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Mexico as the Western Margin of Pangea Based on Biogeographic Evidence from the Permian to the Lower Jurassic

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ABSTRACT

In this paper, ammonite biostratigraphy and biogeography are used as the basis for an investigation of the origin of the Gulf of Mexico. Three key observations indicate a Pacific rather than an Atlantic origin for the Gulf of Mexico:

1) The Bajocian ammonite *Stephanoceras*, which occurs throughout the western American margin (Alaska, Canada, United States, Venezuela, Peru, Argentina, and Chile), has also been recorded in the base of the Tecocoyunca Series in Oaxaca (southern Mexico).

2) The Bathonian and Callovian transgressive cycles, which have been recorded in eastern and southeastern Mexico, have been dated on the basis of the ammonites *Wagnericeras* and *Reineckeia*, which are of East Pacific affinity and have been recorded in the subsurface of the Gulf of Mexico coastal plain. The transgressions started in Oaxaca and ended with the Gulf of Mexico opening around the Tampico and Campeche areas, as well as in locations around the margins of the Gulf (e.g., southeastern United States and Cuba) during the early Oxfordian, justifying this age for the origin of this paleogeographic province.

3) In Mexico, several groups of known cephalopods, from the Permian to the Jurassic, are related only to fauna in the Pacific province. They occur in isolated sequences located to the west of the present coastline of the Gulf of Mexico.

A paleogeographic boundary between these sedimentary sequences and red beds and metamorphic or intrusive rocks is located in eastern Mexico. It can therefore be inferred that this region constituted the western margin of Pangea from the Permian to the Middle Jurassic, and that the Gulf of Mexico did not exist during this time interval.

The Middle and Upper Jurassic marine sedimentary sequence is divided here on the basis of a series of regional transgressions that are named after their type localities, namely:

- the Bajocian Oaxaca transgression in southern Mexico
- the lower Bathonian–lower Callovian Metlaltoyuca-Huehuetla transgression in eastern Mexico
- the lower Oxfordian Mazapil transgression in central Mexico
- the lower Kimmeridgian Samalayuca transgression in northern Mexico
- the middle Callovian–upper Oxfordian Boquiapan-Balam transgression in southeastern Mexico
- the middle Callovian and upper Oxfordian Cedro-Cucurpe transgression in northwestern Mexico
- the lower Kimmeridgian Chiapas transgression in southern Mexico

INTRODUCTION: THE ORIGIN OF THE GULF OF MEXICO

The origin and age of the Gulf of Mexico and the North Atlantic Ocean are generally considered in the context of two very different approaches, namely structural geology and ammonite paleobiogeography. The first approach attempts to understand Atlantic rifting and the formation of new oceanic crust by considering the origin of the various rock types that are present in the Gulf of Mexico and neighboring regions—including evaporites, red beds, and intrusive and metamorphic rocks. The second approach uses ammonites to date the diachronous bases of transgressive marine sequences that were deposited on top of these continental rocks. Different arguments involved in these approaches can be summarized as follows:

Tectonic Arguments

Plate Collisions

The Ouachita orogen that formed at the end of the Paleozoic resulted from the convergence of the North American and Gondwanan Plates, giving rise to the Marathon-Ouachita geosyncline (Ross, 1979; Sedlock et al. 1993; Walper, 1981). According to Ross (1979), biostratigraphic and paleogeographic fusulinid data and paleomagnetic, tectonic, and sedimentologic evidence are relevant only to the formation of the western margin of Pangea and does not shed light on the origin of the Gulf of Mexico.

The "Mojave-Sonora Megashear"

A number of authors have tentatively identified this structure, which supposedly divided north-central Mexico into two parts from Precambrian to Jurassic times (López-Infanzón, 1986; Sedlock et al., 1993, p. 69). However, the megashear's location, structure, and age are questionable when the Permian-to-Jurassic marine succession is considered. These rocks were deposited above this proposed megastructure and do not appear to have been deformed by it, although the ¨Mojave-Sonora Megashear" was apparently active until the Late Jurassic (López-Infanzón, 1986). It is therefore an obvious inconsistency (Figures 1a, b). For other well-documented areas and time intervals, however, it is accepted that the structure of the intrusive or metamorphic basement influenced the transgressive nature of subsequent phases of sedimentation; e.g., the Middle–Upper Jurassic Huasteca Series.

Likewise, examples are known in which the structural attitude of the red beds or the intrusive and metamorphic rocks controlled deposition of the overlying marine sediments; e.g., in wells in the northeast of the Poza Rica district (Cantú-Chapa, 1992, Figure 14). Other examples are discussed below.

Therefore, it appears that the existence of the "Mojave-Sonora Megashear" is questionable, although its existence is often referred to in studies of Mexican geology.

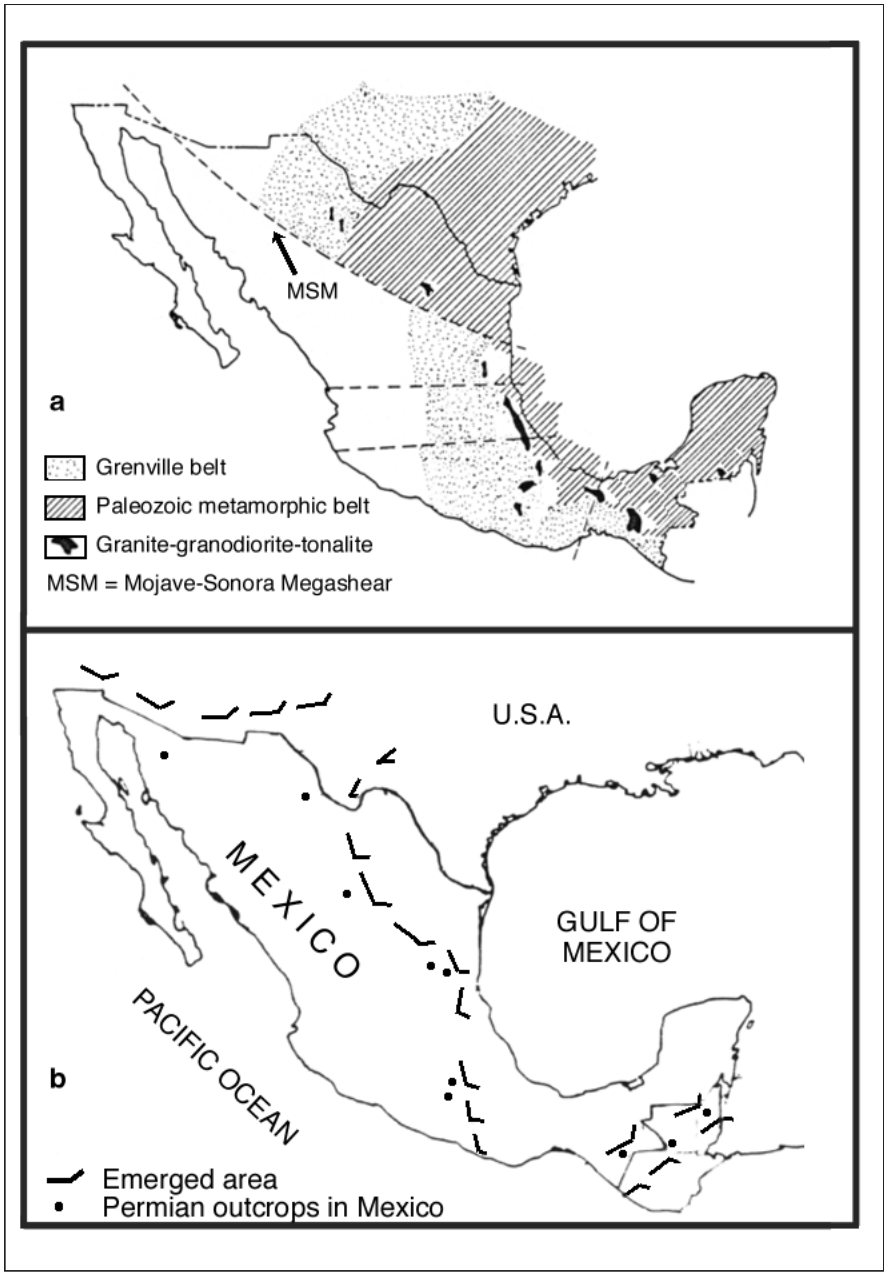

FIGURE 1. Comparison of two Permian paleogeographic models in Mexico: (a) the "Mojave-Sonora Megashear" (MSM), according to the distribution of Permian plutonic rocks (López-Infanzón, 1986); (b) the ammonoid distribution at that time (Cantú-Chapa, 1997).

Separation of North and South America from Mexico

The separation of North and South America accompanied the origin of the Gulf of Mexico. It involved both the southeastward drift of Gondwana, which was joined to North America by Mexico, and the rotation of the Yucatán Block, which was joined to present-day Texas, Louisiana, and Florida during the Upper Paleozoic–Jurassic (White, 1980; Walper, 1981).

Several plate-tectonic studies based on paleomagnetic data have sought to explain the origin of the Gulf of Mexico without specifying the timing and location of plate separation or its relationship with Middle and Upper Jurassic transgressive sedimentary cycles in Mexico (Anderson and Schmidt, 1983; Klitgord and Schouten, 1986). To explain the origin of the Gulf of Mexico, other authors have considered that rotation of the Yucatán Block occurred along the Caltam trend (Michaud, 1987). These authors tried to determine the original position, separation, and subsequent rotation of Yucatán during or before the Middle Jurassic (Anderson and Schmidt, 1983; Michaud, 1987; Sedlock et al., 1993; Walper, 1980; White, 1980).

Tectono-stratigraphic Terrains

Sedlock et al. (1993) arbitrarily divided Mexico into 17 tectono-stratigraphic terrains to which they gave pre-Hispanic names. These authors summarized more than a century of Mesozoic and Cenozoic stratigraphic studies in Mexico. Their results were, however, somewhat oversimplified. For example, Figure 2 compares these authors' model of "Coahuiltecano Terrain" in northeastern Mexico with more detailed stratigraphic models that have been published elsewhere (Cantú-Chapa, 1989a, 1989b, 1999; Imlay, 1980).

Sedlock et al. (1993) did not give any explanation for the origin of the thick sedimentary sequences; they based their arguments solely on the "tectonostratigraphic-terrains" concept. Their model of Gulf of Mexico rifting is vague in both timing and location of the Pangean rifting that occurred.

Sedimentologic and Paleogeographic Arguments

Red Beds and Evaporites

Attempts have been made to explain the origin of the Gulf of Mexico from theoretical studies of the continental sediments and salts deposited during the Late Triassic–Early Jurassic as a result of Pangean rifting (Reed, 1994; Salvador, 1991; Sedlock et al., 1993). The age and origin of these rocks have perhaps been overemphasized, because it is difficult to date them in the absence of reliable biostratigraphic data. None of the above authors considered ammonite dating of the transgressive marine series deposited above the continental rocks. The study of these marine rocks is of great importance because it defines the areas which were affected by the transgressions, and it identifies patterns of oceanic exchange, as well as ammonite migration routes. In eastern Mexico, there are many examples from the subsurface and from outcrop in which the age of evaporites and red beds has been inferred on the basis of their stratigraphic relationship with the overlying marine series. Marine sedimentary rocks have been dated as Bathonian–Lower Cretaceous from their ammonite fauna (Cantú-Chapa, 1989b, 1992).

The "Balsas Portals"

These mythic straits (Figure 3) supposedly allowed oceanic exchange to occur between the Pacific Ocean and the Gulf of Mexico from Callovian times. Some authors have located the portals in western and central Mexico without citing biostratigraphic data confirming their proposed Middle–Late Jurassic age (Imlay, 1980; Salvador, 1991; Schuchert, 1935) (Figure 3). This region of Mexico covered by volcanic rocks is called Eje Neovolcánico.

The "Hispanic Corridor"

This paleogeographic concept has been invoked to explain the transfer of marine fauna (ammonites and corals) from Europe to America during the Jurassic (Stanley and Beauvais, 1994) (Figure 4a). However, to authenticate the corridor, ammonites of different ages were correlated—Sinemurian from Mexico with Bajocian from Venezuela (Bartok et al., 1985) (Figure 4b).

End of Gulf of Mexico Opening

Michaud (1987) suggested that the opening of the Gulf of Mexico ended in the Oxfordian. This appears to have been confirmed by the occurrence of Oxfordian calcarenites and evaporites around the margins of the Gulf. However, a process of this magnitude cannot begin and end in such a short time interval as the Oxfordian. More probably, the marine transgression extended over Mexico and adjacent parts of the Gulf, although isolated emerged areas may have persisted in Poza Rica and Tampico in the east until the Berriasian (Cantú-Chapa, 1989b, 1992).

A Berriasian transgression has also been recorded elsewhere in the Gulf of Mexico. A transgressive succession resting on gneisses, conglomerates, and sandstones has been observed in some Gulf wells (Schlager and Buffler, 1984). In northeastern Mexico and Texas, a transgression covered various types of basement and continental rocks from the Kimmeridgian to the Neocomian (Cantú-Chapa, 1989a, 1989b). In southern Mexico, transgressive sedimentation persisted into the Albian (Cantú-Chapa, 1987b).

These examples of marine transgression point to the continuous opening of the Gulf of Mexico. The sedimentary cycle terminated with a regression, indicated by coal-bearing sediments, which began in northern Mexico (Chihuahua and Coahuila, Sabinas Basin) during the Late Cretaceous (Imlay, 1980). This regression persisted throughout the Cenozoic, ultimately resulting in the present Gulf of Mexico coastline, which corresponds to a marine basin in a generally regressive stage.

STRATIGRAPHIC EVIDENCE FOR THE ORIGIN OF THE GULF OF MEXICO

Drift of the South American continent and the displacement of the Yucatán Block relative to the origin of the Gulf of Mexico must be supported by biostratigraphic data. The breakup of Pangea may not have been a simple process, as has been suggested. For example, many subsurface intrusive and metamorphic structures have been found in the Gulf of Mexico coastal plain. Radiometric age dating of their emplacement gives results which vary from Permian to Early Jurassic.

In this part of Mexico, the Middle Jurassic–Lower Creta-

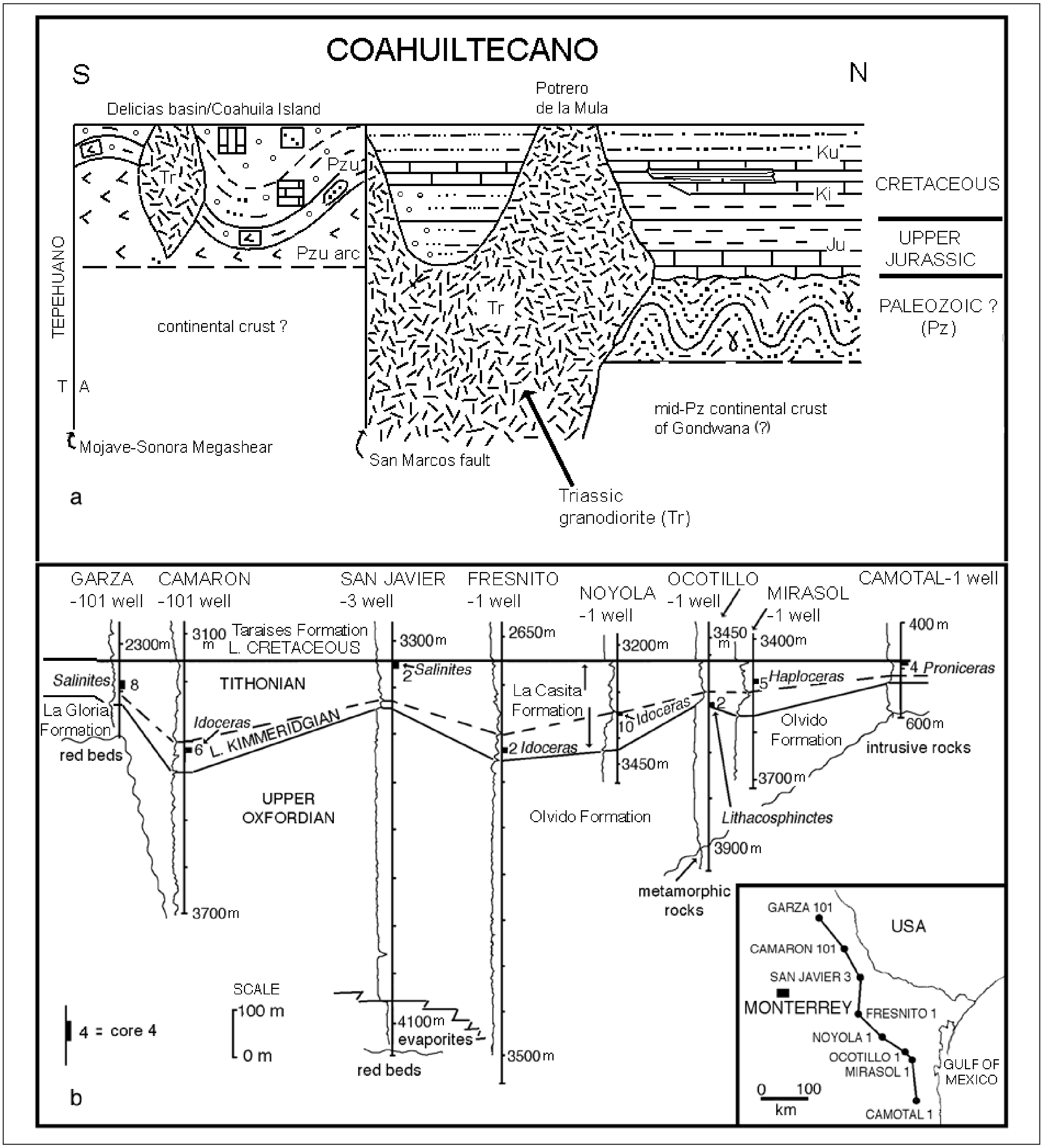

FIGURE 2. Comparison of two stratigraphic models in northeastern Mexico: (a) tectono-stratigraphic interpretation of Mesozoic rocks (Sedlock, et al., 1993). (b) stratigraphy interpretation based on subsurface data of the Upper Jurassic in northeastern Mexico (Cantú-Chapa, 1999).

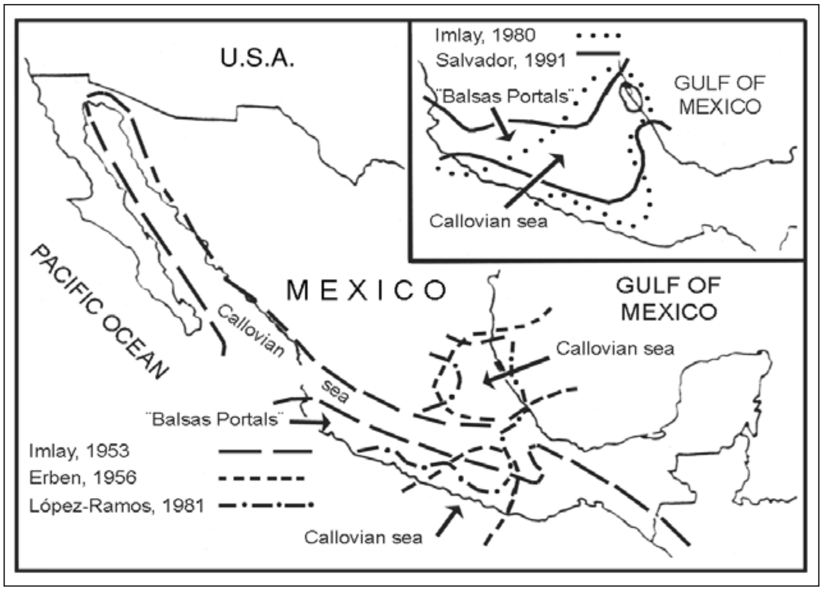

FIGURE 3. Evolution of the "Balsas Portals" and Callovian paleogeographic concepts in Mexico, according to different authors.

ceous transgression covered a variety of lithologies. Biostratigraphic dating of the base of the transgressive series may help to explain the origin and age of the Gulf of Mexico better than arguments based on the emplacement of intrusive rocks or the dating of metamorphic phases. Furthermore, the relationship between the metamorphic and intrusive remnants of eastern Mexico and those in northern South American must also be established (Sedlock et al., 1993, p. 77).

Ammonite biostratigraphy and biogeography have been used to date the bases of the sedimentary series and to establish the routes by which marine incursions occurred. This approach has also led to an understanding of the polarity of the major Middle to Upper Jurassic transgression that covered Mexico and the southern United States. A specific transgression in a particular area can be identified in terms of the ammonite groups present. Ammonites are present in strata above the evaporites and calcarenites, which were deposited from the Middle Jurassic until the origin of the Gulf of Mexico in the Oxfordian.

MEXICAN TRANSGRESSIONS AND THE PALEOBIOGEOGRAPHY OF MIDDLE AND UPPER JURASSIC AMMONITES

In this study, the principal Mexican transgressions are named after their type locations. Seven transgressive events are identified and are briefly described.

The Bajocian Oaxaca Transgression in Southern Mexico

This name is given to the Bajocian depositional event that began in the Oaxaca region and is divisible into two phases:

Bajocian Stephanoceras *in the Eastern Pacific Province*

The occurrence of *Stephanoceras* resolves paleogeographic problems associated with the opening of the Gulf of Mexico and the North Atlantic. It appeared on the eastern margins of the Pacific Ocean in the Bajocian just before invading the Oaxaca region of southern Mexico. It is present in sedimentary successions in western North America and South America, from southern Alaska to Venezuela, Chile, and Argentina, where the genus marks the advanced phases of a transgression (Bartok et al., 1985; Hillebrandt et al., 1992; Imlay, 1980). In Oaxaca, it marks the beginning of the transgressive cycle that is characterized by the base of the Tecocoyunca Series (Figure 5).

Studying the distribution of the genus *Stephanoceras* on the eastern margins of the Pacific Ocean province during the Middle Jurassic may help to explain the marine transgression into southern Mexico through this incipient oceanic route. Certain species are slightly older than those in Oaxaca.

The absence of fossils of Bajocian age from the rest of Mexico and the North Atlantic challenges the model of east-to-west migration of fauna in Mexico that has been proposed by various authors, as well as the existence of the so-called Hispanic Corridor. A Middle Jurassic transgression through the "Balsas Portals" in western Mexico (Figure 3) (López-Ramos, 1981; Sal-

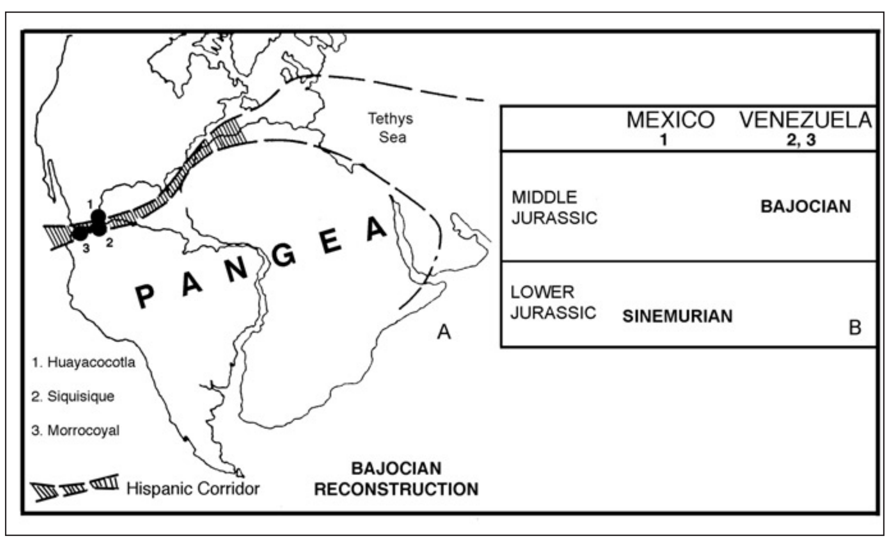

FIGURE 4. **(a) The "Hispanic Corridor," a hypothetical paleogeographic concept, is improperly justified when ammonites from different ages are correlated. (b) Sinemurian of Mexico (Erben, 1956) is correlated with the Bajocian of Venezuela (Bartok et al., 1985).**

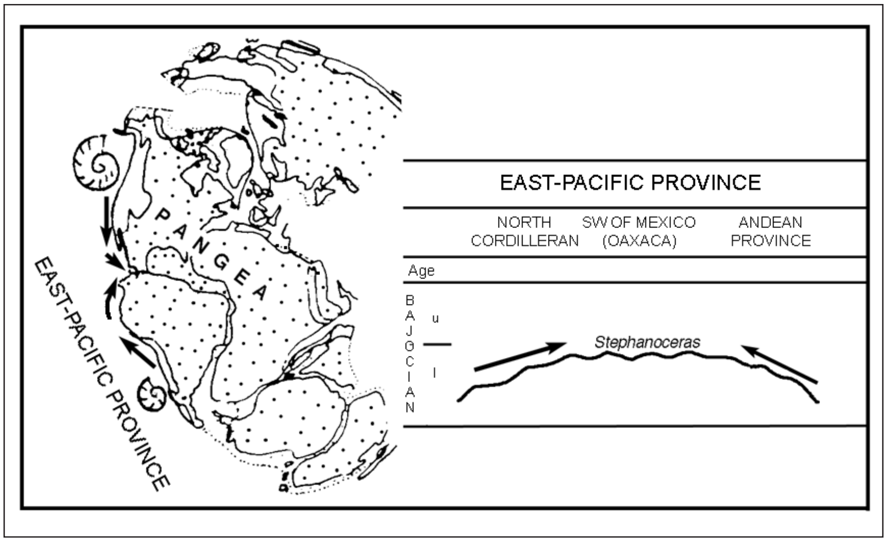

FIGURE 5. ***Stephanoceras*** **marks the basal stage of the transgressive Bajocian Tecocoyunca Series in Oaxaca, southern Mexico. This ammonite was also present in western North and South America and migrated to the study area (Bartok et al., 1985; Hillebrandt et al., 1992; Imlay, 1980).**

vador, 1991) or Central America can similarly be discarded for lack of paleontologic evidence (Schmidt-Effing, 1980).

In the Oaxaca region, the sedimentary sequence begins with the Tecocoyunca Series (Figure 6a). This consists of Upper Bajocian–Callovian sandstones, coal, siltstones, and limestones (the Taberna, Simon, Otatera, and Yucuñuti Formations). These formations are overlain by the Tlaxiaco Series, consisting of Oxfordian limestones (Chimeco Formation) and Kimmeridgian-Tithonian argillaceous limestones and shales (Sabinal Formation) (Figure 6c). A sedimentary basin formed in Oaxaca and the Gulf of Tlaxiaco (Figure 6a). From this basin, two routes of communication, still unknown, could have bifurcated, one toward the east in the lower Bathonian (Metlaltoyuca event pt.) and the other to the southeast in the Callovian (Boquiapan event pt.) (Figure 6b).

Epistrenoceras *(Bathonian)*

The biostratigraphic succession continued through the late Bathonian in the Gulf of Tlaxiaco with different ammonite genera, in which Andean forms such as *Epistrenoceras* predominate; their biogeographic affinity to the Oaxaca fauna is remarkable. There are also other genera of Mediterranean affinity; however, the South American ammonites predominate by 33% in Oaxaca (Sandoval and Westermann, 1989).

The Metlaltoyuca-Huehuetla Transgression (early Bathonian–early Callovian) in Eastern Mexico

The Metlaltoyuca-Huehuetla transgression marks the onset of a sedimentary cycle. Its age varies from Bathonian to Callovian, depending on the location. The transgression occurred in the northwest of Poza Rica, where numerous wells are located (Metlaltoyuca event pt.) (Cantú-Chapa, 1992, Figure 12) and in the Sierra Madre Oriental (Huehuetla event pt.) (Cantú-Chapa, 1971) (Figure 7a, b). Two genera of ammonites (*Wagnericeras* and *Kepplerites*) from the Eastern Pacific province are found in Middle Jurassic sediments in eastern Mexico; they indicate migration from the Pacific to the Atlantic, in contrast to the proposed transgression from the Atlantic.

Wagnericeras *and* Kepplerites *(late Bathonian–early Callovian)*

Ammonites from wells northwest of Poza Rica indicate a very advanced connection during the late Bathonian–early Callovian between the Eastern Pacific province and an area in eastern Mexico adjacent to the future gulf. Here, the sedimentary sequence known as the Huasteca Series (Cantú-Chapa, 1969, 1992) was deposited over red beds as follows (Figure 7b) (from base to top):

- evaporites (Huehuetepec Formation) and calcarenites (Tepexic Formation) of probable early Bathonian age
- siltstones (Palo Blanco Formation) of late Bathonian–early Callovian age
- middle Callovian–Oxfordian shales Santiago Formation)
- early Kimmeridgian argillaceous limestones with shales (Taman Formation)
- Kimmeridigan–early Tithonian calcarenites (San Andres Member)
- late Tithonian argillaceous limestones, shales, and bentonite (Pimienta Formation) (Cantú-Chapa, 1992, Figure 12)

This transgressive sequence is usually restricted to the most recent units in areas relatively close to eastern Mexico and is discussed further in this paper.

Reineckeia *(Callovian)*

Reineckeid ammonites from the lower and middle Callovian also support the proposed marine communication from the Pacific to eastern Mexico, through Oaxaca, where they are abundant.

This group of fossils is also present in the thick calcarenites of the Tepexic Formation (*Neuqueniceras*) and the claystones of the Santiago Formation (*Reineckeia*), both in the subsurface (Poza Rica District) and in outcrop (Huehuetla) in eastern Mexico (Cantú-Chapa, 1969, 1971, 1992). Their presence suggests platform and open-marine facies, respectively. The latter indicates advanced stages of subsidence resulting from maximum transgression across the ancestral Mexican continent from the Pacific Ocean toward the future Atlantic Ocean (Figure 8).

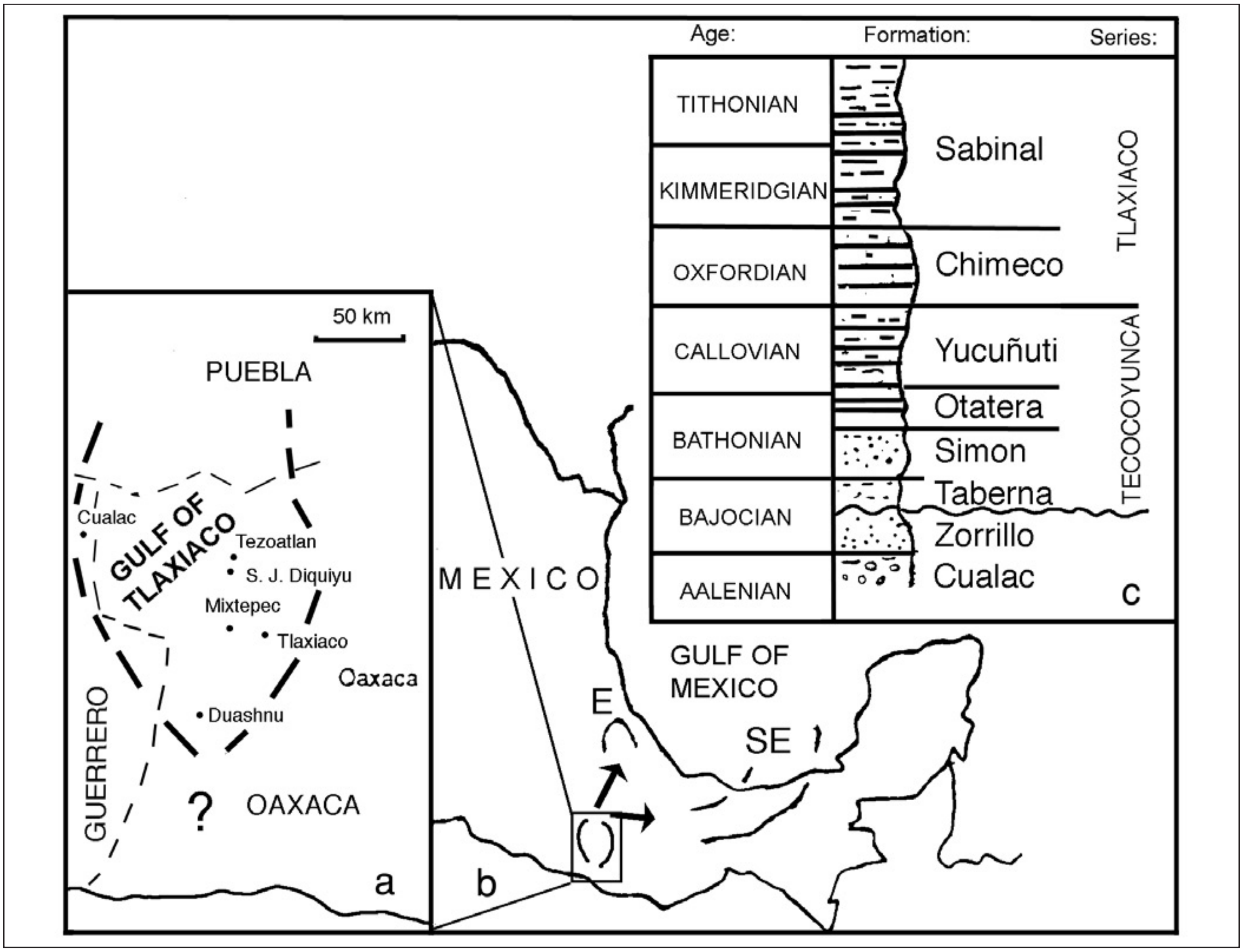

FIGURE 6. **(a) Middle and Upper Jurassic outcrops define the Gulf of Tlaxiaco in Oaxaca, southern Mexico. (b) Two possible lower Bathonian and Callovian transgressive routes toward the east and southeast of Mexico. (c) Middle and Upper Jurassic stratigraphy in Oaxaca.**

Reineckeid ammonites found in Mexico are of Eastern Pacific affinity (South America and Mexico: Oaxaca and Baja California). This group has also been found in Europe, but it has not been identified until now either in the Gulf of Mexico or in the Atlantic province.

Neuqueniceras and the bivalve *Lyogrpyphaea nebrascensis* (Meek and Hayden) characterize another part of the Middle Jurassic sedimentary cycle, which is more recent than those represented by *Wagnericeras*. In Mexico, reineckeid ammonites (*Neuqueniceras*) include large specimens with bulky ornamentation, which indicates that they lived in a carbonate-rich environment. On the other hand, the bivalve forms cockles, which is an irrefutable sign of a particular deposit corresponding to restricted platform regions connected with the Pacific Ocean of that time. The presence of the early and middle Callovian reineckeids over a large area from eastern to southeastern Mexico points to the incipient communication of the Pacific Ocean with the eastern region of Mexico (Figure 8). *Reineckeia* has also been found in the Pacific portion of the Baja California (Geyssant and Rangin, 1979). A bivalve characteristic of the argillaceous facies of the Santiago Formation from the early and middle Callovian is *Posidonia ornati* (Quenstedt), which has been found only in wells in northwestern Poza Rica.

Late Callovian–early Oxfordian

An ammonite group that corresponds to the upper Callovian–middle Oxfordian cardioceratids, which are characteristic of the Boreal and Alpine provinces, is absent in the thick argillaceous sequences of eastern Mexico (Santiago Formation). Manganese nodules at the top of the sequence indicate a reducing environment (Maynard et al., 1990) and would point to restricted-marine depositional conditions and the absence of communication with the Tethyan Ocean across the Paleo-Atlantic Ocean and Gulf of Mexico. However, it should be noted that the presence of the genus *Peltoceras* in Oaxaca is characteristic of the late Callovian (Imlay, 1980). Its presence is not known in the rest of the eastern regions of the country.

The Mazapil Transgression (lower Oxfordian) in Central Mexico

This transgression is recognized in the Mazapil region of central Mexico. Development of the sedimentary cycle advanced from the Tampico region and Poza Rica in eastern Mexico in two directions:

- toward the north-central area, giving rise to deposits of dolomitized limestones (La Gloria Formation, early Oxfordian) that were covered by late Oxfordian–Tithonian shales with calcareous concretions (La Casita Formation) or by phosphatized limestones (La Caja Formation) with bivalves and ammonites of Kimmeridgian to Tithonian age (Figure 7a[d])
- toward the northeast, where evaporites were deposited beginning in the late Oxfordian, either as gypsum, sandstones, and limestones (Minas Viejas Formation) or as limestones and anhydrites (Olvido Formation) over rocks of different origins that made up the preexisting continent. These were covered by highly argillaceous limestones known as the La Casita Formation of Kimmeridgian-Tithonian age (Figure 2b).

If the Yucatán Block was joined to the southern United States during the Triassic to Middle Jurassic, as some authors indicate, it must have been separated before the late Oxfordian to allow this transgression, with its corresponding fauna, to spread from the preexisting Mexican territory toward Louisiana, Campeche (southeastern Mexico), and Cuba. Another possibility is that during the late Oxfordian, various ammonite genera (*Euaspidoceras, Ochetoceras*, and *Discosphinctes*) may have come from the Tethyan Province through the primitive Atlantic Ocean.

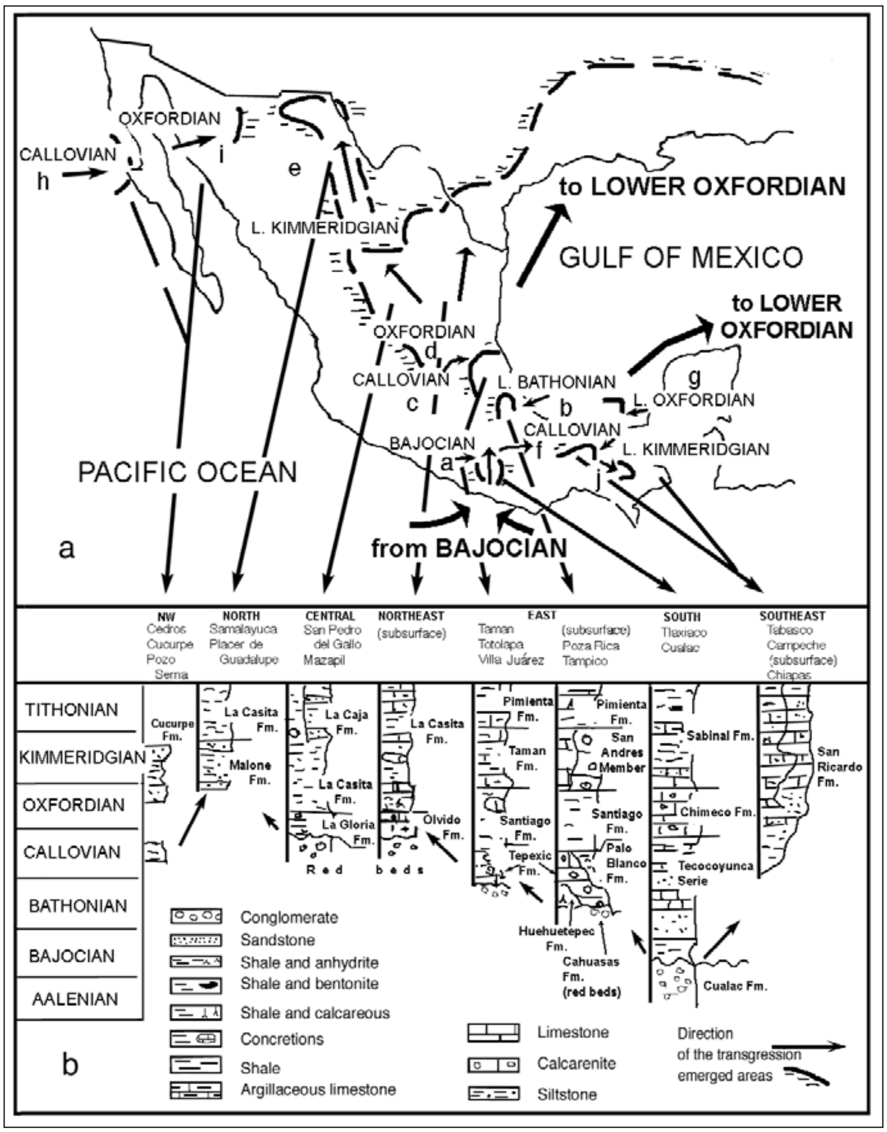

FIGURE 7. (a) Middle and Upper Jurassic transgressive events in Mexico, which originated in the ancestral Pacific Ocean during the Bajocian in the south of the country and Callovian in the northwest. Transgressive events: a, Oaxaca; b, Metlaltoyuca; c, Huehuetla; d, Mazapil; e, Samalayuca; f, Boquiapan; g, Balam; h, Cedro; i, Cucurpe; j, Chiapas. (b) Stratigraphic crosscorrelations. Direction of the transgressions toward the north and the present area of the Gulf of Mexico during the lower Kimmeridgian and the lower Oxfordian, respectively.

These ammonites confirm a late Oxfordian age for the lithologic units located around the Gulf of Mexico. The fossils that indicate the onset of the transgressive event are recorded near the base of different sedimentary sequences:

- calcarenites in the subsurface of Louisiana (Imlay and Hermann, 1984)
- argillaceous limestones overlying sands in the subsurface of Campeche (Ek Balam Group, Angeles-A. and Cantú-Chapa, this volume)
- shales, sandstones, and limestones in outcrops in western Cuba (Judoley and Furrazola, 1968)

However, the same genera of ammonites are found only at the top of the Santiago Formation (thick shale with calcareous concretions) in eastern Mexico (subsurface of Poza Rica–Tampico and the neighboring Sierra Madre Oriental) and at the base of the La Casita Formation (shales with calcareous concretions) in the north-central part of the country (San Pedro del Gallo, Durango). In both regions, they characterize an advanced stage of sedimentation and subsidence that differs from the sedimentary regimes of the locations previously mentioned for the late Oxfordian (Figure 7a[d]).

Therefore, it is inferred that it was from eastern Mexico that one of the two marine invasion routes, coming from Oaxaca, departed toward the region of the present Gulf of Mexico. This is discussed further below. The other route trended directly from the Oaxaca region toward southeastern Mexico and from there toward Cuba (Figure 7a[f, g]).

Ataxioceras, Idoceras, and Glochiceras (lower Kimmeridgian)

The base of this stage has been identified biostratigraphically only in the northeast and east of Mexico with *Ataxioceras* or ammonites of equivalent age (rasenids) of Tethyan affinity (Cantú-Chapa, 1992) (Figures 2b, 8, and 9). On the other hand, the genus *Idoceras*, associated with *Nebrodites* and *Aspidoceras*, is dominant in the second zone of the lower Kimmeridgian. This stage of stabilized subsidence conditions is represented by an argillaceous lithofacies with calcareous concretions (La Casita Formation). The top of the lower Kimmeridgian is characterized by *Glochiceras* throughout practically all Mexico.

Biostratigraphic data described by Imlay (1980), often ignored in later studies, include the discovery of an association between *Ameoboceras-Idoceras* and the bivalve *Aulacomyella* in Sonora, which indicates the presence of the lower Kimmeridgian rather than the upper Oxfordian in northwestern Mexico.

Mazapilites-Durangites *(Tithonian)*

The bi- or tripartite subdivision of the Tithonian in the Tethyan Province has been challenged in European countries. It is adopted here as a particular evolutionary event by which to divide this stage into the lower and upper Tithonian. The sudden occurrence and wide distribution of the genus *Mazapilites* mark the top of the lower Tithonian. This ammonite has been found in the central, eastern, and southeastern parts of the country.

Strata around the Kimmeridgian-Tithonian boundary are characterized by the ammonite *Hybonoticeras*; its distribution is limited to the center of Mexico. It is followed by *Virgatosphinctes* and the bivalve *Aulacomyella neogeae* and by *Mazapilites*. The lower Tithonian cycle represents the sedimentologic stability in central and eastern Mexico (Figure 8). *Virgatosphinctes* is a fossil with clear andine and indomalgach affinity. On the other hand, *Mazapilites* has been found outside Mexico only in Germany (Berckhemer and Holder, 1959).

The upper Tithonian is characterized by *Suarites*, *Kossmatia*, *Durangites*, *Substeueroceras*, and *Parodontoceras* aff. *callistoides* as follows:

- in argillaceous facies (La Casita Formation) in the north and northeast (Figure 2b)

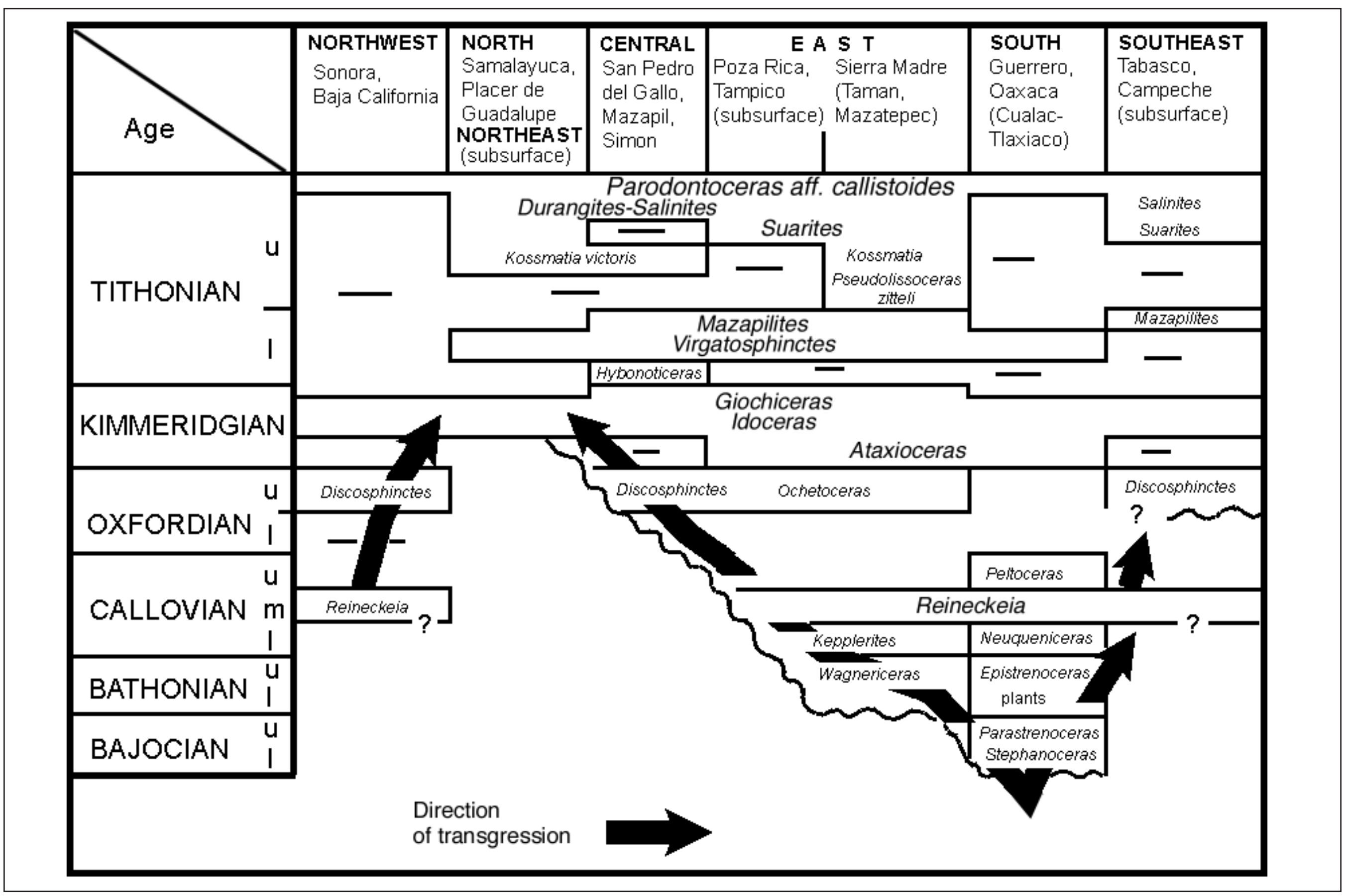

FIGURE 8. **Biostratigraphic correlation of ammonite genera from the Middle and Upper Jurassic in Mexico. Transgressive cycle from the south toward the north and southeast, and most likely from the northwest toward the north-central portions of the country.**

- in calcareous argillaceous facies with bentonite (Pimienta Formation) in the east (Cantú-Chapa, 1989b, 1992, Figures 8 and 12)
- in argillaceous limestones with shales (Sabinal Formation) in the south, Oaxaca (Figure 6a)
- in argillaceous limestones with bentonite (Edzna Formation) in the southeast, Campeche (Angeles-A. and Cantú-Chapa, this volume; Cantú-Chapa, 1977)

It should be noted that Tethyan ammonites predominate in the second, neo-Jurassic sedimentary series (Tlaxiaco Series) of the Kimmeridgian-Tithonian in Oaxaca (Figure 6). These fossils, also found in the east of Mexico, indicate the opening of the Gulf of Mexico and the North Atlantic. Only at the base of the Cretaceous does there exist a strong South American influence, characterized by spiticeratids and berriaselids ammonites.

The Samalayuca Transgression (Lower Kimmeridgian) in Northern Mexico

The most northerly (and youngest) of the major Jurassic transgressions in Mexico is represented in Chihuahua and in southeastern Texas by sandstones and shales containing *Idoceras* (Lower Malone Formation: lower Kimmeridgian), followed by a thick sequence of shales (La Casita Formation) with *Virgatosphinctes*, *Suarites*, and *Kossmatia* (Tithonian) (Cantú-Chapa, 1976a; Imlay, 1980) (Figures 7a[e] and 8).

The Boquiapan-Balam Transgression (Middle Callovian–Upper Oxfordian) in Southeastern Mexico

This name is derived from oil wells in the Tabasco area (Boquiapan event) in southeastern Mexico (Figure 7a[f]). There, a thick, highly carbonaceous and argillaceous sedimentary series of middle Callovian age is covered by limestones of Oxfordian to Tithonian age that are partly calcarenitic and partly argillaceous.

On the other hand, in wells in the Campeche area of the Gulf of Mexico, the sedimentary cycle began with evaporites, limestones, and sands (Balam event) (Figure 7a[g]). The ammonites *Reineckeia* (middle Callovian) and *Ochetoceras* (late Oxfordian) characterize these two transgression in southeastern Mexico, respectively (Figure 8).

The Cedro-Cucurpe Transgression (Middle Callovian and Upper Oxfordian) in Northwestern Mexico

This transgression is recorded in northwestern Mexico. In the western portion of the Baja California peninsula (Cedro event), it is of middle Callovian age (Figure 7a[h]). The sedimentary cycle continued into the Sonora region (Cucurpe event) in the late Oxfordian (Figure 7a[i]). It consists of a volcano-sedimentary sequence (lavas, sandstones, and shales). The most representative ammonites are *Reineckeia* (Callovian) and *Discosphinctes* (late Oxfordian Cucurpe Formation) (Geyssant and Rangin, 1979; Rangin, 1977).

The possibility exists of finding evidence of sedimentary sequences of marine origin dating from the late Oxfordian between Sonora (Cucurpe) and Durango (San Pedro del Gallo), because the same ammonite groups are present in both localities (Rangin, 1977; Imlay, 1980) (Figure 7a[e]).

The Chiapas Transgression (Lower Kimmeridgian) in Southern Mexico

In the central region of Chiapas, Michaud (1987) identified

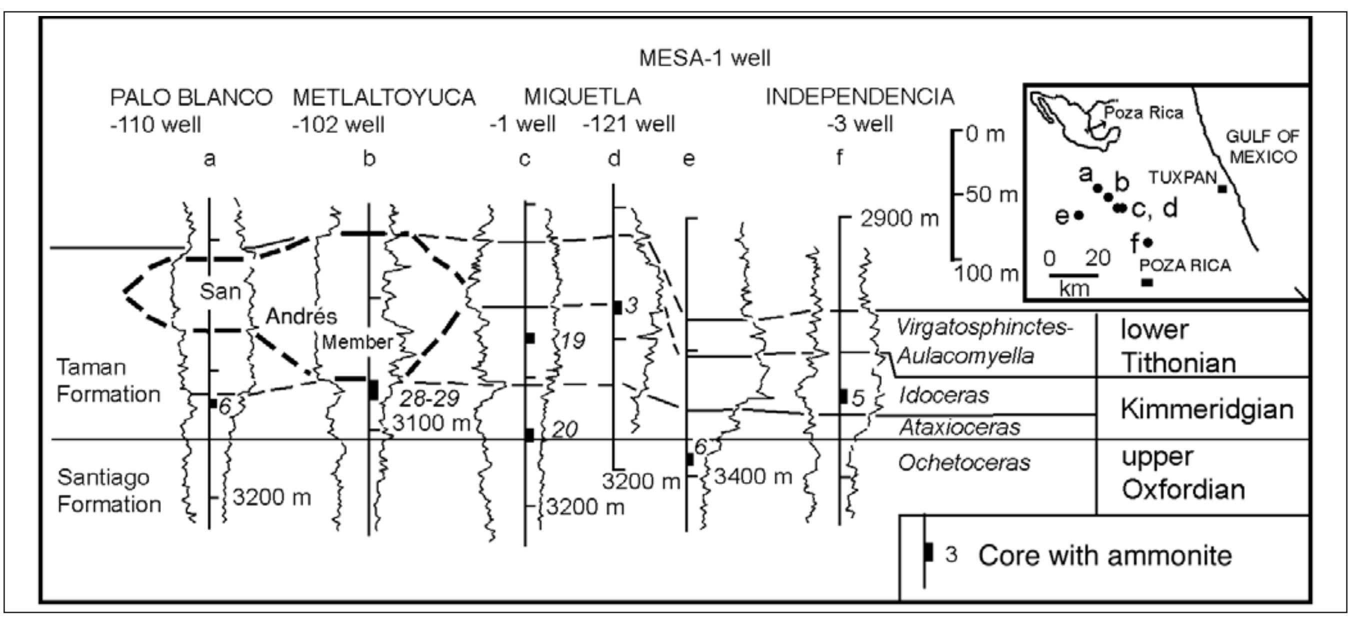

FIGURE 9. **Cross section of wells in northeastern Poza Rica from gamma logs and stratigraphic interpretation showing the Oxfordian-Kimmeridgian boundary, eastern Mexico. The datum is the base of the Kimmeridgian. Arbitrary horizontal scale.**

the presence of a lower Kimmeridgian sequence based on foraminifera and dascycladacean algae associated with calcareous lithofacies that correspond to part of the San Ricardo Formation. This is the only stage in this southern region in Mexico that has been dated definitively. As yet, there is not sufficient biostratigraphic evidence to indicate that an older marine incursion could have occurred there (Figure 7a[j]).

THE DIACHRONOUS BASE OF THE HUASTECA SERIES (MIDDLE AND UPPER JURASSIC) AND THE LOWER CRETACEOUS IN THE SUBSURFACE OF THE TAMPICO REGION, EASTERN MEXICO

Deposition of the Huasteca Series occurred before the opening of the Gulf of Mexico and can be divided into five main transgressions in the Tampico and Poza Rica regions of eastern Mexico: Bathonian, Callovian, Kimmeridgian, Tithonian, and Berriasian-Valanginian. This age range for the base of the sedimentary cycle was the result of the irregular topography of the continental surface on which the series were deposited. Several cross sections based on subsurface data illustrate the apparently isolated depositional regimes that coexisted within short distances of one another. They illustrate the nonconformable relationship between the marine sequence and the underlying strata, which comprise metamorphic, intrusive, and continental rocks (Figures 10, 11, 12, and 14). Two stratigraphic sections are illustrated to date the nonconformable bases of the sedimentary sequence, which are diachronous in this part of Mexico (Figures 13 and 15).

Although the Huasteca Series in the Poza Rica region is characterized by a progressive northwest-to-southeast transgression, sedimentation in Tampico was more isolated in time and space. There, marine waters spread through narrow, fault-bound channels, and emergent areas controlled the routes of marine communication. Some of these sections have been mapped. Three of them were analyzed in a previous study of Poza Rica (Cantú-Chapa, 1992). In these sections, the abrupt change of age at the nonconformable base of the sedimentary sequence found in neighboring wells was affected by the irregular topography. The following sections have been named according to the most abrupt nonconformable stratigraphic elements that characterize them.

Placetas-Ixcatepec Wells

Figure 10 illustrates how the Middle and Upper Jurassic seas invaded the southern part of the Tampico district in different stages and over short distances through channels that allowed the transgression to occur. In fact, the calcarenitic base of the sedimentary sequence is of different ages; it was affected by emergent areas that prevented its simultaneous deposition. In the Placetas-1 well and Santa Maria Ixcatepec-3 well, the transgressive unit is of different ages: Tithonian (San Andrés Member), deposited over intrusive rocks in the first well, and Callovian (Tepexic Formation), deposited over red beds in the second.

Cuachiquitla-Ixtazoquico Wells

In the south of Tampico District, the transgressive cycle occurred in different stages of the Middle and Late Jurassic, as follows (Figure 11):

- In the Cuachiquitla-1 well, the Huasteca Series is complete from the lower Callovian to the Tithonian. Here, the sedimentary cycle began with the deposition

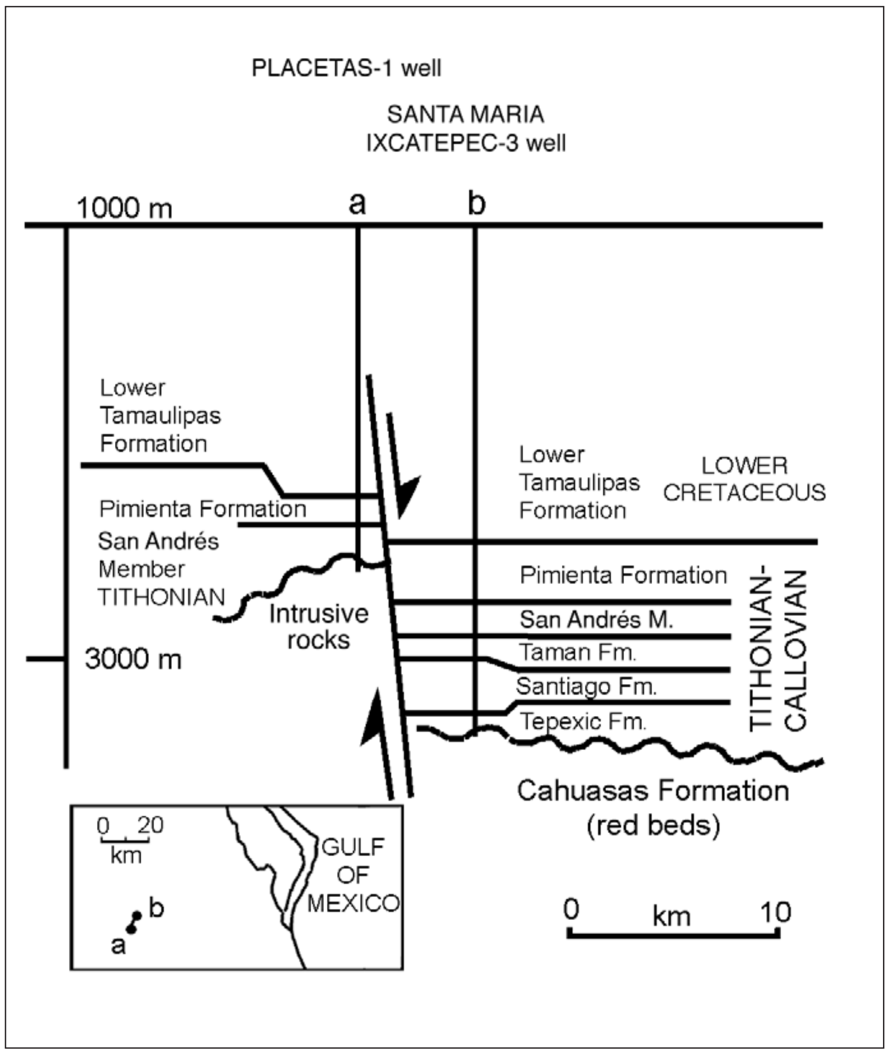

FIGURE 10. **Stratigraphic and structural cross section between the Placetas-1 well and Santa María Ixcatepec-3 well in eastern Mexico, showing how the structure of the ancient continent controlled patterns of sedimentation, resulting in diachronous sequences within very short distances.**

of evaporitic rocks of the Huehuetepec Formation over red beds (Cahuasas Formation).

- In the Ixtazoquico-1 well, marine sedimentation did not begin until the lower Kimmeridgian with cal carenites (San Andrés Member) also deposited above the Cahuasas Formation. At the same time, this latter unit overlies the Huayacocotla Formation of marine origin from the Sinemurian.
- In the Pilcuautla-1 well, located to the southwest of the Cuachiquitla paleochannel, the sedimentary cycle began with the Pimienta Formation of late Tithonian age, also deposited above red beds. The area where this well is located represents one of the margins of the channel.

Los Cues–Cahuayotes Wells

Figure 12 illustrates the stratigraphic-structural relationship of rocks from the Middle and Upper Jurassic in four wells in the Tampico district, as follows:

- The Los Cues-102 well was the only one which penetrated a thick Callovian-to-Tithonian marine sequence deposited in a channel above intrusive rocks, where the Tepexic, Santiago, Taman, and Pimienta Formations and the San Andrés Member were found.
- By contrast, Tamismolon-102 well identified the base of the transgression at the top of the Jurassic (Pimienta Formation).
- The Los Cues-101 well and Cahuayotes-102 well cut the base of the transgression (Lower Cretaceous). The sequence was deposit-ed on a variable substratum: red beds (Cahuasas Formation) and metamorphic and intrusive rocks, as shown in the four wells (Figure 12).

Barcodon-Topila Wells

The gamma-ray curve from three wells in Tampico District was used to correlate the stratigraphic section in Figure 13. This section emphasizes the stratigraphic relationship between the Tithonian and Berriasian transgressions and indicates the types of continental rocks over which the marine sedimentary cycle began in this part of eastern Mexico, as follows:

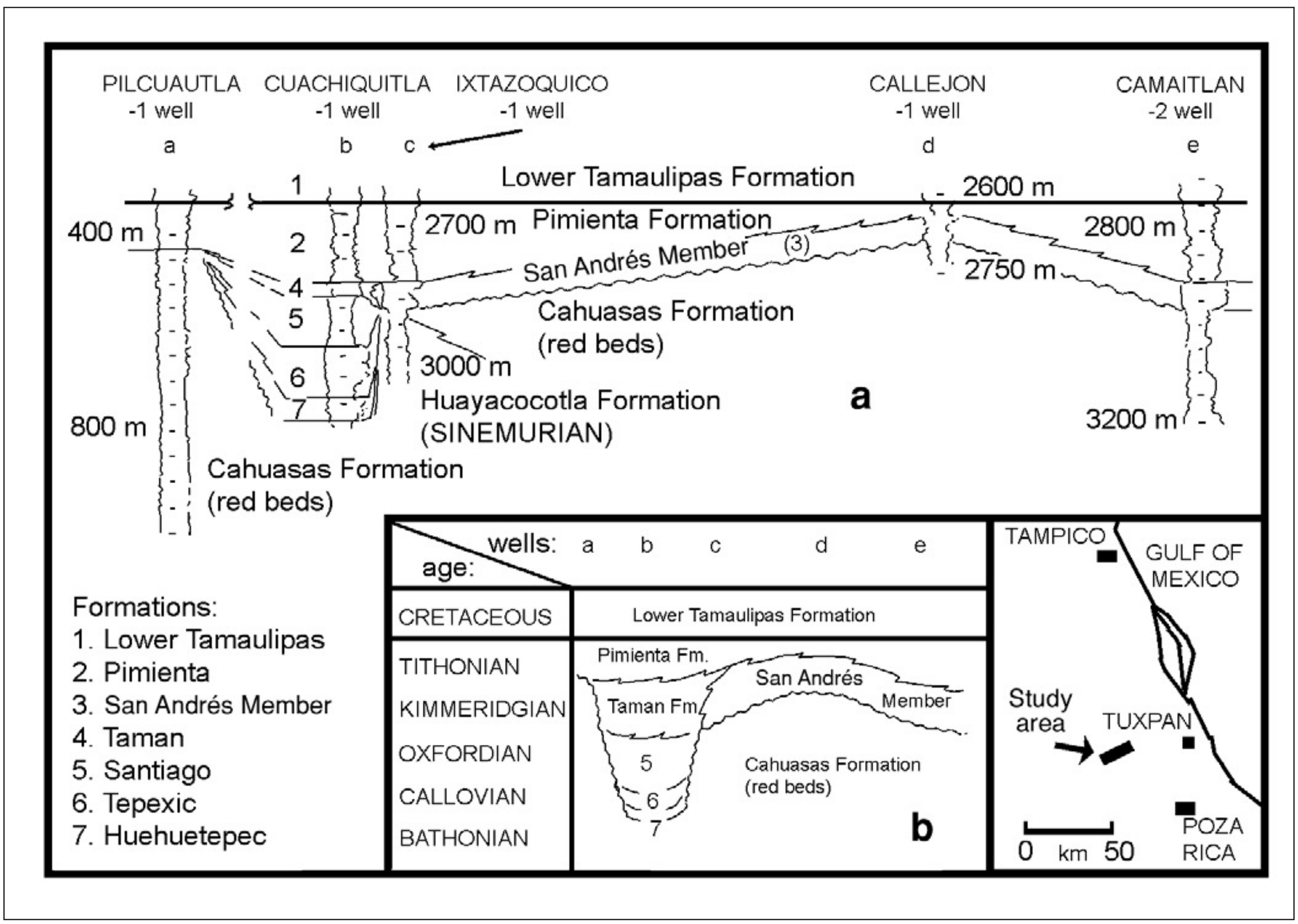

FIGURE 11. **(a) Cross section and stratigraphic interpretation between Pilcuautla-1 and Camaitlan-2 wells based on radioactive logs from eastern Mexico. (b) Sedimentary rocks of Callovian-Tithonian ages were penetrated only in the Cuachiquitla-1 well (b). In contrast, the marine sedimentary cycle began at the Upper Jurassic in the other wells (a, c, d, e). Datum is the Lower Tamaulipas-Pimienta Formations.**

- In the Barcodon-102 well, the calcarenites of the San Andrés Member from the Tithonian were deposited over metamorphic rocks.
- In the Topila 105-well, the marine sequence began in the Berriasian (lower Tamaulipas Formation), also on metamorphic rocks.
- In the Bejuco-6 well, the sedimentary sequence began with calcarenites (San Andrés Member) from the lower Kimmeridgian, deposited over intrusive rocks (Cantú-Chapa, 1987a, Figures 3, 7).

The stratigraphic section identifies microfossils and ammonites recovered from cores, by which the basal units of the transgressive event were dated.

Pueblo Viejo–Bocacajeta Wells

The previous section was complemented by another section perpendicular to it, also located in the Tampico region. It illustrates the stratigraphic-structural relation between the Pueblo Viejo-102 and Bocacajeta-1 wells at Middle and Upper Jurassic levels (Figure 14). A normal fault defines two areas of deposition. The basal units of the sequence are of different ages: Callovian in the Bocacajeta-1 well, and Tithonian in the Chunca-2 and Pueblo Viejo-102 wells.

In the Bocacajeta-1 well, the series lying above intrusive rocks is complete and very thick. It consists of calcarenites from the Callovian Tepexic Formation to argillaceous limestones with bentonite from the upper Tithonian Pimienta Formation. By contrast, in the Pueblo Viejo-102 and Chunca-2 wells located to the west, the Pimienta Formation (Tithonian) represents the base of the sedimentary cycle that was deposited above metamorphic rocks, which most probably formed a structural high in the Late Jurassic. Therefore, the initial phase of the marine transgression was younger in the last two wells than in the Bocacajeta-1 well. This observation is of great significance to explain the origin of the Gulf of Mexico.

Mantarraya–Los Mangles Wells

This section was compiled using offshore well data with the help of fossils and well logs (Figure 15). It shows the different ages of the late transgressive phase in the Tampico region. In this case, the unconformity between the red beds (Cahuasas Formation) and the marine sedimentary sequence also allows us to infer the direction of the transgression that took place over less than 15 km in a short period of time, as follows:

- The Mantarraya-1 well penetrated only 8 m of the Pimienta Formation (upper Tithonian), which overlies the Cahuasas Formation. It is covered by the lower Tamaulipas Formation, in which a sample of *Dichotomites (Dichotomites) mantarraiae* Cantú-Chapa (1990), an upper Valanginian ammonite, was found very close to its base.
- By contrast, in the Los Mangles-1 well, the unconformity between the red beds and the limestones of the lower Tamaulipas Formation is slightly younger. Lack of paleontologic data from the base of the formation does not allow a conclusion to be made as to whether the Berriasian is condensed or absent. On the other hand, calpionellids and nannoconus were recovered from cores 2 and 3 of the Los Mangles-1 well. Correlating with the Mantarraya-1 well, where calpionellids were found, it appears that the age of the two successions is late Valanginian (Figure 15).

LATE JURASSIC OPENING OF THE GULF OF MEXICO THROUGH THE TAMPICO REGION

The base of the transgressive Huasteca Series was deposited during different stages of the Middle and Upper Jurassic throughout Tampico and the Sierra Madre Oriental (Tamazunchale). These two areas in eastern Mexico have paleogeographic relations with the Oxfordian transgression that initiated the Gulf of Mexico. The explanation for the opening of this basin is found in an advanced stage of the transgression, which occurred predominantly in the Tampico region bordering the gulf.

Jurassic sedimentation in the Bejuco (southern Tampico) and Poza Rica areas was discussed by Cantú-Chapa (1987a,

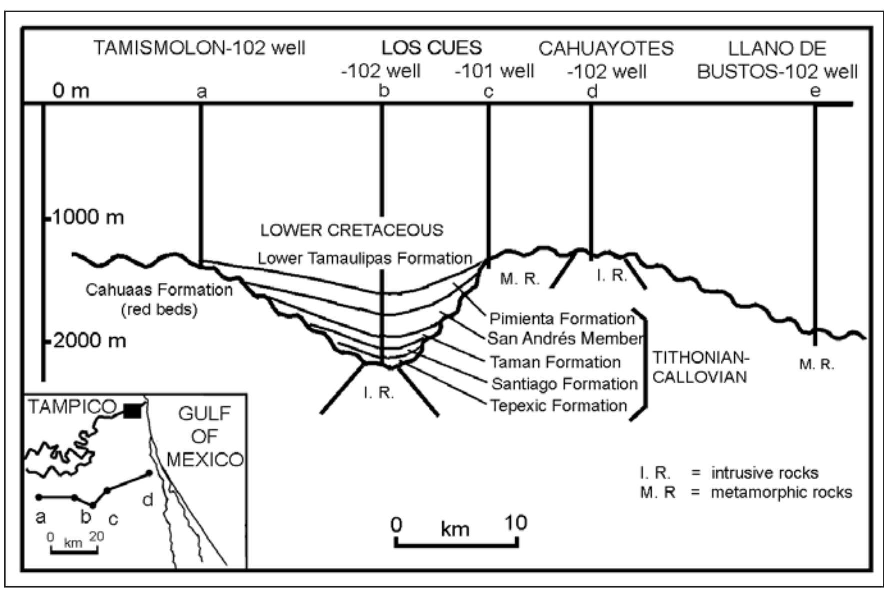

FIGURE 12. Stratigraphic-structural cross section between the Tamismolon-102 and Cahuayotes-102 wells. Sedimentary rocks of Callovian-Tithonian ages were penetrated only by the Los Cues-102 well. In contrast, the marine sedimentary cycle began at the top of the Jurassic or at the base of the Cretaceous in the other wells. Location is south of Tampico in eastern Mexico.

1992). These sections also indicate that the direction of marine incursion was consistently toward the Gulf.

Evidence for a Pre-Jurassic–Lower Cretaceous Continent

Well cuttings from the Tampico region indicate the petrography of the continental surface on which Middle Jurassic–Lower Cretaceous marine sediments were deposited. The contact shows rocks of marine (undifferentiated Upper Paleozoic and Lower Jurassic), continental (Cahuasas Formation), and intrusive and metamorphic origin (Figure 16).

Upper Paleozoic Rocks of Marine Origin

Several wells in northwestern Tampico penetrated undifferentiated Upper Paleozoic rocks, which are overlain by calcarenites (San Andrés Member) or argillaceous limestones (Pimienta Formation) of Tithonian age (Figure 16).

The Huayacocotla Formation (Sinemurian)

This formation is characterized by black shales, siltstones, and sandstones with vermiceratid ammonites of Sinemurian age obtained from several wells. It therefore represents basinal deposition. There is another sequence of shales and paralic sandstones in wells in southwestern Tampico, where benetitial ferns (Pterophyllum) of probable Plienesbachian age (or base Middle Jurassic) predominate (Flores, 1974); the sequence is informally known as the Rosario Formation. These units (the Huayacocotla and Rosario Formations) are confined to an elongate paleobay, 30 to 50 km wide and about 130 km long, which has been identified in the subsurface of Tampico. The paleobay is parallel to the present-day coastline but is without communication to the Gulf of Mexico region. It has paleogeographic relationships with outcrops of the same age located to the southwest in the Sierra Madre Oriental (Erben, 1956; Suter, 1990) (Figure 16).

Erben (1956) named the region where these rocks outcrop the "Huayacocotla paleo-bay" and suggested that there was communication with the present-day Gulf of Mexico. However, this is impossible to prove because of a lack of biostratigraphic data in the subsurface of the Gulf of Mexico margin. Calcarenites of Callovian (Tepexic) or Tithonian age (San Andrés Member) were also deposited over the Huayacocotla Formation; this nonconformable stratigraphic relationship is observed in the subsurface in Tampico and in the Sierra Madre Oriental (Alto Ixtla) (Suter, 1990).

Cahuasas Formation

These red beds have been identified in wells in Tampico and Poza Rica (Figure 16). They are overlain by, from base to top:

- evaporites assigned to the Huehuetepec Formation of Bathonian-Callovian age
- calcarenites assigned to the Callovian Tepexic Formation and Tithonian San Andrés Member
- micritic limestones (Berriasian-Valanginian) assigned to the lower Tamaulipas Formation

Based on subsurface data, the Cahuasas Formation formed islands and also constituted a large emergent area to the southeast of Tampico and east of Poza Rica, parallel to the present coastline, which was not covered until the Lower Cretaceous (Figure 16).

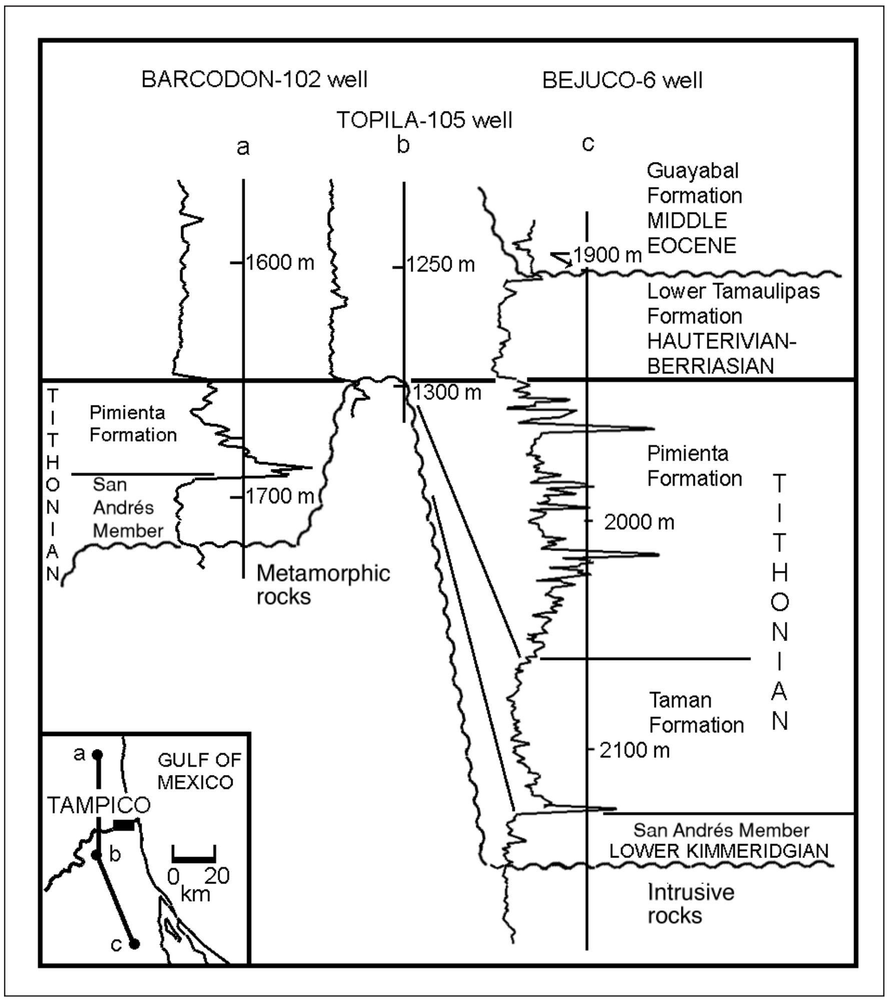

FIGURE 13. Stratigraphic cross section between the Barcodon-102 and Bejuco-6 wells based on gamma logs, ammonites, and microfossils. Datum is the Jurassic-Cretaceous boundary. Different ages exist for the base of the marine sedimentary cycle deposited over metamorphic rocks in wells near Tampico.

Metamorphic and Intrusive Rocks

These widely distributed rocks in the Tampico district were reached by the drill bit after crossing calcarenites (San Andrés Member) and argillaceous limestones (Pimienta Formation) of the Tithonian or micritic limestones (lower Tamaulipas Formation), the base of which is of Berriasian-Valanginian age (Figure 16). Metamorphic or intrusive-sedimentary rocks have also been recorded in wells in the Bejuco region (Cantú-Chapa, 1987a).

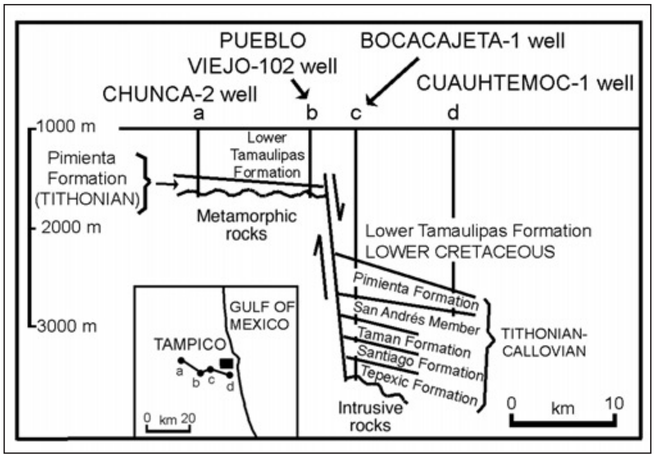

FIGURE 14. **Stratigraphic and structural cross section between the Chunca-2 and Cuauhtemoc-1 wells, Tampico District, eastern Mexico. The unconformable base of the marine sedimentary series is of different ages—Callovian in the east and Tithonian in the west.**

Middle-Upper Jurassic of Tamazunchale Area in the Sierra Madre Oriental

The Huasteca Series has been described from the Callovian in the Sierra Madre Oriental (Pisaflores); at this age, the sequence is already argillaceous and corresponds to the Santiago Formation in which ammonites of the *Reineckeia* genera are found. Therefore, this lithofacies represents an advanced stage of the sedimentary cycle (Cantú-Chapa, 1971). However, in the adjacent Tamazunchale area, Suter (1990) cites calcarenites from the Tepexic Formation without having determined their age from ammonites.

Therefore, we have inferred that this unit represents the base of the sedimentary cycle (Huasteca Series). Outcrop studies complement the stratigraphic data from the subsurface in eastern Mexico (Tampico and Poza Rica) regarding the age of the basal part of this series. Of particular sedimentological interest in the advanced stage of the sedimentary cycle of the Huasteca Series is the presence of:

- layers of manganese-bearing limestones with shale. These were deposited between the top of the argillaceous sequence of the Santiago Formation and the base of the argillaceous limestones of the Taman Formation in the Molango region (Maynard et al., 1990).
- In addition, the calcarenites of the Tepexic Formation contain isolated ferruginous oolites in Mesita-1 well (Poza Rica), as well as fragments of the ammonite *Neuqueniceras* (Cantú-Chapa, 1992, Figure 5).

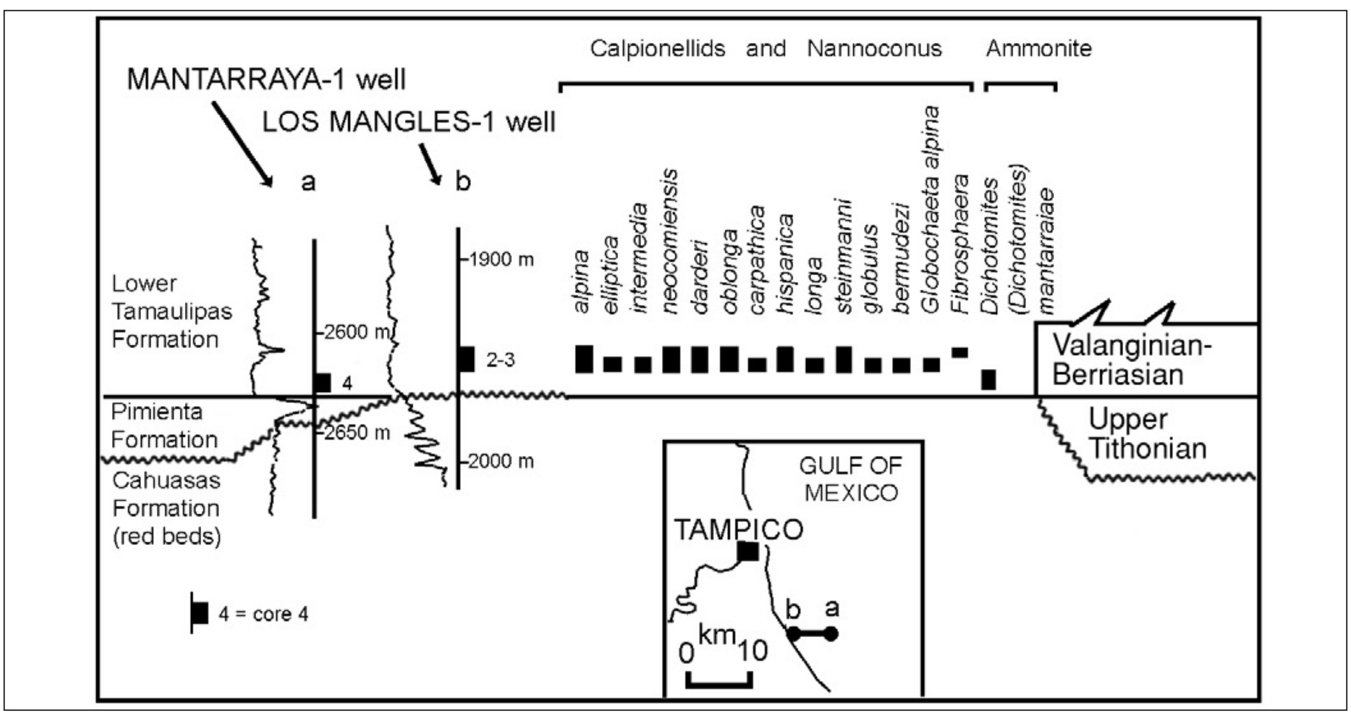

FIGURE 15. **Stratigraphic cross section between the offshore Mantarraya-1 and Los Mangles-1 wells in the Tampico District, eastern Mexico. Datum is the Tithonian-Lower Cretaceous unconformity. Note the different ages of the base of the sedimentary cycle and the stratigraphic position of the microfossils and ammonites taken from the cores. Microfossils studied by F. Bonet (Petróleos Mexicanos); ammonites studied by Cantú-Chapa (1990).**

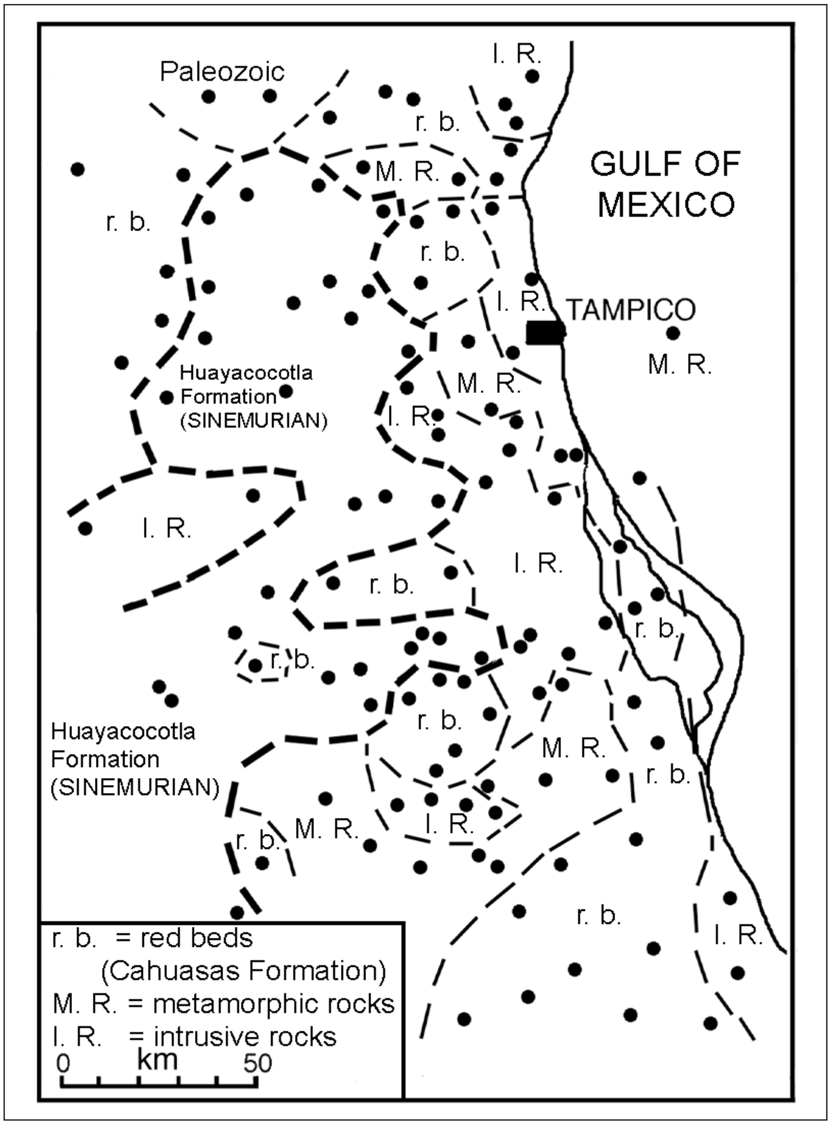

FIGURE 16. **Distribution of the ancient continent in the subsurface of northwestern Poza Rica and Tampico, where the sedimentary series of the Middle-Upper Jurassic and the Lower Cretaceous were deposited. The Huayacocotla Formation (Sinemurian) forms an elongated paleogeographic element, which is parallel to the actual coastline of the Gulf of Mexico without communication with it. (This figure is based on analysis of the study wells.)**

- Similarly, Cantú-Chapa (1971) reported the bivalve *Bositra buchi* (Roemer), generally associated with the *Reineckeia* ammonites, in the dark-gray to black carbonaceous with disseminated pyrite shale of the Santiago Formation, which represents the subsidence phase. Both ammonites are of early to middle Callovian age.

Trends of the Transgressive Middle and Upper Jurassic Cycle in the Subsurface of Tampico

Stratigraphic analysis of the Middle Jurassic in Mexico suggests that the transgression beginning in Oaxaca, in the south of the country, continued northward through areas yet undefined until it became evident in the present Sierra Madre Oriental—Tamazunchale to Huauchinango (Cantú-Chapa, 1971)—where it bifurcated.

One branch advanced toward the northwest of Poza Rica, and the other covered various regions in the Tampico district; both are evident only in the subsurface. Therefore, the basal facies of the Huasteca Series may crop out in the Sierra Madre Oriental, which borders these two regions. This would explain its relation with what until now has been seen only in the subsurface of northwestern Poza Rica: the upper Bathonian.

The Huasteca Series begins with pre–upper Bathonian evaporites, deposited above the Cahuasas Formation (wells of northwestern Poza Rica). From there, the transgression moved toward the southeast of this region, covering it in successive stages during the Middle and Upper Jurassic (Cantú-Chapa, 1992). By contrast, the base of this series is nonconformable and of different ages in the Tampico region; its approximate age varies abruptly from the Callovian to the Valanginian over very small areas. The opening of the present region of the Gulf of Mexico certainly began in this region.

In fact, stratigraphic studies of Middle and Upper Jurassic sequences in the Tampico region, over approximately 1600 km^2, explain the direction of the oceanic communication between the present Mexican territories and the Gulf of Mexico. The above descriptions and a complementary isometric map covering the subsurface of that region and part of the northwestern area of Poza Rica reinforce the explanation of the opening of the Gulf of Mexico from the Tampico region (Figure 17c).

The map uses the Jurassic-Cretaceous boundary identified in Cantú-Chapa (1989b). The formational units of the Huasteca Series deposited over this old continent are suggested by short lines in each well. Their ages are abbreviated: T (Tithonian), C-T (Callovian-Tithonian), and B-T (Bathonian-Tithonian, restricted to northwestern Poza Rica where there is evidence of older sedimentation). In this last case, the Huehue- tepec Formation represents the base of the sedimentary sequence deposited over red beds (Cahuasas Formation) (Figure 17a).

The transgression advanced from this region toward the south of Poza Rica, where it covered a large region during different stages of the Upper Jurassic (Cantú-Chapa, 1992, Figure 11). Simultaneously, the sea invaded the southern part of the Tampico district through a series of closely spaced channels (Figures 10–15). The transgressive base of the Middle and Upper Jurassic sedimentary sequence is almost always calcarenitic and diachronous. Its deposition was not continuous because it was affected by emergent areas.

In the same way, marine communication routes are inferred through wells Metlaltoyuca-102 and Horcones-1001 (Figure 17a, c: 1, 2); their continuity with the other areas is apparently cut off. Another route is across wells Martinica-1, Santa Maria Ixcatepec-3, and Tanquian-1 (Figure17a, c: 3, 4, 5), which suggests an advance of the Middle Jurassic sea toward the north.

Jurassic sedimentary rocks in these wells are about 800 to 1000 m thick and appear to be of pre-Callovian age. In fact, *Hecticoceras* is present in the argillaceous sequence of the Santiago Formation and indicates an advanced stage of the sedimentary cycle in the Silozuchil-2 well. Figure 17a illustrates an area that remained emergent until the beginning of the Cretaceous, corresponding to the present coastline of the southern regions of Tampico and the whole of Poza Rica.

Furthermore, Figure17b shows the distribution of the Huayacocotla Formation from the Lower Jurassic, above which Upper Jurassic sediments were deposited unconformably. In addition, paleoislands, made up of intrusive or metamorphic rocks that remained emergent until the Early Cretaceous, are seen in the center of the study area. Some of them were covered by the calcarenites of the San Andrés Member from the Kimmeridgian-Tithonian.

The advance of the Callovian sea occurred in the center of the Tampico region across restricted areas, as seen in wells Los Cues-102, Eleja-1, and Limon-191 (Figures 12, 17a, c: 7–9, d). The nature of these communication routes is difficult to establish because of lack of data. However, these relations can be inferred from wells Acamaya-1 and Bocacajeta-1 (Figure 17a, c: 6, 10, d), which are located close to the present coastline. Both wells represent the only transgressive communication routes toward the Gulf of Mexico. However, in the case of the Acamaya-1 and Bocacajeta-1 wells bordering the marine region, the Middle and Upper Jurassic sequence is thick. Because they now have more reference elements, the last data somewhat modify the previously expressed concept in regard to the Callovian transgression in the Bejuco area (Cantú-Chapa, 1987a).

The upper Callovian–lower Oxfordian transgression advanced toward the present Gulf of Mexico in the region between the Bocacajeta-1 and Cuauhtemoc-1 wells. This first proto-Atlantic communication route, which originated in the east from the Pacific Ocean, is hereby named the “Tampico paleochannel” (Figures 14 and 17a, d).

Upper Jurassic sediments covered the northern part of Tampico District and overlie the San Andrés Member calcarenites and the argillaceous limestones containing bentonite and chert of the Tithonian Pimienta Formation. These sediments were deposited on a continent surface composed of a variety of rocks: older sedimentary rocks of Late Paleozoic and Early Jurassic age, along with continental, intrusive, and metamorphic rocks (Figures 17a, b, c).

Deposition in eastern Mexico advanced toward the northeast where, in an elongate area of more than 400 km, subsurface data show the stage of the sedimentary cycle corresponding to the upper Oxfordian (Figure 2b). The carbonates and evaporites of the Olvido Formation indicate that the transgressive platform phase that began at that age was deposited over an old continent formed by red beds in the northern part (wells Garza-101 and San Javier-3) and metamorphic (Ocotillo-1) and intrusive rocks (Camotal-1) in the south. At the same time, argillaceous-calcareous basinal deposits corresponding to the La Casita Formation were laid down over the thick sequence of the Olvido Formation. The few ammonites obtained from cores characterize only two substages: *Lithacosphinctes* and *Idoceras* (lower Kimmeridigan) and *Salinites* and *Proniceras* (upper Tithonian).

MIDDLE JURASSIC TO LOWER CRETACEOUS STRATIGRAPHY AROUND THE GULF OF MEXICO

The importance of Middle and Upper Jurassic sedimentation in the Tampico region was discussed above, based on material recovered from oil wells. Figure 16 illustrates the marine invasion of the Gulf region, which advanced from southern Mexico. Middle and Upper Jurassic lithofacies occurring around the Gulf of Mexico are shown, taking the top of the Tithonian as a reference datum.

Dating the base of the sedimentary sequences as Middle Jurassic to Lower Cretaceous in the subsurface of the Gulf of Mexico coastal plain is very significant because it shows their paleogeographic relations and changes of facies with isochronic sequences in the rest of the country. It also explains their biostratigraphic relation with adjoining parts of the Gulf (e.g., Louisiana and Cuba) and establishes chronostratigraphic hierarchies in areas of sedimentation surrounding this basin (Imlay, 1980; Judoley and Furrazola, 1968).

The stratigraphic section in Figure 18 summarizes this large area, approximately 2500 km in length. Biostratigraphic data from the subsurface of the southeastern United States have been added, based on material studied by Imlay and Hermann (1984). Ammonites from characteristic oil wells have been used in its construction, confirming the accuracy of the stratigraphic method because it allows large-scale dating and correlation of sedimentary sequences.

This section shows the different ages of the areas that allowed the passage of the Middle Jurassic transgression until a Pacific-Atlantic communication route was established during the Oxfordian. Depositional areas of different ages are outlined, and their stratigraphic and paleogeographic relationship with the opening of the Gulf of Mexico is illustrated on a regional scale. In the area bordering the Gulf of Mexico, there are no important outcrops of Middle and Upper Jurassic rocks; the only two known are from the Upper Tithonian near Cruillas in Tamaulipas and Chinameca in Veracruz (Cantú-Chapa, 1982).

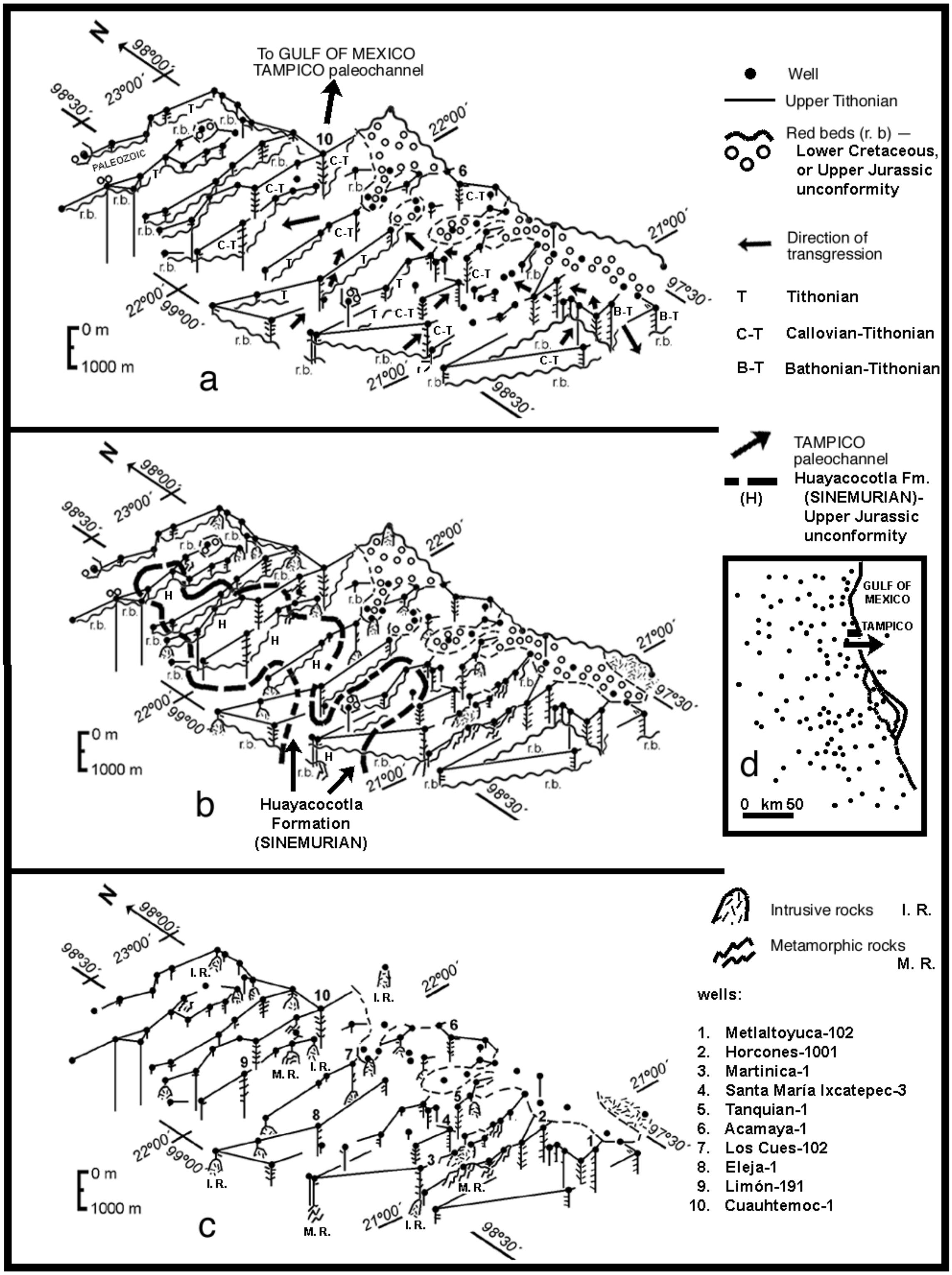

FIGURE 17. (a) Isometric map of wells in northwestern Poza Rica and Tampico regions, eastern Mexico. Reference datum: top of the Jurassic or base of the Lower Cretaceous in contact with red beds (r.b.). Only some wells show a complete sequence of the Huasteca Series (Bathonian-Tithonian) deposited over sedimentary rocks (Paleozoic, red beds, or Huayacocotla Formation), intrusive (I R), or metamorphic rocks (M R). The arrows indicate the direction of Middle Jurassic transgression toward the Gulf of Mexico. The formational units of the Huasteca Series deposited over this old continent are suggested by short lines in each well. Their ages are abbreviated: T (Tithonian), C-T (Callovian-Tithonian), and B-T (Bathonian-Tithonian). (b) Locations of the Huayacocotla Formation (Sinemurian); (c) metamorphic and intrusive rocks; and (d) studied wells.

The section depicts sedimentation beginning in the Bathonian. It defines the oldest lithostratigraphic unit of the Middle Jurassic in eastern Mexico. This constitutes the beginning of a sedimentary cycle in which final transgressive stages did not occur until the early Cretaceous. Construction of the section illustrated here was based on regional sections (Figure 2b), some of which already have been published (Cantú-Chapa, 1989b, 1992).

The Diachronous Base of the Middle Jurassic to Lower Cretaceous Sequences

The base of the sedimentary sequences present in the subsurface of the Gulf of Mexico shows various ages:

Bathonian

The oldest deposits of the Middle Jurassic in eastern Mexico, especially in northwestern Poza Rica (Palo Blanco-102 well), are lower Bathonian. Eighty meters of evaporites, shales, and calcarenites (Huehuetepec Formation) were probably deposited over red beds; these were covered by calcarenites (Tepexic Formation). Neither formation contains fossils. On the other hand, upper Bathonian–lower Callovian ammonites (*Wagnericeras* and *Kepplerites*) have been found in the siltstones (Palo Blanco Formation) that overlie the last unit. Therefore, the evaporitic and calcarenitic units should be of pre–late Bathonian age (Cantú-Chapa, 1969, 1992) (Figure 18).

The sedimentary cycle corresponding to the Huasteca Series continues in the Palo Blanco-112 well with the Santiago Formation (shales from the middle Callovian-Oxfordian), the Taman Formation (argillaceous limestones from the lower Kimmeridgian–lower Tithonian), the San Andrés Member (calcarenites), and the Pimienta Formation (argillaceous limestones with bentonite). These last two also are of Tithonian age (Figure 18).

Middle Callovian

The age of the base of the sedimentary sequence corresponding to this substage was inferred from ammonites found in the overlying unit in two wells.

In the Tampico region, the Silozuchil-2 well contains the ammonite *Hecticoceras* in core 5, characterizing the middle Callovian (Cantú-Chapa, 1963); this allows the argillaceous rocks from the Santiago Formation to be dated. In this well, the Middle Jurassic sedimentary cycle begins with calcarenites (Tepexic Formation) deposited over red beds (Cahuasas Formation). By means of stratigraphic correlation, a middle Callovian–Oxfordian age was inferred for the thick Santiago Formation. In contrast, the overlying Taman Formation is relatively thin and of early Kimmeridgian age. The Pimienta Formation, approximately 125 m thick, is assigned to the Tithonian in this region of eastern Mexico (Figure 18).

In the Tabasco region in southeastern Mexico, the Boquiapan-101 well provided a specimen of *Reineckeia* from a calcareous-argillaceous unit that indicates a middle Callovian age (Figure 18).

Because of the absence of more paleontologic material from this well, this unit (1950 m thick) was dated as middle Callovian to Kimmeridgian by stratigraphic correlation. It is covered by 250 m of argillaceous calcareous sediments with bentonite from the Tithonian. Even though this well drilled the greatest thickness of the Middle and Upper Jurassic, it did not cut the whole sequence; in fact, its base is unknown.

Oxfordian

Significant sedimentologic events took place in the lower and upper Oxfordian, according to ammonites recovered from various wells. The presence of these fossils in argillaceous or calcareous-argillaceous rocks indicates an advanced phase of the sedimentary cycle in the region bordering the Gulf of Mexico, as follows (Figure 18):

Core 3 of the Balam-101 well in southeastern Mexico provided *Ochetoceras* and *Discosphinctes* characterizing the upper Oxfordian. These ammonites come from calcareous rocks that cover sandstones, which overlie anhydrites that correspond to the base of the sedimentary sequence (Ek-Balam Formation). This sequence is overlain by calcareous-argillaceous rocks approximately 560 m thick from the Kimmeridgian (Akimpech Formation) and 150 m of argillaceous limestones with bentonite from the Tithonian (Edzna Formation) (Angeles-A. and Cantú-Chapa, this volume). The last two ages were established by stratigraphic correlation based on previously studied ammonites (Cantú-Chapa, 1977, 1982).

In wells in Louisiana, Imlay and Hermann (1984) indicated the presence of *Ochetoceras* and *Discosphinctes* that also gives a late Oxfordian age for the Smackover Formation containing these fossils. This unit was deposited over evaporitic rocks, the basal contact of which is unknown. In the two previous cases, the base of the sedimentary cycle is probably of early Oxfordian age (Figure 18).

In northeastern Mexico, several wells penetrated thick sequences of evaporitic and calcarenitic rocks almost 550 m thick. Rocks corresponding to the Olvido Formation rest above evaporites in some wells (San Javier-3, Fresnito-1), which cover red beds. None of these units deposited over red beds contains fossils. However, by their stratigraphic position, it is possible to suggest that they may be assigned a late Oxfordian age. In fact, the base of the La Casita Formation contains ammonites (*Lithacosphinctes* and *Idoceras*) from the lower Kimmeridgian (Figures 2b, 18).

In some wells in northeastern Mexico (e.g., Camotal-1), basal calcarenites were deposited over intrusive rocks. These are covered by the La Casita Formation (Kimmeridgian-Tithonian), which is less than 50 m thick. This indicates that the sedimentary cycle began in the late Oxfordian over an old continent made up of intrusive and metamorphic rocks (Ocotillo-1 well and Camotal-1 well) in this part of northeastern Mexico (Figures 2b, 18).

In another part of this section, the present author classified the ammonites from Santa Lucia-10 well in southeastern Poza Rica (Figure 18). The fossil *Discosphinctes* comes from argillaceous units more than 200 m thick assigned to the Santiago Formation and *Ataxioceras* from 220 m of argillaceous limestones assigned to the Taman Formation (lower Kimmeridgian). The Upper Jurassic sedimentary cycle ends in this well with 320 m of calcarenites (San Andrés Member) and 60 m of argillaceous limestones with bentonite (Pimienta Formation), both Tithonian.

Knowledge of the Pinar del Rio region in western Cuba, where abundant ammonites (*Discosphinctes*, *Dichotomosphinctes*, *Euaspidoceras*, *Cubaochetoceras,* and *Ochetoceras*) of the upper Oxfordian have been described, must be added to what is already known about the sedimentation that occurred around the Gulf of Mexico. The base of the Upper Jurassic sequence in Cuba is not known (Judoley and Furrazola, 1968). These fossils appear in a sequence that is calcareous at its base, passing to argillaceous sandstones with limestones at the top, forming part of the Jagua Formation. This unit represents an advanced

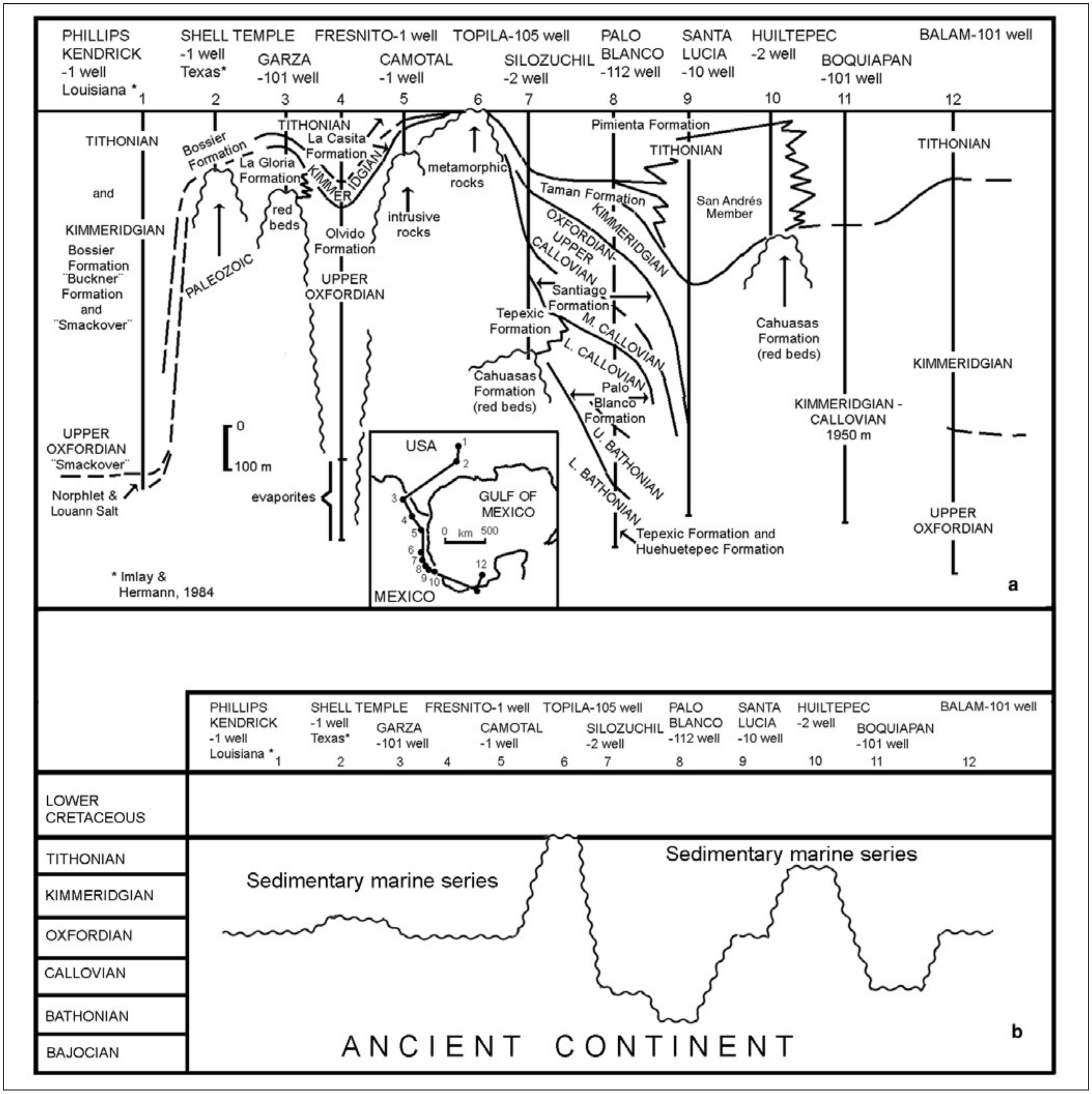

FIGURE 18. **(a) Stratigraphic correlation of the Middle and Upper Jurassic with wells from the Gulf of Mexico coastal plain. Ages and thickness of the sedimentary series are as follows: older in the east, Bathonian (Palo Blanco-112 well), and thicker in the southeast (Boquiapan-101 well). Datum is the top of the Tithonian. (b) Stratigraphic synthesis.**

event of the Upper Jurassic sedimentary cycle with clear biogeographic similarity to other regions of Mexico (San Pedro del Gallo and Taman regions, and Balam-101 well) (Imlay, 1980).

Lower Kimmeridgian

The argillaceous limestone Taman Formation was deposited over red beds in the southeast of Poza Rica. Some wells of the San Andrés field show this transgressive event of the lower Kimmeridgian because of the presence of *Idoceras*, which was found at the base of the Taman Formation (Cantú-Chapa, 1999).

Tithonian

The final Late Jurassic depositional event that took place in the Gulf of Mexico coastal plain is found in southeastern Poza Rica and is represented by Tithonian strata. The sedimentary cycle began there with thick layers of calcarenites deposited over red beds. The San Andrés Member is covered by 30 m of the Pimienta Formation in the Huiltepec-2 well area (Figure 18). Another example of Tithonian sedimentation, similar to that in southeastern Poza Rica, is present in well Barcodon-102 in the Tampico region. Certain wells in Tampico indicate a late stage of sedimentation from the Jurassic (Figures 10–15).

Lower Cretaceous

The Topila-105 well from the Tampico region is included in Figure 18 because it represents the most advanced stage of the transgressive cycle that began in the Middle Jurassic in Oaxaca. In this part of eastern Mexico, the transgression took place in the Early Cretaceous. The Topila-105 well was included in the above chronostratigraphic correlation to underline the aforementioned transgressive stage where ammonites and microfossils (calpionellids and nannoconus) have determined a Berriasian age for this event (Figure 13). The unconformity (Lower Cretaceous) separates micritic limestones of the lower Tamaulipas Formation from metamorphic rocks.

MEXICO AS THE WESTERN MARGIN OF PANGEA

Another biostratigraphic argument that proves that the opening of the Gulf of Mexico was from the Pacific to the Atlantic Ocean through the ancient Mexican territory is the presence of fossils of marine origin, from the Permian to Lower Jurassic, in this part of the country. This presence constitutes further paleogeographic evidence that allows us to delimit and place part of the Mexican territory as an oceanic province (related to the Pacific province). At the same time, this marine evidence also defines the western margin of Pangea, the subsequent rupture of which gave origin to the Gulf of Mexico and the Atlantic Ocean.

Generally, it can be seen that in conceiving the representation of this megacontinent, there is no place to establish the correct location of the present Gulf of Mexico during the time such continental mass existed (Hsu and Bernoulli, 1978). The Tethys and a primitive Atlantic Ocean of Triassic–Lower Jurassic age have been proposed without showing paleontologic evidence of that age for an ocean (Marcoux, et al.,1982; Thierry, 1982).

The manner and time of the dismembering of Pangea constitute a controversial problem in geology. We are concerned with its analysis because it implies explaining the opening of the Gulf of Mexico. However, we think that the biostratigraphic data found in Mexico allow the inference of the marine-continental boundary (Tethys-Pangea) in this part of the American continent, especially because the area occupied an important place as the margin of Pangea in certain geologic periods.

Permian

The boundaries of the subprovince of the eastern Pacific are set in several locations of Mexico and the American continent containing ceratites (araxoceratidae and xenodiscidae) and goniatites of the Permian.

Biogeographic evidence of marine fauna of this age in Mexico and Europe does not allow the establishment of an Atlantic communication route between these two sedimentation areas, because those fossils did not extend beyond Sicily and Tunisia in the Mediterranean province, which are locations that mark the western boundary of the Tethys sea. Paleogeography of the marine Upper Permian of Mexico shows clearly that there were no links between the Pacific Ocean and the Tethys sea. A continental barrier located in the eastern part of Mexico as well as in North and Central America stresses the inexistence of the Gulf of Mexico and the Atlantic Ocean at this time (Spinosa et al., 1975) (Figure 19b).

Upper Triassic

Sequences which correspond to the upper part of this period are known only in northwest and central Mexico (Burckhardt, 1930). Westermann (1973) described the world biogeographic distribution of the bivalve *Monotis* from the marine Upper Triassic, placing them predominantly around the circum-Pacific province, that is, in the west of the American continent and in the eastern part of Asia, which was in communication with Oceania, the Mediterranean, the Middle East, and India. This fossil is found in three locations in Mexico: Baja California, Sonora, and Zacatecas (Figure 19a, c).

Westermann (1973) established the presence of a physical barrier between the eastern part of the Pacific Ocean and the Tethys, corresponding to Pangea, when he studied the distribution of the bivalves. According to Tozer (1980), the biogeographic distribution of the ceratites from the Upper Triassic is also restricted to the provinces of the Arctic, Eastern Pacific Ocean, and the Tethys sea, which coincides with the distribution of *Monotis*. Therefore, the boundary of the western edge of Pangea, which includes Mexico, is inferred by this Upper Triassic biogeographic data. The location of Zacatecas in the center of the country has more biogeographic affinity with the province of the Eastern Pacific (North and South America) than with the Tethys sea, because of the nonexistence of the Atlantic Ocean.

Lower Jurassic

It has always been a great temptation to explain the presence of the Huayacocotla Formation in eastern Mexico as a marine incursion from the Tethys during the Lower Jurassic (Sinemurian) (Erben, 1956; Schmidt-Effing, 1976; Thierry, 1982; Ziegler, 1971). However, it is common to find ammonites (vermiceratids and oxynoceratids) of this formation in the whole western region of North and South America, from Alaska to Sonora, Peru, and Chile (Hillebrandt et al., 1992; Imlay, 1980). They all correspond to the Eastern Pacific province. The same fossils are common in the Tethys province, especially in France, Italy, the northwestern part of Africa, and the Iberian peninsula (Arkell, 1956).

These paleobiogeographic elements located near the coasts of the northern African and European continents have suggested the establishment of a marine communication between eastern Mexico and regions that would correspond to the western edge of the Tethys sea through a paleogeographic province named Proto-Atlantic (Schmidt-Effing, 1976; Thierry, 1982). These ammonites were correlated without evidence of this suggested connection. A relevant fact to consider is the distribution of the Huayacocotla Formation in the subsurface of Tampico District; it is not present in the easternmost region of the Gulf of Mexico coastal plain, as seen above. In fact, this formation defines an elongated paleogeographic unit parallel to the present coastline that connects the southeast with outcrops of the Sierra Madre Oriental to the north (Figures 16 and 19d).

In spite of not having intermediate biostratigraphic data of Sinemurian age between the northwest and the east of Mexico, where vermiceratid and oxynoceratid ammonites are found, we insist on considering that these two distant marine sedimentation areas justify the definition of the Eastern Pacific province in contact with the western edge of Pangea.

Rocks of Continental Origin

Alternating with the marine-origin sequences of the Upper Permian, Upper Triassic, and Lower to Middle Jurassic are rocks of continental origin. Each of these continental events indicates the establishment of the western edge of Pangea in Mexico.

CONCLUSIONS

Incoherent and sometimes naïve geologic concepts have been used to explain the origin and age of the Gulf of Mexico. In some studies, “suspect terrains” are displaced in a manner that induces vertigo in the reader. Furthermore, the “Mojave-Sonora Megashear,” which has little basis in fact, is referred to in almost every synthesis of Mexican geology. Likewise, the “Xolapa terrain” in southern Oaxaca, which is very poorly known, is always shown to have the same distribution throughout the Jurassic and Cretaceous (Meneses-R. et al., 1994).

The persistent interpretation of the distribution of the metamorphic rocks of this “Xolapa Terrain” as an immutable monolithic structure represents a problem in explaining the Pacific origin of the Gulf of Mexico. These metamorphic complexes must be studied in accordance with the subsurface model of the Tampico region presented above, whereas in nearby areas, metamorphic and intrusive rocks were covered

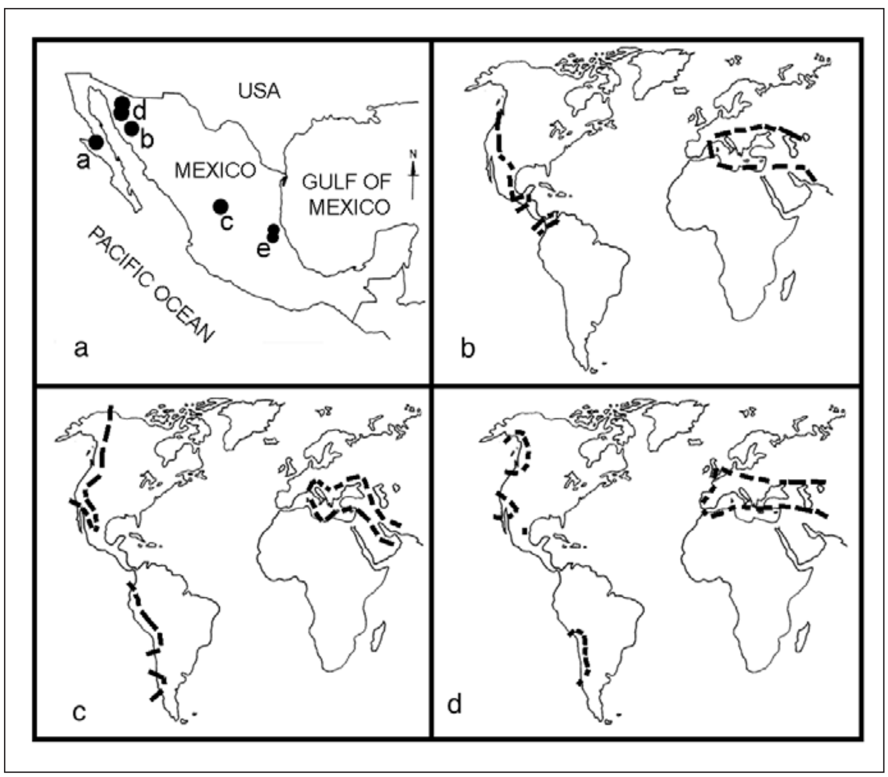

Figure 19. **(a) Locations of the Triassic (a, b, c) and Lower Jurassic (Sinemurian, d, e) marine rocks in Mexico. Paleogeography of the Permian (b), Triassic (c), and Lower Jurassic (d) marine rocks in the American, European, and African continents, based on ammonite and bivalve distribution (after Imlay, 1980; Spinosa et al., 1975; Westermann, 1973). The absence of these fossils in some regions of eastern Mexico (d, this work), as well as in the Gulf of Mexico and the North Atlantic Ocean, suggests that the western edge of Pangea was located in this country during the Triassic to Middle Jurassic. For distribution of the Permian localities of Mexico, see Figure 1b (Cantú-Chapa, 1997).**

by different phases of the Upper Jurassic and Lower Cretaceous transgression during its advance toward the Gulf of Mexico. The possibility that southern Mexico paleogeographic elements allowed the passage of the Bajocian transgression toward the future Gulf region must be considered. The presented evidence points to the consideration that this opening began through Oaxaca, and not through hypothetical passages in western Mexico.

Paleontologists always make reference to paleogeographic elements with marked fixation. They place an impossible and nonexistent communication route from the western Tethys to the eastern Pacific through a supposed "Hispanic Corridor" that would pass through Mexico, or they correlate paleogeographic provinces of different ages, e.g., the Bajocian of Venezuela with the Sinemurian of eastern Mexico (Bartok et al., 1985). All the above makes the study of the Gulf of Mexico opening illogical in many aspects.

The Bajocian-Oxfordian ammonites found at the base of the sedimentary series always show a transgressive trend from the Pacific Province (Oaxaca in southern Mexico) to the Gulf of Mexico (Louisiana and Cuba) (Figure 20).

Intermediate locations between Oaxaca and northwestern Poza Rica or in the Sierra Madre Oriental that are linked paleogeographically and which justify the upper Bajocian–middle Callovian transgression from the Pacific toward the Gulf of Mexico are still to be found. The same arguments are valid to establish communication between the subsurface of Tabasco and Campeche in southeastern Mexico and the Gulf of Tlaxiaco (Figures 21 and 22).

Biogeographic fauna-distribution maps of Mexico from the Permian to the Middle Jurassic always show a Pacific more than an Atlantic relation. Until now, there has been no biostratigraphic evidence of these ages that proves a communication route across the Gulf of Mexico coastal plain, not even in wells of the North Atlantic.

On the other hand, one cannot discard the possibility of finding, in the vast region of the North Atlantic, paleontologic material of marine origin from the Permian to the Middle Jurassic that would relate to both the Pacific origin of the Gulf of Mexico and the distribution of the western margin of the old Pangea continent. Such discoveries would substantially modify this study.

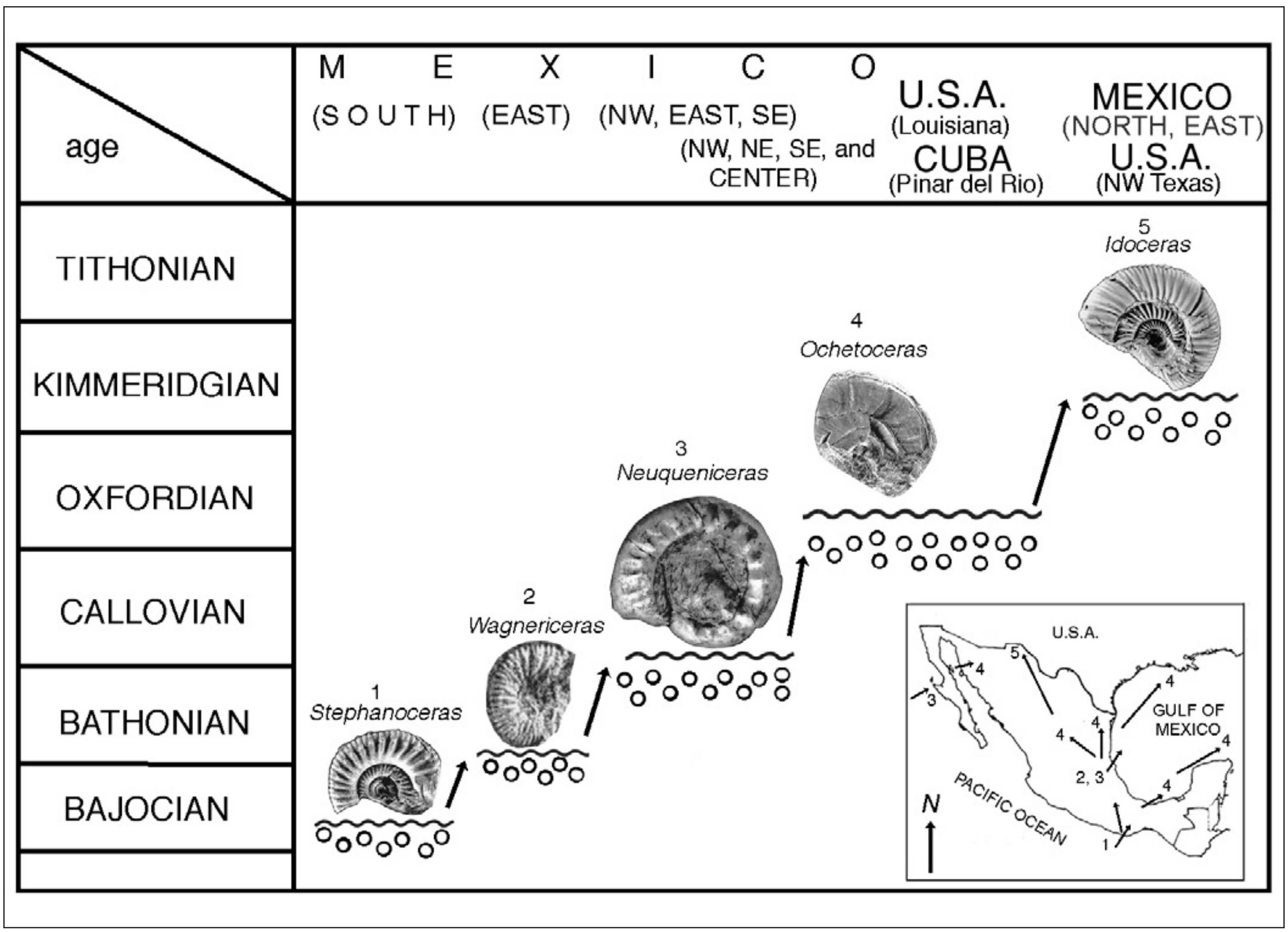

FIGURE 20. **Middle and Upper Jurassic transgressive events from southern Mexico (Bajocian) to the Gulf of Mexico (United States and Cuba) (lower Oxfordian) determined by ammonites. Small map shows transgressive events explained in Figure 7a.**

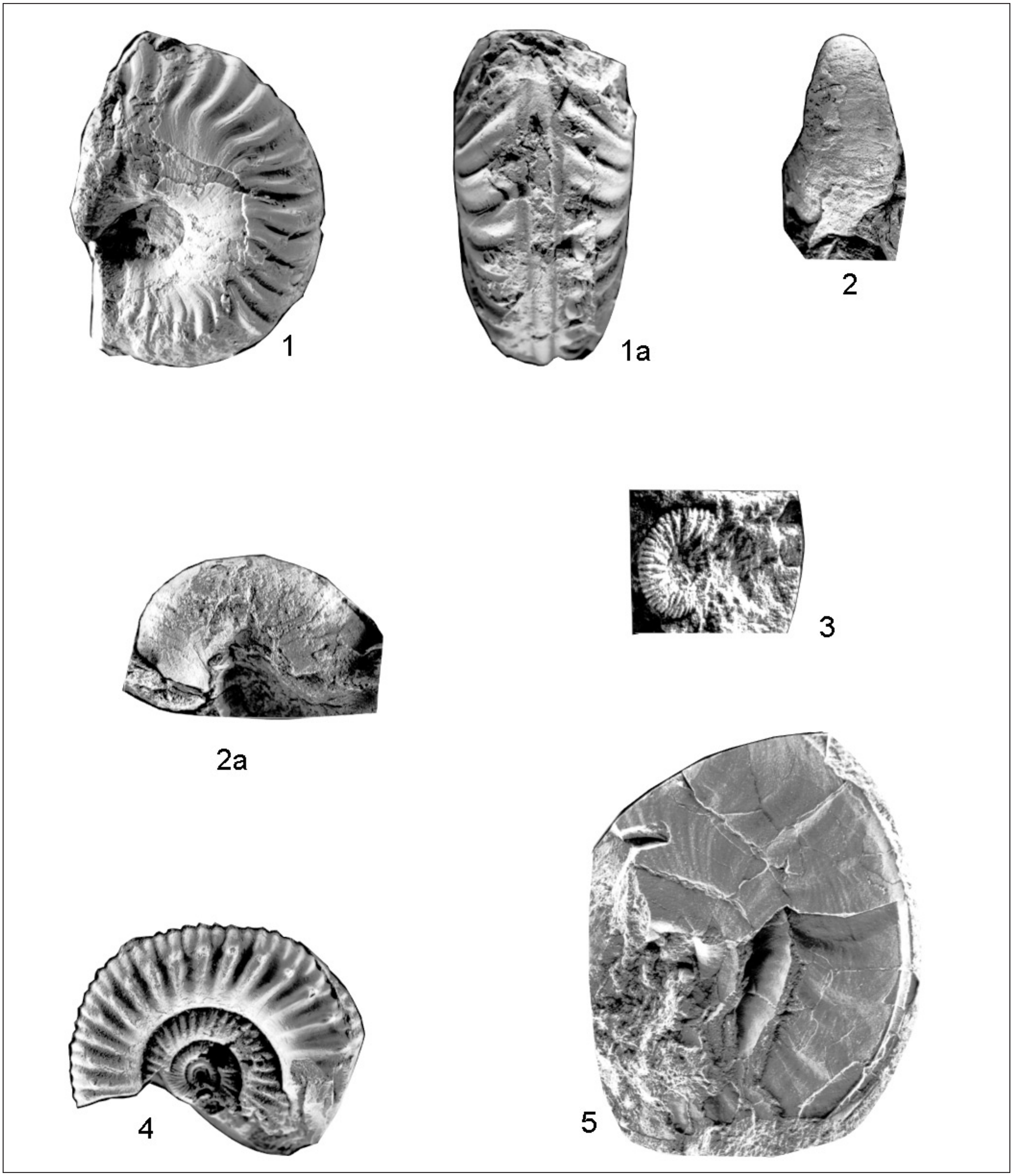

FIGURE 21. Ammonites and bivalves observed in cores and outcrops of Middle and Upper Jurassic ages, from southern (1, 1a, and 4), eastern (2, 2a, and 3), and southeastern (5) Mexico. 1, 1a. *Guerrericeras inflatum* (Westermann), lower Callovian. Coahuilote, Guerrero. 2, 2a. *Liogryphaea nebrascensis* (Meek and Hayden), middle Callovian, Poza Rica-162 well, core 5, Poza Rica District. 3. *Wagnericeras* aff. *wagneri* (Oppel), upper Bathonian, Palo Blanco-112 well, core 6, Poza Rica District (Cantú-Chapa, 1969). 4. *Stephanoceras* sp., Nuyoo, Oaxaca, middle Bajocian, Oaxaca. 5. *Ochetoceras* sp., upper Oxfordian, Balam-101 well, core 3, Campeche District, Gulf of Mexico. All specimens are 1 x.

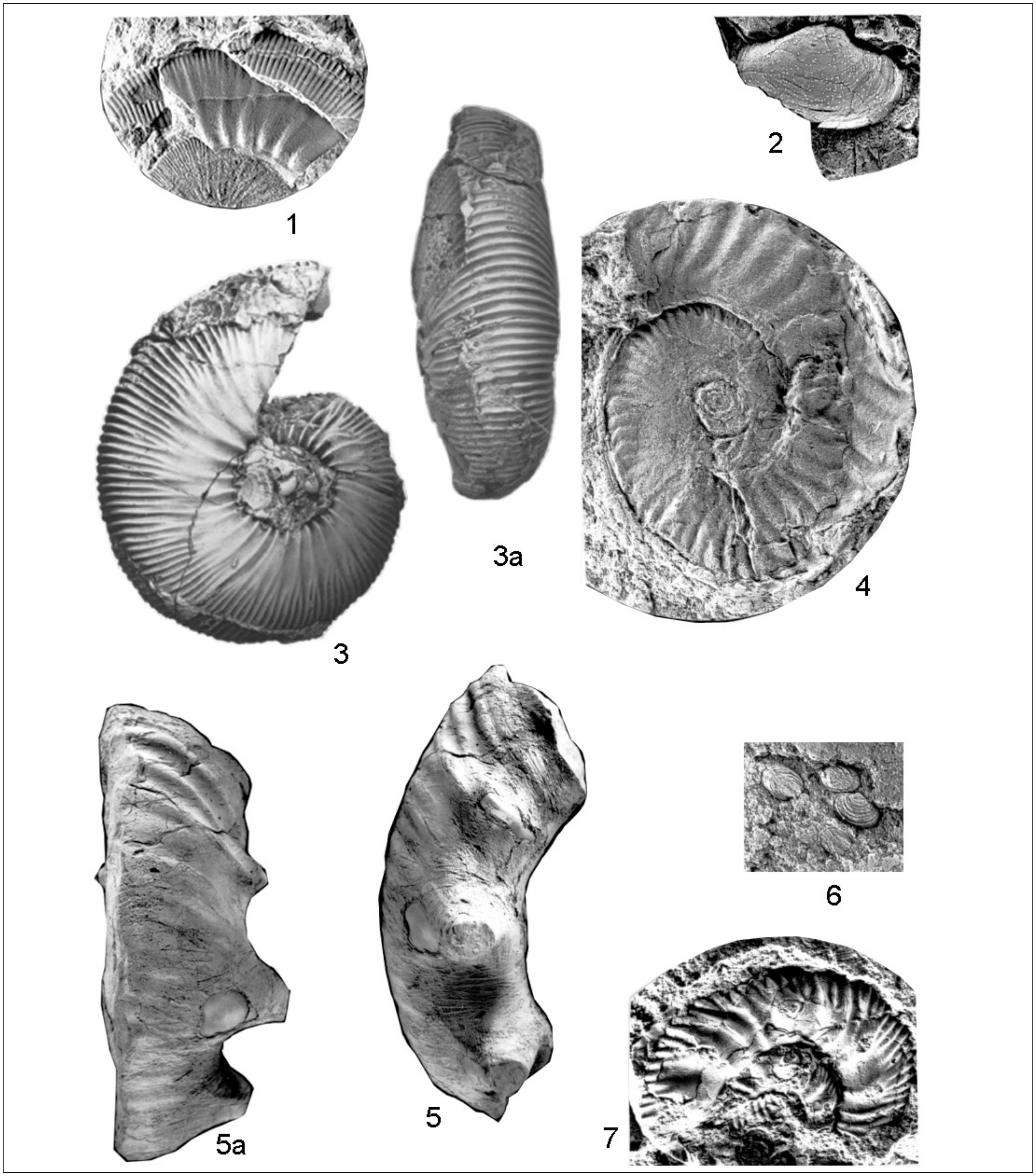

FIGURE 22. Ammonites and bivalves observed in cores and outcrops of Middle Jurassic age, from southern (5 and 5a) and eastern (1, 2, 3, 3a, 4, 6, and 7) Mexico. 1. *Ataxioceras* (*Shneidia*) sp., lower Kimmeridigian, Papantla-1 well, core 10, Poza Rica District. 2. *Posidonia ornati* (Quenstedt), middle Callovian, Talaxca-2 well, core 6, Poza Rica District. 3, 3a. *Virgatosphinctes mexicanus* (Burkhardt), lower Tithonian. Taman, San Luis Potosí. 4. *Hecticoceras* sp., middle Callovian. Silozuchil-2 well, core 5, Tampico District (Cantú-Chapa, 1963). 5, 5a. *Neuqueniceras* sp., lower Callovian, Tecocoyunca, Guerrero. 6. *Bositra buchi* (Roemer), middle Callovian, Huauchinango, Puebla (Cantú-Chapa, 1971). 7. *Reineckeia* sp., middle Callovian. Palo Blanco-112 well, core 4, Poza Rica District. Specimens 1 and 5 are x 0.5; 2, 4, 6, and 7 are x 1.5; 3 and 3a are x 1.

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