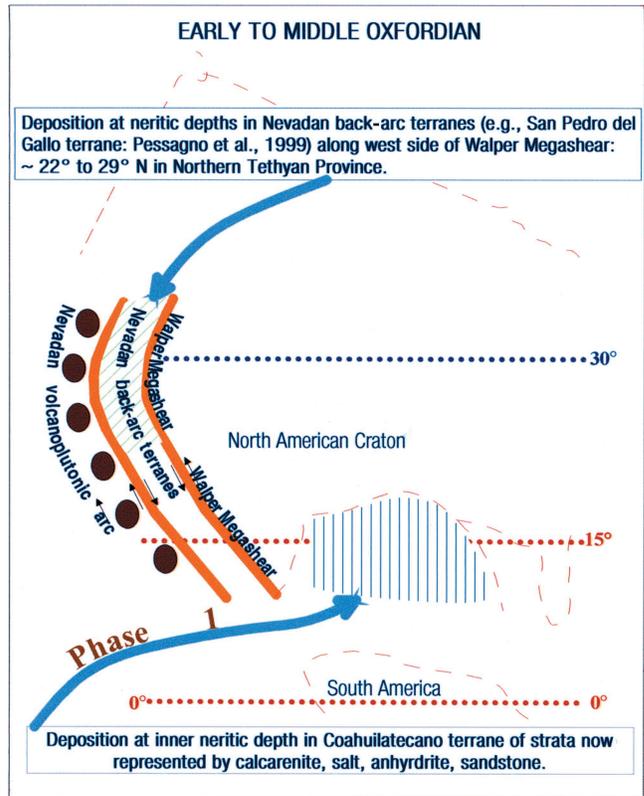

Figure 20. Paleogeographic reconstruction for the Oxfordian. Note that during the early to middle Oxfordian, no remnants were farther south than ∼22° to 29° degrees north.

stylolites, suggests that these strata are more meta-morphose than overlying strata and were exposed to a pre-Nevadan orogenic event— the opening of the Gulf of Mexico.

Tectonostratigraphic data from our investigations in west-central and east-central Mexico suggest that the Gulf of Mexico formed in two phases:

1) Rifting and subsequent sea floor spreading during the Late Jurassic (middle–late Oxfordian). Phase 1 deposition included oolitic calcareous sand, calcareous mud, and evaporite. All but the southwestern portion of the Gulf of Mexico formed during Phase 1 (Figure 21).

2) Northwest-to-southeast tectonic transport of the allochthonous San Pedro del Gallo terrane along the west side of Walper Megashear during the late Bathonian/early Callovian to latest Tithonian/earliest Berriasian. Phase 2 deposition in the Nevadan back-arc domain during the Kimmeridgian and Tithonian (Late Jurassic) included calcareous mud, radiolarian ooze, and siliciclastics (turbidites) (Figures 8, 13, 16, and 21).

This interpretation differs from that of Pessagno et al. (1984, 1987, 1999), Buffler et al. (1981), and other workers by suggesting that the Gulf of Mexico formed in the Oxfordian rather than the late Bathonian or early Callovian. Given that all remnants of the SPG were at higher latitudes (Boreal realm: 30° to 40° N) during the late Bathonian to Oxfordian interval, it is likely that this earlier hypothesis is incorrect. Combined faunal and floral data indicate that the San Pedro del Gallo terrane was in a back-arc position at approximately the same latitude as the Foot Hills terrane of the Sierra Nevada during the middle Oxfordian. Given the faunal data (not just Radiolaria, but megafossils such as *Buchia* and ammonites), as well as some paleomagnetic data from Ogg, it is probable that these SPG remnants might represent some of the missing Upper Jurassic back arc from farther north (Nevada?)

In spite of the fact that the San Pedro del Gallo terrane was situated at higher latitudes, its stratigraphy also reflects the opening of the Gulf of Mexico orogenic event. This thesis is supported by:

1) The sudden change in paleobathymetry from neritic to upper abyssal depths between the middle Oxfordian and early Kimmeridgian in the successions of all San Pedro del Gallo remnants (Figures 3, 4, 8, 13, 16, and 19).
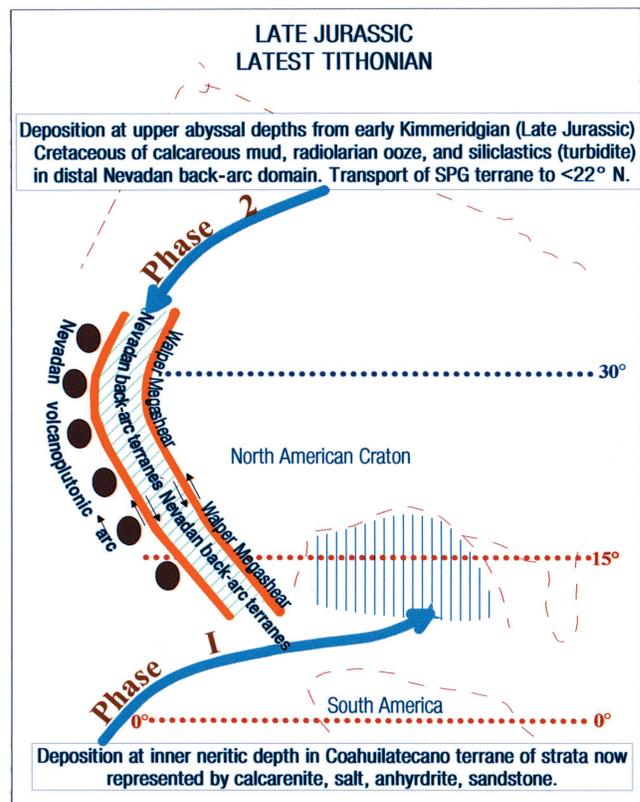

Figure 21. Paleogeographic reconstruction for the latest Tithonian. Note that by the latest Tithonian, the San Pedro del Gallo terrane back-arc area had become part of the Gulf of Mexico.

2) The presence of a prominent disconformity between the Caja Formation and unnamed siltstones in the San Pedro del Gallo and Mazapil remnants (Figures 4, 8, 13, and 16) and between the Taman Formation and the Santiago Formation in the Huayacocotla Anticlinorium (Figure 13).

The sudden influx of siliciclastics in the Sierra Nevada (Mariposa and Monte del Oro Formations) and the Klamath Mountains (Galice Formation) during the middle Oxfordian may be a direct reflection of the same event (Imlay, 1980; Pessagno et al., 1993b, 2000).

ACKNOWLEDGMENTS

REFERENCES CITED

Addate, T., W. Stinnesbeck, and J. Remane, 1995, The Jurassic-Cretaceous boundary in Northeastern Mexico: Confrontation and correlations by microfacies, clay minerals, mineralogy, calpionellids, and ammonites: Geobios, no. 17, p. 37–56.

Aita, Y., and J. A. Grant-Mackie, 1992, Late Jurassic Radiolaria from Kowhai Point Siltstone, Murihku terrane, North Island, New Zealand, in K. Ishizaki and T. Saito, eds., Centenary of Japanese micropaleontology: Tokyo, Terra Scientific Publishing Co., p. 375–382.

Arkell, W. J., 1956, Jurassic geology of the world: London, Oliver and Boyd, 806 p.

Baumgartner, P. O., 1984, Middle Jurassic–Early Cretaceous low latitude radiolarian zonation based on unitary associations and age of Tethyan radiolarites: Eclogae Geologicae Helvetiae, v. 77, no. 3, p. 729–837.

Baumgartner, P. O., 1987, Age and genesis of Tethyan Jurassic radiolarites: Eclogae Geologicae Helvetiae, v. 80, p. 831–879.

Blome, C. D., and K. M. Reed, 1993, Acid processing of pre-Tertiary radiolarian cherts and its impact on faunal content and biostratigraphic correlation: Geology, v. 21, p. 177–188.

Buffler, R. T., J. S. Watkins, F. J. Shaub, and J. L. Worzel, 1981, Structure and early geologic history of the deep central Gulf of Mexico Basin, in R. H. Pilger Jr., ed., The origin of the Gulf of Mexico and early opening of the Central North Atlantic Ocean: Proceedings of a symposium of Louisiana State University, Baton Rouge, Louisiana, March, 1980, p. 41–51.

Burckhardt, C., 1903, Beiträge zur Kenntniss der Jura- und der Kreide-formation der Cordillere: Palaeontographica, v. 50, p. 1–144.

Burckhardt, C., 1910, Estudio geologico de la región de San Pedro del Gallo (Durango): Instituto de Geologico de México, Parergones tomo III, v. 6, p. 30–357.

Burckhardt, C., 1912, Faunes jurassiques et crétaciques de San Pedro del Gallo: Institudo de Geologico México Boletin 29, 264 p.

Burckhardt, C., 1919, 1921, Faunas jurásicas de Symon (Zacatecas): Instituto Geologico México Boletin, v. 33, 135 p.

Burckhardt, C., 1927, Cefalópodos del Jurásico medio de Oaxaca y Guerrero: Instituto Geologico México Boletin , v. 47, 108 p.

Burckhardt, C., 1930, Étude synthétique sur le Mésozoïque Méxicain: Mémoire de la Société Paléontologique Suise, v. 49, p. 1–123.

Campa, M. F., 1983, The Mexican thrust belt, in D. G. Howell, ed., Tectonostratigraphic terranes of the Circum-Pacific Region: Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 1, p. 299–313.

Cantú-Chapa, A., 1969, Estratigrafía del Jurásico medio-superior del subsuelo de Poza Rica, Veracruz: Revista del Instituto Mexicano del Petróleo, v. 1, no. 1, p. 3–9.

Cantú-Chapa, A., 1971, La serie Huasteca (Jurásico medio-superior) del centro este de México: Revista del Instituto Mexicano del Petróleo, v. 3, no. 2, p. 17–40.

Cantú-Chapa, A., 1989, Precisiones sobre el limite Jurásico-Cretácico en el subsuelo del este de México: Revista de la Sociedad Mexicana de Paleontolgía, v. 3, no. 1, p. 26–69.

Contreras-Montero, B., A. Martinez-Cortez, M. Gomez-Luna, 1988, Bioestratigrafia y sedimentologia del Jurásico Superior en San Pedro del Gallo, Durango, Mexico: Revista del Instituto Mexicano del Petróleo, v. 20, no. 3, p. 5–49.

Cross, E. K., 1999, Petrochemical, microfacies, and stratigraphic investigations of the upper Tithonian phosphorite interval, La Caja Formation, Zacatecas, Northeastern Mexico: Master's thesis, The University of Texas at Dallas, 208 p.

Cross, E. K., 2001, Tectonic evolution of phosphorite bearing hydrocarbon sourced deep water remnants of the San Pedro del Gallo terrane in northeastern Mexico: Ph. D. dissertation, The University of Texas at Dallas, 331 p.

Diaz, T., 1956, Ruta: Ciudad Victoria, Tamaulipas— Cañon de Peregrina, in Estratigrafía del Cenozoico y del Mesozoico a lo largo de la Carretera entre Reynosa, Tamaulipas, y México, D. F., Tectónica de la Sierra Madre Oriental; Volcanismo en el Valle de México: 20th Congreso Geológico Internacional, Excursions A-14 and C-6, p. 63–68.

Erben, H. K., 1956, El Jurásico Inferior de México y sus amonitas, México D. F.: 20th Congreso Geológico Internacional, 393 p.

Haczewski, G., 1976, Sedimentological reconnaissance of the San Cayetano Formation; an accumulative continental margin in the Jurassic of Western Cuba: Acta Geologica Polonica, v. 26, p. 331–353.

Hagstrum, J. T., and Murchey, B. L., 1996, Paleomagnetism of Jurassic radiolarian chert above the Coast Range Ophiolite at Stanley Mountain, California and implications for its paleogeographic origins: Bulletin of the Geological Society of America, v. 108, p. 643–652.

Hopson, C. A., J. M. Mattinson, and E. A. Pessagno Jr., 1981, Coast Range ophiolite, western California, in W. G. Ernst, ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, Rubey v. 1, p. 419–510.

Hopson, C. A., E. A. Pessagno Jr., J. M. Mattinson, B. P. Luyendyk, W. Beebe, D. M. Hull, I. M. Muñoz, and C. D. Blome, 1996, Coast Range ophiolite as paleo-equatorial mid-ocean lithosphere, in W. R. Dickinson, C. A. Hopson, and J. B. Saleeby, Alternate origins of the Coast Range Ophiolite (California): Introduction and implications. GSA Today, v. 6, no. 2, p. 1–10.

Hull, D. M., 1991, Upper Jurassic radiolarian biostratigraphy of the lower member of the Taman Formation, east-central Mexico, and of volcanopelagic strata overlying the Coast Range Ophiolite, Stanley Mountain,

southern California Coast Ranges: Ph.D. dissertation, The University of Texas at Dallas, 696 p.

Hull, D. M., 1995, Morphologic diversity and paleogeographic significance of the Family Parvicingulidae (Radiolaria): Micropaleontology, v. 41, no. 1, p. 1–48.

Hull, D. M., E. A. Pessagno Jr., C. D. Blome, C. A. Hopson, and I. M. Muñoz, 1993, Chronostratigraphic assignment of volcanopelagic strata above the Coast Range ophiolite, in G. Dunn and K. McDougall, eds., Mesozoic paleogeography of the West United States— II: Pacific Section Society for Sedimentary Geology (SEPM), Book 71, p. 157–170.

Hull, D. M., C. D. Blome, and E. A. Pessagno Jr., 1997, Paleomagnetism of Jurassic radiolarian chert above the Coast Range Ophiolite at Stanley Mountain, California, and its implications for its paleogeographic origins: Discussion and reply: Geological Society of America Bulletin, v. 109, p. 1633–1639.

Imlay, R. W., 1936, Evolution of the Coahuila Peninsula, Mexico, Part IV, Geology of the western part of the Sierra de Parras, Coahuila, Mexico: Geological Society of America Bulletin 49, p. 1651–1694.

Imlay, R. W., 1937, Geology of the middle part of the Sierra de Parras, Coahuila, Mexico: Geological Society of America Bulletin, v. 48, p. 587–630.

Imlay, R. W., 1938, Studies in the Mexican Geosyncline: Geological Society of America Bulletin, v. 49, p. 1651–1694.

Imlay, R. W., 1939, Upper Jurassic ammonites from Mexico: Geological Society of America Bulletin, v. 50, p. 1–78.

Imlay, R. W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U. S. Geological Survey Professional. Paper 106, p. 1–134.

Jones, D. L., N. J. Silberling, and J. Hillhouse, 1977, Wrangellia— a displaced terrane in northwestern North America: Canadian Journal of Earth Sciences, v. 14, no. 11, p. 2565–2577.

Kennett, J. P., 1982, Marine Geology: Prentice Hall, Englewood Cliffs, New Jersey, 646 p.

Kiessling, W., 1995, Palökologische Verwertbarkeit Ober-Jurassisch Unterkretazischer Radiolarienfaunen mit Beispielen: Ph.D. dissertation, Erlangen University, Erlangen, Germany, 465 p.

Kiessling, W., 1999, Late Jurassic Radiolarians from the Antarctic Peninsula: Micropaleontology, v. 45, suppl. 1, p. 1–96.

Kiessling, W., and R. Scasso, 1996, Ecological perspectives of Late Jurassic radiolarian faunas from the Antarctic Peninsula, in A. C. Riccardi, ed., Advances in Jurassic research: GeoResearch Forum, v. 1–2, p. 317–326.

Lewis, J. F., and G. Draper, 1990, Geology and tectonic evolution of the northern Caribbean margin, in G. Dengo and J. E. Case, eds., The Caribbean region: The Geology of North America, v. H,: Boulder, Colorado, Geological Society of America, p. 77–140.

Longoria, J. F., 1984, Mesozoic tectostratigraphic domains in east-central Mexico, in G. E .G. Westermann, ed., Jurassic-Cretaceous biochronology and paleogeography of North America: Geological Association of Canada Special Paper 27, 65–76.

Longoria, J. F., 1985a, Tectonic transpression in the Sierra Madre Oriental, northeastern Mexico: An alternative model. Geology, v. 13, no. 7, p. 453–456.

Longoria, J. F., 1985b, Tectonic transpression in northeast Mexico: Its relation to sea floor spreading in the Gulf of Mexico: Gulf Coast Association of Geological Societies, Transactions, v. 35, p. 199.

Longoria, J. F., 1986, Tectonic transpression in the Sierra Madre Oriental, northeast Mexico: An alternative model. Reply: Geology, v. 14, no. 10, p. 809–810.

Longoria, J. F., 1987, Oblique subduction and kinematics of the American Plate: Evidence from the stratigraphic record of Mexico, in T. W. C. Hilde and R. L. Carlson, conveners, Geodynamics Symposium, Texas A & M University, College Station, 2 p.

Longoria, J. F., 1994, Recognition and characteristics of a strike-slip fault system in Mexico and its Mesozoic transpressional regime: Implications in plate tectonics and paleogeographic reconstruction: Departmento de Geologia, Universidad de Sonora, Boletin 11, no. 1, p. 77–104.

López-Ramos, E., 1985, Geología de México, Tomo II: Impresiones Resendiz, Mexico, D. F., 453 p.

Martin, C. B., 1996, Tectonostratigraphic analysis of the Upper Jurassic through Lower Cretaceous in the Mazapil, Sierra de Jimulco, and San Pedro del Gallo regions of north-central Mexico: Master's thesis, The University of Texas at Dallas, p. 1–148.

McWilliams, M. O., and D. G. Howell, 1982, Exotic terranes of western California: Nature, v. 297, p. 215–217.

Meng, X, 1997, Radiolarian biostratigraphy of the Upper Jurassic of San Pedro del Gallo terrane, north-central Mexico, and the Lower Cretaceous of Nooksack Group, Nooksack terrane, Northwestern Washington: Ph.D. dissertation, the University of Texas at Dallas, 352 p.

Montgomery, H. A., E. A. Pessagno, Jr., and I. Muñoz, 1992, Jurassic (Tithonian) Radiolaria from La Désirade (Lesser Antilles): Preliminary Paleontological and Tectonic Implications: Tectonics, v. 11, no. 6, p. 1426–1432.

Montgomery, H. A., E. A. Pessagno Jr., and J. L. Pindell, 1994a, A 195 Ma terrane in a 165 Ma sea: Pacific origin of Caribbean Plate. GSA Today, v. 4, no. 1, p. 3–6.

Montgomery, H., E. A. Pessagno Jr., J. A. Lewis, and J. H. Schellekens, J. H., 1994b, Paleogeography of the Jurassic fragments in the Caribbean: Tectonics, v. 13, p. 725–732.

Muir, J. M., 1936, Geology of the Tampico Embayment area: AAPG, 280 p.

Murray, G. E., 1961, Geology of the Atlantic and Gulf Coastal Province of North America , C. Croneis, ed.: New York, Harper and Brothers, p. 1–692.

Myczynski, R., 1989, Ammonite biostratigraphy of the Tithonian of western Cuba: Annales Societatis Geologorum Poliniae, v. 59, p. 43–125.

Myczynski, R., 1994, Caribbean ammonite assemblages from Upper Jurassic–Lower Cretaceous sequences of Cuba: Studia Geologica Polonica, v. 105, p. 91–108.

Myczynski, R., and A. Pszczólkowski, 1994, Tithonian stratigraphy and microfacies in the Sierra del Rosario, western Cuba: Studia Geologica Polonica, v. 105, p. 7–38.

Nestell, M. K., 1979, Lower Permian fusulinids from the vicinity of Tianguistengo, Hidalgo, Mexico [abs.]: Texas Academy of Sciences Meeting, Arlington, Texas, Program of Abstracts, p. 40.

Ogg, J. G., 1983, Magnetostratigraphy of Upper Jurassic and lowest Cretaceous sediments, Deep Sea Drilling Site 534, Western North Atlantic, in S. Orlofsky, ed., Initial Reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 76, p. 685–697.

Pessagno Jr., E. A., 1995, Stratigraphic evidence for Northwest to Southeast movement along the west side of the Walper Lineament: Geological Society of America Abstracts with Programs, v. 27, no. 6, p. A-75.

Pessagno Jr., E. A., and C. D. Blome, 1980, Upper Triassic and Jurassic Pantanelliinae from California, Oregon and British Columbia: Micropaleontology, v. 26, no. 3, p. 225–273, pl. 1–11.

Pessagno Jr., E. A., and R. L. Newport, R. L., 1972, A technique for extracting Radiolaria from radiolarian cherts: Micropaleontology, v. 18, no. 2, p. 231–234.

Pessagno Jr., E. A., and C. D. Blome, 1986, Faunal affinities and tectonogenesis of Mesozoic rocks in the Blue Mountains Province of eastern Oregon and western Idaho, in T. L. Vallier and H. C. Brooks, eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington: Geologic implications of Paleozoic and Mesozoic paleontology and biostratigraphy: U. S. Geological Survey Professional Paper 1435, p. 65–78.

Pessagno Jr., E. A., and D. M. Hull, 2002, Upper Jurassic (middle Oxfordian Radiolaria) from the Sula Islands (East Indies): Their taxonomic, biostratigraphic, and paleogeographic significance: Micropaleontology, v. 48, no. 3, p. 229–256.

Pessagno Jr., E. A., C. D. Blome, and J. F. Longoria, 1984, A revised radiolarian zonation for the Upper Jurassic of western North America: Bulletin of American Paleontology, v. 87, no. 320, p. 1–51.

Pessagno Jr., E. A., P. A. Whalen, and K. Y. Yeh, 1986, Jurassic Nassellariina (Radiolaria) from North American Geologic Terranes: Bulletins of American Paleontologyeoe, v. 91, no. 326, p. 1–75.

Pessagno Jr., E. A., J. F. Longoria, N. MacLeod, and W. M. Six, W. M., 1987, Upper Jurassic (Kimmeridgian-upper Tithonian) Pantanelliidae from the Taman Formation, east-central Mexico: Tectonostratigraphic, chronostratigraphic, and phylogenetic implications, in S. J. Culver, ed., Studies of North American Jurassic Radiolaria, Part. I: Cushman Foundation for Foramineral Research. Special Publication 23, p. 1–51.

Pessagno Jr., E. A., W. M. Six, and Q. Yang, 1989, The Xiphostylidae Haeckel and Parvivaccidae, n. fam. (Radiolaria), from the North American Jurassic: Micropaleontology, v. 35, no. 3, p. 193–255.

Pessagno Jr., E. A., D. M. Hull, and I. Pujana, 1991, Correlation of Circum-Pacific upper Tithonian Boreal and Tethyan strata in Northern and Southern Hemispheres: Synthesis of radiolarian and ammonite biostratigraphic and chronostratigraphic data: 3rd International Symposium on Jurassic Stratigraphy, Poitiers, France, Abstract Volume, p. 97.

Pessagno Jr., E. A., C. D. Blome, D. Hull, and W. M. Six Jr., 1993a, Middle and Upper Jurassic Radiolaria from the Western Klamath terrane, Smith River subterrane, northwestern California— their biostratigraphic, chronostratigraphic, geochronologic, and paleolatitudinal significance: Micropaleontology, v. 39, no. 2, p. 93–166.

Pessagno Jr., E. A., D. M. Hull, J. F. Longoria, and M. E. Kelldorf, M. E., 1993b, Tectonostratigraphic significance of the San Pedro del Gallo area, Durango, Western Mexico, in G. Dunn and K. McDougall, eds., Mesozoic aleogeography of the Western United States— II: Pacific Section Society for Sedimentry Geology (SEPM), Book 71, p. 141–156.

Pessagno Jr., E. A., A. Cantú-Chapa, D. M. Hull, J. G. Ogg, and J. Urrutia-Fucugauchi, 1996, New data from North America on the Placement of the Jurassic-Cretaceous Boundary: Boletin do 4° Simpósio sobre Cretáceo do Brasil, p. 15–20.

Pessagno Jr., E. A., D. M. Hull, C. B. Martin, X. Meng, H. Montgomery, J. G. Ogg, and J. Urrutia-Fucugauchi, 1999, Stratigraphic evidence for northwest to southeast tectonic transport of Jurassic terranes in Central Mexico and the Caribbean (western Cuba), in P. Mann, ed., Caribbean Sedimentary Basins: Sedimentary Basins of the World, v. 4, p. 123–150.

Pessagno Jr., E. A., D. M. Hull, and C. A. Hopson, 2000, Tectonostratigraphic significance of sedimentary strata occurring within and above the Coast Range ophiolite (California Coast Ranges) and the Josephine ophiolite (Klamath Mountains), northwest California, in Y. Dilek, E. M. Moores, D. Elthon, and A. Nicolas, eds., Ophiolites and oceanic crust: New insights from field studies and the Ocean Drilling Program: Geological Society of America Special Paper 349, p. 383–394.

Pujana, Ignacio, 1989, Stratigraphical distribution of the multicyrtid Nassellariina (Radiolaria) at the Jurassic-Cretaceous boundary in the Neuquén Basin, Argentina: Zentralblatt für Geologie und Paläontologie, v. 5–6, p. 1043–1052.

Pujana, Ignacio, 1991, Pantanelliidae (Radiolaria) from the Tithonian of the Vaca Muerta Formation, Neuquén, Argentina: Neues Jarbruch Geologie Paläontologie Abhandlung, v. 180, no. 3, p. 391–408.

Pujana, Ignacio, 1993, Middle Jurassic (Bathonian-Callovian) Radiolaria from Chacay Melehue, Cordillera del Viento, Province of Neuquén, Argentina: Master's thesis, the University of Texas at Dallas, 87 p.

Pujana, Ignacio, 1996, Occurrence of Vallupinae (Radiolaria) in the Neuquén Basin: Biostratigraphic Implications, *in* A. C. Riccardi, ed., Advances in Jurassic research,: GeoResearch Forum, v. 1–2, p. 459–456.

Salvador, A., G. E. G Westermann, F. Olóritz, M. B. Gordon, and H. J. Gursky, 1992, Meso-America, *in* G. E. G Westermann, ed., The Jurassic of the Circum-Pacific, Chapter 5: Cambridge, U.K., Cambridge University Press, 676 p.

Sandoval, J., and G. E. G. Westermann, G. E. G, 1988, The Bajocian (Jurassic) ammonite fauna of Oaxaca, Mexico: Journal of Paleontology, v. 60, p. 1220–1271.

Sandoval, J., G. E. G. Westermann, and M. C. Marshall, 1990, Ammonite fauna, stratigraphy, and ecology of the Bathonian-Callovian (Jurassic) Tecocoynca Group, south Mexico: Paleontographica, v. A210, p. 93–149.

Sedlock, R. L., F. Ortega-Gutiérrez, and R. C. Speed, 1993, Tectonostratigraphic terranes and tectonic evolution of Mexico: Geogical Society of America Special Paper No. 278, p. 1–153.

Taylor, D. G., J. H. Callomon, R. Hall, P. L. Smith, H. W. Tipper, and G. E. G. Westermann, 1984, Jurassic ammonite biogeography of western North America: The tectonic implications, *in* G. E. G. Westermann, ed., Jurassic-Cretaceous biochronology and paleogeography of North America: Geological Society of Canada Special Paper No. 27, p. 121–141.

Verma, H. M., and G. E. G. Westermann, 1973, The Tithonian (Jurassic) ammonite fauna and stratigraphy of Sierra de Catorce, San Luis Potosí, Mexico: Bulletins of American Paleontology, v. 63, p. 107–278.

von Hillebrandt, A., P. Smith, G. E. G. Westermann, and J. H. Callomon, 1992, Ammonite zones of the circum-Pacific region *in* G. E. G. Westermann, ed., The Jurassic of the circum-Pacific: Cambridge, England, Cambridge University Press, 676 p.

Yeh, K., and Y. Cheng, 1996, Jurassic Radiolarians from the northwest coast of Busuanga Island, North Palawan Block, Philippines: Micropaleontology, v. 42, no. 2, p. 93–124.