8

Horbury, A. D., S. Hall, F. González-P., D. Rodríguez-F., A. Reyes-F., P. Ortiz-G., M. Martínez-M., and G. Quintanilla-R., 2003, Tectonic sequence stratigraphy of the western margin of the Gulf of Mexico in the late Mesozoic and Cenozoic: Less passive than previously imagined, *in* C. Bartolini, R. T. Buffler, and J. Blickwede, eds., The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics: AAPG Memoir 79, p. 184–245.

Tectonic Sequence Stratigraphy of the Western Margin of the Gulf of Mexico in the Late Mesozoic and Cenozoic: Less Passive than Previously Imagined

Andrew D. Horbury
Cambridge Carbonates Ltd., Solihull, West Midlands, U.K. and Royal Holloway College, University of London, U.K.

Stephen Hall[1]
StrucOil Inc., Houston, Texas, U.S.A.

Francisco González-P.
PEP, Tampico, Mexico

Dioniso Rodríguez-F.
PEP, Tampico, Mexico

Armando Reyes-F.
PEP, Tampico, Mexico

Patricia Ortiz-G.
PEP, Tampico, Mexico

Martín Martínez-M.
PEP, Tampico, Mexico

Guillermo Quintanilla-R.
PEP, Tampico, Mexico

ABSTRACT

Middle Eocene compression resulted in formation of the Sierra Madre Oriental fold and thrust belt and end-early Miocene compression resulted in formation of the Chiapas-Campeche fold and thrust belt. These events mask the importance of other periods of deformation, principally in the Middle–Late Jurassic, Late Cretaceous, and Paleogene. Deformation is represented by folding, thick-skinned thrusting, basin inversion, and development of major angular unconformities. Associated features include development of karstification, production of breccias, onlap, lowstand wedges, seeding of carbonate platforms, entry of siliciclastic sediments into carbonate basins, significant switches in input directions of clastic sedimentary systems, initiation of extensional tectonism basinward of the compressive deformation front and igneous activity.

We propose that, during the late Mesozoic and the Cenozoic, Pacific plate-margin compressive deformation often extended eastward into the Gulf of

[1]*Present affiliation*: Woodside Petroleum Ltd., Perth, Australia.

Mexico. Two main belts of deformation are identified, which are linked back to Pacific plate-margin processes by postulated deep-seated faults. The first and outer (easternmost) belt is seen on regional seismic lines as a long-wavelength, easterly facing, monoclonal fold that developed close to the transition of thick into thinned continental crust. The Sierra Madre Oriental is the second belt of which the structural history already has been well described in the literature. Where salt is present at depth, compressional events are expressed only as laterally propagated thin-skinned folds and thrusts.

These events are of critical importance in that they contribute many unique geologic features that cumulatively give Mexico a world-class petroleum system.

INTRODUCTION

Along the western margin of the Gulf of Mexico, a series of unusual stratigraphic, structural, sedimentological, and diagenetic events have been noted. The best known comprise breccia deposits, which are variously attributed to meteorite impact (Grajales et al., 2000) carbonate slope processes (Angeles et al., 1994), or karstification (Miranda, 2000). Discussion also has focused on the possible origin of the Tamabra Formation as a platform slope (Viniegra and Castillo, 1970) or as a shelf-margin (Coogan et al., 1972), which sits approximately 1,000 m below the ''correlative'' platform interior and which contains meteoric cements (Enos, 1988). Erosional features include development of ''paleocanyons'' (Busch and Govela, 1978; Carrillo, 1980) and deep karstification of platform systems (Viniegra and Castillo, 1970). In addition, initiation of shelf carbonates directly upon basinal sediments in both the Jurassic and Cretaceous (e.g., data presented in González, 1970; Wilson, 1990; Goldhammer, 1999), and easterly onlap of Paleogene sediment onto the Cretaceous Tuxpan platform (Viniegra and Castillo, 1970; Coogan et al., 1972) are other examples of stratigraphic dynamism. Many features have been explained in the context of local models, which are not always applicable to similar phenomena in other parts of the Gulf Coast (e.g., origins of breccias proposed in both Coogan et al., 1972, and Grajales et al., 2000) or single phenomena, which have been analyzed in very general regional terms and in isolation from the other features (e.g., Carrillo, 1980). At the same time, neither plate-scale analysis (e.g., Pindell and Kennan, 2001) nor whole margin-scale studies (e.g., Salvador 1987, 1991) have addressed the origin of these features. Only at the basin scale (e.g., Pérez, 1992) are some of the issues discussed, but a full understanding requires a more regional picture. It is therefore the aim of this paper to correlate all of these events and examine whether they can be explained in one unified tectonostratigraphic process.

Study Area and Scope of Paper

The study area comprises the basins that border the western side of the Gulf of Mexico, roughly incorporating the Sierra Madre Oriental and all basins to the east of it, as far south as the Sierra de Chiapas and the margin of the Yucatán platform. This area and localities mentioned in the text are given in Figure 1. In this paper, we give a brief overview of structural elements, followed by descriptions of the major sequences, their upper boundaries, and the interpretation and context of these surfaces along the Gulf Coast of Mexico.

Nomenclature

At this stage, we do not attempt a formal naming or ranking of the sequences (megasequence, sequence, parasequence, etc.) since this paper is concerned primarily with identifying sequence boundaries and their origin, rather than attempting a complete definition of the sequence stratigraphy of the Mexican Gulf Coast. Please note that we have anglicized various terms where appropriate; e.g., the Cuenca (Terciario) del Sureste becomes the Southeast Basin, and the Formación Tamaulipas Superior becomes the Upper Tamaulipas Formation. In addition, for the sake of consistency and to avoid arguments over semantics, we have referred to most units as formations, although there are many instances in which other terms have been used. For example, González (1970) has described Kimmeridgian age oolites as the San Andrés Member of the Tamán Formation, and Stabler (1972) has described the same unit as the San Andrés Formation. Similarly, the Jurassic red beds have been referred to variously both as the Huizachal Formation of Middle Jurassic age (*sensu* Imlay et al., 1948) or of Late Triassic age (*sensu* Carrillo, 1961); there are also descriptions of a Huizachal Group (*sensu* Mixon et al.,

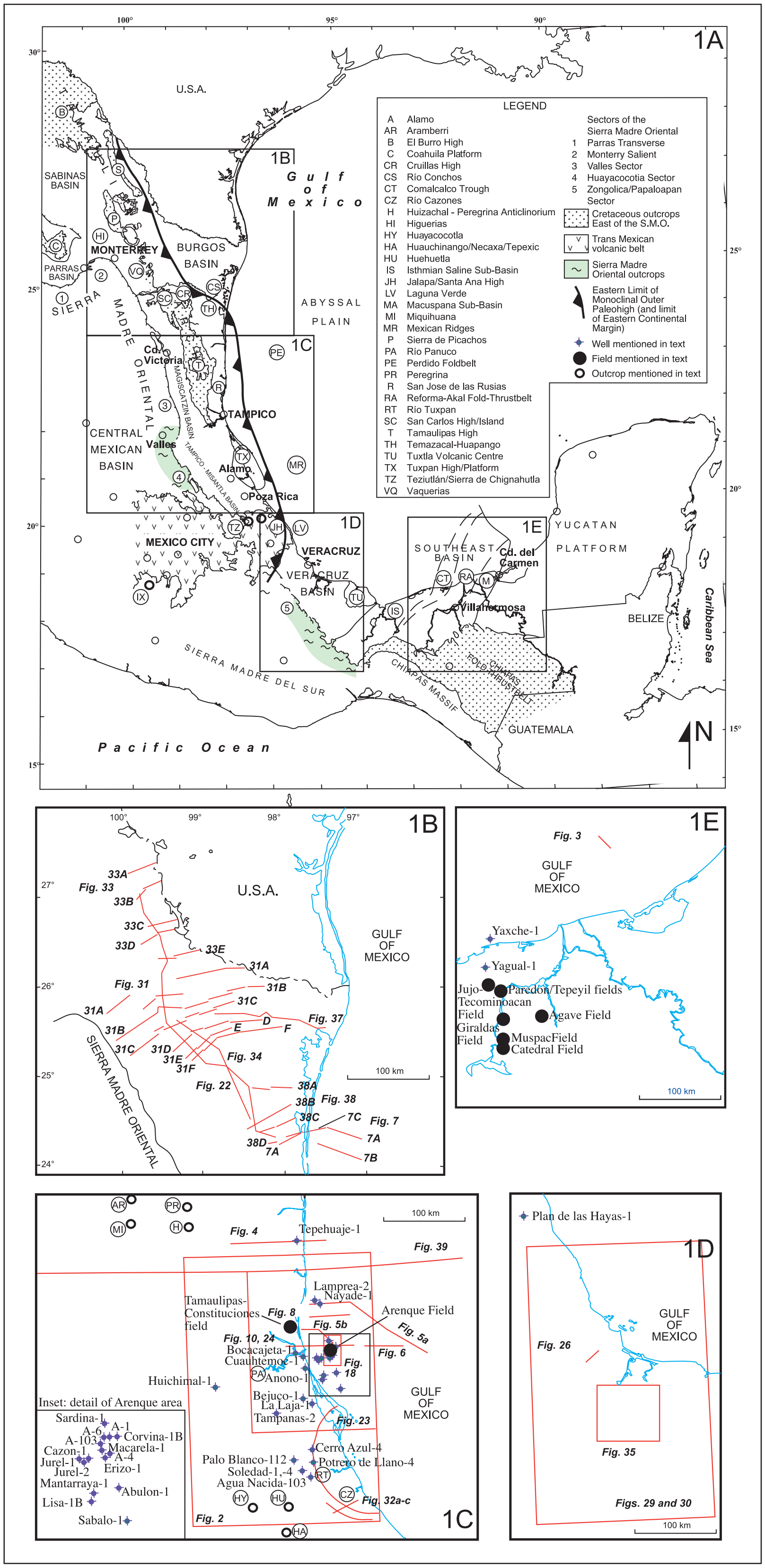


Figure 1. Location map. (a) Principal paleogeographic elements. (b–e). Location of maps, cross sections, outcrop localities, wells, fields and seismic lines used in this paper, ranging from the Burgos Basin to the Southeast Basin.

1959). In these cases, we have applied the terms most commonly used at present by Petróleos Mexicanos (Pemex). We also have abbreviated many commonly used terms.

Data

This publication is based on original observations in the Tampico area that is supported by other studies on original material in the Veracruz area and some original observations from southeastern Mexico. To complete the model, data from public-domain literature has been integrated. Unfortunately, many of the observations, concepts, and paradigms that are key to this publication are unpublished or are in unedited conference abstracts; however, we have tried to illustrate and substantiate elements of these by adapting public-domain data.

Paleontological Control

The quality of paleontological control is critical to correlation of tectono-stratigraphic events in and between basins. This has generally been possible, although problems still arise where major stratigraphic gaps occur above or below boundaries. López (1982), a veritable Mexican ''lexicon'' of stratigraphic ages and formations, still gives the broadest review. The Jurassic and Early Cretaceous in deeper-water facies have been dated best on ammonites, e.g., Burckhardt (1930), Erben (1956a), and Cantú (1992). Micropaleontology and non-ammonite macropaleontology also have been used, although there is debate about the usefulness of different paleontological determinations (Adatte et al., 1994; Cantú, 1996; Remane et al., 1999). Continental and shallower-marine sediments have proved difficult to calibrate; diagnostic fossils sometimes used include *Gryphaea, Favreina salevensis, Acicularia,* and *Nautiloculina oolithica*, all of which have long ranges and may be strongly facies-controlled. In the Southeast Basin, instances occur where ''Kimmeridgian'' interbeds with ''Tithonian,'' since the Kimmeridgian is traditionally identified by long-ranging benthic microfossils and the Tithonian by long-ranging planktonics. Such situations clearly represent progradation of shallow-water parasequences and/or input of turbidites into deeper-water environments. Detailed stratigraphic control of younger Cretaceous units mostly lies in unpublished reports, and where biostratigraphy is applied, it is generally of good quality. Micropalaeontology has been the main method of analysis (e.g., Bonet, 1956; Trejo, 1975).

Because of the economic necessity of understanding the Mesozoic, Cenozoic units have been studied less thoroughly, and stratigraphic schemes either are very lithostratigraphic, or purely chronostratigraphic at the expense of lithostratigraphy, and problems have arisen. For example the Chicontepec Formation is named on the presence of sandstones in a generally argillaceous basin (Cantú, 2001a) and, as such, may be exclusively of Paleocene age in outcrops along the Sierra Madre Oriental (López, 1982)(Figure 2) and near Tampico (Carrillo, 1980). The same formation is then exclusively Eocene in age in the subsurface of Poza Rica (Busch and Govela, 1978). This has led to problems of interpretation: namely, the placing of a major regional unconformity between the two developments of this formation (Busch and Govela, 1978), which probably does not exist (Cantú, 2001a). Conversely, in many basins "formations" are named purely on their contained fauna, which leads to environments from paralic to bathyal being placed in the same stratigraphic unit without regard to lithology, as pointed out by Sánchez and Salmerón (1996). Another area of complexity is the description of sediments in the Tampico area as "Oligo-Miocene" (e.g., Carrillo, 1980), about which more precision is now required. Only recently has a rigorous multidisciplinary biostratigraphic/sequence-stratigraphic approach been established, resulting in improved Cenozoic basin analysis (e.g., Pérez, 1992; Sánchez and Salmerón, 1996; Hernández, 2000).

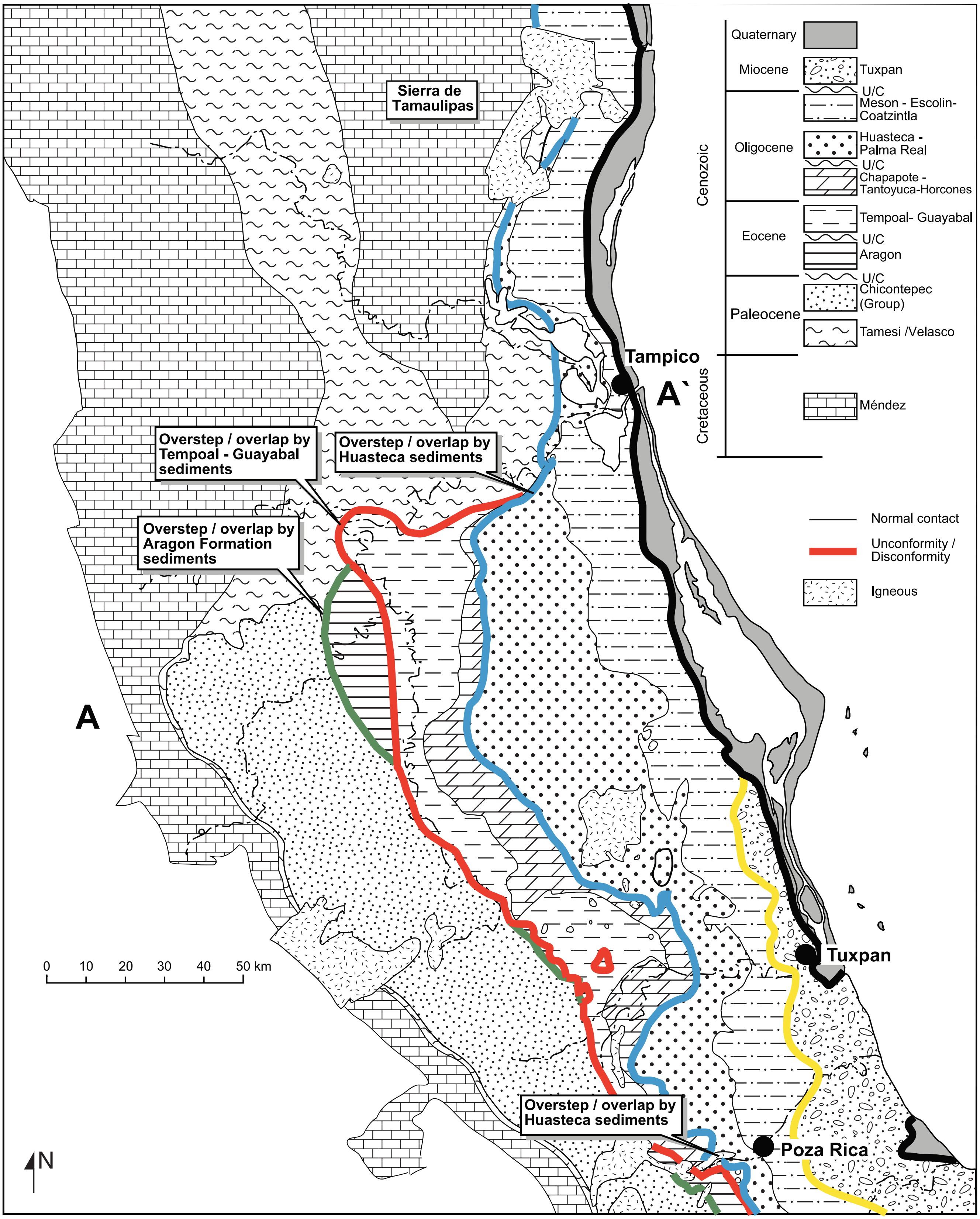
BASIN STRUCTURE

Structural Elements

The Mexican part of the Gulf of Mexico basin can be divided into five areas: (1) Burgos Basin, (2) Southeast Basin, (3) Eastern Continental Margin (ECM), (4) Yucatán Peninsula, and (5) Abyssal Plain (Figure 1). Of these, areas 1 and 2 developed over transitional or stretched continental crust and have thick, earliest Late Jurassic salt deposits areas 3 and 4 developed over rifted continental crust; and area 5 is thought to have developed over very stretched continental or oceanic crust (Pindell and Kennan, 2001). Each area has a distinctive stratigraphy, and responds differently to structural events, although areas 4 and 5 really do not concern us here.

In detail, traveling southward, and as also reviewed in Wilson (1990), there are the following major Mesozoic paleostructural elements (Figure 1): The Coahuila platform and the Tamaulipas Arch are two paleogeographic positive areas in northeastern Mexico; the Sabinas Basin separates these two highs. The Tamaulipas Arch is divided from northwest to southeast into the El Burro–Picachos Peninsula, San Carlos "Island"– Cruillas High, and the Tamaulipas High; these functioned as paleogeographic positive elements during the Jurassic but were covered largely by sediment by the Cretaceous. To the east of the Tamaulipas High/San Carlos Island in the Temazcal-Huapango area is a structural terrace that represents the southern flank of the Burgos Basin and that dips eastward into the Gulf of Mexico. In northern Veracruz, another large Mesozoic high, the Tuxpan High, resides at the eastern side of the Eastern Mesozoic Basin. In the basin is an archipelago of small fault blocks that are often erroneously referred to in the literature as "islands" (e.g., López, 1982). Most of these features are primarily erosional in origin, and only occasionally did they possess features such as tidal-flat carbonates (e.g., the Arenque High,

Figure 2. **Map of the Cenozoic outcrop, onshore Tamaulipas and Veracruz, showing zone of possible transfer fault development (along line A-A′). To the south of this line, the Tertiary basin is stratigraphically complete, while to the north, the Tertiary sedimentary column is much reduced. In detail, the Chicontepec/Velasco Group sediments sit directly on top of the Late Cretaceous over all the map area (contrast with Figures 34 and 35), although there appears to be a lateral facies change between dominantly Chicontepec Group to Velasco Group northward across the possible transfer fault; the Chicontepec group also thickens into this fault. To the east, the Aragon Formation of early Eocene age is only patchily distributed, and Tempoal Formation sediments rest directly on the Paleocene, indicating a major intra-early Eocene break. Similarly, Huasteca sediments (Palma Real Formation) overstep the Chapapote Formation to rest on the Paleocene in the northern area, indicating a major end–early Oligocene break. The Tuxpan Formation also sits disconformably on top of the Meson/Escolin/Coatzintla Formation. Based on López (1982), his figure V1-22.**


Sierra de Tamaulipas
Overstep / overlap by Tempoal - Guayabal sediments
Overstep / overlap by Huasteca sediments
Overstep / overlap by Aragon Formation sediments
Overstep / overlap by Huasteca sediments
A
A`
Tampico
Tuxpan
Poza Rica
0 10 20 30 40 50 km
N
Quaternary
Miocene
Tuxpan
U/C
Meson - Escolin-Coatzintla
Oligocene
Huasteca - Palma Real
U/C
Chapapote - Tantoyuca-Horcones
Cenozoic
Eocene
Tempoal- Guayabal
U/C
Aragon
U/C
Paleocene
Chicontepec (Group)
Tamesi /Velasco
Cretaceous
Méndez
Normal contact
Unconformity / Disconformity
Igneous

Horbury et al., 1996) or fringing siliciclastics (e.g., the Tamaulipas–Constituciones High, Stabler, 1972), which are indicative of true emergence and local sediment supply. Subbasins are small and often have very thick sediment fills; for example, as much as 1.3 km of Late Jurassic in the Alamo area (González, 1970). To the southeast is the Jalapa or Santa Ana Uplift (Cruz et al., 1977), which effectively marks the southern limit of the ECM. To the southeast, the southeastern Veracruz-Tabasco-Campeche-Chiapas areas all form one essentially continuous Mesozoic depocenter, the Southeast Basin, with no significant intra-basin basement highs developed and with proven subsurface Callovian salt (Viniegra, 1981) or salt springs indicating salt (Imlay et al., 1948). In the Campeche Bay and Tabasco areas, the Mesozoic structural grain runs southwest-northeast (Figure 3) and reflects a northwest-southeast extension above salt (Angeles et al., 1994). Bounding this basin to the east is the rigid, stable Yucatán platform.

Along the western margin of the Gulf of Mexico and superimposed on the Mesozoic–earliest Paleogene basin system is the Sierra Madre Oriental (SMO) fold and thrust belt (Figure 1). In front of the fold and thrust belt are a series of Cenozoic foreland basins, namely the Parras, Burgos, San José de las Rusias, and Tampico-Misantla basins (as defined by Pérez, 1992, and Sánchez and Salmerón, 1996). The fold and thrust belt has a largely middle Eocene origin and comprises five sectors before becoming buried beneath the Trans-Mexican Volcanic Belt (Eguiluz et al., 2000). The fold and thrust belt emerges to the southeast as the Zongolica or Papaloapan fold and thrust belt, defining the southwestern margin of the Veracruz Basin, and converges to the southeast with the Sierra Madre del Sur. In southeastern Mexico, Cenozoic basin elements are defined from west to east as the Isthmian Saline Basin, the Comalcalco Trough, the Reforma-Akal fold and thrust belt, and the Macuspana Basin, all of which have onshore and offshore expressions. The Tuxtla Volcanic Center is a Neogene feature that separates the Veracruz Basin from the Isthmian Saline Basin. Finally, the Chiapas fold and thrust belt and the Chiapas Massif mark the surface expression of Cenozoic compression and basement high in southeastern Mexico.

Deep Structures

In the foreland basins of Tamaulipas and northern Veracruz, basement dips eastward by a gentle homocline (Figure 4). Regional seismic lines across the ECM show a very large pseudo-monoclinal fold belt at the outer part of this homocline (Figure 5a), termed here the Monoclinal Outer Paleohigh (MOP), which runs approximately parallel to the continental margin. The MOP is situated underneath the present-day continental slope break in central/northern Veracruz and southern Tamaulipas, and defines the eastern margin of the Tamaulipas Arch/western margin of the Burgos Basin (Figure 1). It represents the eastern limit to the ECM. The western (flattest) limb contains most of the new features that we have observed during this study. The steeper eastern limb may pass down into lower folds (Figure 5a). Controlling faults

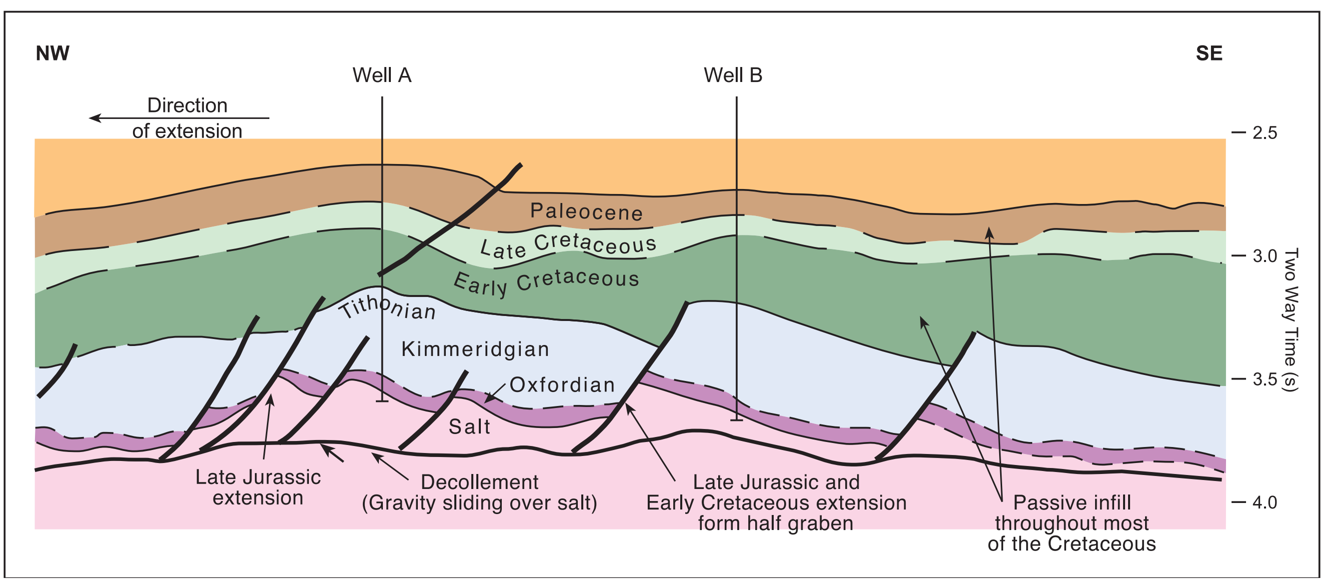


Figure 3. **Northwest–southeast-oriented seismic line interpretation, Cantarell area. Salina anhydrites and red beds are present in some Kimmeridgian half graben, and highstand sediments are represented by deep-water carbonates.**

are steeply dipping northeast-to-east verging thrusts, with shallower dips on southwest-verging backthrusts, which accounts for the steep western limbs of parasitic folds (Pérez, 1992). The fold shows rotation of the covering shallow-water Jurassic and deeper-water Early Cretaceous carbonates and onlap of the ?Late Cretaceous and Paleogene onto its lower flank, which argues against it being a simple relict fault footwall/ fault scarp dating from opening of the Gulf of Mexico. Such fold development postdates the breakup margin itself, which, when it can be seen (due to seismic imaging problems at depth), lies at the toe of the fold and contains small down-to-the-basin faults (Figures 5A, 6, and 7A–C). To the east of the point where the MOP dips most steeply, a system of Cenozoic growth faults developed that throw down to the east (Figures 5A and 8).

Other deep structures are implicit in outcrop maps that show strong west-east to west-southwest–north-northeast oriented zones of dislocation of Cenozoic and sometimes Mesozoic outcrop belts. Formations and facies change across these zones; they also were foci for igneous intrusive and extrusive activity, as well as being exploited by the Conchos, Panuco, Tuxpan, and Cazones rivers (e.g., Figure 2). The best example is probably the Río Conchos zone, to the south of which Cenozoic outcrop belts change strike, stratigraphic condensation of the Late Cretaceous and Paleocene–late Eocene takes place, and unconformities appear that indicate the presence of a paleohigh. In addition, blocks of Mesozoic are reported that are elevated significantly above regional normal along the line of the lineament (Pérez, 1992). Similar structures include the graben-like feature in Figure 5B that extends eastward from the mouth of the Río Panuco, as well as the Parras Transverse Sector of the SMO and the Sierra de San Carlos–Cruillas outcrop (Pérez, 1992; Eguiluz et al., 2000)(Figure 1).

Overview of the Structural Evolution of the Western Gulf of Mexico

The opening of the Gulf of Mexico to its present width was primarily a late Jurassic phenomenon (Pindell and Kennan, 2001). The basin underwent crustal extension, probably in the Bathonian/Callovian, and rifting resulted in the Yucatán microplate, traveling along the eastern coast of Mexico by a transform fault system (Pindell, 1985; Pindell and Dewey, 1982; Salvador, 1987; Ross and Scotese, 1988). It is thought now that Yucatán came to rest in its present position by the end of the Neocomian (130 Ma) (Pindell and Kennan, 2001).

Many workers note or imply that the Cretaceous and early Paleogene history of this basin was relatively passive (Enos, 1983; Salvador, 1991; Galloway et al., 1991). Strong orogenic movement of middle Eocene age formed the Sierra Madre Oriental fold and thrust belt (Eguiluz et al, 2000), while development of a major fold thrust belt in southeastern Mexico is an early–middle Miocene feature (Angeles et al., 1994). In the Neogene, there was strong isostatic uplift of the Sierra Madre Oriental and the northern coastal plain area (Pérez, 1992; Gray et al., 2001) as well as in the Sierra de Chiapas, resulting in deposition of a thick clastic-sediment wedge in the Gulf of Mexico. Failure of this wedge resulted in updip-extensional and downdip-compressional structural regimes, including the ''Mexican Ridges'' of Buffler et al. (1979).

GEOLOGICAL EVOLUTION AS DEFINED BY REGIONAL UNCONFORMITIES

Late Paleozoic to Early Triassic

Background

The pre–late Mesozoic history of the Gulf of Mexico area is not well known (Salvador, 1987). At the end of the Paleozoic, the Gulf was part of the supercontinent Pangea, which had developed as a result of fusion along the Mauritanide Megasuture of the South American–African continent with North America (Pindell, 1985). Facies are flyschoid in northeastern Mexico, and carbonate shelves in southwestern Mexico (Wilson, 1990).

Sequence Boundary

Unmetamorphosed to low-grade metamorphic Late Triassic non-marine red beds and associated igneous rocks unconformably overlie Paleozoic and Early Triassic age igneous, high-grade metamorphic and metavolcanic/metasedimentary rocks in northeastern Mexico (Burckhardt, 1930; Muir, 1936; Imlay, 1943; Salvador, 1987; Blickwede, 2001).

Interpretation

During the Early Triassic, orogenesis resulted in metamorphism of Paleozoic rocks and intrusion of a suite of granites along the ECM. This, in turn, resulted in formation of paleohighs such as the Tamaulipas Arch (Madrid and Rivera, 1976; cited in Pérez, 1992; Alfonso, 1978; Salvador, 1987; Wilson, 1990) (Figures 8 and 9).

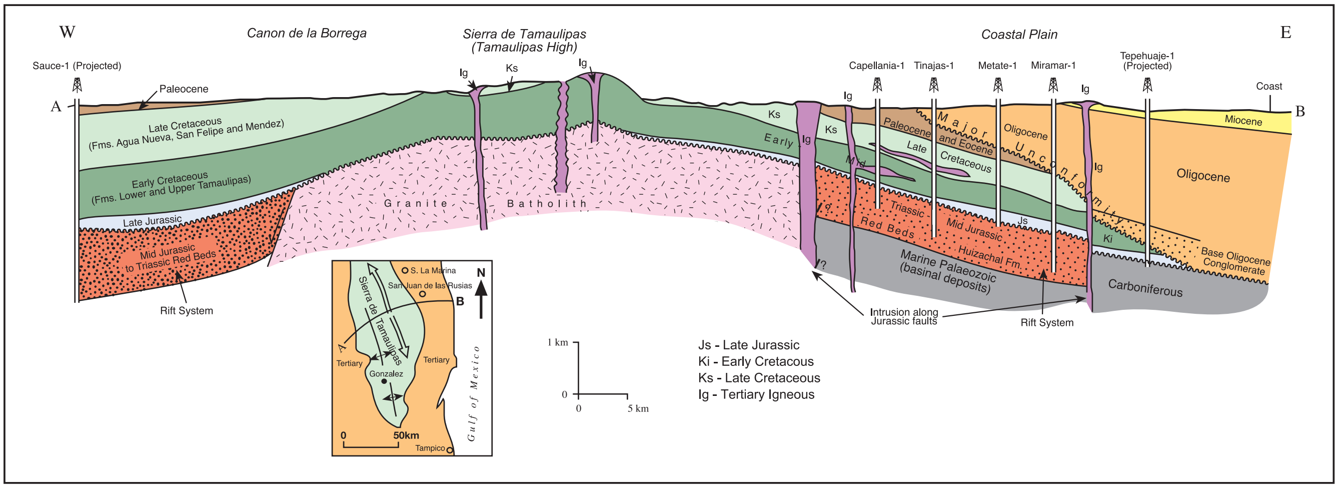


Figure 4. **Schematic section through the Sierra de Tamaulipas. Note how the Cretaceous stratigraphy thickens westwards. Modified after López, 1982, his figure V1-3.**

Late Triassic-Early Hettangian

Background

Initial breakup of Pangea occurred in response to both proto-GOM rifting influences and Pacific margin back-arc influences. Due to plate-reconstruction space considerations, many terranes in ''Mexican Pangea'' had to sit much farther to the northwest than they do at present; these terranes moved into place during the Late Triassic and Jurassic, in response to initial southerly drift of South America–Africa from North America (Winker and Buffler, 1988; Pindell and Kennan, 2001). Basin systems created during this process are oriented north-south, and are best developed between granitic highs on the eastern side of the ECM and Paleozoic metasediment belts of central Mexico (Figures 4 and 8; Madrid, 1980, quoted in Pérez, 1992; Salvador, 1987). These systems may have a strong strike-slip component; for example, they may relate to the Sonora–Mojave Megashear, along which there were many hundreds of kilometers of sinistral displacement (Anderson and Schmidt, 1983). In the Late Triassic, as much as 2500 m of fine-grained red beds, with a lesser proportion of sandstones, conglomerates, associated intrusive diabase/basaltic dikes and sills, and extrusive igneous rocks and tuffs, were deposited along the ECM (Figure 8; Huizachal and La Boca Formations; Salvador, 1987). Dates of the red beds are bracketed by plant remains and by strong Liassic ammonite data in overlying shales (Salvador, 1987). Red beds typically represent alluvial fans, fluvial to delta-plain sediments, and freshwater lakes (Imlay, 1943; Erben, 1956a; Mixon, 1958; Mixon et al., 1959; Carrillo, 1961). Farther to the northwest are back-arc basins in which Mount St. Helens–type volcanics of the Nazas Formation are overlain by red beds (Blickwede, 2001; Pindell and Kennan, 2001).

Sequence Boundary

The sequence boundary is marked by the late Hettangian hiatus, which locally may have the status of an unconformity (Erben, 1956a; Salvador, 1987), although red beds such as the Nazas Formation apparently extend up into the Liassic without a break (Blickwede, 2001).

Interpretation

It appears that the sequence boundary was a relatively mild event and may have little tectonostratigraphic significance.

Early Sinemurian–Early Pliensbachian

Background

This interval comprises as much as 1500 m of richly fossiliferous marine shales that pass upward and laterally into shallow-marine and locally paralic sandstones (Huayacocotla Formation; Erben, 1956a). Continental sediments of the upper part of the Nazas Formation are found to the northwest (Blickwede, 2001). Abundant ammonite faunas in the early and very latest Sinemurian (Erben, 1956a) may define maximum flooding surfaces to two ''subsequences'' in the marine part of the basin system.

Sequence Boundary

In the Río Pantepec section, halfway between Huayacocotla and Huauchinango, the Huayacocotla Formation is considerably more folded and mudrocks

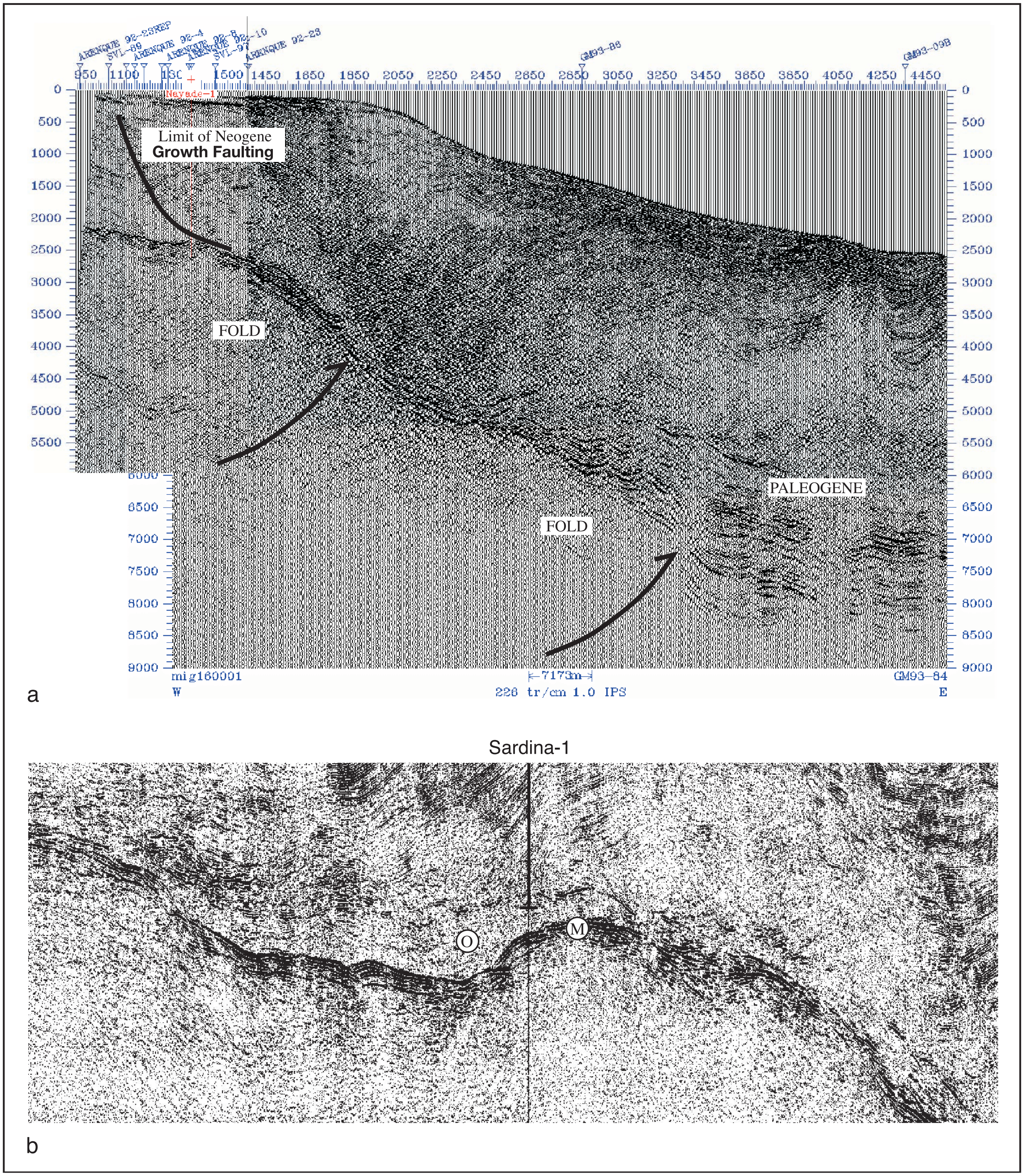


Figure 5. Offshore Matamoros seismic lines. (a) Seismic line running west-east and then northwest-southeast, offshore Tampico, crossing the Nayade-1 well. The Mesozoic descends into the Gulf of Mexico via two monoclinal folds. It is notable that the Paleogene onlaps the lowermost fold, suggesting a mostly Mesozoic origin for the monoclines. Neogene growth faulting coincides with the break in slope controlled by the uppermost monocline. (b) Seismic line running northwest-southeast, offshore Tampico, crossing the Sardina-1 well. O = Oligocene; M = Mesozoic.

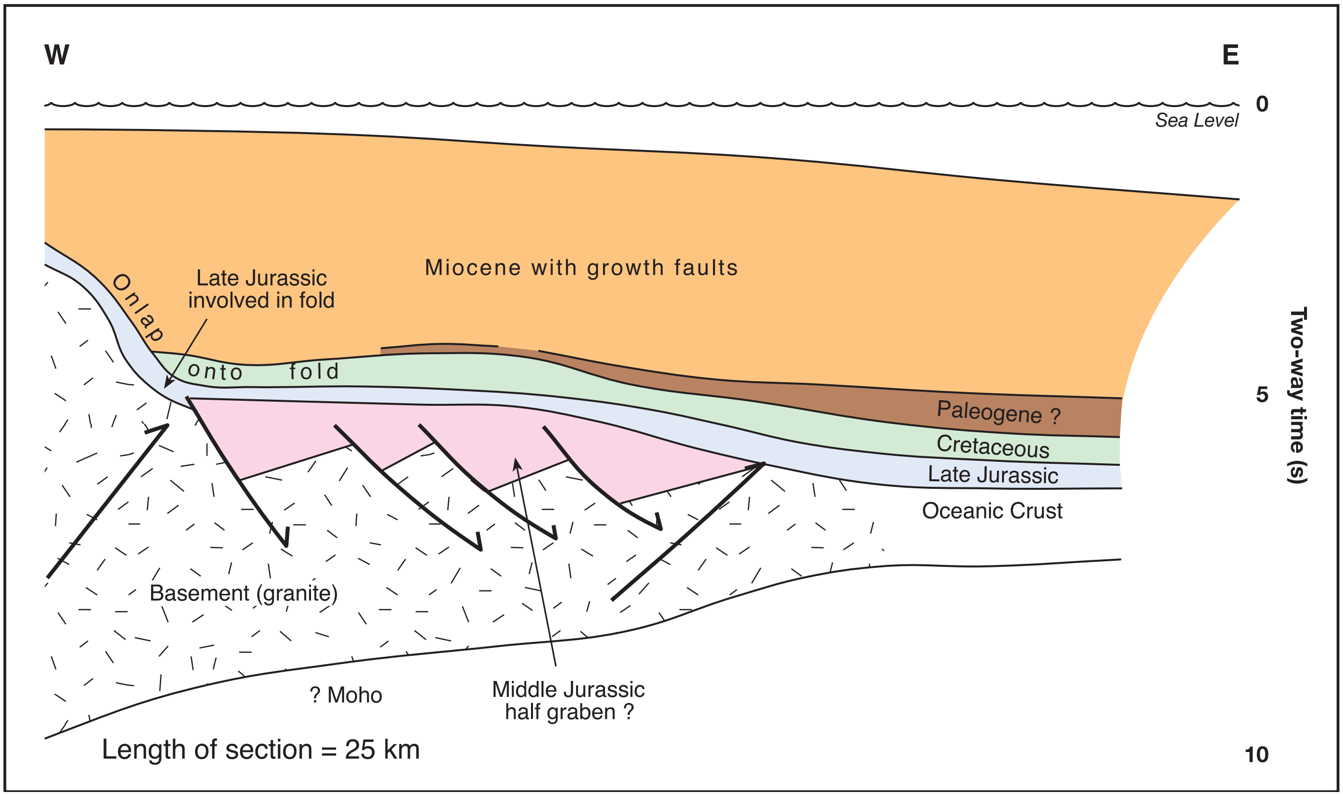


Figure 6. **Tracing of deep-water 2-D seismic line, offshore Tampico.**

are notably more phyllitic than in the overlying Cahuasas Formation. In addition, there is intrusion by basalt and quartz porphyry dikes, which may account for the metamorphism (Fehr and Bonard, 1930, reported in Imlay et al., 1948). Radiometric dates for these igneous units range from 200–180 Ma (cited in Salvador, 1987), which corresponds to the Sinemurian-Toarcian. In addition, basal conglomerates of the overlying Middle Jurassic age Cahuasas Formation near Huehuetla, Hidalgo, often contain slate and phyllite clasts of Liassic age (Fehr and Bonnard, reported in Imlay et al., 1948). In the Sierra de Chignahutla, to the west of Teziutlán, beds of conglomerate with well-developed igneous clasts derived from underlying units also are present at the base of the Middle Jurassic (Jenny, reported in Imlay et al., 1948). However, in areas that initially were more "basinal" toward the southwest of the basin system (e.g., around Huauchinango), contacts are conformable (Erben, 1956a). Erben (1956a) suggested that this unconformity spans the late Pliensbachian–early Aalenian.

Interpretation

A minor orogenic event with associated igneous activity appears to be marked by this boundary. It is unlikely that this could have been the result of a simple intragraben process; more likely, it represents a major phase of inversion and uplift that affected certain basin geometries and not others. From the data available, it is not possible to distinguish if the mechanism for basin inversion was caused by regional compression or transpression, but it is likely that elements of both were present.

?Late Aalenian–?Bathonian

Background

Middle Jurassic units consist of red beds, mostly shales with minor proportions of sandstones of the Cahuasas and the La Joya Formations, along the ECM (Salvador, 1987). Thicknesses may attain nearly 3 km, e.g., in the Huichimal-1 well (Galicia, 1997), and Imlay et al. (1948) note 424 m in the Huehuetla outcrop, thinning westward; however, Salvador (1987) suggests that thicknesses of less than 100 m are more representative. In the absence of Liassic units in the stratigraphy, red beds may be confused with the Triassic-Hettangian age red beds of the Huizachal Formation (e.g., as in Imlay et al., 1948, and Erben, 1956a).

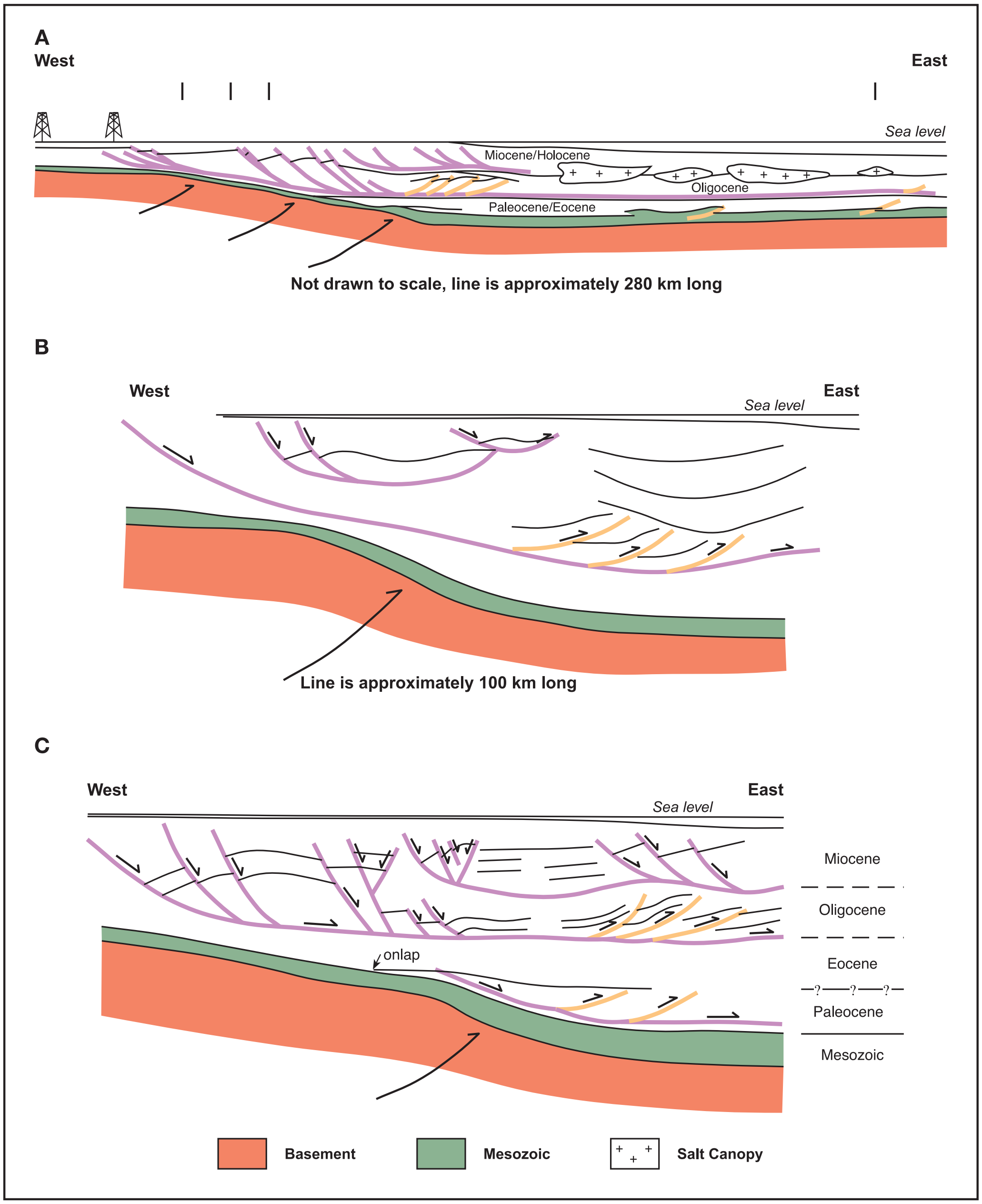


Figure 7. Compressional features of the Matamoros offshore area. (a) Sketch of Regional line. Monoclinal fold in the basement and Mesozoic cover, onlapped by the Paleocene-Eocene, and related to three thrust faults, prior to Tertiary deposition and extensional faulting. (b) Detail of Line 56. (c) Detail of western part of Line 64. Note the vertical stacking (nesting) of extensional systems in front of the Mesozoic monocline.

Sequence Boundary

An angular unconformity is present in the Huauchinango area of Puebla, where the Tepexic Formation (of Callovian age) contains clasts of Liassic as well as Middle Jurassic age (Erben, 1956a). Elsewhere, angular unconformities also are well-developed, although they may not tie as precisely to this event because of the time gap concerned. For example at Aramberri, the Zuloaga Formation (Oxfordian) oversteps older red beds to rest directly upon basement mica schists (Müllerried, 1946), and the same break at Cañón La Presa in the Huizachal Anticlinorium shows an angular discordance of 30° (Heim, 1940). At Teziutlán, Jenny and Cepeda (cited in Imlay et al., 1948) noted that strongly folded red beds are overlain sharply by gently dipping marine Late Jurassic limestones, with basal conglomerates containing clasts of red beds, gneiss, schist and granite. Along the Río Vinasco to the west of Rancho Zopilote near Huayacocotla, approximately 30 m of conglomerates in the basal Late Jurassic contain pebbles of shale, sandstone, and quartzite of Early Jurassic provenance; the Huayacocotla Formation also can be seen to be overlain by Late Jurassic marine limestone (Burckhardt, 1930). In the offshore Tampico area, the Late Jurassic frequently onlaps major highs developed as a result of inversion of Triassic–?Middle Jurassic basins; e.g., the Jurel High (Figure 10) and the Lisa-Mantarraya High (Figure 11A). The contact also can be concordant and conformable, as at La Calera near Huayacocotla in Veracruz, and at Tepexic, Puebla, and Tenango de San Agustín, Hidalgo (Erben, 1956a).

Interpretation

The unconformity is angular and may be extremely eroded, although not all basins appear to have been affected equally. It is unlikely that such breaks

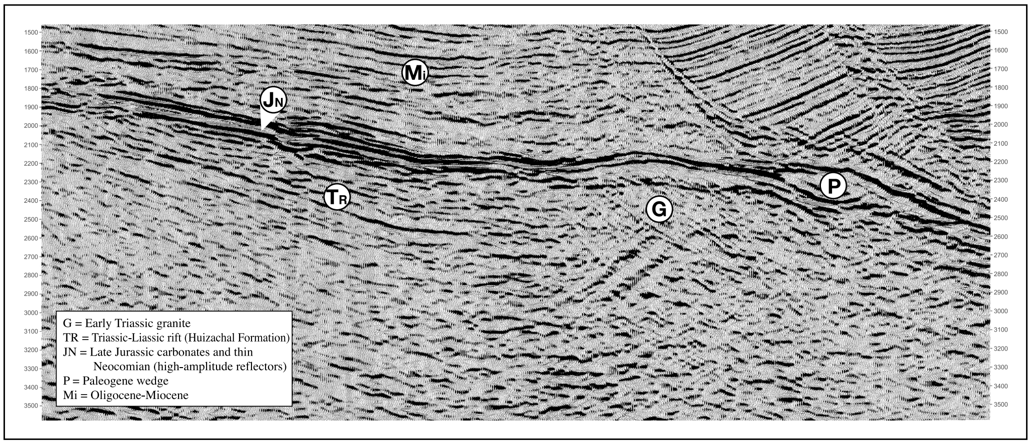


Figure 8. Offshore Tampico 3-D seismic data, Nayade area. Note how growth faults are initiated to the east at the point that the Mesozoic starts to dip strongly, and onlap of Paleogene.

represent simple intragraben processes; more likely they represent major phases of inversion and uplift that affect certain basin geometries and not others. From the data available, it is not possible to distinguish if the mechanism for basin inversion was caused by regional compression or transpression, but it is likely that elements of both were present.

Late Bathonian–Callovian

Background

Limited transgression resulted in deposition of the ''calcarenite and argillaceous micrite horizon'' of the Huehuetepec Formation to the northwest of Poza Rica, which is approximately 20–30-m thick (González, 1970). Marine siltstones of the Palo Blanco Formation are correlatives in the Alamo area and contain the ammonites *Wagnericeras* and *Kepplerites,* indicating a late Bathonian–early Callovian age and a Boreal affinity (Cantú, 1969, 1971, 1979, 1992; Longoria, 1993). These represent the first post-Liassic flooding event and indicate the first possible timing of entry of open-marine water into the ancestral Gulf of Mexico.

Subsequent deposition to the northwest of Poza Rica was of 120–150 m of basin-filling halite, anhydrite, and red shales (González, 1970), which is significant, since this is the only time when it can be argued that the entire basin was desiccating. As such, the Huehuetepec basin is suggested to be part of the ancestral recharge channel that connected the GOM to the Pacific (Salvador, 1987). At this time, red bed clastics of the La Gloria Formation and Lechos Rojos Formation were deposited on the Sabinas and Burgos Basin margins; these thin towards the basin centers, which were sites of anhydrite and halite deposition (Metate and Minas Viejas Formations)(Figure 9)(Pérez, 1992). Halite deposition extends from the U.S. border to 17°N (Rodríguez et al., 2000) and is present again in the Southeast Basin (Isthmian Salt Formation), from southeastern Veracruz into Guatemala. Southern basins were fringed by red bed clastics of the Todos Santos Formation (Salvador, 1987).

During the middle Callovian, a transgression that was more extensive than the late Bathonian event established open-marine shelf-carbonate environments, which are represented by the Tepexic Formation. This formation developed in the Sierra Madre Oriental (Erben, 1956a) and above Huehuetepec Formation evaporites in the Tampico–Poza Rica area (González, 1970); age-equivalent shelf carbonates of the Yucuñuti Formation with Tethyan faunas also are known from clastic-dominated systems in northeastern Guerrero (Erben, 1956a). Dates are well-constrained by the presence of the Tethyan ammonites *Reineckeia* and *Neuqueniceras* (Burckhardt, 1930; Imlay, 1952; Imlay et al., 1948; Erben, 1956a; Longoria, 1993), although Cantú (2001b) is at variance with these dates, instead suggesting pre-late Bathonian ages. This transgression probably resulted only in further evaporite deposition, rather than open-marine deposition, in the main Gulf of Mexico; no Callovian flooding event has yet been proven above the halite in other Mexican or U.S. basins (Imlay, 1943). However, in Mexico micropaleontological resolution between the Callovian and the (often dolomitized) Oxfordian shelf-carbonate systems is very poor, and it is possible that some units described as being Oxfordian are, in fact, Callovian (e.g., Lower Zuloaga Formation) and may be correlatives of the Tepexic Formation.

Sequence Boundary

Frequently, the Tepexic Formation grades up into the deeper-water Santiago Formation in the Necaxa and Huayacocotla areas where ammonites such as *Creniceras renggeri* indicate a basal early Oxfordian age (Erben, 1956a). In the Poza Rica area, there may be a significant siltstone component in the lowermost 100 m of the overlying Santiago Formation

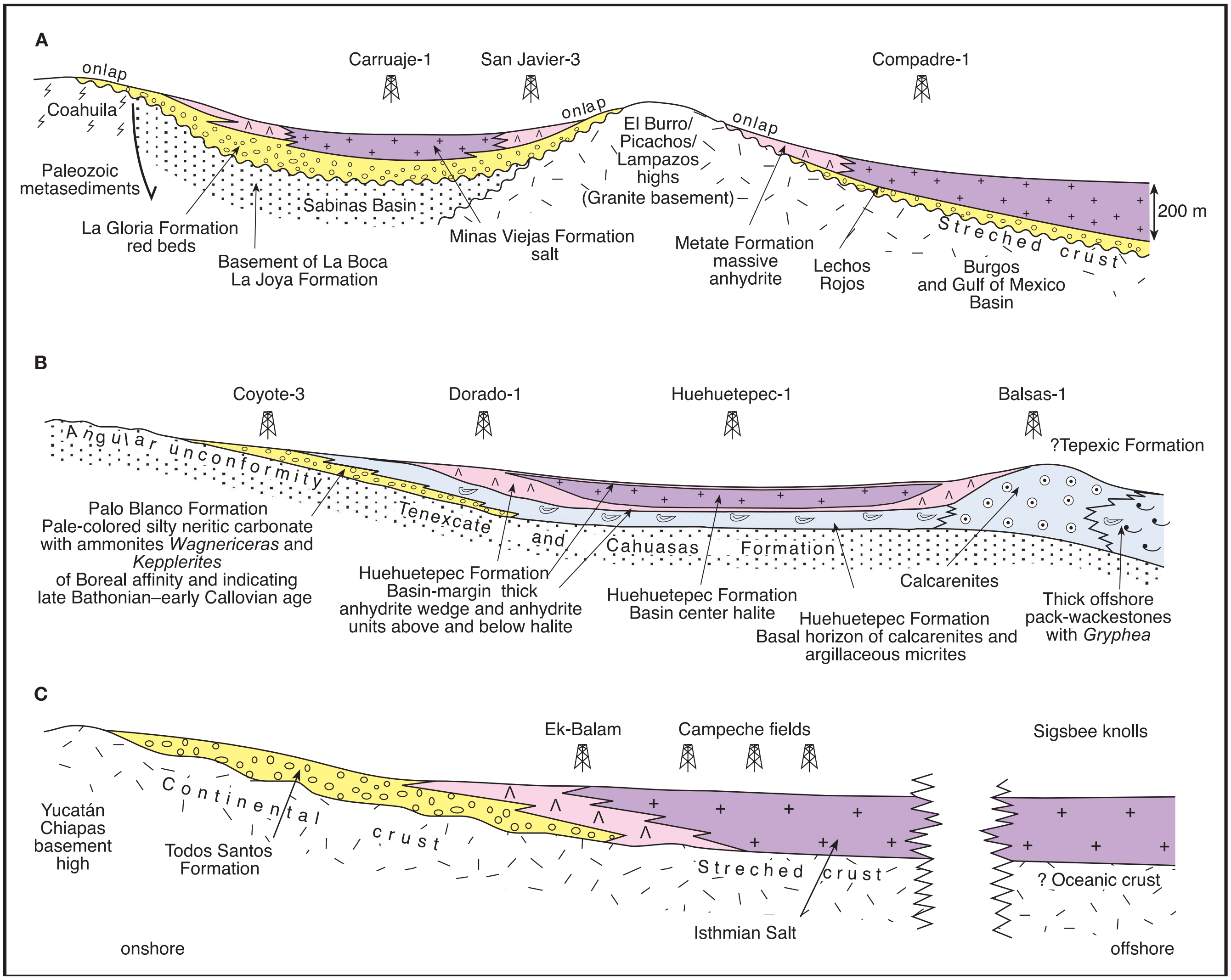


Figure 9. Models of deposition in late Bathonian–Callovian basins. (a) Burgos/Sabinas/Temazcal-Huapango area (after González, 1976 [quoted in Pérez, 1992] and Sawyer et al., 1991). (b) Tampico-Misantla (after González, 1970; Cantú, 1969, 1979, 1992). (c) Onshore Yucatán, Chiapas, Tabasco and Gulf of Campeche (after Sawyer et al., 1991; Angeles et al., 1994). Note the broad similarity of models (a) and (c).

(González, 1970). On the Burgos Basin margin, as much as 200 m of continental clastics of the Novillo Formation developed above evaporites (Pérez, 1992).

Interpretation

The upper-sequence boundary is resolved only in shelf areas, suggesting that it may not represent a major tectonic or eustatic event as in the previous two sequence boundaries, although clastic input indicates basin-margin uplift. Longoria (1993) noted the pronounced change at this time from Boreal into Tethyan ammonite faunas, which he attributes to terrane accretion in the early–middle Callovian. However, it is also possible that this marks initial rifting of the Gulf of Mexico, which, in turn, resulted in the first open connection to Tethys.

"Early" Oxfordian

Background

The Oxfordian represents the first establishment of deep-water open-marine conditions along the ECM, although Salvador (1987) and Pindell and Kennan (2001) note that salt deposition may have continued in the Gulf of Mexico into the early Oxfordian. Onlap margins such as the Burgos and Southeast Basins became sites of shelf-carbonate deposition. In the Burgos Basin, euxinic ramp and shallow-water

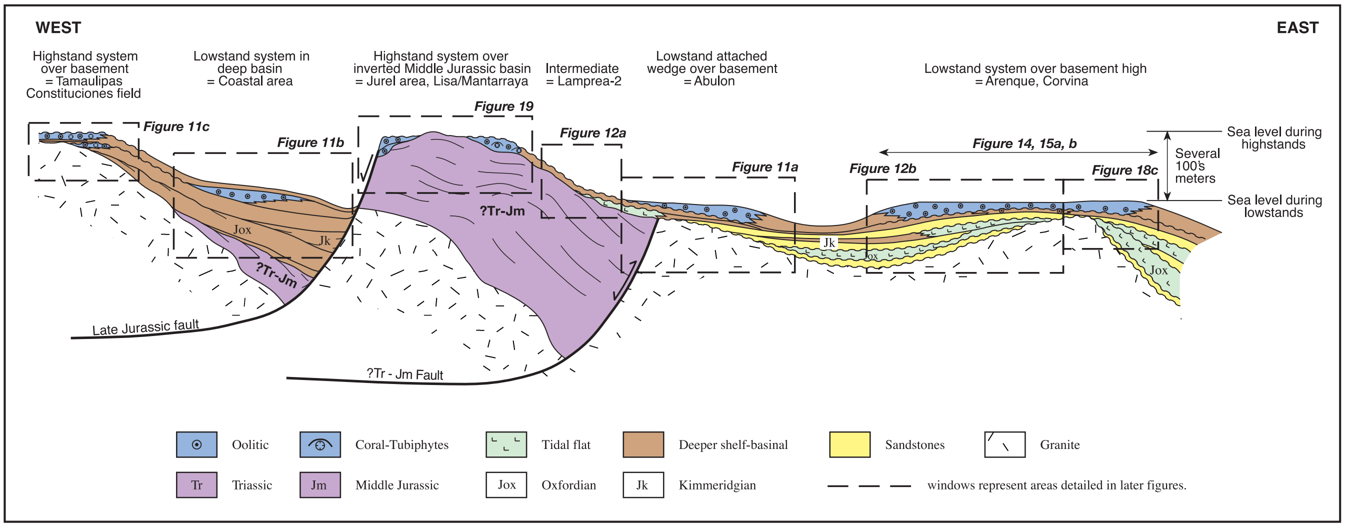


Figure 10. **Summary of the Late Jurassic basin geometry and stratigraphy in the Tampico area.**

shoal carbonates of the lowermost Zuloaga Formation thin onto paleohigh elements such as the El Burro–Picachos Peninsula and the San Carlos Island, where siliciclastic continental facies (La Gloria Formation) developed (Figure 12). In the Sierra Madre Oriental (Erben, 1956a) and Poza Rica areas (González, 1970), truly deep-water sediments developed; here, the total Oxfordian may be as much as 500 m thick.

In the Southeast Basin, deposition of the lowest penetrated part of the Ek Balam Formation is probably in this sequence; lithologies consist of ''lumpy'' (?nodular) peloidal carbonates that have a fauna content of *Ochetoceras* and *Discosphinctes,* indicating a late Oxfordian age (Angeles and Cantú, 2001).

Sequence Boundary

In the Tenango and Huauchinango areas, the first recorded ammonite dates above the Callovian are sometimes of late Oxfordian age, suggesting that there is a major sequence boundary followed by flooding in the middle Oxfordian (Erben, 1956a). Late Oxfordian age units with a well-developed basal conglomerate also overstep onto the Huizachal Formation close to Peregrina in the Huizachal area (Muir, 1936; Imlay, 1943). On the western margin of the Burgos Basin in the Temazcal-Huapango area, and in the Tamaulipas Constituciones and Arenque oil fields, sandstones sit unconformably on top of the Zuloaga Formation (Stabler, 1972; Pérez, 1992). In the Southeast Basin, a thick siliciclastic package consisting of eolian and fluvial facies overlie the sequence boundary; ammonite dates from above and below the siliciclastics suggest that the sequence boundary actually falls in the earliest late Oxfordian (Angeles et al. 1994; Angeles and Cantú, 2001) (Figure 12).

Interpretation

Despite the input of siliciclastics suggesting uplift of the basin margins, the sequence boundary shows only minor evidence of disconformity in shelf areas, suggesting that it may not represent a major tectonic or eustatic event.

''Late'' Oxfordian

Background

This sequence shows essentially the same pattern of development as the ''early'' Oxfordian sequence. A clastic-shelf carbonate-evaporite sequence (upper Zuloaga Formation and Olvido Formation) as much as 500 m thick was deposited in a half-graben bordering the Burgos Basin (Pérez, 1992). This extended onto the Tamaulipas Arch, where an oolitic unit (Miembro Oolitico Inferior [MOI] of the Olvido Formation) is overlain by massive salina-type anhydrites that developed behind a rimmed-platform margin (Figure 12). In the Arenque oil field (Figure 13B), peritidal micrites mark the onlap margin of a granitic basement high. Similarly, the Zuloaga Formation onlaps basement as a land-attached shelf in the Tamaulipas-Constituciones oil field (Stabler, 1972) and, in the Nayade-Lamprea area of offshore Tampico, a mixed clastic-carbonate shelf developed (Figure 14). In the Sierra Madre Oriental (Erben, 1956a) and Poza Rica areas (González, 1970), basinal carbonate deposition continued. In the Southeast Basin, deposition of the upper part of the Ek Balam Formation is characterized by bentonitic shales and locally calcareous sandstones up to 231 m thick, prior to anhydrites 5–200 m thick and an uppermost limestone bed approximately 50 m thick (Figure 12). These are organized as wide carbonate-clastic ramp systems (Angeles et al. 1994; Angeles and Cantú, 2001). As a result of the onset of gravity-driven extension over salt, listric normal faults began to develop; these strike southwest-northeast and throw to the northwest (Angeles et al., 1994) (Figure 3).

Sequence Boundary

Angular unconformities developed along the ECM, where there was local erosion down to basinal sediments on intrabasinal highs. For example, to the northeast of Poza Rica, Cantú (1992) shows, from studies of the Cañas-101 and Mesita-1 wells, that the Tepexic Formation is overlain unconformably by the Tamán Formation. In the Tampico area, Kimmeridgian age carbonates sit unconformably upon Middle Jurassic red beds (Burckhardt, 1930; Muir, 1936; Imlay, 1943). In the Tamaulipas Constituciones (Stabler 1972) and Arenque oil fields (Figure 13B), conglomerates and sandstones were deposited upon the sequence boundary. In Arenque, there is evidence of meteoric water within early, primary fluid-inclusion populations beneath this karstic surface (Horbury et al., 1996). End-Oxfordian karst is also interpreted in the Lamprea-1 well (Figures 13A and 14). There is no strong evidence for a major sequence boundary in the Southeast Basin; paralic silty mudstones sit conformably above shelf carbonates.

Interpretation

The sequence boundary indicates active uplift of the ECM, particularly in the Poza Rica area, since erosion affected basinal sediment on intrabasinal highs as well as shelf sediment. Salt-floored basin centers remained sites of continuous sedimentation, with little evidence of sequence-boundary development.

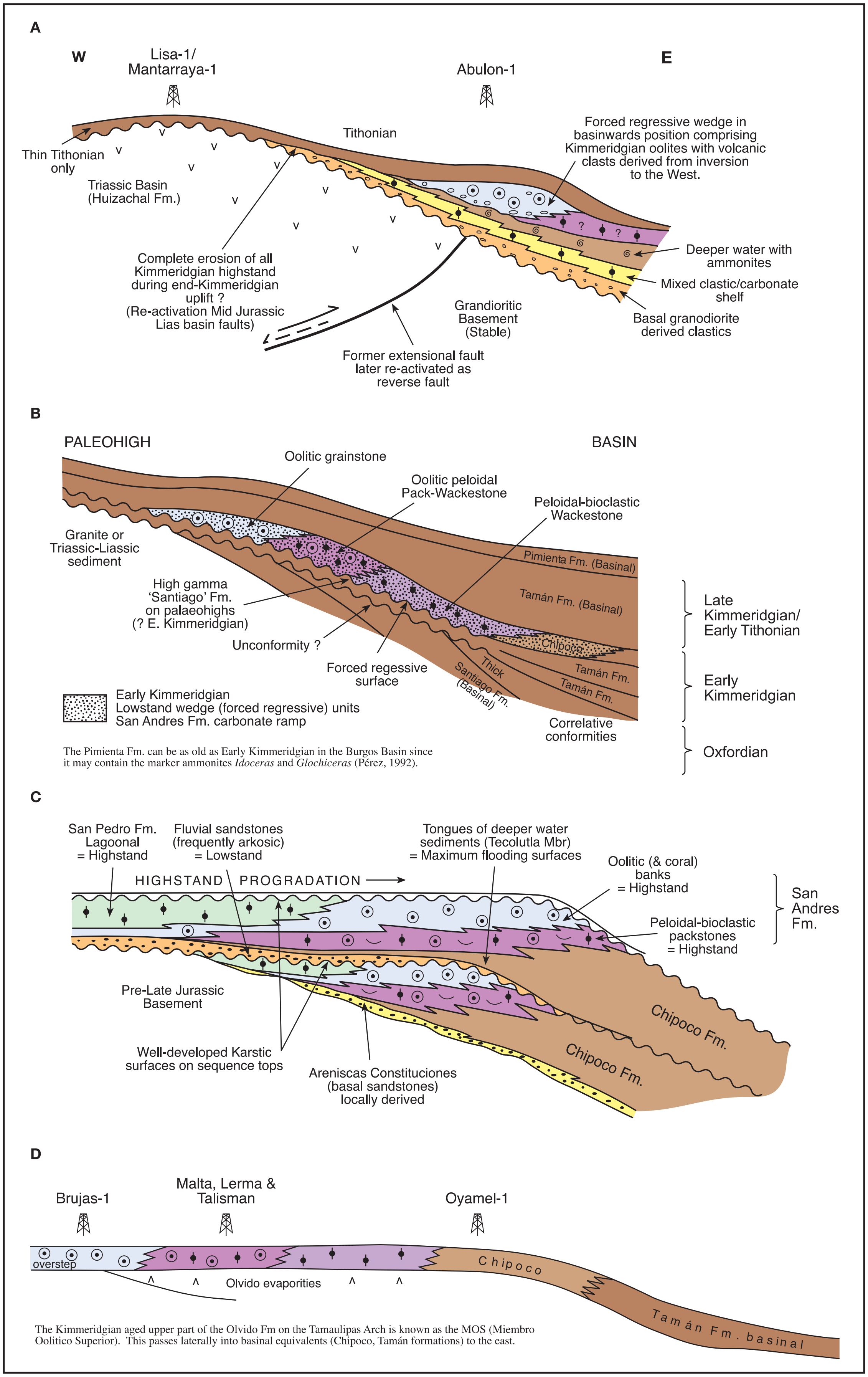
''Early'' Kimmeridgian

Background

Along the ECM, facies are represented by the Tamán Formation (basinal), Chipoco Formation (''slope,'' but more realistically mid-ramp) and Lower San Andrés Formation (inner ramp). Core and logs show that the inner to mid-ramp sediments are upward-shoaling and prograde a few km into deeper-water areas, e.g., in the Tamaulipas-Constituciones field (Stabler, 1972), Jurel and Lamprea-2 wells in offshore Tampico (Figures 10, 11C, and 13A). Cycle tops comprise oolitic grainstones with locally developed coral/algal-patch reefs (Stabler, 1972). On very positive areas, such as the Tamaulipas Arch, only thin single-cycle carbonates were deposited (MOS of the Olvido Formation) (Figure 11D). Shallow-water highstand carbonate deposition on smaller highs in more offshore areas consisted of a variety of oolitic bank and pinnacle-like reefal carbonate systems, with morphologies developing according to water depths in adjacent areas (González, 1999) (Figures 8 and 10). In the offshore Abulon-1 well, cores taken immediately beneath the San Andrés Formation show basal clastics grading up into mixed carbonate-clastic inner ramp, then dark-gray/brown ammonitic and locally *Pecten*-rich mudstone-wackestones which indicate outer ramp to shallow basinal environments (Figures 11A and 15). In the Southeast Basin, the basal Akimpech Formation of early Kimmeridgian age (member ''B'') comprises monotonous, slightly silty, and locally sandy bentonitic mudstones, probably of an inner ramp/paralic setting with thicknesses of 100–200 m; the presence of *Nebrodites* and *Taramelliceras* indicate an early Kimmeridgian age (Cantú, 1977; Angeles and Cantú, 2001). In Chiapas, oolitic and oncolitic grainstones and carbonate mudstones are developed (Quezada, 1983).

Sequence Boundary

On paleohighs, there was karstification and entry of siliciclastic sediment into karstic cavities (e.g., in the Jurel-1 well); porosities are often low but with well-connected vugs and fractures controlling permeability. Downdip, slope deposits may be karst collapse brecciated (Figure 17A), with sandstones developed on the sequence boundary (Figure 14). Stratigraphy in deeper sub-basinal paleolows is exemplified by data from the northwest of Poza Rica shown in González (1970). Here, the San Andrés Formation bank/inner-ramp oolite sits abruptly as a sheet of at least 400 km^2 area on basinal Tamán Formation limestones (Figure 11B). As shown in González (1970), this stratigraphy is developed in both true basin-center settings with thick stratigraphy (e.g., the Palo Blanco-112 and Agua Nacida-103 wells), as well as on relatively condensed intrabasinal highs (e.g., the Soledad-1 and -4 wells). Lateral facies changes of the San Andrés Formation are related to the basin geometry (Figure 11B).


A
W
Lisa-1/
Mantarraya-1
Abulon-1
E
Thin Tithonian
only
Triassic Basin
(Huizachal Fm.)
Tithonian
Forced regressive wedge in
basinwards position comprising
Kimmeridgian oolites with volcanic
clasts derived from inversion
to the West.
Deeper water with
ammonites
Mixed clastic/carbonate
shelf
Basal granodiorite
derived clastics
Complete erosion of all
Kimmeridgian highstand
during end-Kimmeridgian
uplift ?
(Re-activation Mid Jurassic
Lias basin faults)
Grandioritic
Basement
(Stable)
Former extensional fault
later re-activated as
reverse fault
B
PALEOHIGH
BASIN
Oolitic grainstone
Oolitic peloidal
Pack-Wackestone
Peloidal-bioclastic
Wackestone
Granite or
Triassic-Liassic
sediment
Pimienta Fm. (Basinal)
Tamán Fm. (Basinal)
High gamma
'Santiago' Fm.
on palaeohighs
(? E. Kimmeridgian)
Unconformity ?
Chipoco
Forced regessive
surface
Thick
Santiago Fm.
(Basinal)
Tamán Fm.
Tamán Fm.
Late
Kimmeridgian/
Early Tithonian
Early
Kimmeridgian
Early Kimmeridgian
Lowstand wedge (forced regressive) units
San Andres Fm. carbonate ramp
Correlative
conformities
Oxfordian
The Pimienta Fm. can be as old as Early Kimmeridgian in the Burgos Basin since
it may contain the marker ammonites Idoceras and Glochiceras (Pérez, 1992).
C
San Pedro Fm.
Lagoonal
= Highstand
Fluvial sandstones
(frequently arkosic)
= Lowstand
Tongues of deeper water
sediments (Tecolutla Mbr)
= Maximum flooding surfaces
HIGHSTAND PROGRADATION
Oolitic (& coral)
banks
= Highstand
San
Andres
Fm.
Peloidal-bioclastic
packstones
= Highstand
Pre-Late Jurassic
Basement
Chipoco Fm.
Chipoco Fm.
Well-developed Karstic
surfaces on sequence tops
Areniscas Constituciones
(basal sandstones)
locally derived
D
Brujas-1
Malta, Lerma &
Talisman
Oyamel-1
overstep
Olvido evaporities
Chipoco
Tamán Fm. basinal
The Kimmeridgian aged upper part of the Olvido Fm on the Tamaulipas Arch is known as the MOS (Miembro
Oolitico Superior). This passes laterally into basinal equivalents (Chipoco, Tamán formations) to the east.

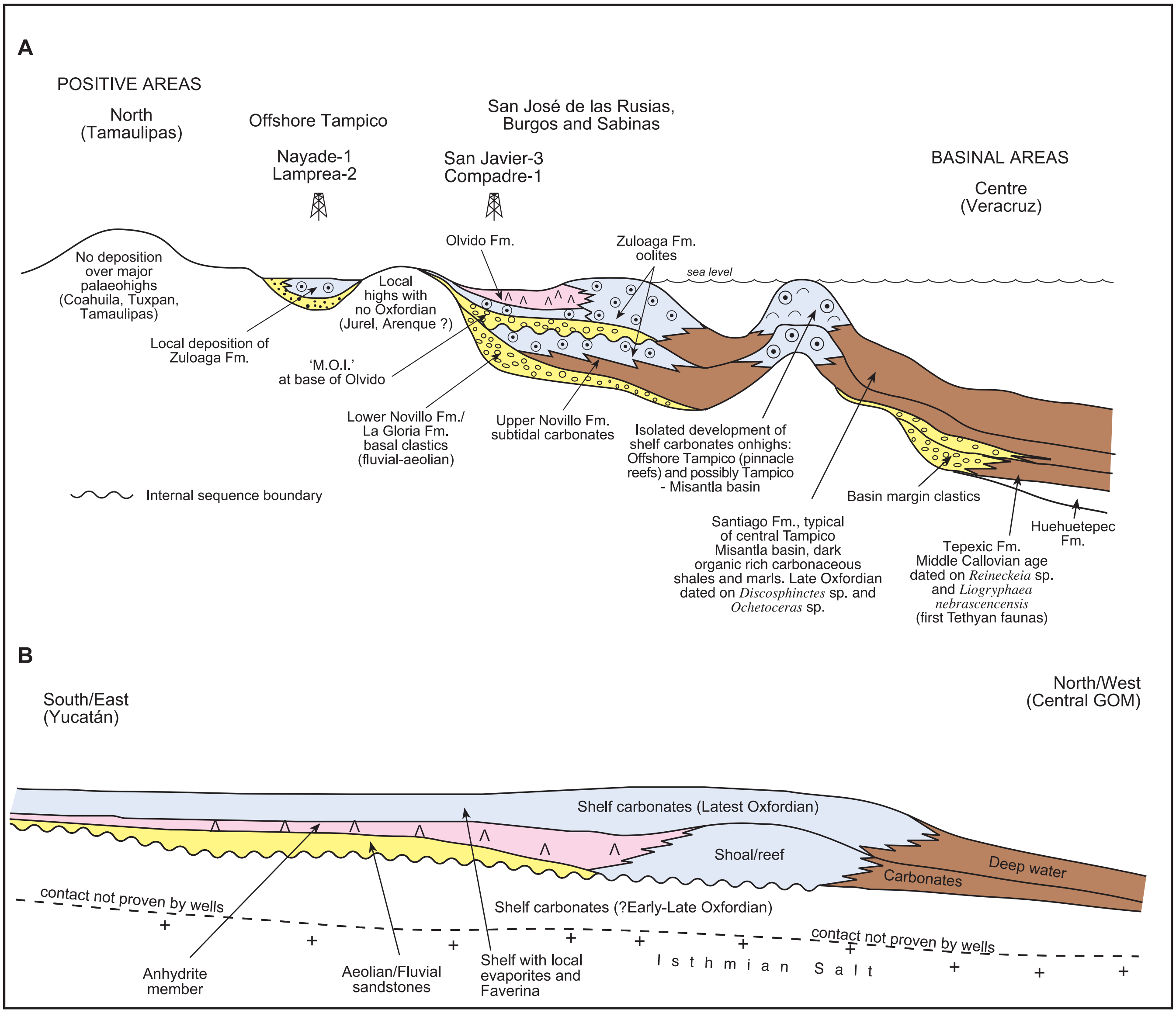


Figure 12. **Oxfordian depositional systems. (a) Eastern Continental Margin (schematic) (after Pérez, 1992; Cantú, 1992; González, 1999). MOI = Membro Oolitico Inferior. (b) Southeastern Basin, Ek Balam Formation (after Angeles et al., 1994; Angeles and Cantú, 2001).**

In the Abulon-1 well, core through the base of such a facies change shows that the San Andrés Formation contains some reworked volcaniclastic material, particularly in its basal part (Figure 15). This material could only have been derived from the Huizachal Formation on a paleohigh to the west (Figure 11A). The Arenque field (Horbury et al., 1996) (Figures 10, 13B, and 16) is comparable, in that oolites sit abruptly on top of subtidal sediments. In all of these cases, the ''lowstand'' San Andrés Formation is overlain then by deeper-water sediments. Unless modified by end-Kimmeridgian uplift, there is usually no

Figure 11. **Kimmeridgian depositional systems. (a) Lowstand oolitic wedge in the Abulon–Lisa/Mantarraya area. (b) Structural lows to the south and west of Tampico (after González, 1970, and Horbury personal observations). The Pimienta Formation can be as old as early Kimmeridgian in the Burgos Basin, as it may contain the marker ammonites *Idoceras* and *Glochiceras* (Pérez, 1992). (c) Structural highs in the Tampico area (Jurel/Cazon and Tamaulipas Constituciones)(after Stabler, 1972, and Horbury personal observations). (d) Structural highs (Tamaulipas Arch). The Kimmeridgian-aged upper part of the Olvido Formation on the Tamaulipas Arch is known as the MOS (Miembro Oolitico Superior), which passes laterally into basinal equivalents (Chipoco and Tamán Formations) to the east.**

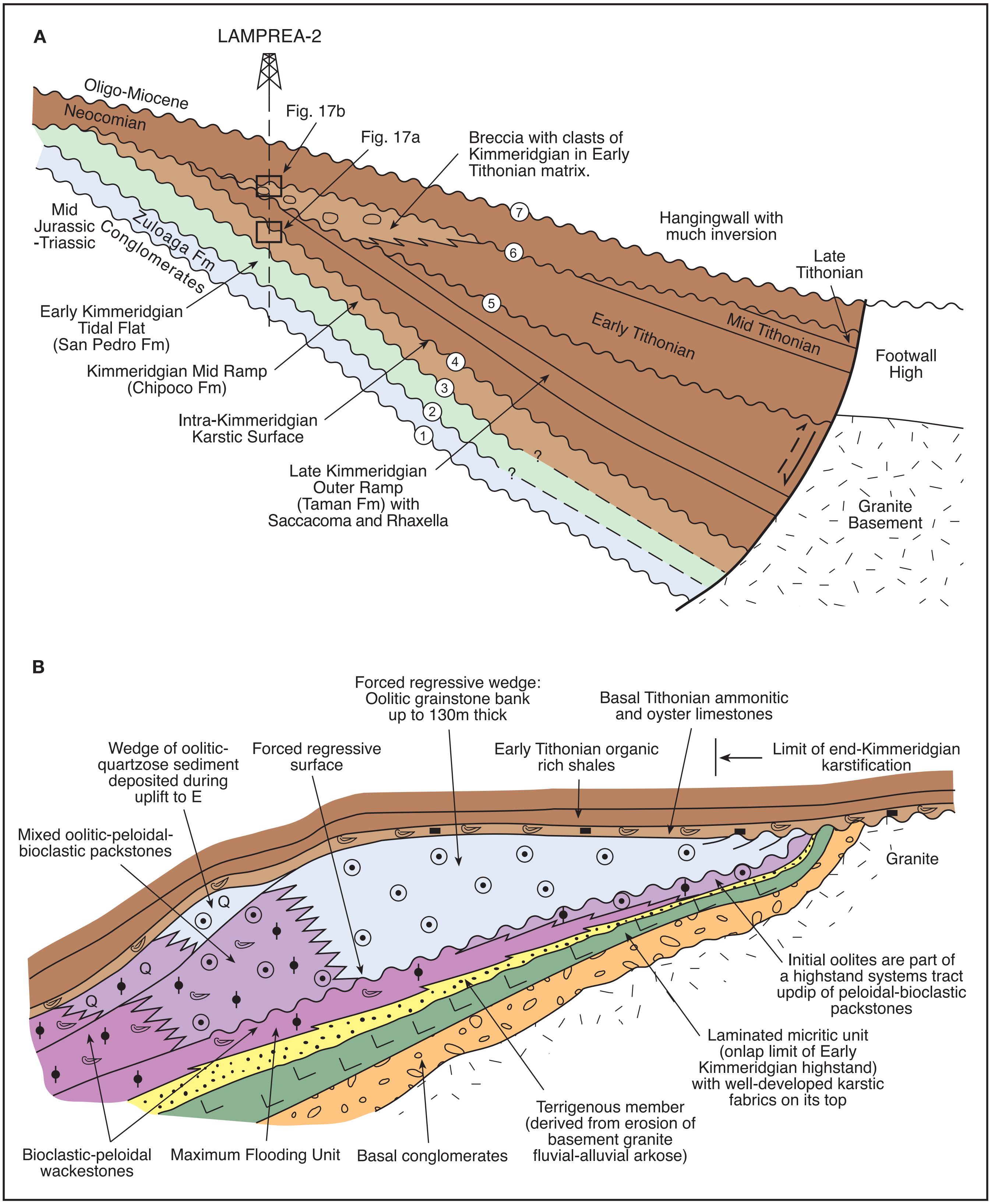


Figure 13. Kimmeridgian-Tithonian of the offshore Tampico area. (a) Model of Kimmeridgian-Tithonian evolution in the Lamprea area. Circled numbers 1–7 represent unconformities, of which (4) indicates sea-level falls of 200 m, (5) resulted in reworking of Kimmeridgian basinal sediment into the early Tithonian, and (6) cuts out the middle and late Tithonian. (b) Model of the Arenque bank system (based on Horbury et al., 1996).

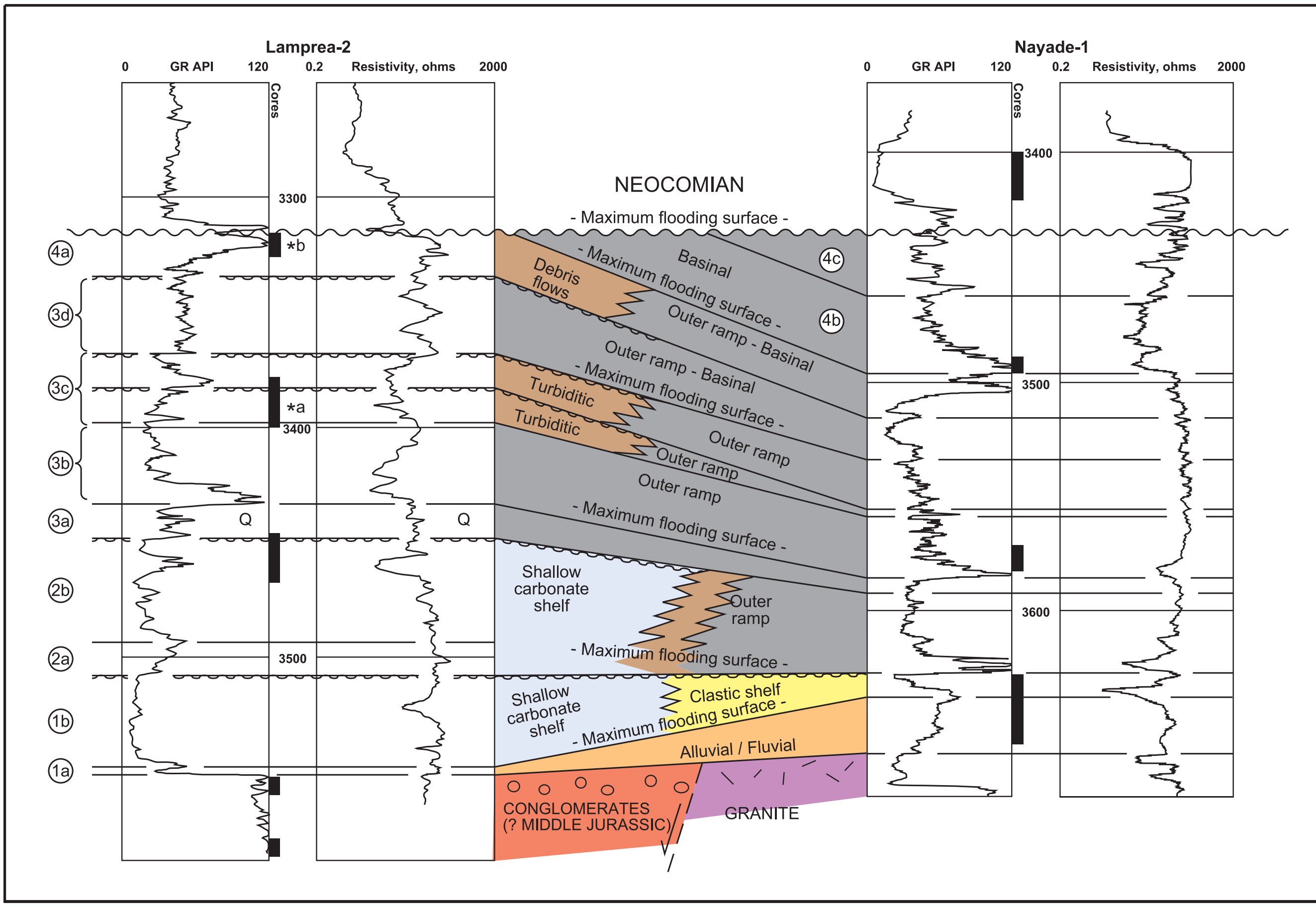


Figure 14. Correlation of gamma-ray and resistivity logs in Lamprea-2 and Nayade-1 wells . The basal interval of supposed Oxfordian age (1) shows basal sandstones in Nayade-1 passing into shelf carbonates in Lamprea-2. Overlying units of supposed Kimmeridgian age (2–3) show deepening of facies in the upper section between Lamprea-2 and Nayade-1. In addition, karstified sequence boundaries in Lamprea-2 pass downdip into correlative conformities in Nayade-1. Also of note are karstic fabrics in Kimmeridgian slope facies in Lamprea-2 (core marked *a, detailed in Figure 17a) and the base-Tithonian unconformity (contact of 3 and 4) overlain by breccia in the early Tithonian (core marked *b, detailed in Figure 17b). There is also an end-Tithonian unconformity, again seen in the reduced stratigraphy of Lamprea-2 compared to Nayade-1.

evidence of karstification on the top of the San Andrés Formation; diagenesis in the Arenque field is notable because early cements are exclusively hypersaline (Horbury et al., 1996). Porosities in these reservoirs are high but are often dominated by microporous systems; reservoir quality depends on the proportion of preserved intergranular porosity or dolomitization. In the Southeast Basin, the contact is conformable and is marked by a pronounced flooding event in the middle Kimmeridgian, such that late–early Kimmeridgian marine carbonates of the Akimpech Formation member ''C'' sit abruptly on top of member ''B'' facies (Angeles and Cantú, 2001).

Interpretation

Along the ECM, detached oolitic, lowstand basin-margin wedges sit directly (without evidence of progradation) on basinal sediment. Facies in the wedges pass laterally into basinal sediments over distances of tens of kilometers, and, finally, a correlative conformity is present in basin center settings. Paleohighs were subaerially emergent and undergoing karstification and erosion; basement-derived sandstones were supplied to flanking areas. It is probable that this was a tectonic event, since the sequence-boundary development is affected by underlying geology, resulting in contrasting expressions along the ECM and the Southeast Basin. However, a coeval drawdown of the GOM is also possible. This could have been produced by a temporary isolation of the GOM from the Pacific and proto-Atlantic ocean as a result of tectonic forcing or ''choking''' of the marine connection by highstand carbonate-platform development. Evidence consists of the absence of good open-marine indicators

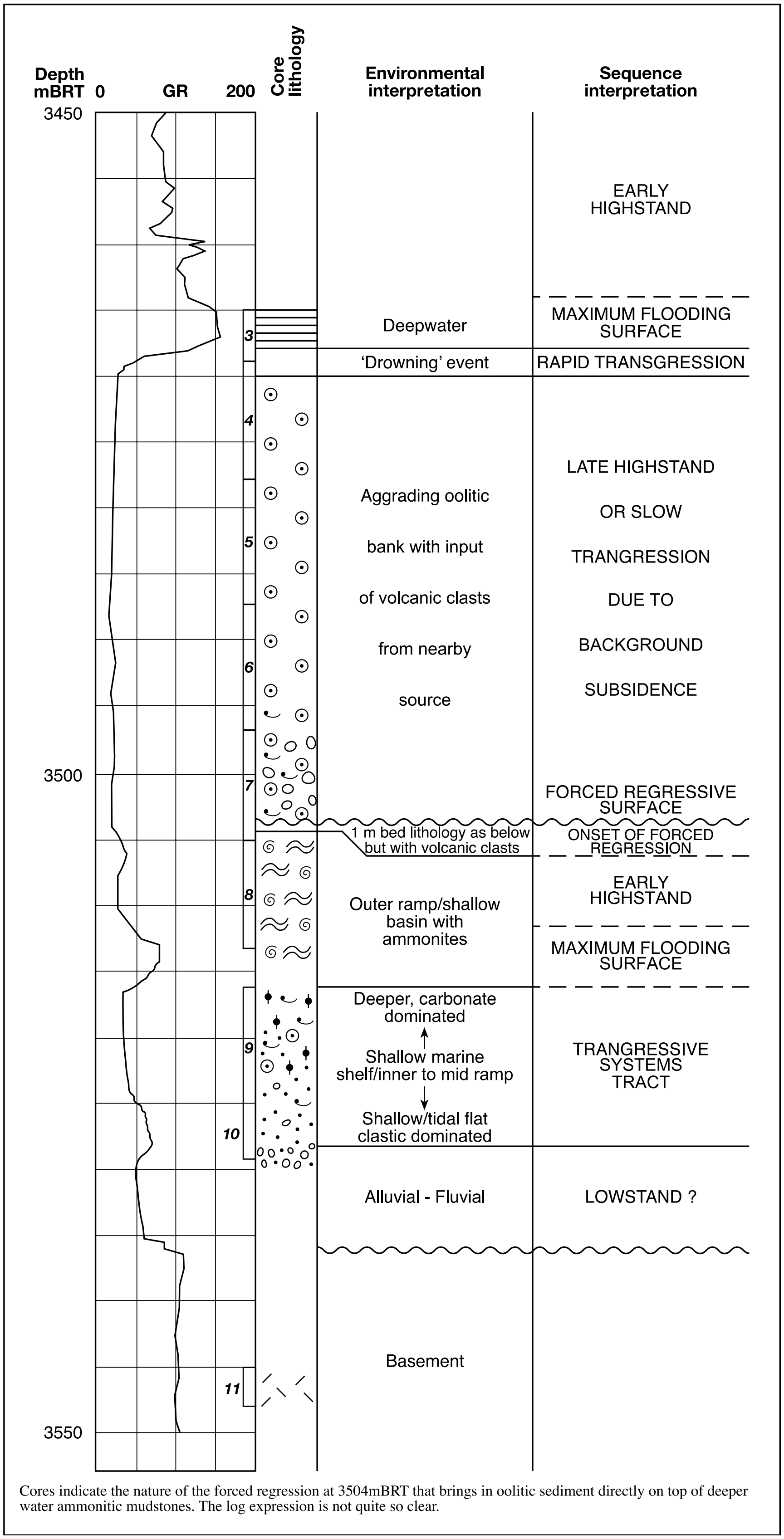


Figure 15. Stratigraphy of Abulon-1. Cores indicate the nature of the forced regression at 3504 m BRT that brings in oolitic sediment directly on top of deeper-water ammonitic mudstones. The log expression is not quite so clear.

(e.g., corals) in the lowstand systems, whereas these are common constituents of highstand oolitic bank systems; there also are hypersaline early cements in lowstand oolites. Normal third-order eustatic processes are unlikely to be responsible, given that the fall in sea level was rapid and of sufficient magnitude (100–250 m is suggested) to subaerially expose, karstify, and erode mid- to outer-ramp or even shallow basinal carbonates.

"Late" Kimmeridgian

Background

During transgression, the middle Kimmeridgian lowstand oolites in basin centers were immediately drowned (e.g., in the Palo Blanco area), although lowstand oolites sitting on intrabasinal basement paleohighs (e.g., Arenque, Abulon) appear to have kept up with transgression. Once the transgression reached the flat-topped carbonate platforms on the highs, flooding was rapid, and there was no time to form significant transgressive systems-tract sediments. Highstand depositional environments and cyclicity are almost identical to, or of slightly deeper-water character than, early Kimmeridgian equivalents, e.g., in the Lamprea-2 well (Figures 13A and 14), where gamma-ray logs suggest upward-shoaling. On paleohighs, the basal flooding surface beneath the San Andrés Formation comprises deeper-ramp carbonate mudstones of the Tecolutla Member (Figure 11C).

In the Southeast Basin, late Kimmeridgian thicknesses on the order of 300–400 m (Akimpech C-E) are typically ten times those along the ECM (Angeles and Cantú, 2001) (Figure 3). The abrupt appearance of shallow-water carbonates of (member 'C') above paralic silty mudstones indicates that transgression was rapid. The presence of early Kimmeridgian ammonites (*Nebrodites* and

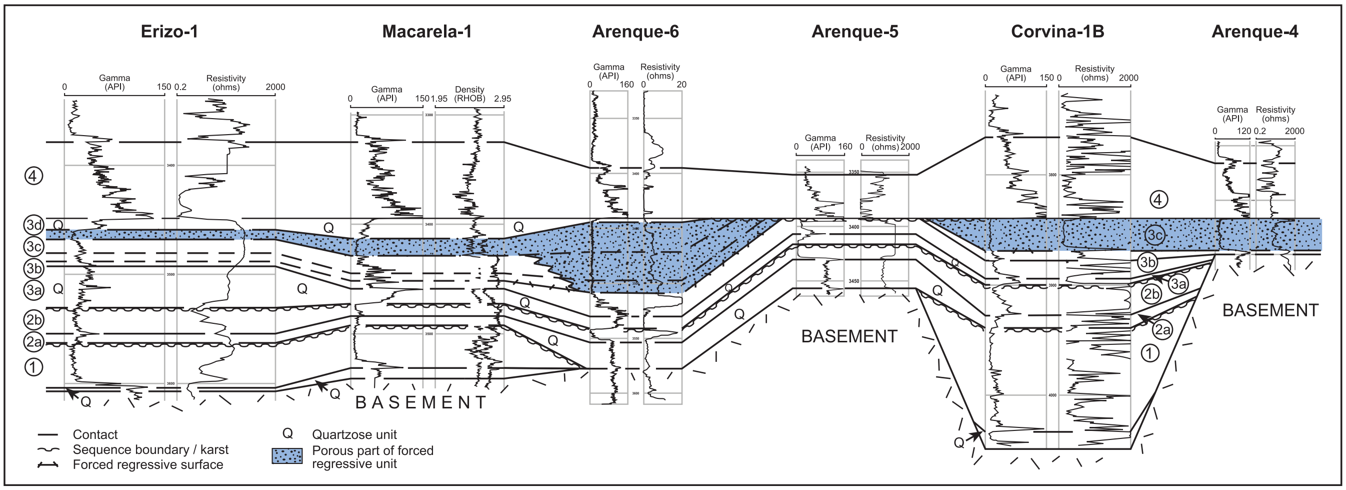


Figure 16. **Correlation panel of Erizo-1, Macarela-1, Arenque-4, -5, and -6, and Corvina-1B wells. Four sequences have been identified: These are (1) Oxfordian (Zuloaga Formation) above basal Oxfordian sandstones. (2) Early Kimmeridgian, comprising 2a. TST (transgressive systems tract), 2b. HST (highstand systems tract), usually a porcelanous limestone. (3) Late Kimmeridgian, comprising 3a. basal LST (lowstand systems tract) and TST alluvial-fluvial sandstones, best developed in Macarela-1, Arenque-5, and Arenque-6 but as marine calcareous sandstones in Erizo-1; 3b. early HST, dense subtidal carbonates; 3c. forced regressive unit, oolitic bank; 3c (stippled pattern) forced regressive wedge (late HST) dominated by oolitic grainstone; 3d. quartz-rich oolitic wedge representing LST and subaerial exposure of the central area of Isla Arenque. (4) Tithonian units, comprising a basal TST, followed by a high-gamma-ray MFS with overlying HST. Note how unit 1 pinches out onto the crestal area of the Arenque field, while part of unit 2 and all of unit 3 is truncated in Arenque-5, indicating the severity of the end-Kimmeridgian uplift. The forced regressive unit (3c) is oolite-dominated in Arenque-6 and Corvina-1, while it is more peloidal in Macarela-1 and Arenque-4 and bioclastic in Erizo-1.**

Taramelliceras) at the base suggests that this event is of late-early Kimmeridgian age. Overlying highstand units (members D-E) are of a general late Kimmeridgian age (Angeles and Cantú, 2001). Facies are dominated by massive to cyclic oolitic- and pisolitic-dominated platform-margin-bank systems, which pass toward Yucatán into a wide belt of mixed carbonate-clastic sediments of lagoonal to paralic affinity (Angeles et al., 1994; Angeles and Cantú, 2001). Sediments are organized within a third-order transgressive systems tract, such that cycles show a general upward-decreasing thickness and, often, an upward increase of interbedding with deep-water- (*Saccacoma*, *Rhaxella*) dominated facies. Although there may be much karstification at a parasequence level, no significant unconformities appear to be developed in these sediments. Unconformities and lateral thickness changes often can be accounted for by early salt diapirism.

Sequence Boundary

There is clear evidence from core, log correlation, and seismic data of an end-Kimmeridgian unconformity that resulted in erosion down to basement in the east of the Arenque oil field (Figures 16 and 18). The eastern limit of erosion is bounded by east-vergent reverse faults that cut basement between the Arenque-1 and Corvina-1 wells (Figure 18A). Products of the erosion were redeposited on the western flank of Arenque as a quartz-rich oolite wedge, e.g., in Arenque-103 (Figure 13B). Horbury et al. (1996) identified cements in this field that are associated with the onset of compaction and temperatures of about 50–60°C (i.e., burial depths of about 1 km). These have a fluid-inclusion population that indicates prior entry into the reservoir of a subseawater-salinity pore fluid of suboxic, meteoric origin that had to be postdepositional and which was originally interpreted as being sourced from the Cretaceous-Cenozoic unconformity (Horbury et al., 1996). However, after recent 3-D mapping (which has provided a better understanding of the sequence stratigraphy) early Tithonian deep-water shales are clearly present over the entire area (Figure 16); these would have acted as a downward seal (aquitard) against meteoric influx, just as the same unit presently acts as a seal to oil accumulation in the field. Therefore, it is now thought that meteoric water is most probably a relict water that could have entered only prior to deposition of the Tithonian shales; i.e., following end-Kimmeridgian exposure in the east of the field.

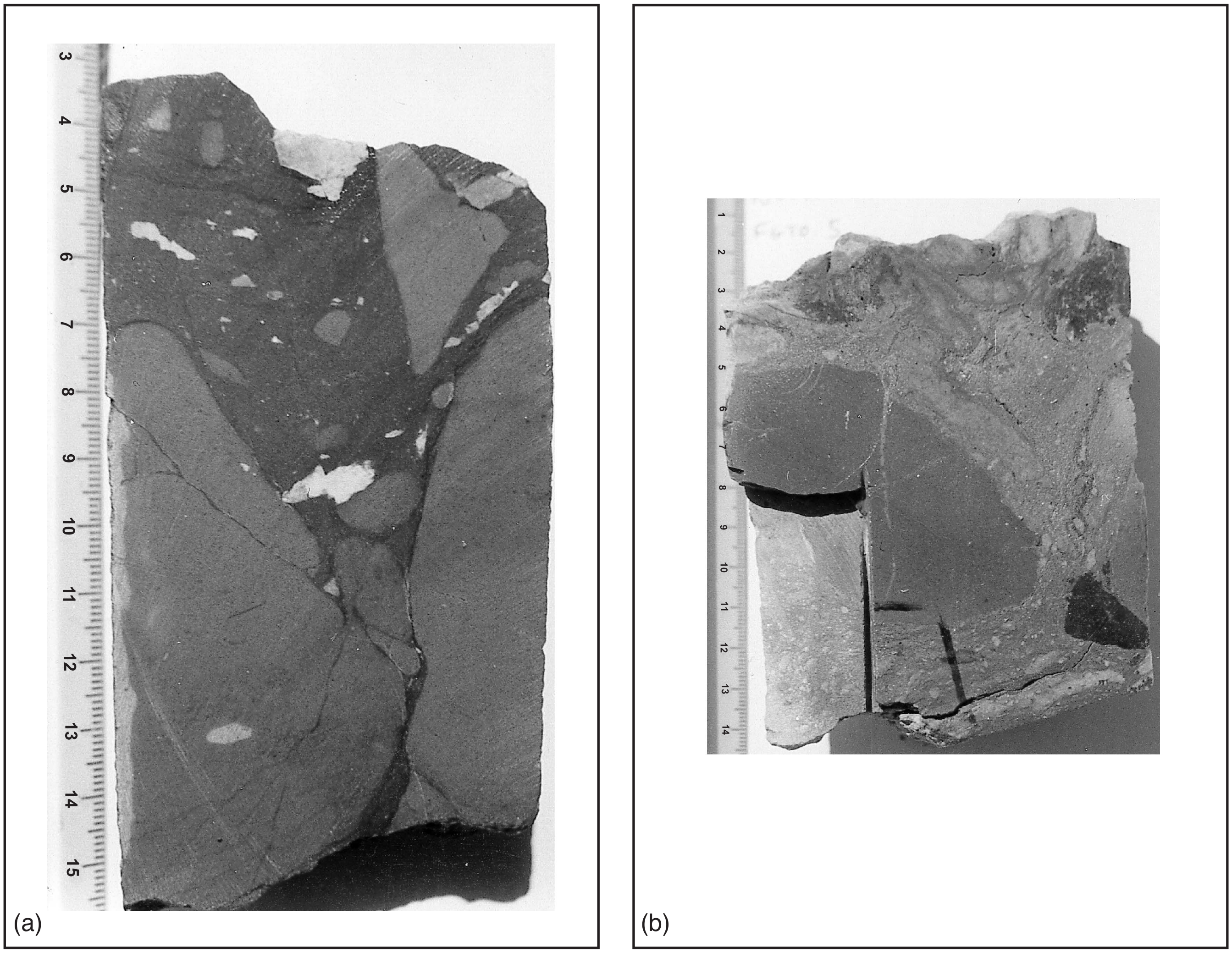


Figure 17. **Cores from Lamprea-2. (a) Core 3. Karstic fabrics (mosaic breccia and infill) associated with intra-Kimmeridgian regression. Basinal carbonate infills fractures in karstified basinal sediment. (b) Core 1. Angular clasts of basinal carbonate of Kimmeridgian age in a matrix of basinal shale of early Tithonian age.**

Breccias and siliciclastic rocks were deposited on the flanks of highs that seismic data show to be inverted, older Mesozoic basins. Angular clasts of basinal limestones of Kimmeridgian age in cores of the Pimienta Formation (Tithonian) in Lamprea-2 well (Figure 17B) most probably were derived off the high to the west (Figure 13A). An end-Kimmeridgian age breccia with a matrix of fenestral micrites and clasts of volcanic rock is present in the Cazon-1 well on the eastern flank of the Jurel High, while the base of the Pimienta Formation is sandy in the Jurel-1 well on the western flank (Figure 19). In all cases, the clastic component could have been derived only off the crest of nearby paleohighs where Kimmeridgian age sediment is absent and where the Pimienta Formation rests unconformably on the Huizachal Formation (e.g., Jurel-2, Lisa-1, and Mantarraya-1 wells)(Figures 11 and 19).

In the Southeast Basin (Ortuño, 1999; Angeles and Cantú, 2001) the "contact" is lost in a gradually deepening upward stratigraphy. In this respect, there does not appear to be a major event expressed— merely parasequence boundaries.

Interpretation

Along the ECM, inversion of older Jurassic basins (e.g., Jurel and Mantarraya paleohighs) and thick-skinned deformation of granitic basement highs (e.g., Arenque) are the main expressions of compression. In the Southeast Basin, which, by contrast, was in an extensional setting, transgression was taking place. The lack of "lowstand" platforms on this boundary is notable, suggesting that this event was different from the middle Kimmeridgian lowstand.

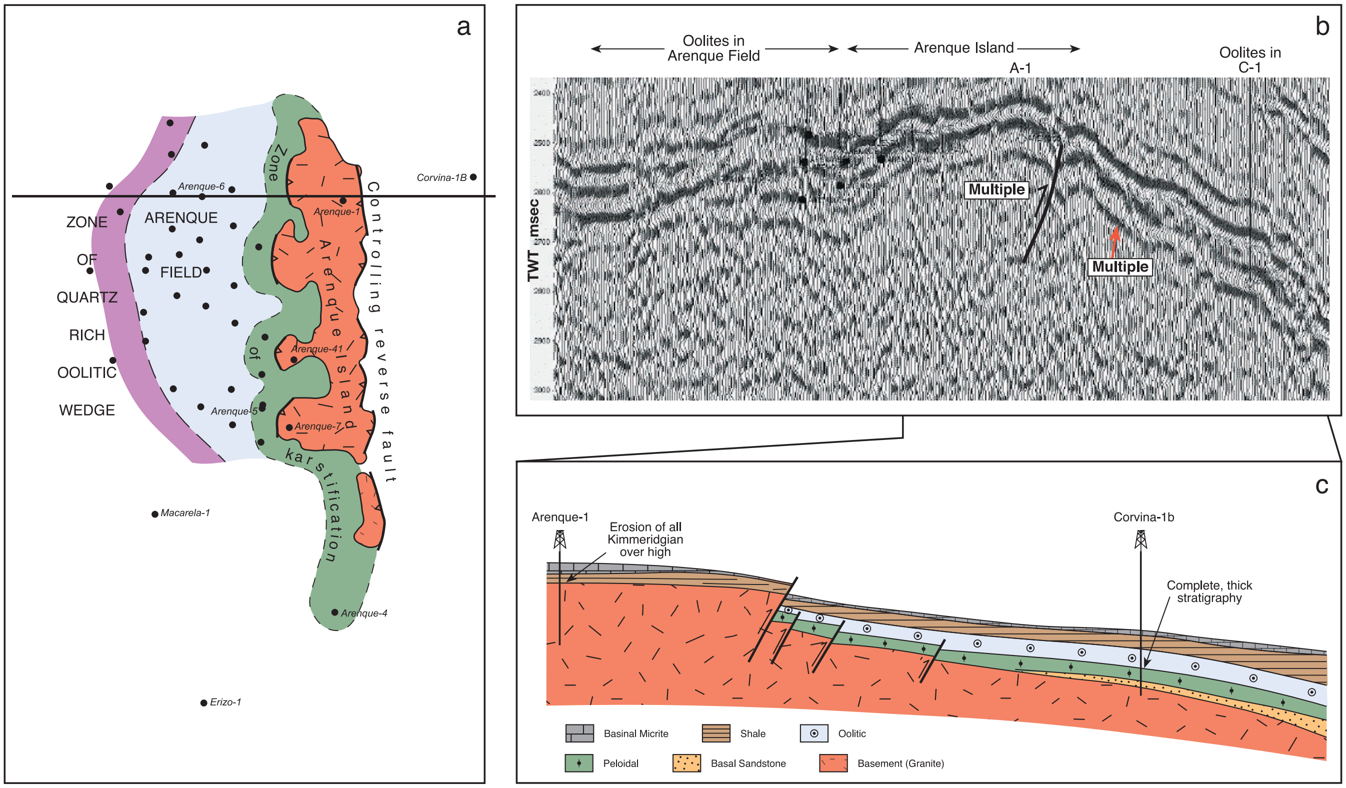


Figure 18. Details of the Arenque high at the end of the Kimmeridgian. (a) Subcrop map of the Arenque High at base Tithonian showing location of the seismic section (b). Wells A-1, A-7, and A-41 show complete lack of Kimmeridgian strata. Partial section is present in A-5, vuggy karstic fabrics are developed in cores A-4 and A-17. Quartz-rich sediment derived from basement exposure was deposited on the western flank of the field. (b) Seismic (crossline 6500). (c) Interpretation of the eastern portion of crossline 6500. Note that oolite facies are present in both Corvina-1B (shown in c) and the Arenque field, indicating that these locations were both at sea level during the Kimmeridgian, despite differences in present time depth. The present high is a later (end-Kimmeridgian and later) feature, such that the oolites have been eroded off the elevated crestal area of the high, as determined by faults controlling the eastern flank of the high, as well as by general folding on the frontal limits of a monocline.

Tithonian

Background

Early/middle Tithonian sediments, as typified by member F of the Edzna Formation of the Southeast Basin (Ortuño, 1999; Angeles and Cantú, 2001), show deeper-water facies than underlying Kimmeridgian age units. Transgression generally was rapid along the ECM; these differences perhaps are due to regional structural controls. The same relationship can be seen in other basins, such as Burgos (Pérez, 1992), and along the ECM, Tithonian age sediments generally comprise basinal argillaceous limestones of the Pimienta Formation. Highs such as the Tamaulipas Arch (Pérez, 1992) and Tuxpan High (Viniegra and Castillo, 1970) were covered for the first time. Cantú (1982) suggests that shoal facies (San Andrés Formation) of this age exist locally above Kimmeridgian age basinal carbonates along the ECM. Similarly, in the Southeast Basin, oolitic carbonates and shallow basinal facies are known in the early Tithonian stratigraphy of the Jujo field (Santiago and Baro, 1990). The succeeding Edzna Formation member G of early–late Tithonian age, as dated by Angeles and Cantú (2001), contains a second-order maximum flooding surface (Salvador, 1987; Wilson, 1990); this interval is the main period of source rock deposition across the whole basin (González and Holguín, 1992). Latest Tithonian sediments are typified by member H of the Edzna Formation with *Durangites*, *Salinites*, and *Protancyloceras* (Ortuño, 1999; Angeles and Cantú, 2001). These sediments are always slightly shallower-water than underlying sediments; for example loose ooliths are present in slope sediments in the latest Tithonian to the west of Comalcalco in the Southeast basin (Horbury, personal observation, 1997). However, in situ evidence of shelf carbonates of late Tithonian age is known only from Chiapas (Quezada, 1983).

There is a notable first appearance along the ECM of significant quantities of green-green bentonites

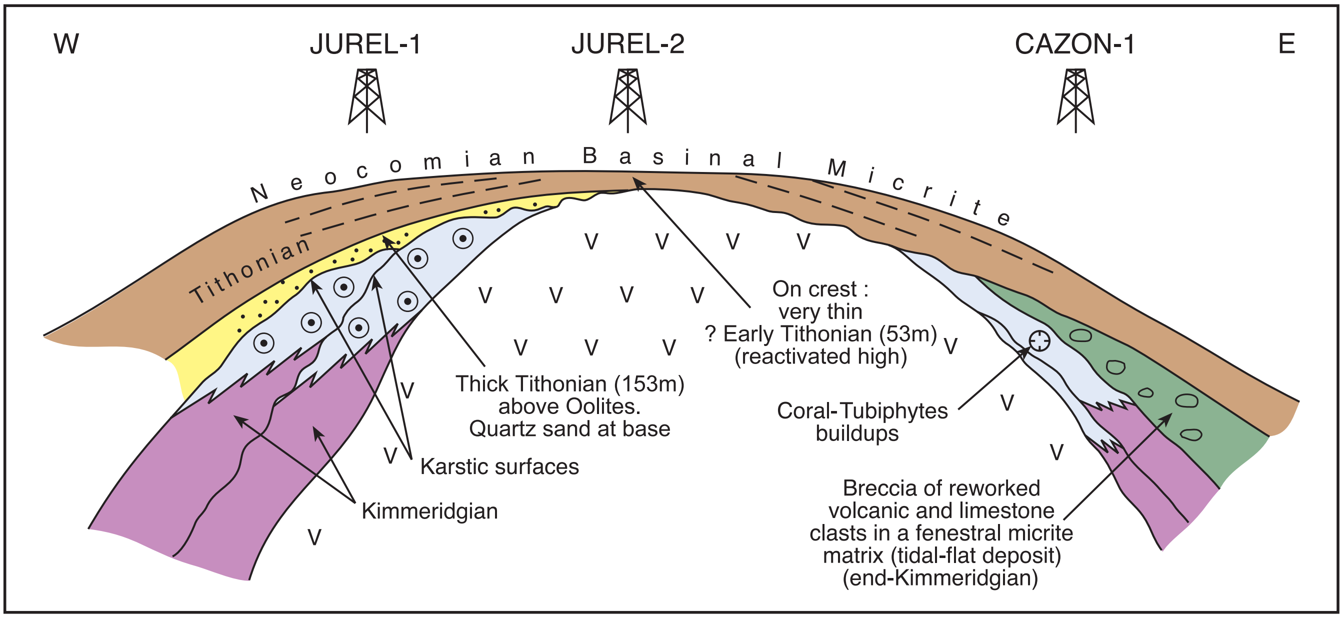


Figure 19. **Model showing the end-Kimmeridgian uplift in the Jurel area. The Jurel-2 well is typical of Tithonian deposition over Middle Jurassic volcaniclastic and red bed–dominated paleohighs that were inverted at the end of the Kimmeridgian; comparable with Mantarraya-1 and Lisa-1 wells (Figure 11a).**

(Salvador, 1987), while Tithonian basinal marls (Paltoltecoya Formation) are tuffaceous in the Necaxa area (Erben, 1956a).

Sequence Boundary

Burckhardt (1930) first noted an uplift and erosion event of about this age in the Tampico area, in which Cretaceous units often sit above Middle Jurassic red beds. Where the uppermost Tithonian is a carbonate rock, karstic breccia fabrics are sometimes described, e.g., from cores in Arenque-6 well (Horbury, personal observation, 1998). Complete loss of the middle and late Tithonian is noted from the Jurel-2 well, where the thickness of the Pimienta Formation is 53 m, contrasting with a complete stratigraphy in the Jurel-1 well (133 m) down the western flank (Figure 19). The Tithonian is also absent or partly eroded in the Lamprea-2 well (Figures 13 and 14) and Arenque-7 and 9 wells(Carrillo, 1980; Horbury, personal observation, 2001). The Lower Tamaulipas Formation, which overlies this boundary in the Eastern Mesozoic Basin, often has a member of ''calcarenites'' (peloidal/oolitic/pisolitic-shelf carbonates) at its base, e.g., along the eastern side of the Valles platform (Basáñez et al., 1993). Additionally, deposition of up to 200 m of shallow-marine/beach sandstones is often observed near intrabasinal highs in northeastern Mexico (the La Casita and Alamitos Sandstone Formations) (Salvador, 1987; Celestino, 1982, quoted in Basáñez et al., 1993; Goldhammer, 1999). These often sit on top of an unconformity that resulted in the local removal of all underlying Tithonian and Kimmeridgian sediment (López, 1982) (Figure 20).

In the Southeast Basin, an angular unconformity also is developed at the end of the Late Jurassic (Figure 3; Angeles et al., 1994; Williams and Hurley, 2001). The break is such that later Neocomian sediments may onlap the middle Tithonian sediments in many parts of the Southeast Basin. For example, all the bank systems that once supplied oolites to slope settings of late Tithonian age have been lost because of end-Tithonian erosion (Horbury, personal observation, 1998).

Interpretation

Shallowing followed by end-Tithonian uplift, emergence, and erosion is noted in both the Southeast Basin and along the ECM, but the mechanisms to explain these phenomena have to be different for each basin. In the Southeast Basin, seismic-scale geometries suggest that the uplift event is related to renewed northwest-southeast extension and generation of footwall unconformities (Figure 3). Uplift along the ECM (Figures 14 and 19) is more likely to be compressional in origin, with the main breaks being developed in inverted hanging-wall successions of a former half graben, as well as on elevated regional basement highs.

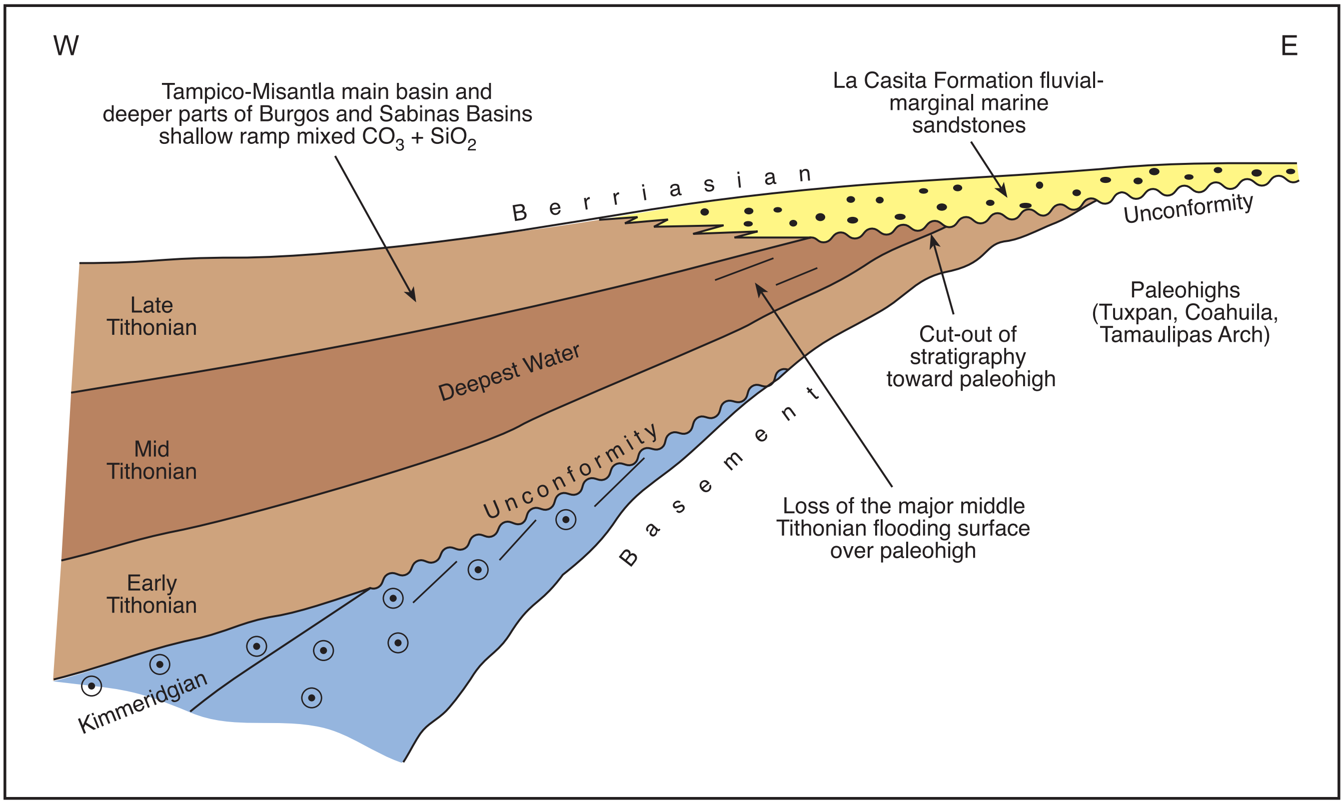


Figure 20. Model showing end-Kimmeridgian and end-Tithonian uplift in the onshore northern basins.

"Neocomian"

Background

The Neocomian is marked by a localized early shallow-water deposition, followed by slow transgression. Basinal carbonates were established in both basins and across paleohighs such as the Tamaulipas Arch, and, as seen in the Plan de las Hayas-1 well on Jalapa Uplift, where the Lower Tamaulipas Formation rests directly on granitic basement. Maximum flooding probably was reached in the Valanginian, as noted by Pérez (1992) for the Burgos Basin. An early Neocomian platform in the Southeast Basin (Cerro Pelon) was drowned at this time (Horbury, personal observation, 1994), while Valanginian basinal carbonates sit directly upon Middle Jurassic units near Miquihuana in southwestern Tamaulipas (Imlay, 1937). However, Salvador (1987) suggests the Valanginian as a time of maximum regression without citing evidence for this assertion. Stratigraphic sections typically are complete in basinal sections, although the Hauterivian is often absent in the Eastern Mesozoic Basin (Daniel Velez, personal communication, 2001), probably because of a submarine hiatus. Lateral thickness variations often are significant in the Southeast Basin after the development of half-graben topography (Figure 3) (Angeles et al., 1994). During the Hauterivian/Barremian, there was widespread establishment of highstand carbonate platforms (e.g., Cupido and Lower El Abra Formations) with locally evaporitic cores (e.g., Guaxcama and La Virgen formations) on paleohighs, notably in the Coahuila, Valles, Tuxpan, Cordoba, Artesa–Mundo Nuevo, and Chiapas-Yucatán areas (Pérez, 1992; Wilson and Ward, 1993; Goldhammer, 1999). These platform systems often prograde rapidly (e.g., 80 km for the Cupido Formation; Wilson and Ward, 1993), which is notable in that it is the only clear example of platform establishment by progradation in the Mesozoic and Cenozoic of Mexico. Shelf margins also aggraded such that as much as 1 km of topography had been created by the Aptian (Wilson and Ward, 1993). Deposition was generally quiescent, although platforms closer to coastal onlap, such as in the Sabinas and Chihuahua Basins, show a more dynamic stratigraphy with more formations and internal stratigraphic breaks (Goldhammer, 1999; Monreal and Longoria, 1999; Lehmann et al., 2000).

Sequence Boundary

In the middle Aptian, a major lowstand wedge developed in northeastern Mexico that comprises the Cupidito Formation, which sits directly on top of basinal facies of the Lower Tamaulipas Formation (Goldhammer, 1999). In the late Aptian, widespread organic-rich and cherty shales of the La Peña and Otates Formations (equivalent to the Pearsall Formation of the U.S.A) were developed across the whole Gulf of Mexico (Pérez, 1992; Wilson and Ward, 1993). These frequently contain a pelagic fauna and represent the demise of the Cupido platform system of northeastern Mexico (Wilson and Ward, 1993). All other platforms appear to have survived this maximum-flooding event, but geometries changed from progradational to aggradational (Wilson and Ward, 1993). A carbonate-evaporite platform was rapidly reestablished in the Coahuila-Sabinas area (represented by the Aurora/Acatita Formations); this was more extensive than the preceding platform. Miranda (2000) has recently proposed that small platforms also were established directly above basinal carbonates at about this time across much of the Southeast Basin (Reforma area)(Figure 21A). The evidence for this is provided by cores of early Albian-age rudist bank facies from the Yagual-1 well.

Interpretation

The late Aptian maximum-flooding event is probably as good an example of a major eustatic sea-level rise as can be demonstrated in this basin. However, it is unusual that of the major platform systems, only the Cupido was drowned at this time. Similarly, it is not clear why platform systems were reestablished in northeastern Mexico; some form of local tectonic forcing may explain both features. Platform-carbonate development in the Southeast Basin also requires localized uplift of intrabasinal highs, although at present it is not possible to distinguish conclusively between the possible role of salt uplift and lateral compression as a cause in this basin.

Late Aptian–Early Cenomanian

Background

Along the Gulf Coast of Mexico, Middle Cretaceous platforms comprising the El Abra Formation and its correlatives are typically from 1.5 to 2 km thick, often with well-developed reefal margins (Taninul Member) (Muir, 1936; Rockwell and Rojas, 1953; Minero, 1988, 1991). Slope carbonates (Tamabra Formation) comprising breccias, resedimented rudists, and deep-water carbonates are found; these may be in the order of 1.5 km thick (Enos and Stephens, 1993). Only relatively thin (hundreds of meters) deep-water facies were deposited; namely, the Upper Tamaulipas Formation (Viniegra and Castillo, 1970) along the ECM and the Akal Formation in the Southeast Basin (Angeles et al., 1994). Deposition generally was quiescent, although local platform drowning took place on the Valles platform during the late Albian–early Cenomanian (Basáñez et al., 1993). Platforms closer to coastal onlap, such as in the Sabinas and Chihuahua Basins, show a more dynamic stratigraphy with more formations and internal stratigraphic breaks (Goldhammer, 1999; Monreal and Longoria, 1999; Lehmann et al., 2000).

Sequence Boundary

In basinal areas, upper contacts generally are conformable; for example, as documented by Pérez (1992) in Burgos and in the deeper basinal areas between Tampico and Poza Rica (Viniegra and Castillo, 1970)(Figures 22, 23A, B, and 24). The middle Cenomanian marks the demise of the large Albian-Cenomanian platform systems, which commonly are capped by unconformities (Smith, 1986; Wilson and Ward, 1993). Overlying sediments usually comprise the Agua Nueva Formation (Figure 21C, D), indicating bathyal water depths, although there are shallow basinal and locally reefal facies of the Lower Tamasopo /La Muralla /"Late" El Abra Formation on the Valles platform (Smith, 1986; Basáñez et al., 1993) and possibly on the Tuxpan platform (Muir, 1936; Viniegra and Castillo, 1970) that locally overlie the late Aptian–early Cenomanian sediments. Similar shelf systems are the Maltrata Formation (in shelf facies) in the Mecayucan field of the Veracruz Basin and the Muspac and Catedral fields of the Southeast Basin (Williams and Hurley, 2001)(Figure 21). Reefs are known to be isolated and elongate (Smith, 1986); a preferential north-south direction is suggested by data in Basáñez et al. (1993).

The Tamabra Formation in the Poza Rica area consists of up to 200 m of rudist and breccia facies, which is locally deposited around the southwestern margin of the Tuxpan platform. Rudists identified as in situ reefs are notably present only over paleohighs, as identified by core and isopach data (Coogan et al., 1972). This unit also has interbedded pelagic micrites in its lower and western parts that demonstrate an early Albian to Cenomanian age; these micrites are associated with breccia facies but not with facies interpreted as in situ reefs (Coogan et al., 1972). Other features of note are the presence the "pseudodetrital facies" of Coogan et al. (1972) in the lower part of the Tamabra that can be reinterpreted as a collapse breccia in light of modern work on karstic systems (e.g., Loucks,

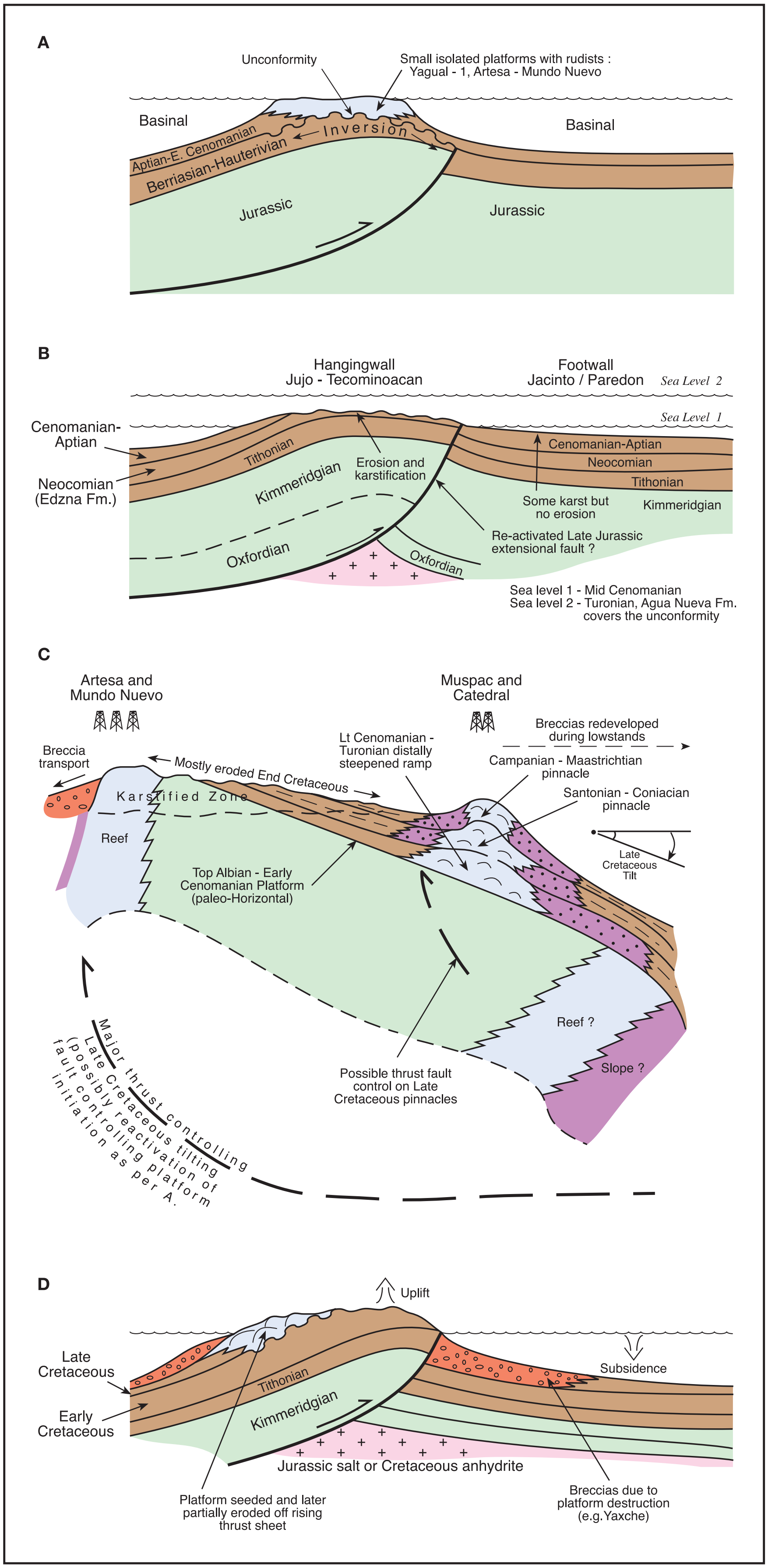


Figure 21. Model showing phases of uplift and erosion in the Cretaceous of the salt-floored basin of Tabasco and southern Veracruz. (a) Early Cretaceous (Aptian–early Cenomanian). The unconformity shown is probably partly eustatic but also associated with some localized uplift in order to initiate shallow-water platforms (c.f., Otates–La Peña events) (b) Middle Cenomanian erosion. (c) Artesa–Mundo Nuevo platform (after Williams, 2001, and Williams and Hurley, 2001). (d) Late Cretaceous attached platform, which was seeded and later partially eroded off rising thrust sheet (Artesa–Mundo Nuevo, Veracruz Platforms: Upper Maltrata (Turonian), Upper Guzmantla (Santonian), Atoyac (Maastrichtian).

1999). The top of the Tamabra Formation possibly is laterally equivalent to basinal sediment dated as late Cenomanian–Turonian, and near the Tuxpan platform, it may be overlain by basinal sediment of Coniacian-Santonian age. These relationships suggest that the upper part could be at least as young as Turonian in age (also noted by Wilson and Ward, 1993). Enos (1988) showed that these sediments had suffered significant meteoric dissolution and cementation; without this diagenesis, reservoir quality would be poor.

Immediately to the south of Tampico, between the Bocacajeta-1 and Anono-1 wells (Figure 23A), there is loss of most or all of the Upper Tamaulipas Formation. The Lower Tamaulipas is onlapped by the Agua Nueva Formation and then by the San Felipe Formation (Figure 23B). In the onshore part of the Southeastern Basin, there was a similar loss of middle and Early Cretaceous basinal carbonates. Examples such as those in the Jujo-Tecominoacán field have only basal Early Cretaceous and/or Late Jurassic basinal carbonates

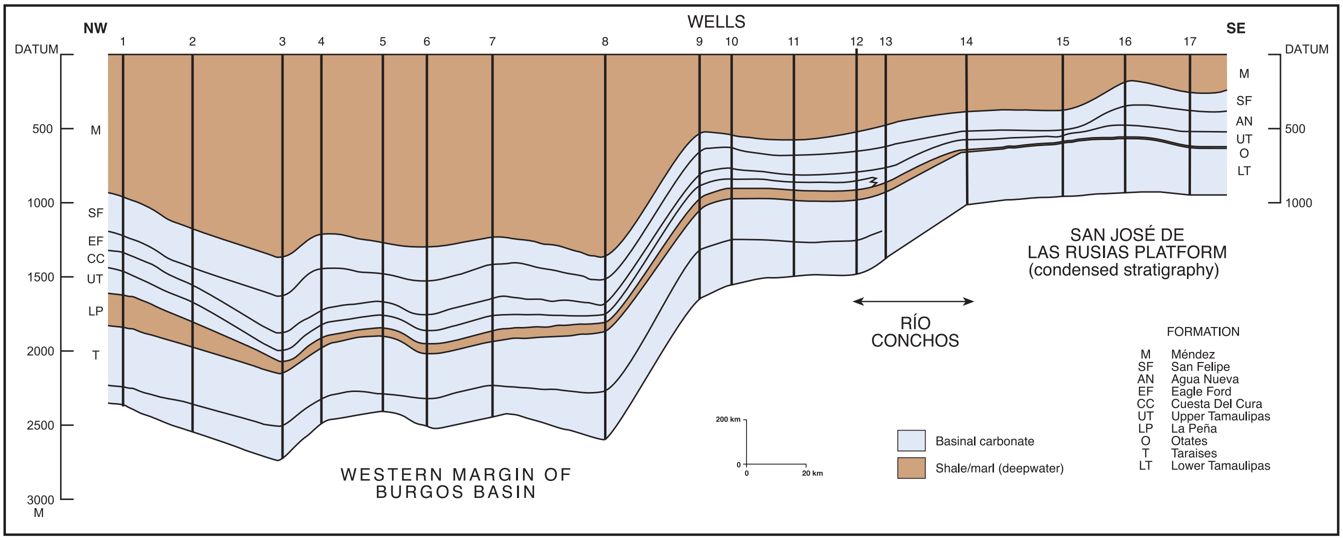


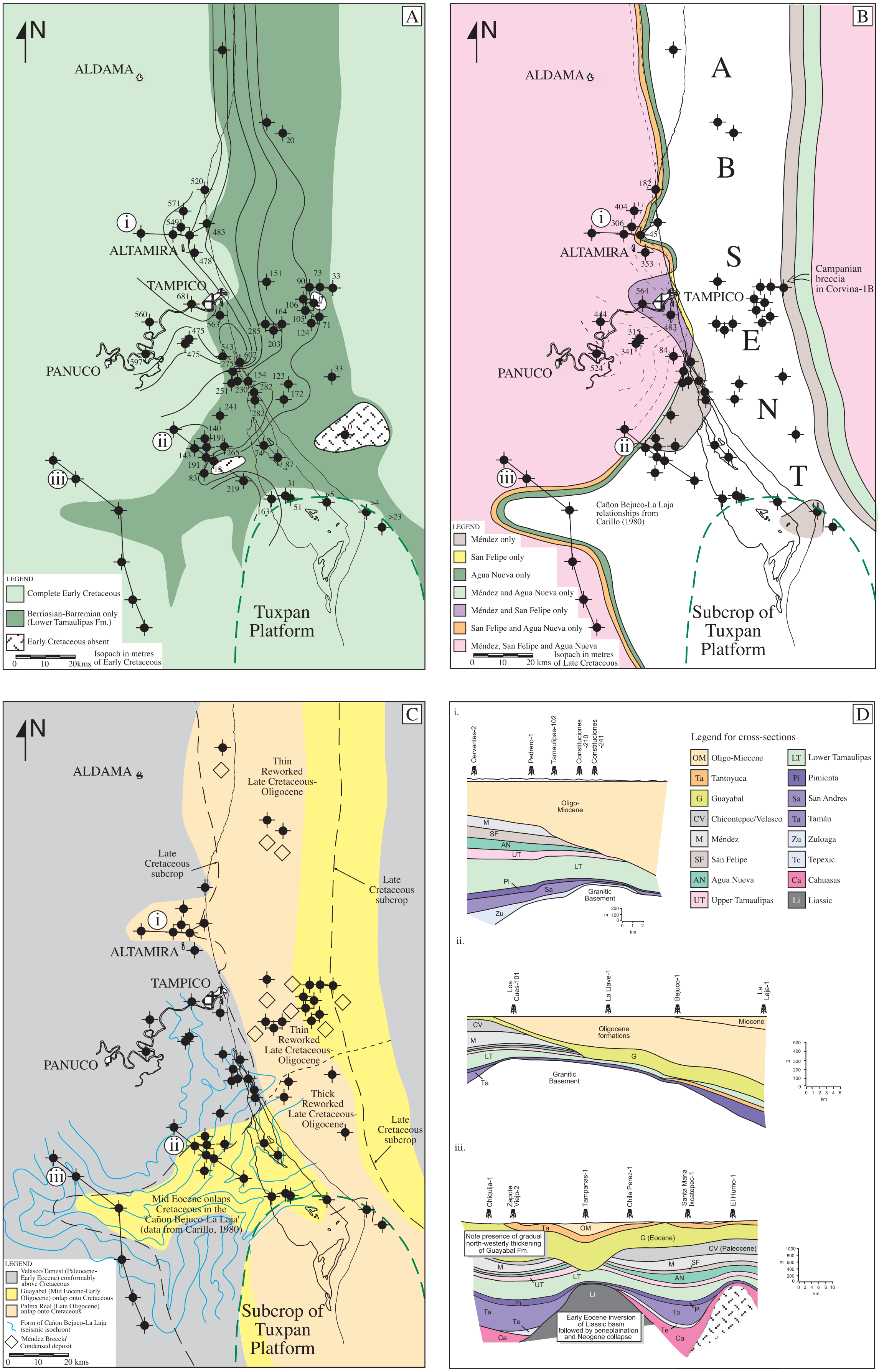
Figure 22. **Stratigraphic strike section of the Cretaceous along the Burgos Basin rim. The section is flattened on top-Cretaceous. The onset of deposition of the Cuesta del Cura Formation marks a period of major basin reorganization and a significantly increased rate of subsidence of the northwestern side of the Burgos Basin compared to the southeastern side. Modified after Pérez (1992).**

(Figure 21B); these show karstic collapse-breccia fabrics with sediment-filled fractures (Figure 25) and are overlain by the Agua Nueva Formation. Even where complete stratigraphies are present, e.g., in parts of the Tepeyil and Jacinto fields, these also often have strongly developed karstic fracture systems in them. Miranda (2000) suggests that many middle Cretaceous platforms were karstified at about this time, which resulted in the development of extensive breccia sheets.

Interpretation

Differentiation of wide shallow-water middle Cretaceous platforms into smaller platforms and deep-water basins throughout the Late Cretaceous suggest that a structural event of middle Cenomanian age catalyzed platform breakup. The Tamabra Formation has to be understood in the context of this event. It has been previously interpreted as an in-situ coral-rudist platform-margin complex (Barnetche and Illing, 1956; Coogan et al., 1972; Wilson, 1987) and as fore-reef talus (Viniegra and Castillo, 1970; Enos, 1977; 1985). The platform margin model, as originally conceived, required that the margin had been downfaulted 1000 m with respect to its coeval platform interior. Such faulting is clearly not present either on seismic data or as constrained by well data. Enos (1988) suggested that a lens of meteoric water in the Tamabra Formation was fed from the top of the platform, approximately 1–1.5 km higher than the position of the meteoric lens. Conventional understanding of greenhouse-type high-frequency, low-amplitude (1–10 m) cyclicity as developed on Mesozoic platform tops (Goldhammer et al., 1990) does not allow such synsedimentary lenses to develop. Also, the climate probably was relatively arid at this time, as implied by the presence of traces of platform-interior evaporites (Wilson and Ward, 1993). Even Pleistocene icehouse land-attached, carbonate-platform systems that have been subject to sea-level changes of as much as 100 m and within a

Figure 23. **Stratigraphic relationships in the Tampico area constrained by well and seismic data. (a) Isopach and subcrop map of Early Cretaceous units in the Tampico area. (b) Map showing isopachs of Late Cretaceous and onlap onto the Early Cretaceous in the Tampico area. Relationships in the Cañon Bejuco–La Laja and Tamaulipas-Constituciones areas are from Carrillo (1980). (c) Map showing onlap onto the Mesozoic in the Tampico area. Data regarding Oligocene-Miocene onlaps of the Cretaceous in Tamaulipas-Constituciones and middle Eocene onlaps onto the Cretaceous in the Cañon Bejuco–La Laja are from Carrillo (1980). (d) Cross sections (positions marked on maps a–c) showing Cenozoic erosion through (i) Tamaulipas-Constituciones, (ii) eastern part of the Cañon Bejuco–La Laja, and (iii) western part of the Cañon Bejuco–La Laja.**


A
N
ALDAMA
ALTAMIRA
TAMPICO
PANUCO
i
ii
iii
Tuxpan
Platform
LEGEND
Complete Early Cretaceous
Berriasian-Barremian only (Lower Tamaulipas Fm.)
Early Cretaceous absent
0 10 20kms
Isopach in metres of Early Cretaceous
B
A
B
S
E
N
T
Campanian breccia in Corvina-1B
Cañon Bejuco-La Laja relationships from Carillo (1980)
Subcrop of Tuxpan Platform
LEGEND
Méndez only
San Felipe only
Agua Nueva only
Méndez and Agua Nueva only
Méndez and San Felipe only
San Felipe and Agua Nueva only
Méndez, San Felipe and Agua Nueva
0 10 20 kms
Isopach in metres of Late Cretaceous
C
Thin Reworked Late Cretaceous-Oligocene
Late Cretaceous subcrop
Thin Reworked Late Cretaceous-Oligocene
Thick Reworked Late Cretaceous-Oligocene
Mid Eocene onlaps Cretaceous in the 'Cañon Bejuco-La Laja' (data from Carillo, 1980)
Subcrop of Tuxpan Platform
LEGEND
Velasco/Tamesí (Paleocene-Early Eocene) conformably above Cretaceous
Guayabal (Mid Eocene-Early Oligocene) onlap onto Cretaceous
Palma Real (Late Oligocene) onlap onto Cretaceous
Form of Cañon Bejuco-La Laja (seismic isochron)
'Méndez Breccia' Condensed deposit
0 10 20 kms
D
i.
Cervantes-2
Pedrero-1
Tamaulipas-102
Constituciones -210
Constituciones -241
Oligo-Miocene
Granitic Basement
ii.
Los Cues-101
La Llave-1
Bejuco-1
La Laja-1
Oligocene formations
Miocene
Granitic Basement
iii.
Chiquija-1
Zapote Viejo-2
Tampanas-1
Chila Perez-1
Santa Maria Ixcatepec-1
El Humo-1
Note presence of gradual north-westerly thickening of Guayabal Fm.
G (Eocene)
CV (Paleocene)
Early Eocene inversion of Liassic basin followed by peneplaination and Neogene collapse
Legend for cross-sections
OM Oligo-Miocene
Ta Tantoyuca
G Guayabal
CV Chicontepec/Velasco
M Méndez
SF San Felipe
AN Agua Nueva
UT Upper Tamaulipas
LT Lower Tamaulipas
Pi Pimienta
Sa San Andres
Ta Tamán
Zu Zuloaga
Te Tepexic
Ca Cahuasas
Li Liassic

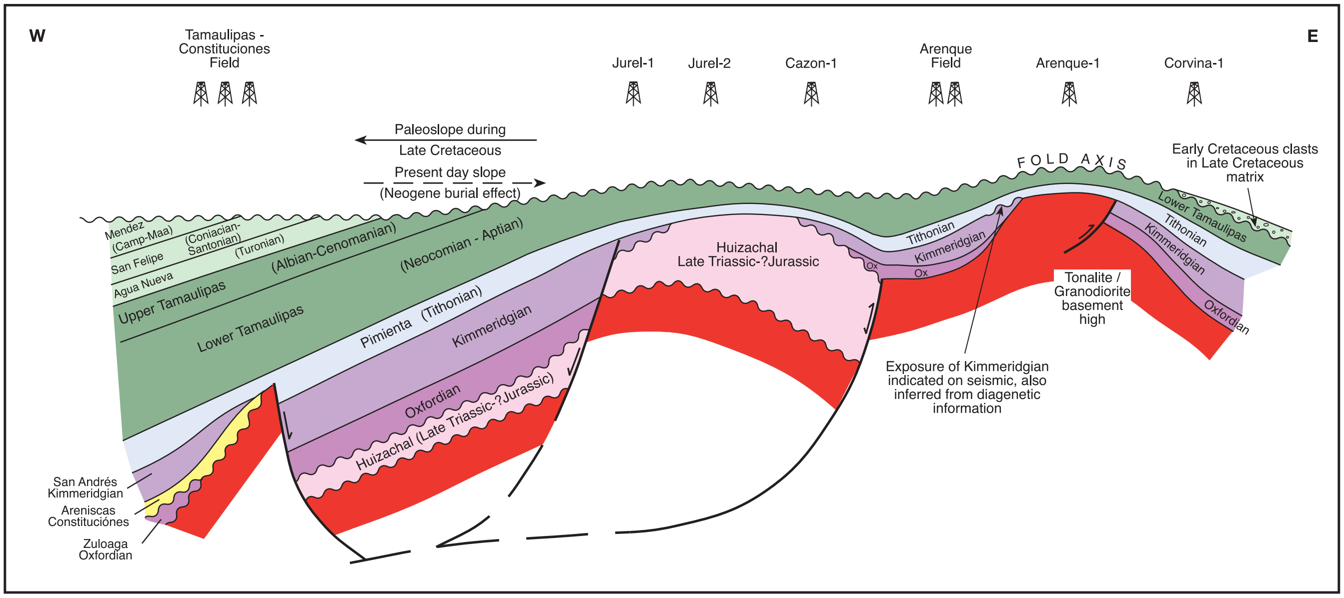


Figure 24. **Sketch section across the offshore Tampico area prior to Oligocene tilting. Late Jurassic extensional systems are succeeded by Early Cretaceous deep-water postrift sediments. The Albian-Maastrichtian and formations only appear above a more complete pre–Late Cretaceous stratigraphy toward the onshore area, where the succession is conformable, and in the extreme east where Campanian-age conglomerate rests upon Valanginian. This suggests that most of the erosion seen in the section is pre-Tertiary. Paleocene-Eocene rocks are only recorded in situ in the onshore area.**

more humid climatic setting show a deepest meteoric lens penetration of only 700 m. This example (Back and Hanshaw, 1970) from Florida also relies on a substantial input of river water to maintain the lens. Having said this, if meteoric water had reached the necessary depth of 1–1.5 km, it also is highly unlikely that it would have been undersaturated sufficiently to have achieved all of the diagenetic processes that Enos (1988) attributes to it. The Tamabra Formation would probably have been well within the stagnant meteoric phreatic zone where little diagenesis takes place (Longman, 1980).

We propose an alternative to the above mechanisms. Major regional uplift of middle Cenomanian age in the area of the Tuxpan platform, accompanied by local uplift of Jurassic highs that sit parallel but southwest of the margin of the basement-dominated Tuxpan High, could better explain both localized deposition of lowstand platform carbonates over highs, and also their meteoric diagenesis. An analog may be the middle Aptian-age Cupidito lowstand to the Cupido highstand, which has been identified in northeastern Mexico by Goldhammer (1999). If this is the case, the lower part of the Tamabra Formation (of Albian–early Cenomanian age) may be a true slope deposit with interbedded pelagic sediment that was karstified, while the upper part of Tamabra Formation (of late Cenomanian to possible Turonian age) may be much shallower-water. Correlative breaks in other parts of the basin system clearly indicate significant erosion of basinal sediments. Southwest of Tampico, an unconformity developed above very thick Early Cretaceous (Figure 23A) and Middle–Late Jurassic basin fill; this unconformity, sits along the west-southwest–east-northeast Río Panuco paleolineament (A-A′ on Figure 2). Both of these features suggest basin inversion at this locality.

Late Cenomanian–Turonian

Background

Deposition across most of the Gulf Coast of Mexico was generally of deep-water and often organic-rich carbonates with scattered shelf and reef facies.

Sequence Boundary

Smith (1986) documents a well-developed unconformity at the top of the Turonian stratigraphy in the Valles platform, such that Coniacian platform carbonates may sit directly on top of deeper-water Turonian age sediments. In the Veracruz Basin, folding results in karstification and brecciation of the underlying Maltrata Formation platform as well as strong onlap by the Guzmantla Pelagic Formation of

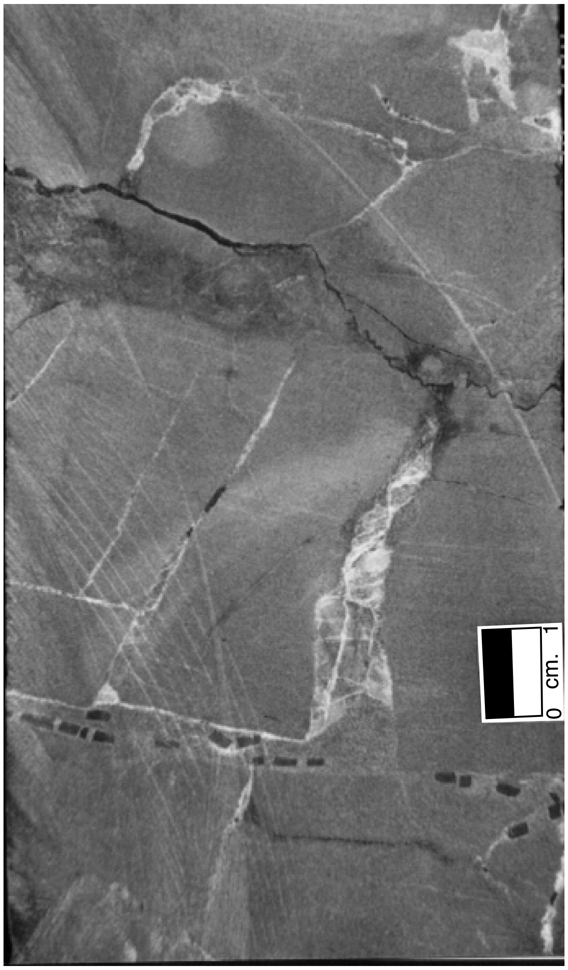


Figure 25. **Karstic crackle/mosaic breccia fractures in the Tithonian of the Tecominoacán-147, core 1, 5356–5364 m (Tithonian), showing sediment fills and cement.**

Coniacian age (Figure 26). Cantú (2001a) documents the San Felipe Formation sitting directly upon the Lower Tamaulipas Formation in the Mesa Chica-10 well to the southeast of Poza Rica, which provides strong evidence for a break of this age. Viniegra and Castillo (1970) and Coogan et al. (1972) show that the San Felipe Formation of Coniacian-Santonian age sits directly upon the El Abra Formation of Albian-Cenomanian age on the Tuxpan platform. However, the Lower Tamasopo Formation of Turonian age may be difficult to differentiate from the lithologically similar El Abra Formation shelf facies; for that reason, Turonian age sediment may have been "lost" in a section that is actually complete (Viniegra and Castillo, 1970). In the Southeast Basin, Angeles et al. (1994) note that the Turonian-Coniacian boundary marks a major lowstand.

Interpretation

Initiation of a fold and thrust belt is suggested by the development of unconformities and later localized seeding of small carbonate platforms over thrust-uplifted areas. In downthrown areas, basinal environments developed.

Coniacian-Santonian

Background

In basinal areas, San Felipe Formation carbonates with a relatively high siliciclastic and volcaniclastic component were deposited in a deep-marine environment. Localized shelf carbonates were deposited on top of former middle Cretaceous platforms of the Upper Tamasopo Formation (Valles platform) and the Guzmantla Formation (Cordoba platform); the latter comprises a 1,000-m-thick shoaling cycle culminating in reefal limestones (Figures 21C, 26, 29). On the Tuxpan platform, the San Felipe Formation appears to be present only on the southwestern flank (Viniegra and Castillo, 1970).

In the Southeast Basin, breccia systems of this age have been attributed to shedding of sediment from the Yucatán and Artesa–Mundo Nuevo platforms. However, Williams and Hurley (2001) document that most Late Cretaceous breccias on top of the Artesa–Mundo Nuevo platform are of only limited lateral extent and relate to small, late-stage, pinnacle-type platforms deposited on a platform that was undergoing strong subsidence (Figure 21D).

Sequence Boundary

The upper-sequence boundary is a major angular unconformity. The most significant data point is recorded in the Corvina-1 well, where the contact of an angular clast breccia above Valanginian basinal limestones was cored (Figure 27). Micropaleontology (Table 1; Figure 28) has given a Campanian age for the matrix sediment, although it also contains some reworked Coniacian-Santonian microfossils. Clasts range in age from Albian–Cenomanian to as old as Valanginian–Berriasian. There is a complete Cretaceous stratigraphy inland within a few km of the coast; e.g., in the west of the Tamaulipas-Constituciones field (Carrillo, 1980) (Figure 23D), which indicates that the actual eroded belt is, at most, approximately 50 km wide. Along strike from the Conchos River, as far south as the Sabalo-1 well and probably farther south than this, a distance of some 400 km, the Cretaceous is often eroded such that basement rocks are overlain by Cenozoic rocks (González, 1999). Seismic data

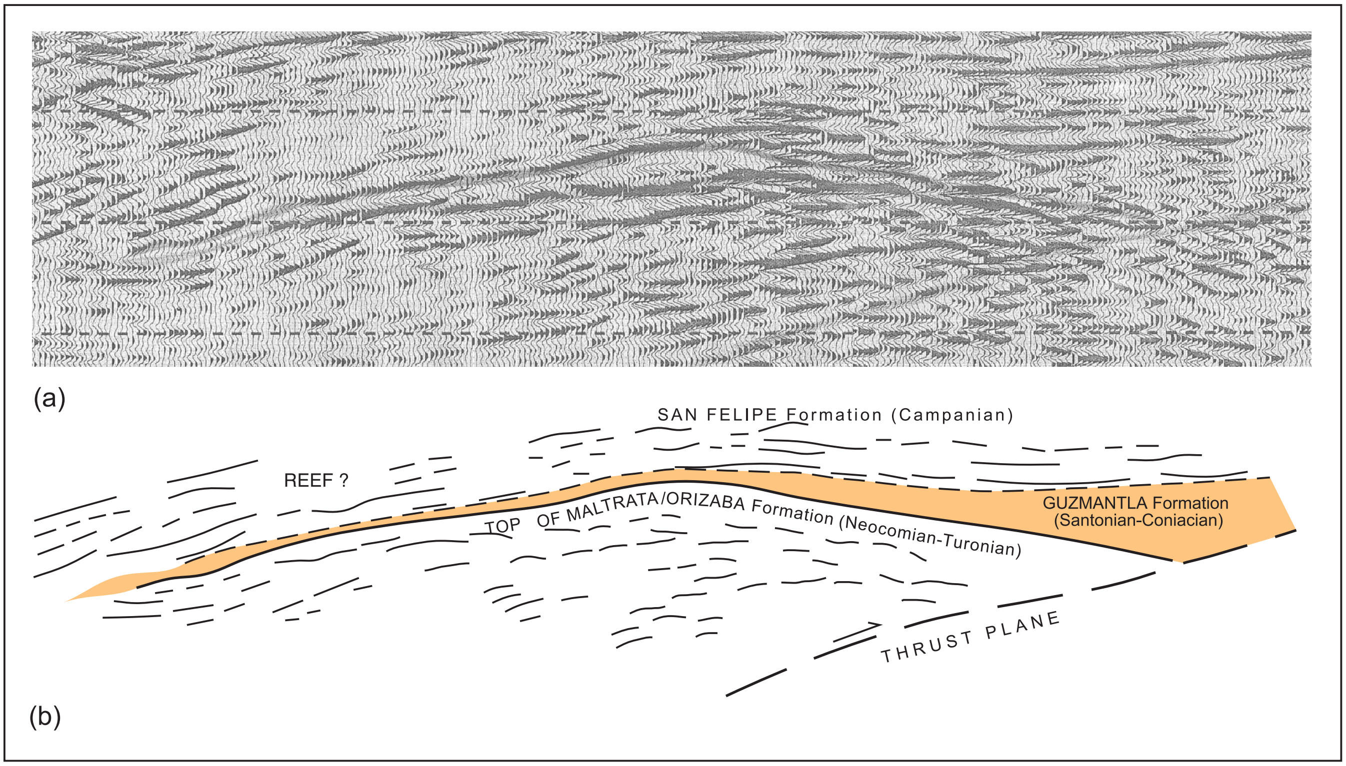


Figure 26. **Onlap of Lower Guzmantla Formation onto the Maltrata/Orizaba Formations to the northeast of the Angostura field. (a) Seismic line. (b) Interpretation of seismic line.**

suggest that the Corvina deposit represents the feather edge of a Late Cretaceous sediment wedge that onlaps the western margin of the MOP (Figures 7 and 23B).

In the Faja de Oro-1 well on the Tuxpan platform, a core taken approximately 1,000 m below the top of the platform shows a breccia in which clasts comprise Albian–Cenomanian shelf facies. In the matrix are planktonic foraminifera that are a mixture of Maastrichtian and early and middle Paleocene (P1d-P2 and P3-P4) forms (Table 2). A karstic system is known to have developed at shallower levels of the platform itself (Viniegra and Castillo, 1970), and, although the karst is difficult to date more precisely than pre-early Eocene, probably it is mostly of Santonian-Campanian age. It is this karst system that is most susceptible to well-control problems, which is indicative of its extent and connectivity. In 1910, the Potrero de Llano-4 well was drilled into it; the total production from this single well is thought to have been 95 MMBO, while the Cerro Azul-4 well drilled in 1916 had an estimated initial daily production of 260,000 BOPD, after running wild for a period of time (Viniegra and Castillo, 1970). Stalactites were recovered during these blowouts (Ordóñez, in Viniegra and Castillo, 1970). The Méndez Formation occurs locally and always unconformably on top of the Tuxpan platform. The same formation sits unconformably on Neocomian rocks to the southeast of the Tuxpan platform, e.g., in the Plan de las Hayas-1 well on the Jalapa Uplift.

In the Veracruz Basin, karstification of Guzmantla Superior Formation platform systems resulted in deposition of lowstand breccias of Campanian age (San Felipe Breccias), usually as a wedge in front of the platform (Figure 29). The Atoyac Limestone Formation platform carbonate (Viniegra, 1965) was then seeded on this surface. Similar platforms developed above relatively deeper-water carbonates in the Southeast Basin, for example in the Muspac and Catedral fields (Williams and Hurley, 2001) (Figure 21A, D). Platforms often have a northwest-southeast orientation (e.g., Figure 30). Similarly, Late Cretaceous shelf carbonate clasts containing *Orbitoides* (as well as older Cretaceous- and Tithonian-aged clasts) are present in a Campanian–Maastrichtian-age breccia, in the Yaxche-1 well, offshore Tabasco. This apparently is surrounded and underlain by basinal sediment (Figure 21) and is approximately 150 km from the nearest proven age-equivalent platform in Yucatán.

Interpretation

The breccia in the Corvina-1 well shows that deep erosion of the Mesozoic on the outer part of the ECM

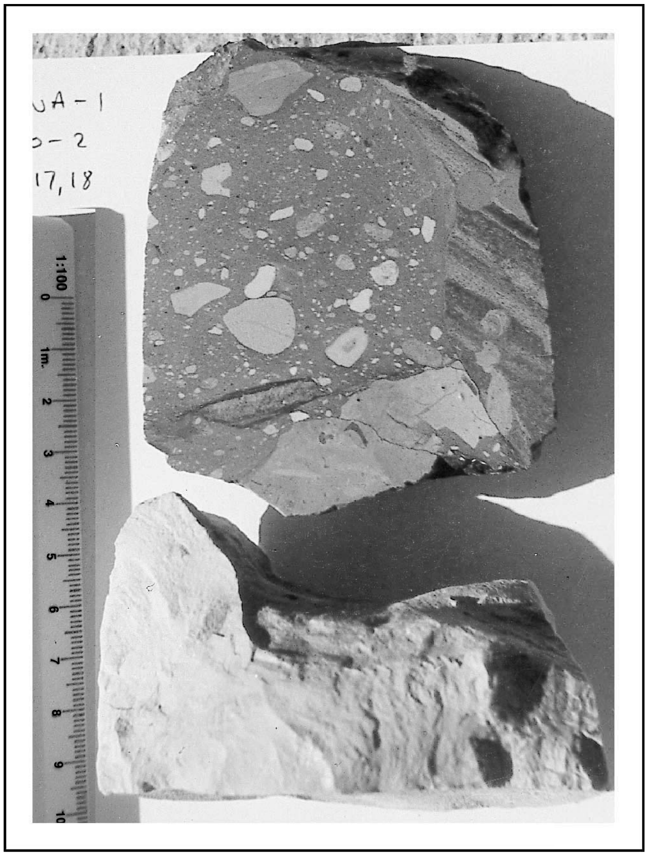


Figure 27. Breccia at the base of the Méndez Formation in Corvina-1B well, showing polymict clasts above pale-colored Lower Tamaulipas Formation basinal limestones.

has to be Campanian or older in age, given the youngest age (Campanian) of the matrix sediment sitting above the unconformity. This means that the apparent middle-Oligocene erosion of the continental shelf usually inferred from seismic data alone (Figure 8), and which was cited by Carrillo (1980) as a submarine paleocanyon event, in fact is much older and occurred on top of basinal carbonates, not in a clastic shelf-slope system. Presence of some clasts of Albian–Cenomanian age in the breccia is problematic, since no rocks of this age are known to exist in nearby updip locations. This may suggest modification of sediment source areas by later erosion, which makes it difficult to suggest the original extent of the end-Santonian unconformity. Major karstic penetration of this age or earlier is also required to create the channels that allow deep infiltration of Maastrichtian and Paleocene faunas in the Tuxpan platform. Such features may relate to development of regional uplift along the ECM. Further development of a fold and thrust belt in Veracruz and southeast Mexico is expressed by the presence of breccias and localized seeding of small carbonate platforms on the elevated (and possibly locally emergent) parts of folds or thrust sheets.

The appearance of abundant bentonite in this system may be linked to magmatism in Texas, where volcanoes were of sufficient size to seed atoll-like carbonates (Anacacho Formation) of Coniacian age (Lutterell, 1977) and/or to increased hot-spot activity in the Caribbean (90–70 Ma; roughly Coniacian–Campanian inclusive) (Pindell and Kennan, 2001).

Campanian–Maastrichtian

Background

Along the ECM, the flysch facies of the Cárdenas Formation and Difunta Group condense eastward into the Méndez Formation marls and cleaner carbonates (Pérez, 1992; Basáñez et al., 1993). In the Veracruz and Southeast Basins are small carbonate platforms that are locally oolitic (Viniegra, 1965; Williams and Hurley, 2001) (Figures 21A,C,D and 30). Correlative units of the offshore Southeast Basin (Angeles et al., 1994) are comparable with the deep-water Veracruz stratigraphy and comprise bentonitic limestones, shales, and calcareous to dolomitic breccias.

Sequence Boundary

Intense deformation is observed in the Rayones area in the Sierra Madre Oriental, where folds with 4 km spacing involve Late Jurassic to Maastrichtian units with décollement in Late Jurassic evaporites (Pérez, 1992). In the Burgos Basin, end-Cretaceous, down-to-the-east tilting resulted in development of salt-cored folds (Figure 31B,C,D) that are onlapped by thick Paleocene shales containing outer-platform sand bodies; these may be chaotic and slumped (Pérez, 1992).

The "Chicontepec Canal" of Busch and Govela (1978) recently has been re-interpreted, and all evidence of intra-Paleogene erosion has been dismissed as lateral facies changes in a turbiditic system (Cantú, 2001a). Paleontological data cited by Busch and Govela (1978) still indicates an earliest Eocene and not Paleocene age, according to our reinterpretation (Table 3); however, the context of the original paleontological data was not given by Busch and Govela (1978), so the use of this age data is not without its own problems. Whatever the final result of this debate, there are still features in the Poza Rica area that are relevant to understanding basin evolution. Incised Mesozoic stratigraphy now termed the San Andrés Paleocanyon by Cantú (1992, 2001a) shows

Table 1. Faunal composition of matrix and clasts in the Corvina-1 breccia.

Assemblage	*Microfossils*	*Comments*
Campanian (matrix)	*Globigerinelloides* sp.; *G. bolli*; *Archeoglobigerina blowi*; *Rugoglobigerina* sp.; *Rugotruncana* sp.; *R. cesarensis*; *Globotruncanita stuartiformis*; *G. elevata*; *Rugoglobotruncana* sp.; *Gublerina* sp.; *Marginotruncana* sp.; *Marginotruncana undulata*; *M. pendens*; *M. leopoldi*; *M.paraconcavata*; *Hedbergella* sp.; *Globotruncana* sp. and *G.* spp.; *G. elevata*; *G. plummerae*; *G. linneiana*; *G. rosetta*; *G. lapparenti*; *G. ventricosa*; *Globotruncanella* sp.; *G. havanensis*; *G. kefennsoura*; *Dicarinella* sp.; *D. concavata*; *D. hagni*; *Heterohelix* sp., scattered radiolaria	Assemblage in many cases gives only a broad Late Cretaceous or Maastrichtian-Santonian age
Cenomanian-Aptian (clasts)	*Calcisphaerula innominata*; *Pithonella ovalis*; *Rotalids* sp.; *Stromosphaera sphaerica*; *S. conoidea*; *Bishopella* sp.[1]; *Favusella* sp[1].; *Microcalamoides diversus*[2]; *Ticinella* sp[2]; *Colomiella mexicana*[2]; molluscan fragments and radiolara	[1]Albian-only clasts [2]diagnostic of the Aptian
Barremian-Berriasian (clasts)	*Nannoconus* sp[1]. and spp.; *N. globulus*[1]; *N. steinmanni*[1]; *Tintinnids* spp.[2]; *Tintinopsella carpathica*[2]; *Calpionellopsis* spp.[2]; *C. simplex*[2]; *Remaniella* sp.; common radiolaria and ostracods and some echinoderm debris	[1]Barremian-Hauterivian [2]Berriasian-Valanginian

the Chicontepec Formation to rest unconformably upon the San Andrés Formation in the President Aleman and San Andrés fields (Busch and Govela, 1978; Cantú, 1992). Erosional loss appears to be greatest on the southwestern side of the feature; a total loss of about 300 m of Mesozoic stratigraphy can be calculated for the east-southeast of the canal from the cross sections in Busch and Govela (1978) (Figure 32). Mesozoic subcrop shows a strong westward dip. An end-Maastrichtian breccia is present to the northwest of the Tuxpan platform; Coogan et al. (1972) show that this extends nearly 8 km westward from the margin of the Tuxpan platform.

Detailed studies of outcrops in Veracruz and Tamaulipas indicate that the basal Velasco Formation is usually conformable upon the Méndez Formation, although spherulites, shocked quartz, and an iridium anomaly are reported (Smit et al., 1992). However, some workers have identified stratigraphic breaks in the same succession (López et al., 1995).

In the Veracruz Basin, latest Cretaceous shelf carbonates show evidence of karstification and erosion, while breccias were redeposited in slope settings to the northeast of the shelf (Figure 30).

In the Southeast Basin, basinwide deposition of conglomerates and breccias is noted, which marks the end of the remaining platform/pinnacle development (e.g., in Muspac and Catedral fields; Williams and Hurley, 2001). Breccias range in thickness from 50 m in deep-water Comalcalco to 38 m in the Sierra de Chiapas (Longoria and Grajales, 1993; Montanari et al., 1994; Sánchez and Salmerón, 1996). Unconformities also are present; for example, in the Carmito field there is a Late Cretaceous–Paleocene unconformity, and the Agave field shows Paleocene onlap onto Santonian (Pemex, 2000). Viniegra (1981) also notes that Paleocene rocks may rest on Late Jurassic units in Campeche Bay. In the Sierra de Chiapas, Sánchez and Salmerón (1996) describe the Cretaceous–Cenozoic contact as being completely conformable in some places and unconformable in others, indicating considerable stratigraphic heterogeneity.

Interpretation

In the Burgos Basin, deformation is limited to possible gentle eastward tilting which could have initiated the salt-cored folds as well as formed the incline above which detached the Paleogene growth-fault systems. Condensation of fine-grained Paleogene sediment onto the paleohigh bounded by the Río Panuco–Río Conchos lineaments and concentration

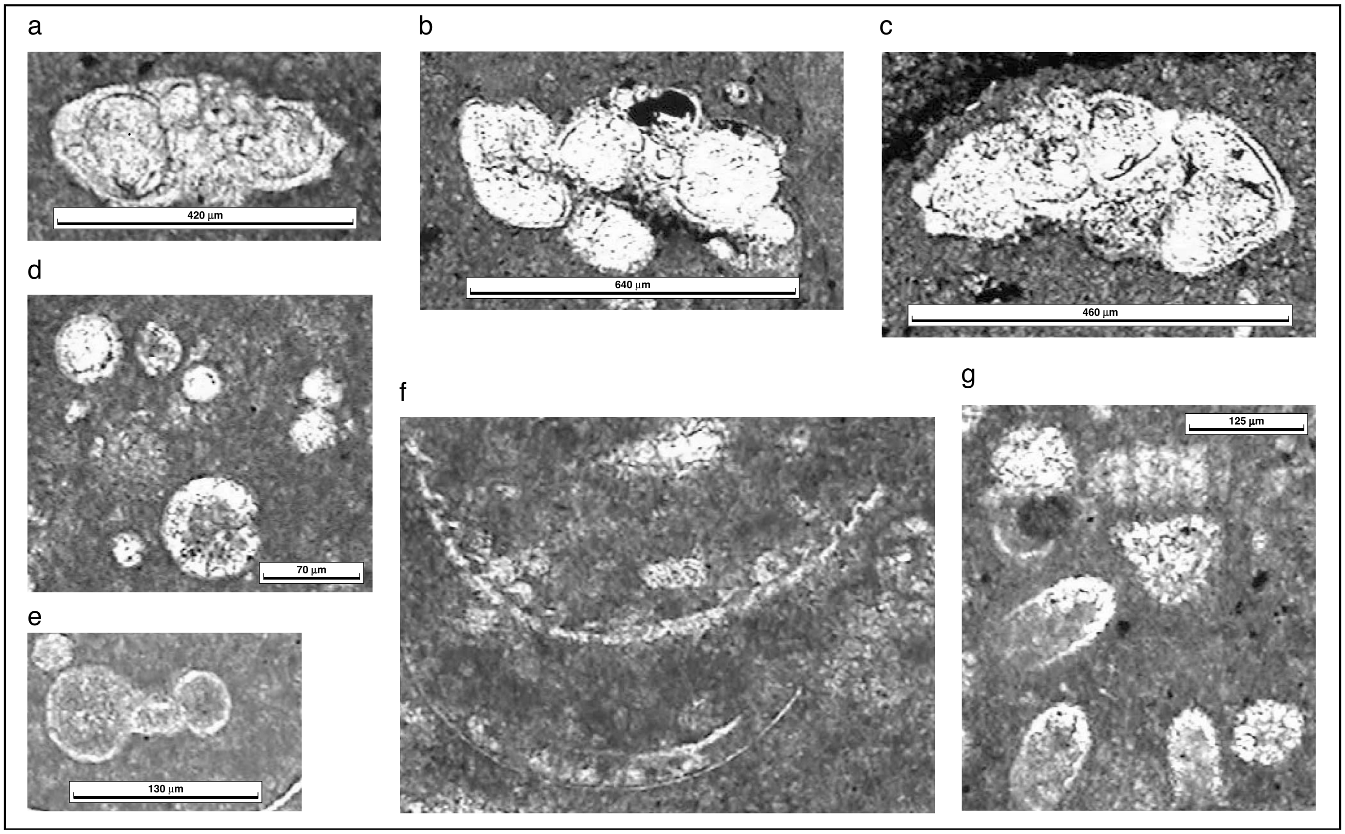


Figure 28. Selected microfossils from the Corvina-1B breccia of Campanian age. Scale bars in microns unless stated. In the matrix are forms such as (a) *Globotruncana bulloides* (Campanian), as well as reworked (b) *Dicarinella hagni* and (c) *Globutruncana plummerae* (Coniacian-Santonian). Clasts contain (d)*Stomiosphaera sphaerica,* (e), *Globigerinelloides* sp. (all Albian or Albian-Cenomanian), (f) *Microcalamoides diversus* (Aptian) (field of view 1 mm), and (g) *Tintinnids* sp. (Berriasian-Valanginian).

Table 2. Faja de Oro-2, core 2 (1866–1875 m).

	Fauna	*Age interpretation*
Paleogene matrix components*	*G. pseudobulloides*	base P1d – top P2/base P3
	G. trinidadensis	base P1d – near top P2
	G. angulata	base P3 – near top P4
	Globorotalia velascoensis	mid P3 – mid P6
	Ciclogrira angigyra	
	Anomalina sp.	
	Heterohelix sp.	
	Flavelina sp.	
Late Cretaceous matrix components*	*Globotruncana conica*	Maastrichtian
	Globotruncana stuarti	
	Globotruncana gagnebini	
	Globortuncana stuartiformis	
	Globotruncana contusa	
	Gausericea ganseri	
	Heterohelix globulosa	
	Pseudotextularia sp.	
Early Cretaceous cream-coloured limestone clasts	*Nummuloclulina heimi* Miliolids	Albian-Cenomanian

**In a slightly sandy marl, grey to grey-green, friable, bentonitic in part, abundant pyrite.*

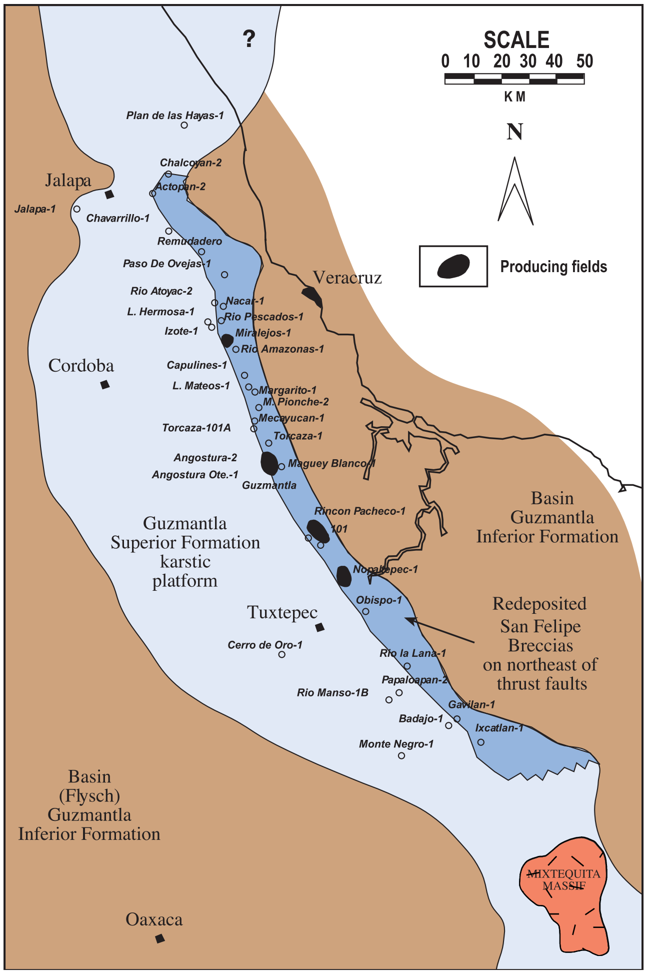


Figure 29. **Paleogeography for the late Santonian–early Campanian of the Veracruz Basin. After Meneses et al., 1997.**

of Paleogene coarse-clastic sediments in basins north and south also suggest elevation of this structure.

Development of the San Andrés Paleocanyon is a major end-Cretaceous feature according to Cantú (2001a). Onlap of the thinnest (and possibly youngest?) infill sediments over the oldest (and most strongly dipping) subcrop indicates the development of a major elongated northwest-southeast high with a culmination to the southeast of the paleocanyon. Origin of the paleohigh is not discussed by Busch and Govela (1978), but it could be related to inversion of Jurassic basins along the southwestern margin of the Tuxpan paleohigh. Considering the scale of the features involved, it seems likely that if the typical water depths during the paleocanyon's initial fill were between 135–500 m (Busch and Govela, 1978), then the flanks and updip part of the canal, if not the entire system, may have been subaerially emergent at various times. In this case, the Tuxpan platform would have to have stood as an elevated ''mesita,'' perhaps 1 km or more above the surrounding end-Paleocene basin, with its top dipping westward. An early fluvial phase to account for the erosion of this and other paleocanyon features already has been proposed by Carrillo (1980); expanding on this theme, if the Tuxpan platform were emergent, it is highly likely that base-of-scarp springs would have developed. Such an abundant multisourced supply of water could, in turn, account for both the platform-hugging geometry and strong erosion on the platform side of the canal.

End-Cretaceous compression in Veracruz and the Southeast Basin was also pronounced, but in this case resulted in renewed thrusting and uplift of fold axes; evidence is seen in the karstification of the Atoyac Limestone platform.

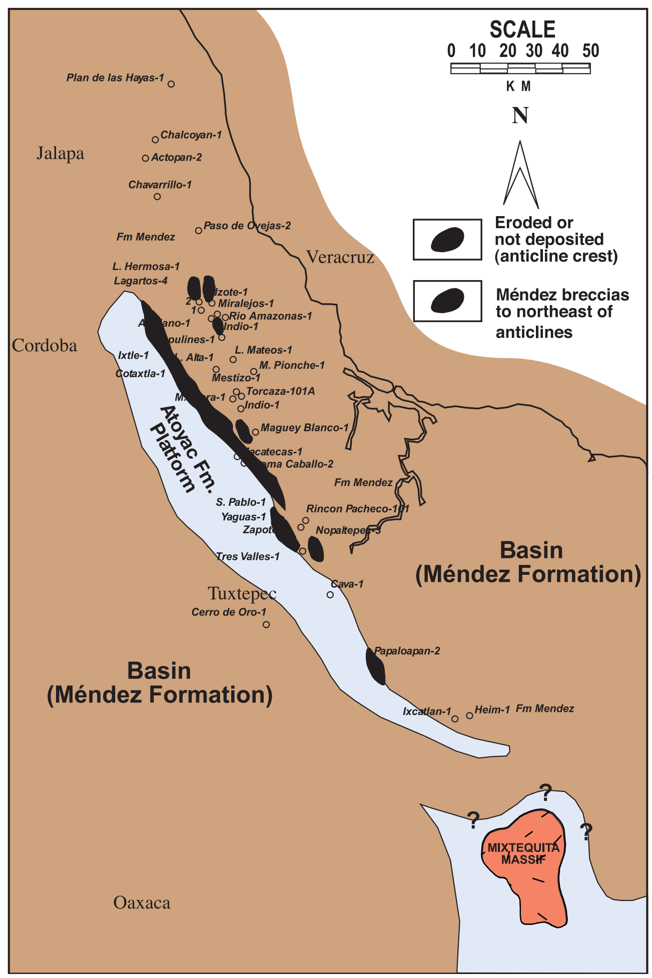


Figure 30. **Paleogeography for the Maastrichtian of the Veracruz Basin. After Meneses et al., 1997.**

At this time and as recently as the early Paleocene, there apparently was a regression that resulted in exposure of the Yucatán Bank and provoked carbonate rocks to slide off into the Sonda de Campeche. This resulted in the breccia reservoirs from which the bulk of Mexican hydrocarbon production comes from (Angeles et al., 1994). Breccia systems of this age also have been attributed to the Chicxulub event (Grajales et al., 2000, 2001), although this mechanism is controversial (e.g., Stinnesbeck et al., 2001). Miranda (2000) also suggests that breccias may have been of an uplift/karstic origin, which is quite compatible with our observations in areas to the north.

Paleocene

Background

Paleocene deposition over much of the ECM was relatively quiescent. In the Burgos Basin, deposition commenced with deep-water shales of the Velasco and Midway Formations followed by entry of the Wilcox Formation deltaic sandstones and shales in the late Paleocene. Correlatives in the Tampico–Poza Rica area commence with the deep-water shales of the Tamesí and Velasco Formations (Sánchez and Salméron, 1996). In the middle Paleocene, coarse siliciclastics that initially had a western provenance entered the basin; these are known as the Chicontepec Group in outcrops in and in front of the Sierra Madre Oriental (Figure 2). This turbidite system reached the Bejuco area near Tampico (Carrillo, 1980) but did not cross onto the high north of the Panuco River, where shale deposition continued (Figures 2 and 23C). Equally, Paleocene deposits in the southeastern part of the Tampico-Misantla and Veracruz Basins are deep-water shales of the Velasco Formation, followed by deposition of Lower Chicontepec Formation turbidites (Viniegra, 1965; Viniegra and Castillo, 1970; Carrillo, 1980). In the Southeast Basin, Paleocene deposition is typified by deep-water mudstones (Chac and Nanchital (Shale) Formations; Angeles et al., 1994; and Sánchez and Salméron, 1996), although some fields (e.g., the Cantarell complex) contain Paleocene calcarenites or breccias that are interpreted as turbidite deposits (Santiago and Baro, 1990).

Down-to-the-basin growth faults that detach on the top-Cretaceous began to develop in the early Paleocene in the northwest of the Burgos Basin (Pérez, 1992) (Figure 33D, E). Toward the south of the Burgos Basin are as much as 3,200 m of early Paleogene sediments in the Morralito-1 well, which thin by condensation to 280 m in the Tres Palos-1 well on the southern side of the Río Conchos, suggesting the continued presence of a long-lived paleohigh in this area (Figure 34). Paleocene (and Paleogene, in general) sediments also onlap the eastern margin of the MOP in the offshore Tamaulipas-Veracruz areas (e.g., Figure 7A–C). Paleocene sediments are thick in the area to the southwest of the Río Panuco and near the Sierra Madre Oriental fold and thrust belt, although outcrop maps suggest that this interval thins towards Poza Rica in the southeast (Figure 2). On the Tuxpan platform, Paleocene sediments (broadly zone P2-P3) have been found only in probable karstic cavities in the platform itself (see Table 2) and are notably absent on the platform top (Viniegra and Castillo, 1970; Coogan et al., 1972) (Figure 32B).

Sequence Boundary

The Sierra de San Carlos–Cruillas region has surface exposures of Mesozoic and lower Paleocene units gently folded into elongate, closely spaced, east-west-trending anticlines and synclines. These are cut by an unconformity, with the middle Paleocene being missing (Pérez, 1992); on outcrop maps (e.g., in López, 1982) the whole Paleocene stratigraphy appears condensed to the northeast of this high. Tardy (1980) and Padilla y Sánchez (1982) both described late Paleocene–early Eocene deformation with structures striking 110° in the SMO. De Cserna (1956) also noted thin-skinned detachment in Albian evaporites of the SMO of intra-early Eocene timing. As noted, Cantú (2001a) has recently dismissed the main erosion of the Chicontepec Canal of this age as being an artifact of poor stratigraphic interpretation. However, the early Eocene–age Upper Chicontepec Formation turbidites have paleocurrent directions indicating flow toward the northwest rather than from the southwest, as in underlying Late Cretaceous and Paleogene flysch units; the sediment source is held by Busch and Govela (1978) as being the Jalapa (Santa Ana) Uplift. In addition, there is also entry of clasts derived from the Tuxpan platform (Busch and Govela, 1978). Curiously, Busch and Govela (1978) report no reworking of Paleocene fossils into the Upper Chicontepec Formation, supporting Cantú's (2001a) contention that there is no major Paleocene–Eocene break actually in the basin itself.

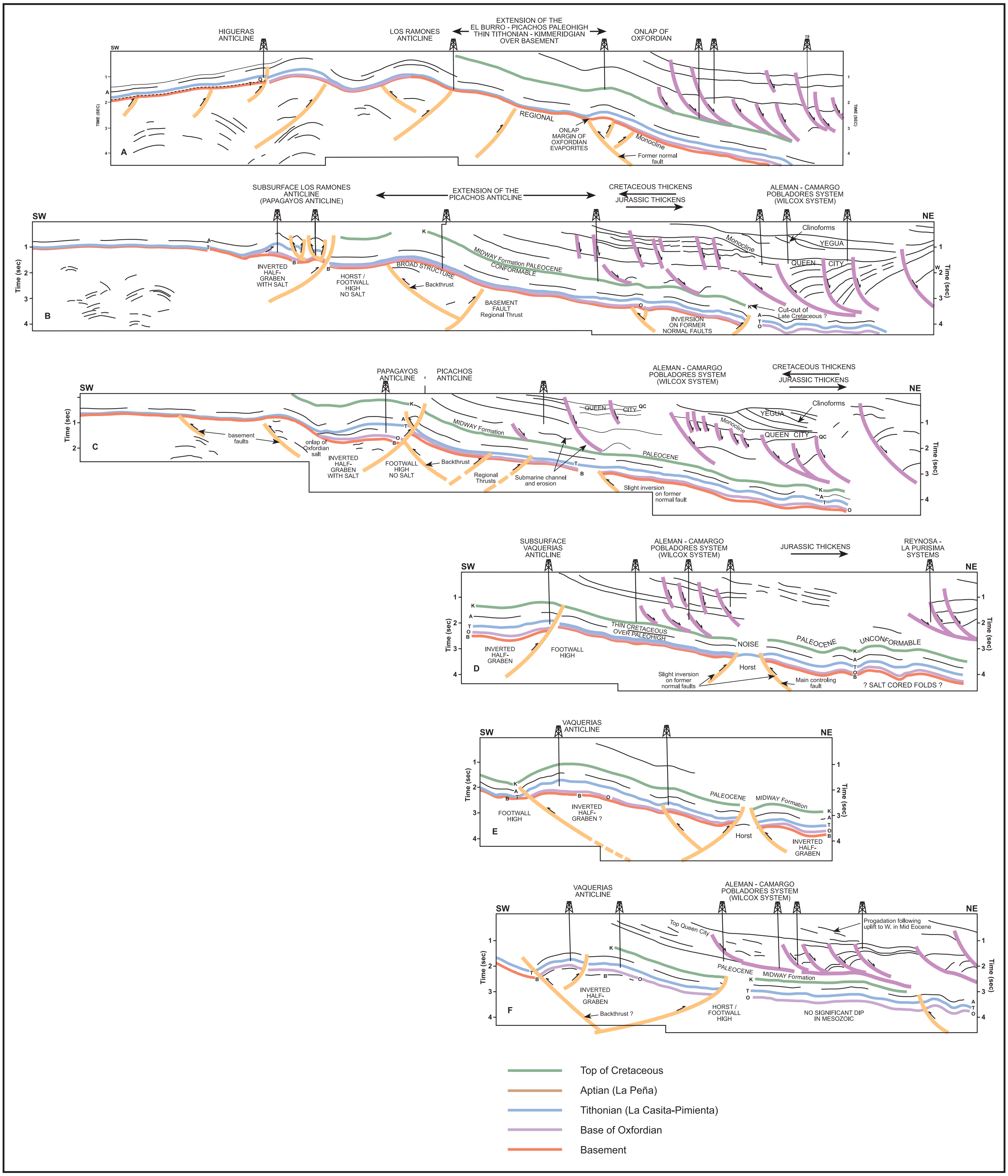
Interpretation

Localized uplift and emergence across parts of the ECM took place after zone P3, since any subaerial emergence must have post-dated the age of the youngest pelagic microfossils reworked into karstic cavities in the Tuxpan platform. Elevation and erosion along the east of the ECM is further supported by switching of the paleocurrents and sediment source areas for the Chicontepec Formation.

Early to middle–Middle Eocene

Background

In the Burgos Basin, Wilcox Group neritic sandstones and shales passed up into the Carrizo, Recklaw,



and Queen City Formations, representing inner shelf and continental sediments (Sánchez and Salméron, 1996). Early to early–middle Eocene deposition over much of the ECM was quiescent. The Chicontepec Formation depocenter is oriented west-northwest–east-southeast and runs along the western margin of the Tuxpan platform; sediments thin towards the east-southeast and were deposited in water depths of 135–500 m (Busch and Govela, 1978). Paleocurrents indicate flow toward the north-northwest; basinal shales are present to the southwest. There are also many reworked Mesozoic microfossils in the infill sediment. They are thought to be derived from the Tuxpan platform, in which direction there is also a notable increase of input in calcareous debris (Busch and Govela, 1978). The Chicontepec Formation is succeeded by Aragón Formation deep-water shales in the east of the Tampico-Misantla Basin and in the Veracruz Basin (Viniegra, 1965; Viniegra and Castillo, 1970). A thin veneer of both formations represent the oldest Paleogene sediments to onlap the top of the Tuxpan platform, but these deposits are found only locally along its most northwestern and southeastern extremities (Figure 32B). Aragón Formation shales dominate this entire sequence in the western part of the Tampico-Misantla Basin, and in the Veracruz Basin (Figure 2) (Viniegra, 1965; Viniegra and Castillo, 1970). In the Southeast Basin, deposition was of deep-water Nanchital Shale Formation and equivalents, with continued input of some calcarenites and breccias.

The Sierra Madre Oriental fold and thrust belt developed at this time. Older thinner-skinned thrusts detach on basal Middle Jurassic evaporites; younger, thick-skinned thrusts have a spacing of about 8 km and a décollement in metamorphic basement, e.g., in

Figure 31. **Transects across the west-central part of the Burgos Basin (modified after Pérez, 1992, his VI to XI transects) showing westerly onlap of the Picachos anticline by Oxfordian and older Jurassic rocks (all lines); to the west, half graben of Late Jurassic age are present with thick evaporite infills. Cretaceous sediments generally thin toward the east (a, b, c) and locally over paleohighs. End-Cretaceous deformation comprises irregular folds that affect all the Mesozoic section but not the Tertiary; these folds are thought to be salt-cored and are assumed to result in an unconformable Cretaceous-Tertiary contact (seen on the east of all lines). Large-wavelength basement structures such as the subsurface expression of the Picachos paleohigh (a, b, c) are basement-involved and have a paleoexpression much larger than their later expression as smaller thrust-bounded highs, e.g., on line (b). The main faults of middle Eocene age appear to be southwest vergent, but these are most likely linked to bigger, east-vergent faults that control the entire monoclinal structure. Such linkages are seen in (a) where a back thrust developed in the Los Ramones anticline. The monoclinal dip on the top-Mesozoic is gradual to the east; however, it flattens out in places (e.g., in the east of [f], limited by an inverted normal fault) suggesting points at which major east-vergent faults (often as ex-normal faults) may define differences in structural dip. In lines (b) and (c), only the Tithonian and Kimmeridgian are present over the stable high to the west of the lines; deformation here is limited to small, basement-involved faults because of the lack of evaporites at depth. The Papagayos/Los Ramones structure is part of the large Higueras-Vaquerias system. It is typified by development of Bathonian-Oxfordian sediments, including evaporites in half graben that have inverted to give intensely deformed, tight folds that ramp up again the western area, which is devoid of incompetent rocks (b). The main controlling faults are east-verging, as seen in (a). The Vaquerias structure (lines d, e, f) is a former half graben that has a thick, Late Jurassic infill and has inverted; in this case, the subbasin shows a flip in polarity of the controlling fault, from east-vergent (d) to west-vergent (e, f), probably a consequence of the original graben morphology. Footwalls of the graben (often present as horst blocks; e.g., on line [a] between Higueras and Los Ramones inversion anticlines) have thin, Late Jurassic and sometimes Cretaceous stratigraphies. Both Vaquerias and Papagayos folds are oriented northwest-southeast. The basement-faulting and basin-inversion events are both of middle Eocene age, since units as young as the Queen City Formation are involved in the deformation and have been eroded; the late Eocene Yegua Formation shows onlap onto and progradation away from the zone of deformation (east of lines [b, c]). Note that the middle Eocene is involved in the Papagayos and Los Ramones folding, giving the timing of these as middle Eocene. Later extensional faulting (e.g., the system affecting the Wilcox Group of Paleocene age) and rotation within fault blocks is most severe where the gradient on the underlying monocline is steepest. These faults also have been rotated by the middle Eocene compressive event. Line (b): Pérez (1992) notes salt-cored folds caused by "Cenozoic loading" (probably end-Cretaceous deformation). He also notes a rapid deepening of the Mesozoic being coincident with an east-verging thrust near well 26 and, to the east of this, gentle folds. Line (c): Paleocene comprises chaotic, undulose reflectors that may indicate unstable paleoslopes, which would have to be due to end-Cretaceous instability. There are also gentle, short-wavelength folds on the eastern limb of the monocline that decouple on evaporites, as well as east-verging thrusts near well 40 (similar to [b] above). Line (e): "...minor asymmetric folds...involve basement and are probably associated with dominant southwest-vergent thrusts within basement" (Pérez, 1992, p. 117); these involve the middle Eocene in their deformation and comprise the Aleman-Camargo-Pobladores complex (north-south oriented). Line (f): Very gentle folds, possibly associated with east-vergent, basement-involved thrusts to the northeast of Vaquerias. Also, the Mesozoic to early Eocene is folded, and the Paleocene and early Eocene are also exposed and eroded.**

Table 3. Age of globorotalid assemblage in the Chicontepec Canal.

Microfossil	*Age range*
Globorotalia wilcoxensis-quertra	P6 – mid P9
G. formosa formosa	Top P6 – Top P8
G. formosa gracilis	Base P6 – Top P7
G. rex	P6 – P9
Overall age of assemblage	Top P6 – P7 (earliest Eocene)

data from Busch and Govela (1978); stages interpreted by M. Simmons

the Monterrey and Rayones areas (De Cserna, 1956; Pérez, 1992; Eguiluz et al., 2000). Evidence of coeval deformation extends at least 100 km eastward. First, there are broad, basement-involved asymmetric anticlines several kilometers long with wavelengths of 12 to 24 km, trending northwest-southeast (Salado, Picachos, San Carlos–Cruillas structures) (Figures 31, 33, and 35; Pérez, 1992). The southwestern flanks of these folds typically are steeper than their northeastern flanks, suggesting southwest-vergent thrusts (Figure 31D,E). Problems of seismic quality mean that fault traces often cannot be resolved directly; consequently, faults often have to be inferred from the geometry of the associated fold (Pérez, personal communication, 2002). Northeast-vergent thrusts only occasionally have been identified; examples can be seen in the Aleman-Camargo-Pobladores area, prior to dips in the Mesozoic stratigraphy flattening out eastward (Figure 31a). This deformation resulted in localized emergence of the Burro-Picachos Peninsula and the San Carlos Island (González, 1976, quoted in Pérez, 1992). The Cenozoic folds are of shorter wavelength than the Jurassic paleohighs on which they are superimposed. For example, compare the Picachos anticline with the Burro-Picachos Peninsula paleohigh (Figures 31B and C).

Tight folds that trend northwest-southeast and decouple in Jurassic evaporites include the Papagayos/Los Ramones anticlines in the Higueras-Vaquerias area located between the frontal ranges of the SMO and the Picachos structure (Figure 31). These are related to inversion of evaporitic infills of Late Jurassic half graben (Pérez, 1992).

The Falcon fault system also developed at this time; this system runs parallel but to the east of the Salado fold for approximately 100 km (Figure 33A–D). It is the only normal fault system in the Burgos Basin to detach in the Jurassic salt (work of González, 1976, and Rivera, 1976, quoted in Pérez, 1992; Alfonso, 1978) (Figure 33e).

Sequence Boundary

In the center-west of the Burgos Basin, a family of gentle folds rotated deltaic sediments of the Queen City Formation, resulting in an unconformity with strong "exposure and erosion" of the front of the delta system, which increased in intensity southward (Pérez, 1992, p. 59) (Figure 31B and C). Younger (Weches Formation) sediments onlap this fold and unconformity.

In the Monterrey sector of the SMO, there was deposition of the syn/postorogenic conglomerates of middle–late Eocene age (Padilla y Sánchez, 1985). In the Cañon Bejuco–La Laja area south of Tampico, the Guayabal Formation (late middle Eocene) onlaps units as old as the Jurassic, indicating the development of a major unconformity. Over Liassic paleohighs, such as in the Tampanas-1 well, erosion appears to have been most severe, although overlying sediments are not notably thicker than in adjacent wells with complete stratigraphy (Carrillo, 1980; Cantú, 2001a; Figures 23C and 34). Outcrop maps also show a major overstep of middle Eocene units onto remnants of early Eocene and Paleocene rocks in the west of the Tampico-Misantla Basin; this unconformity appears to cut down more strongly towards the southeast (Figure 2).

In the Zongolica part of the fold and thrust belt, Paleocene to early Eocene sediments are intimately involved in thrust sheets. Middle Eocene syntectonic conglomerates rest on the incised eastern and northeastern front of the fold and thrust belt (Cruz et al., 1977; Viniegra, 1981). All this stratigraphy was then erosionally truncated, and middle–late Eocene-age conglomerates were deposited in paleodrainage courses cut down into the underlying stratigraphy (Cruz et al., 1977) (Figure 35). To date there is no published evidence of such an event in the Southeast Basin, although recent work to the southwest of Villahermosa indicates that a highly erosive event of about this age may be present (Andrew Jalbert, personal communication, 2002). In addition, deposition in

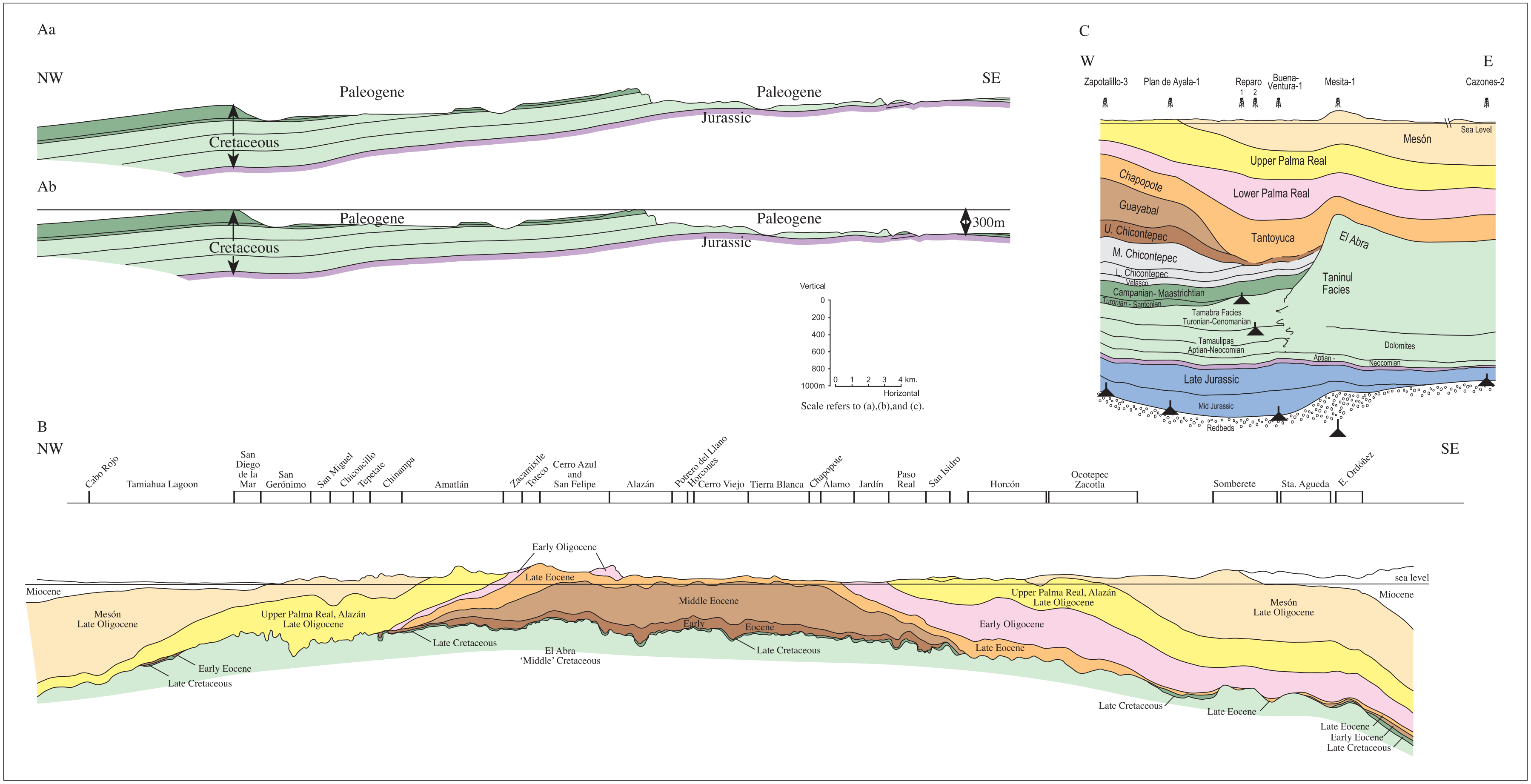


Figure 32. Stratigraphic sections in the vicinity of the Tuxpan platform. (Aa) Relief and erosion of the Mesozoic beneath the Cenozoic in the Chicontepec Canal. Unflattened. Modified after Busch and Govela, 1978. (Ab) As in Aa, but approximately flattened to show paleotopography. (B) Tertiary stratigraphy above the fields of the Golden Lane. Modified after Sotomayor, 1954. (C) Stratigraphy across the margin of the Tuxpan platform. Modified after Coogan et al., 1972. Figure scale refers to (A), (B), and (C).

the Sierra de Chiapas of the El Bosque Formation of middle–late Eocene age comprises as much as 900 m of sandstones and conglomerates (Sánchez and Salmerón, 1996) with a sediment provenance that suggests erosion of basement.

Interpretation

Culmination of the Sierra Madre Oriental orogenesis and formation of the Tampico-Misantla, Burgos, and Veracruz foreland basins is undoubtedly the major event at this time (the ''Hidalgoense'' event of De Cserna, 1956, 1989) in northern Mexico (Eguiluz et al., 2000). A middle–middle Eocene timing is constrained most accurately by the folding and onlap

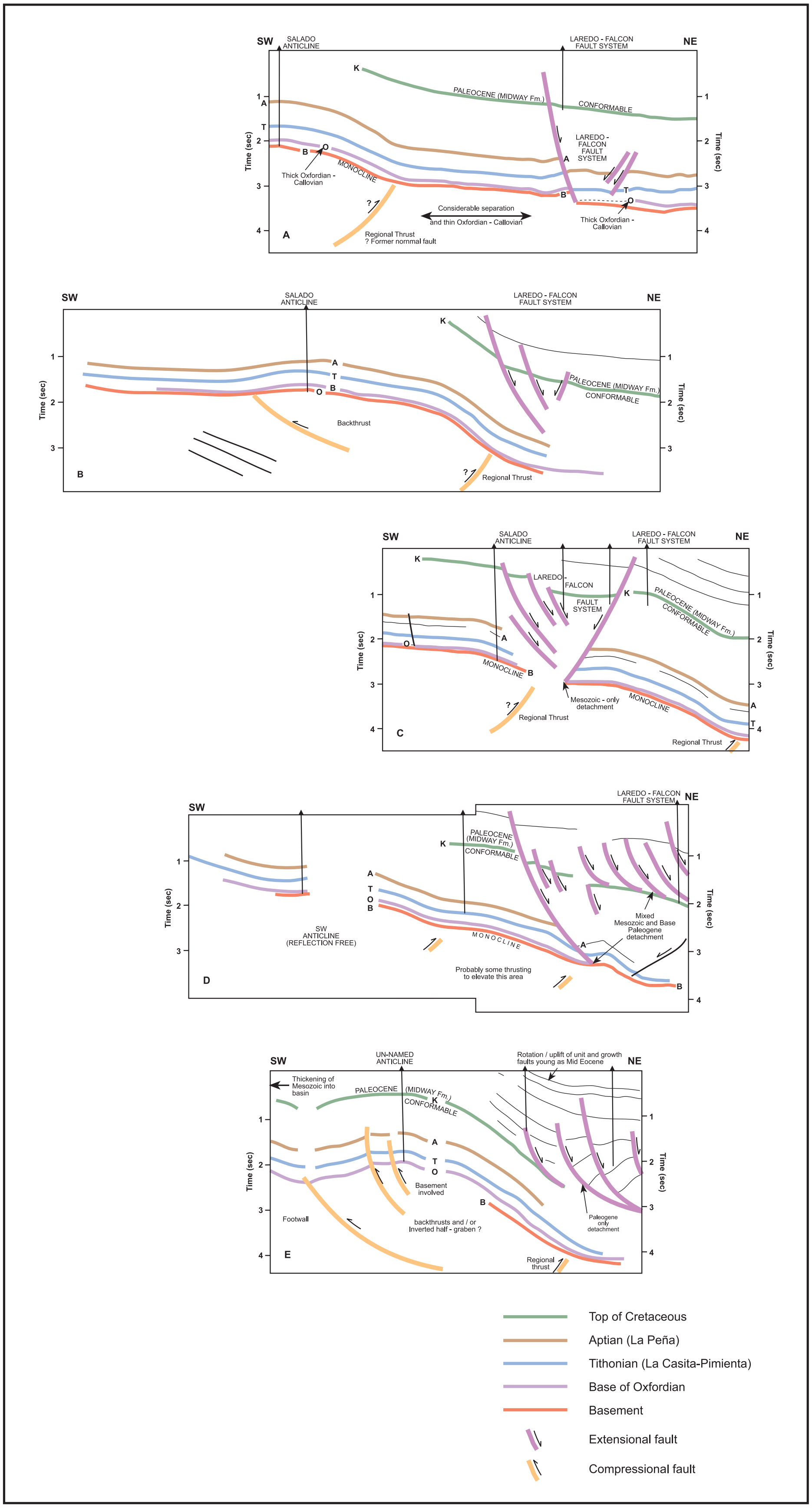


Figure 33. Transects across the northern part of the Burgos Basin. The Salado anticline appears to be a basement-involved structure and has no notable Mesozoic expression; the Paleocene is conformable on the Mesozoic. The main controlling faults that are visible verge to the southwest but must be related to easterly verging master faults that cause the whole system to ramp up. To the south, an unnamed anticline (e) appears to be an inverted half graben. Lines also show the Laredo-Falcon system, detaching downdip to the east of the Salado anticline. It is notable that the two structural systems are widely separated in the north (a) and much closer to overlapping in the south (c, d). To the south (d, e), there is an increase in the degree of normal faulting that soles out onto top-Mesozoic (Wilcox system). In (e), normal faulting is completely dominant; such faulting probably indicates a steeper top-Mesozoic paleoslope. These faults are rotated by the elevation of the Salado anticline and predate the main phase of compression in the middle Miocene. Modified after Pérez (1992), his transects I–V.

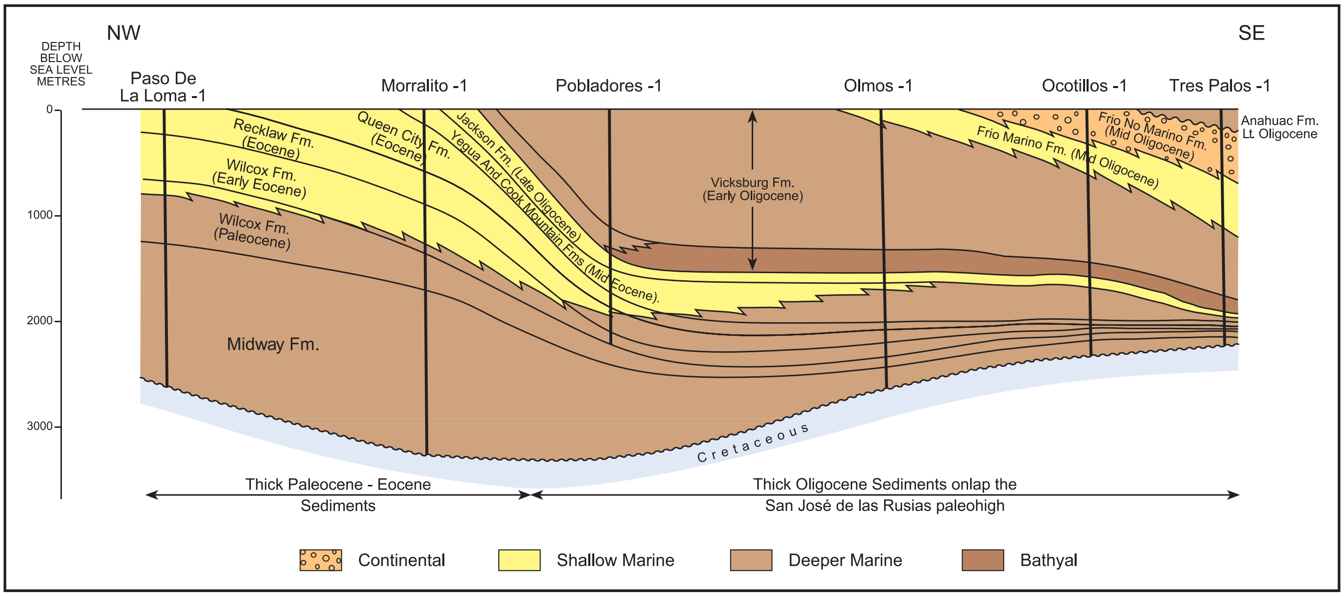


Figure 34. North-south correlation of the Burgos Basin through the Paleogene. Modified after Pérez, 1992.

relationships in the Burgos Basin. The southwest-vergent faults noted by Pérez (1992) as ''controlling'' the western margin of the Burgos Basin must be backthrusts that, in turn, were controlled by deeper, northeast-verging thrusts. Compression of this whole system steepened the overall monoclinal dip of the MOP along the margin of the Burgos Basin, e.g., by elevation of the Salado, El Burro–Picachos, Higueras-Vaquerias, and San Carlos–Cruillas anticlines. Gentle folds in the Aleman-Camargo-Pobladores and Conchos River areas are all probably secondary expressions of monocline steepening. Development of the Falcon fault system has been related to the orogeny by monoclinal tilting and/or input of sediment-provoking collapse of the eastern limb of the Salado monocline, and/or due to salt evacuation (Pérez, 1992). The development of a widespread unconformity and subsequent onlap of the Guayabal Formation in the Tampico-Misantla Basin also suggests major uplift and erosion. In particular, the erosional relationships figured in Carrillo (1980) for the Tampanas-1 well (Figure 23D) are more consistent with inversion of Jurassic basins and erosion of overlying sediment followed by relatively uniform deposition of Guyabal sediment than with pure ''canyoning'' cut and fill processes.

Late Middle Eocene

Background

In the Burgos Basin there was very rapid subsidence. Large volumes of fine clastic sediment were carried in from the west, resulting in progradation of inner-middle neritic sediments of the Crockett/Weches Formations; they are developed to the east of the Sierra de Picachos, Vaquerias, and San Carlos anticlines (Figure 31A, B). At the same time, many down-to-the-basin growth faults were initiated that detach at a depth of approximately 7 km (Pérez, 1992). In the Tampico-Misantla and Veracruz Basins, deeper-shelf shales of the Guayabal Formation are widespread (Sánchez and Salmerón, 1996) (Figure 36). Deposition of Nanchital Formation shales with occasional breccia beds and calcarenites continued in the Southeast Basin.

Sequence Boundary

Easterly overstep of late Eocene units onto remnants of middle Eocene and older units is seen on the northwestern margin of the Tuxpan platform. Late Eocene remnants often sit on top of early Eocene remnants, for example in the area of the Chinampa/Amatlán fields and to the south of the Ezequiel Ordóñez field (Viniegra and Castillo, 1970) (Figure 32B). Off the southwestern side of the platform, late Eocene–age Tantoyuca Formation littoral/shallow-shelf conglomerates, sandstones, and shales with a larger benthic foraminifera biota infill a channel as much as 500-m deep that cuts out middle and some early Eocene stratigraphy (Figure 32c). Westward, a correlative conformity is developed in slope/basinal sediments (Figure 2).

Interpretation

Appearance of littoral facies in the east and deeper-water facies in the west and south of the

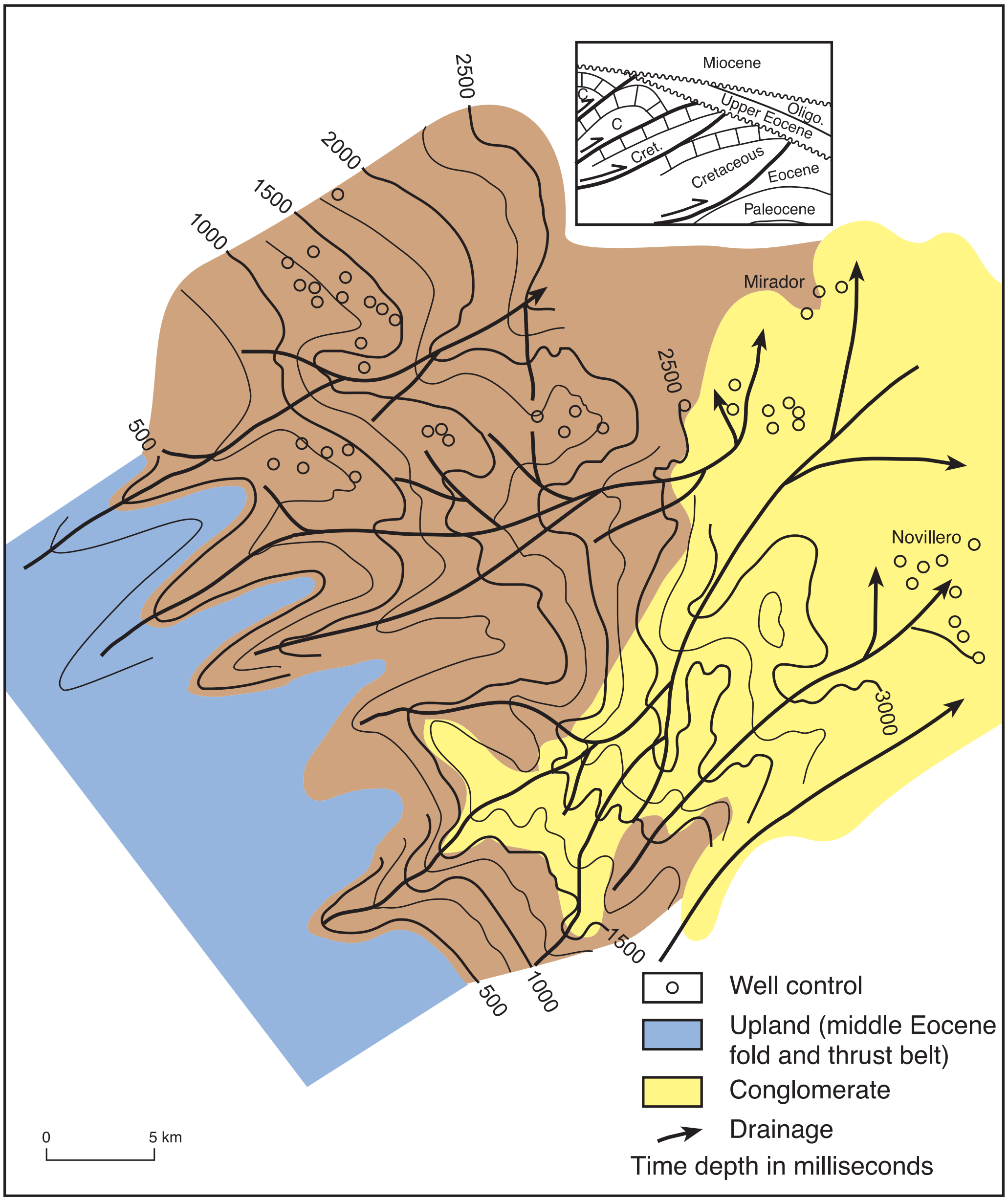


Figure 35. **Middle and late Eocene paleogeography in part of the Veracruz Basin. After Cruz et al., 1977.**

Tampico-Misantla Basin suggests continued uplift to the northeast and possible renewed fluvial incision around the margin of the Tuxpan platform.

Late Eocene to Early Oligocene

Background

Geochemical data (fluid inclusions, fission track analysis, and K/Ar isotopes) indicate that isostatic uplift and unloading of the SMO fold and thrust belt started at about the late Eocene to early Oligocene (Gray et al., 2001). This provided a major source of sediment and resulted in rapid progradation of late Paleogene clastic deposystems. Deposition of the Yegua and Jackson Formations in the Burgos Basin represents a change from paralic to shelf environments of a third-order transgressive systems tract, culminating with the basal Vicksburg Formation upper bathyal shales (Pérez, 1992). As much as 2500 m of Vicksburg Formation is recorded in the Olmos-1, Ocotillos-1, and Tres Palos-1 wells; subsequently, the thick Frío Formation deltaic deposystem prograded into the basin (Hernández, 2000). There is significant growth faulting in these units (Figure 37).

In the Tampico-Misantla Basin, late Eocene paralic to shelf facies of the Tantoyuca Formation are present in the east and locally drape the northwest of the Faja de Oro (Viniegra and Castillo, 1970) (Figure 32B and C). This shelf passes westward into deep-water shale facies of the Chapopote Formation (Figures 32C and 36). It is overlain by deep-water shales of the Horcones Formation and then by the Lower Palma Real turbidite system (Sánchez and Salméron, 1996) (Figure 36) suggesting a maximum-flooding surface at the Eocene–Oligocene boundary. In the Veracruz basin, the Chapopote Formation deep-water shales contain posttectonic conglomerates shed by the fold and thrust belt to the southwest. These pass up into the La Laja Formation deep-water shales (Sánchez and Salmerón, 1996).

In the Southeast Basin, the uppermost deep-water Nanchital Shales of late Eocene age were succeeded by the La Laja Formation shales of early Oligocene

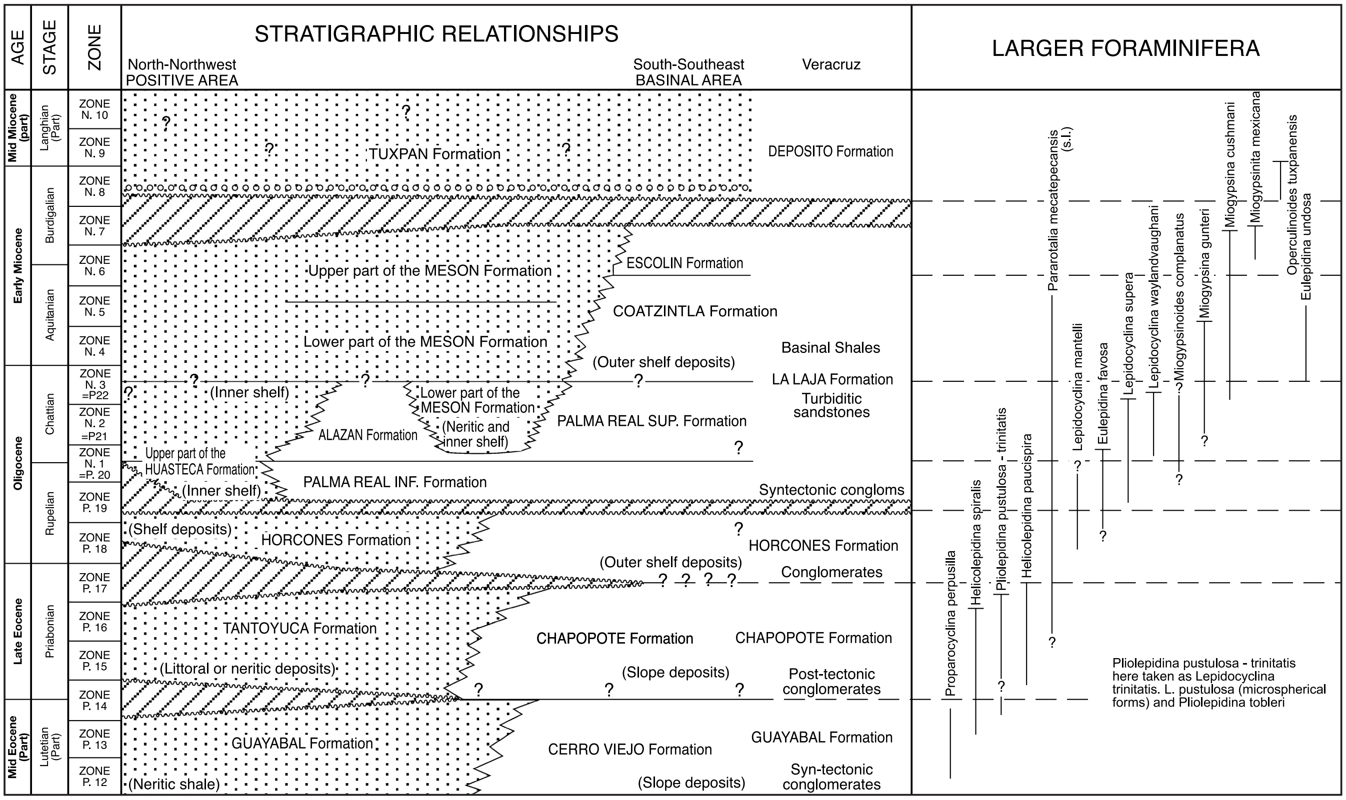


Figure 36. Later Cenozoic-age and facies relationships in the Tampico-Misantla and Veracruz Basins, from north to south. Modified after López (1982), his figure V1-24.

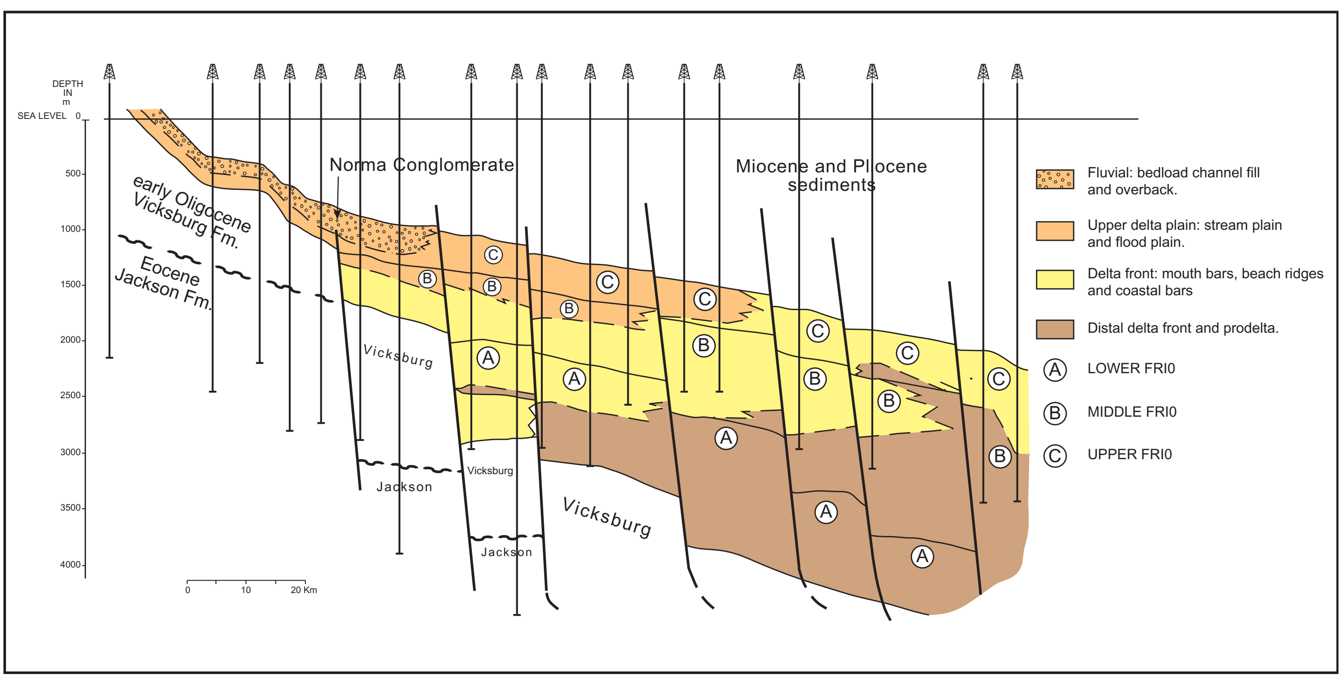


Figure 37. Stratigraphic dip section of the Oligocene across the Burgos Basin. The Norma Conglomerate Formation (as much as 300-m thick) and proximal Frio Formation can be seen to be sitting above a major sequence boundary that truncates the underlying Vicksburg Formation. Modified from Pérez, 1992 (foldout 21) and Hernández, 2000.

age. These are also deep-water, but have a notable appearance of a significant benthic biota (Sánchez and Salméron, 1996). In the Sierra de Chiapas, development of Mompuyial Formation reefs and shelf carbonates, and conglomerates farther to the southeast indicate shallow-water to paralic deposition (Sánchez and Salméron, 1996).

Sequence Boundary

The major break is at the end of the early Oligocene, although two minor end-Eocene (intra- P17 and P18/P19) breaks are recorded in the north and northeast of the Tampico Misantla Basin (Figure 36). In the northwestern part of the Burgos basin, a monoclinal fold deformed Mesozoic and Paleogene units and produced a highly eroded, ''tectonically enhanced'' sequence boundary at 30 Ma (middle Oligocene) (Figure 37) (Pérez, 1992). Outcrop maps show that ''late'' Oligocene onlaps directly onto Late Cretaceous with Eocene and Paleocene units being absent to the northeast of the Sierra de San Carlos and immediately to the east of the Sierra de Tamaulipas (e.g., Figure 2). Erosion is developed southward from the Conchos River (compare Figures 33 and 31 showing the full succession to the north of the river, with Figure 38 to the south; also see Figures 23C and 24). Subsurface data show that early Oligocene, Eocene, and then Paleocene units are progressively cut out eastward in the San José de las Rusias area (partly illustrated in Figures 4 and 32D). Paleogene units only reappear south of the Río Panuco (line A-A′ on Figure 2); the thin Méndez Formation of Campanian age is present again to the east only in the Corvina-1B well (Figure 23B).

Conglomerates frequently rest on the unconformity, e.g., in the Tepehuaje-1 well (partly illustrated in Figure 4). On the tectonically enhanced sequence boundary, on a gentle, east-facing limb of the MOP defining the northwestern Burgos Basin margin, as much as 300 m of alluvial conglomerates of the Norma Formation were deposited (Hernández, 2000). Seismic and well data show that these erode through the Frío Formation and onlap onto pre–late Oligocene units (Figure 37). At the same time, there was

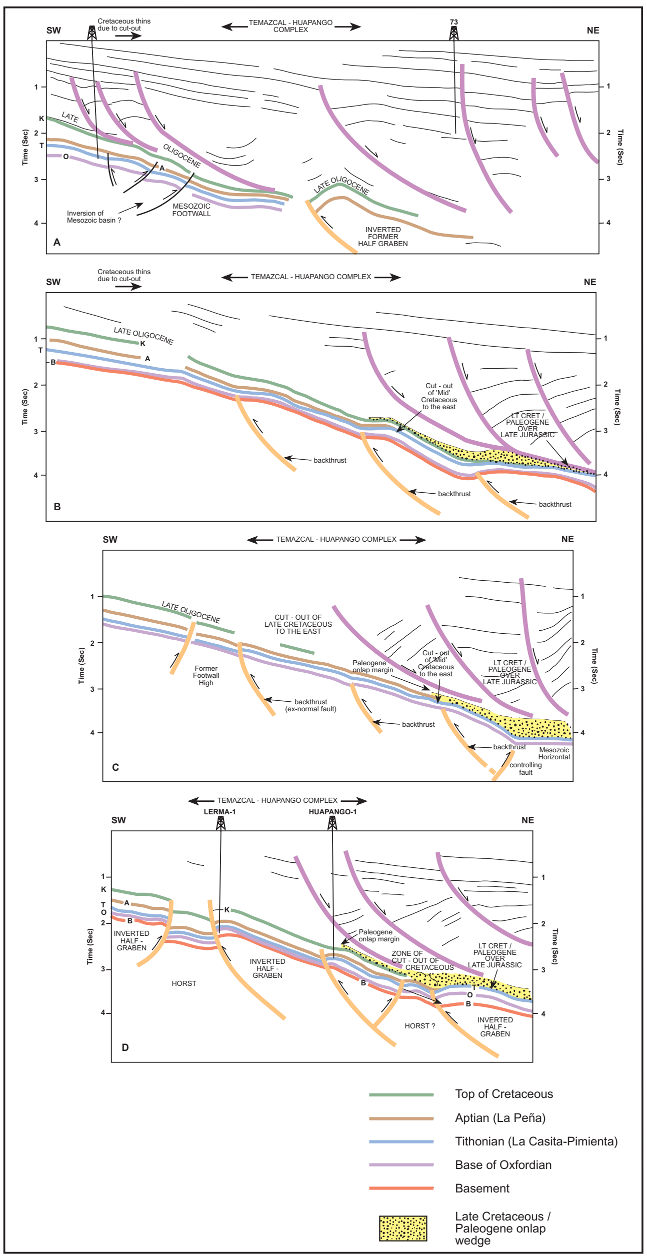


Figure 38. **Transects across the southern part of the Burgos Basin, showing easterly cut-out of the Mesozoic section during pre-Vicksburg times, particularly farther south (b, c, and d). Nearby wells such as Huapango-1 have early Oligocene resting on the Jurassic. Most faults that cut basement are thrusts (Temazcal-Huapango complex)—probably back thrusts that relate to a bigger fault located to the east; cf. Figure 7, but also suggested in (c). There is also inversion of former extensional faults that once threw down toward the Gulf of Mexico (a). Also note the former footwall highs in (c) and horst-like feature(s) seen in (d). Paleocene-Eocene sediments (thought to be reworked, probably in the middle Oligocene) are present in a wedge onlapping eroded Mesozoic to the east of the lines (b, c, and d; also compare to Figures 7a, c and 39). This would suggest uplift of the Mesozoic, followed by subsidence and onlap. Normal faults seed over areas where there is significant loss of Mesozoic section and a significantly steep gradient on the Mesozoic monocline. Modified after Pérez (1992), his transects XV to XVIII.**

down-to-the east tilting in front of the MOP, which resulted in rapid subsidence and initiated growth faulting (Pérez, 1992). In Sabalo-1 well, a core was taken from a conglomerate unit a little more than 100-m thick that sits on the San Andrés Formation (Kimmeridgian). Clasts comprise rounded limestone pebbles of Late Jurassic to Late Cretaceous age, of both basinal and shelf lithologies, including rudist reefal material. A thin shale interbed yielded poorly preserved examples of *Globigerinodes primordius* that has a range of late Oligocene–early Miocene (Juan Rico, personal communication, 2002). A conglomerate sitting at the total depth of the Sardina-1 well is possibly similar; it comprises clasts that are dominantly of igneous basement rock; seismic data show that this conglomerate is from the basal part of the infill of a graben-like feature that extends eastward from Tampico (Figure 5b).

Elsewhere to the northeast of Tampico and sitting unconformably upon the Neocomian, cuttings data indicate the presence of a shale unit 15–50-m thick—the badly named "Méndez Breccia" (Figure 23C)— in which 99% of the Cretaceous fauna comprise loose but badly preserved Campanian–Maastrichtian pelagic foraminifera. These are mixed with loose and also poorly preserved Paleocene, Eocene, Oligocene, and sometimes Miocene planktonic foraminifera. A similar zone of reworked Paleocene/Eocene/Oligocene stratigraphy is present in the Corvina-1B well on the eastern limb of the MOP, sitting directly upon the Méndez Formation and dated as Campanian (Figure 18B). A core from the Erizo-1 well shows at the base of this unit a minor contribution of very well-rounded to angular clasts as much as 2 cm in diameter. These are of exactly the same age as the underlying, truncated Neocomian section; for this reason, Albian to Santonian clasts are absent in the 'Méndez Breccia' because units of these ages do not subcrop in the offshore area (Figures 23B and 24). To the south of Arenque, the Méndez Breccia passes into an interval often as much as 1–2-km thick of reworked loose and very poorly preserved Campanian–Maastrichtian and Paleogene fauna as young as Oligocene in wells such as Abulon-1 and Sabalo-1 (Figure 23C). In this area are many horizons where fauna is reworked from older into younger stratigraphy (Aurelio Garza, personal communication, 2001), although information is from cuttings and significant problems in cavings may compromise data quality. Farther north, Pérez (1992) identified a similar package of Oligocene with "reworked Paleocene-Eocene" onlapping an erosionally truncated Mesozoic-age stratigraphy (of the eastern limb of the MOP) in the San José de las Rusias area; this is seen as a stippled unit in Figure 38.

In the vicinity of Tampico, well and seismic data show eroded remnants of turbidite-fan sandstones (Lower Palma Real Formation) to be present (Trujillo et al., 2000); these are typically overlain by Upper Palma Real Formation basinal shales. Carrillo (1980) notes that the Oligocene–Miocene rests unconformably upon middle–late Eocene sediments in the south of the Cañon Bejuco–La Laja. The offshore Jurel and Lisa-Mantarraya highs both have Oligocene–Miocene stratigraphy that onlaps onto Neocomian stratigraphy (S. Hall, personal observation, 1999). Therefore, the late Oligocene and early Miocene onlaps/oversteps eastward onto the early Oligocene, Eocene, Mesozoic, and then finally basement around Abulon-1 well (González, 1999) (Figure 23c).

The end-early Oligocene break also is particularly well-developed in the south and west of the Tampico-Misantla; in outcrop, sandstones of the Lower Palma Real Formation (zones P19/P20 or N1; Figure 36) are preserved only locally as subcrop below an unconformity. Preservation appears to be controlled by southwest-northeast-oriented lineaments that also control the major rivers (e.g., the rivers Tecolutla, Cazones, and Tuxpan), as the Lower Palma Real Formation is present only on the southeast (?hanging wall) side of these lineaments. (Note: this formation is not identified in Figure 2). On the northern (?footwall) side of the Río Cazones, the Upper Palma Real Formation rests unconformably on the Chapopote Formation or even the Guyabal Formation, and much farther to the south of Poza Rica, the Upper Palma Real Formation may onlap units as old as the Chicontepec Formation (Figure 2).

The maximum-flooding event represented by the Upper Palma Real and Alazán Formations (approximately the top of zone P20 or N1; Figure 36) results in onlap onto the older Paleogene sediments and covers the whole area. As part of an overall easterly onlap, the Upper Palma Real is the final unit to onlap the Tuxpan platform. The upper Palma Real Formation of late Oligocene age directly overlies the Cretaceous to the north of the Chinampa field (Viniegra and Castillo, 1970)(Figure 32b), indicating a major erosional break. Marine sediments of this age also infill karstic cavities in the top of the platform, e.g., in Mozutal-1 well (Viniegra and Castillo, 1970).

In southeastern Mexico, the middle Oligocene marks the onset of large-scale, coarse clastic input into the basin, which, in turn, led to salt mobilization (Angeles et al., 1994).

A mixed alkaline to calc-alkaline magmatic suite was emplaced along a 1400-km zone extending between the southwestern Texas and the Sierra de Tamaulipas and has also been encountered in wells in the San José de las Rusias area (Figure 4). Stocks, laccoliths, and dikes are in contact with Aptian to late Eocene units, suggesting that the activity is post–late Eocene. Radiometric dates have been obtained of 28.8 (± 0.6) Ma (early–late Oligocene) (Bloomfield and Cepeda, 1973).

Interpretation

The middle Oligocene event resulted in renewed uplift of the western and southern margin of the Burgos Basin and the Tamaulipas High (Pérez, 1992); at the same time, the southeastern portion of the Tampico–Misantla Basin also was uplifted. Basement-involved west-southwest-vergent (back)-thrusting appears to have caused much of the uplift in the onshore area (San José de las Rusias Basin). Strong inversion of Mesozoic half-graben occurred in both the San José de las Rusias (Figure 38A–D) and the offshore Jurel and Lisa-Mantarraya areas, although precise dating of this event is difficult when there is much stratigraphy missing below the onlap (Pérez, 1992).

There is considerable evidence of conglomerates being shed eastward into basins (e.g., the Norma and Tepehuaje conglomerates and possibly the conglomerate in the Sabalo-1 well). Clast compositions in the Sabalo-1 conglomerate, which have cobbles of Cretaceous shelf and reefal carbonates as well as the presence of a late Oligocene–early Miocene fauna, indicate that deposition had to be late Oligocene, because by the end of the late Oligocene, the Tuxpan platform was covered by sediment and would not have been able to supply the clasts. The depositional setting of the Sabalo-1 conglomerate is not well understood; features such as the massive bedding and approximately a hundred meters of thickness argue against a deep-marine (or even submarine) origin, although rare interbedded shales have a pelagic biota. The Méndez Breccia in offshore Tampico is also difficult to interpret. Since clasts are exclusively of the same age as the underlying Neocomian basinal carbonates, there is clearly little reworking of deep stratigraphy. This is significant because it argues against a ''mass transport'' origin for the unit, or the unit being a direct product of erosion of the surface it sits on. It is significant that all the microfossils are very poorly preserved and normally are associated with sediments that would have disaggregated easily. For this reason, we suggest that the Méndez Breccia represents fines material derived from the rising Sierra Madre Oriental and transported eastward. The depocenter to the south of the Río Panuco then could have funneled sediment into the Abulon-Sabalo area, but only when regional dip had flipped to the east.

The alkaline igneous units have been related to the development of the ''Rio Grande Rift'' (Falcon fault system) (Bloomfield and Cepeda, 1973). It is more likely that both these features are related and are aligned to the rising MOP. Normal faulting (''rifting'' of Bloomfield and Cepeda, 1973) was a consequence of gravity sliding of Paleogene, Cretaceous, and late Jurassic sediments off the southeastern flank of the rising MOP; at the same time, igneous activity probably made use of the deep faults that controlled the uplift.

Late Oligocene–middle Miocene

Background

A major flooding event initially drowned topography associated with the middle Oligocene uplift. Across the whole basin, clastic shelf systems appear to have become established rapidly and were strongly progradational.

In the Burgos Basin, the Anahuac Formation represents renewed deep-water deposition (Hernández, 2000). In the Tampico and Poza Rica area, initial deposition was of the deep-water shales of the Palma Real Superior and Alazan Formation, followed by the Mesón Formation, which represents easterly progradation of inner-shelf environments with larger benthic foraminifera over bathyal environments. As a consequence, siliciclastic shelves were being established in the Tampico area as early as the late Oligocene (López, 1982; Trujillo et al., 2000) (Figure 36). Along southern Tamaulipas and northern/central Veracruz, Cenozoic sediments become involved in easterly-dipping normal faulting as progradation for the first time crossed the MOP. These and similar faults in the Burgos Basin all detached in the shales at the base of this sequence (Pérez, 1992). Faults steepened to the east, and rotation of individual blocks was controlled by the dip of the underlying units (Figure 8). Counterregional growth faults resulted in development of Oligocene and Miocene minibasins (Pérez, 1992).

In the Southeast Basin, elevation of shale diapirs and salt domes resulted in erosion of the middle–late Oligocene sediment (Angeles et al., 1994), and localized seeding of atoll-like carbonate platforms of

Oligocene–Miocene age (Macuspana Limestone Formation). Extension began in the Macuspana Basin in the Oligocene, with a major down-to-the-northwest controlling fault on the southeastern side of the basin (Miranda et al., 1999; Ambrose et al., 2001). Younger sediments of Burdigalian–Langhian age comprise shales with thin, interbedded sandstones deposited in an open-marine, outer-shelf setting (Miranda et al., 1999).

Sequence Boundary

Two slightly separated events are recognized in this interval. In the Tampico-Misantla Basin there is a regional disconformity of intra–early Miocene age, over which the Tuxpan Formation (upper N8 and younger) rests on top of the Meson and Escolin Formations (N7 at their top). This break shows a subtle increase toward the east and north (Figure 36).

In the Southeast Basin, the ''Chiapaneco'' event (Quezada-Muñeton, 1990) is of early middle Miocene age (Serravalian; 12.5 Ma); this marks the onset of development of major compressive structures in the Southeast Basin and the Chiapas fold and thrust belt (Angeles et al., 1994; Miranda, 1997). Structures comprise folds bounded by thrusts that strike northwest-southeast; structures are often offset by southwest-northeast-oriented lateral ramps (Angeles et al., 1994). This event resulted locally in uplift and erosion of sediment over large areas of offshore Campeche (Angeles et al., 1994). Onshore, the northern margin of the Artesa–Mundo Nuevo platform was very heavily karstified and brecciated (Figure 21D), to the extent that Miocene rocks may rest directly upon the those of Albian-Cenomanian age (Williams, 2001). Farther to the southeast, the Nanchital Conglomerate marks the onset of local uplift and erosion and was deposited in a deep-water environment (Sánchez and Salméron, 1996); similar erosion is noted in the southwest of the Macuspana Basin (Carrillo, 1980; Miranda et al., 1999). In the Veracruz Basin, evidence of the same pre-middle-Miocene event is present. Middle-Miocene-aged sediment (variously attributed to the La Laja or Deposito Formations; Viniegra, 1965; Cruz et al., 1977; López, 1982) sits with strong unconformity on top of rocks as old as Cretaceous in age (Cruz et al., 1977). In this case, conglomerates were shed by the rising fold and thrust belt and transported down large channels into bathyal deep-water fans now represented in the Viente and Mirador fields (Cruz et al., 1977). Tardy (1980) also identified evidence of orogenesis in the SMO, expressed as a set of broad anticlines with a strike of 150° between Torreon and Saltillo in Coahuila to which he could assign only a broad Miocene age.

Interpretation

It was during the early–middle Miocene that major compressive thin- and thick-skinned structures and major unconformity development occurred in southeastern Mexico (Angeles et al., 1994). The plate-tectonic events that controlled this comprise (1) left-lateral movements of the Motagua-Polochic fault system (Burkhart, 1983); (2) a dynamic metamorphic event along the Tonalá-Motozointla fault, located on the southwestern side of the Chiapas massif (Angeles et al., 1994); and (3) left-lateral movements along the detachment faults that throw down from the Sierra de Chiapas (Sánchez, 1979). The sum of these movements plus northeast-directed subduction of the Cocos plate resulted in generation of oblique compression toward the northeast, where the initial thick-skinned compression was transferred to thin-skinned compression as a result of detachment in the autochthonous Isthmian Salt. Development of lateral ramps may be due, in part, to reactivation of the original Jurassic extensional fault system. Cenozoic extensional basins, such as the southern part of Macuspana, suffered a period of inversion, which was strongest along east-west faults (Miranda et al., 1999).

There was some compressional influence farther north, as indicated by Tardy's (1980) data as well as the intra–early Miocene unconformities, but these are minor in comparison to the deformation seen farther south.

Middle Miocene–Holocene

Background

The onshore part of the Burgos, Veracruz, Tampico-Misantla, and Southeastern Basins near the Sierra Madre Oriental and Sierra de Chiapas underwent uplift, giving a regional homoclinal dip toward the Gulf of Mexico. This uplift also provided an abundant source of sediment, to the extent that coastal areas prograded steadily eastward, which, in turn, resulted in development of a very thick sediment wedge in the offshore of Tamaulipas and Veracruz. In the Southeast Basin, middle Miocene sediments comprise outer-mid-shelf sediments; by the late Miocene, deposition was of delta front/lagoonal or inner-mid-shelf mixed carbonate/clastic facies sourced from the Yucatán margin. From the early Pliocene to the Holocene, inner-shelf and fluvial environments had become established. As such, coarse siliciclastic slope to deltaic and coastal plain systems entered the Reforma-Akal subbasin for the first time (Angeles et al., 1994).

Deposition was accompanied by continued development of listric normal faults; in the Southeast Basin, these are middle–late Miocene in age and detach on middle Miocene shales (Angeles et al., 1994). In the Macuspana Basin, extension along the eastern margin resulted in development of nested listric faults that throw down to the northwest (Miranda et al., 1999; Ambrose et al., 2001). As a result, the late Miocene and then the Pliocene onlap/downlap a paleohigh to the southwest in the Sierra de Chiapas area, so that the youngest units often rest on the very oldest (Miranda et al., 1999). In the early Pliocene, listric faults throwing to the southeast developed along the western margin (Ambrose et al., 2001).

Volcanic activity increased in the late Neogene with basaltic extrusion and some intrusion along the Trans-Mexican Volcanic Belt, which reaches the Gulf Coast just north of Veracruz at Laguna Verde and extends some distance offshore (López, 1982). Alkaline volcanics of Miocene–Pliocene age are present in the San José de las Rusias and parts of the Tampico-Misantla Basins (Bloomfield and Cepeda, 1973).

The Neogene of the deeper offshore areas is not considered in this paper, since active exploration efforts have been presented so far only in provisional form at conferences. Most data relate to the extensional top-of-slope and compressional toe-of-slope systems (e.g., Brito et al., 1999; Rodríguez et al., 2000).

Interpretation

Continuing uplift in most of the coastal areas is probably due to regional epeirogeny, analogous to a similar style of uplift in the southern cordillera in the United States (Chapin, 1979; Dickinson, 1981; Galloway, 1989). In Mexico, this is likely to be a relict expression of isostatic uplift of the Sierra Madre Oriental, which started in the late Eocene (Gray et al., 2001).

DISCUSSION

Subaerial Versus Submarine Erosion

Submarine Erosion

A key element of the historical interpretation of many erosional events along the Gulf Coast of Mexico is that young deep-water sediments directly overlie older deep-water sediments, and these all dip into the Gulf of Mexico basin. This was the not-unreasonable foundation for interpretation of most of these features as submarine (e.g., Carrillo, 1980). However, several assumptions in this model need to be examined. First, it is assumed that the present-day dip is a paleodip, which is not the case. Westerly dip was present as late as the middle Oligocene, as indicated by easterly onlap of Paleogene sediments onto the Tuxpan platform (Viniegra and Castillo, 1970; Coogan et al., 1972) and the present easterly tilt of a paleo oil-water contact in the Arenque oil field (Horbury et al., 1996). Even Carrillo (1980) shows uplift in the offshore Veracruz and Tamaulipas areas during the Eocene and Oligocene, which is the timing of his major "paleocanyon" development.

Second, canyon geometries have been inferred, when the actual geometry may be partly an artifact of how the data is hung when stratigraphic sections are prepared; the Chicontepec Paleocanyon was identified after the data was hung on a combination of Horizon C in the Eocene stratigraphy and extrapolations from the top-Méndez Formation (Busch and Govela, 1978). However, in many cases these paleocanyons correspond closely to axes of uplift and erosion followed by more-or-less sheetlike deposition; both the Tampanas-1 well in the upper part of the Bejuco-La Laja canyon (Carrillo, 1980) (Figure 23D) and the San Andrés Paleocanyon (Busch and Govela, 1978) (Figure 32A) are good examples. Orientation of the Chicontepec Paleocanyon parallel to basin strike is also difficult to explain by conventional models, whereas an eroded paleo-anticlinal crest can be fitted more reasonably into such an orientation.

Third, there is an assumption that canyons can strip off sediment along a 400 × 50 km (or greater) area. Typical submarine channels and shelf-margin channels are not capable of such erosion; known channels are approximately 10 km wide by 100 km long, with widths of a few kilometers and depths of a few hundreds of meters to 1 kilometer; in addition, younger canyons are located generally over the positions of older canyons (Steve Cossey, personal communication, 2002). The bulk of modern canyons are in clastic-shelf settings and are usually in front of rivers, where spacings are controlled by entry points of fluvial systems (Kuenen, 1963). Canyons may be the result of shelf-edge collapse (Steve Cossey, personal communication, 2002), which would also be expected in areas of highest sediment input. With respect to these controls, there are no published examples of submarine paleocanyons in Mexico where we would most expect them, for example in front of the Burgos Basin delta, and in front of slope systems in the Southeast Basin. It is, in fact, unusual that most of Carrillo's channels occur in areas of slowest and most condensed sedimentation (i.e., on paleohighs). Submarine channels and shelf-margin channels (in the sense of clastic systems) do not exist in carbonate environments; because of the early lithified nature of most carbonate depositional environments, there are neither point-sourced sediment supply nor inherent problems in slope stability. For example, in offshore Florida and the Bahamas, 90° (escarpment) slopes are maintained locally down to depths of several kilometers (Schlager et al., 1984). There are very few examples of paleocanyons in carbonates, one of which is the Helez paleocanyon in Israel, which is more than 1.5 km deep (Cohen, 1976), although paleocanyons initiated in clastics may cut down into carbonates, e.g., the Lagoa Parda paleocanyon in Brazil, which is more than 1 km deep and cuts into Cretaceous carbonates (Cosmo et al., 1991). In neither case do the geometries of these paleocanyons approach the scale of the feature observed at offshore Tampico and described as a channel by Carrillo (1980) from the Tamaulipas-Constituciones and Arenque areas.

Subaerial Erosion

In carbonate depositional environments, typical indicators of subaerial exposure are "paleosol" fabrics (e.g., Esteban and Klappa, 1983). However, these are developed only where there is subaerial hiatus; they are lost when there is significant erosion, which is the case here. Where there is more active erosion and dissolution, karstic fabrics (e.g., Loucks, 1999) are usually developed. Direct evidence of the karstification related to major lowstands of as much as 1 km or more is seen easily in the geology of the Tuxpan platform, as well as within other platform systems and even karstic fabrics in basinal carbonates in the Southeast Basin. Direct evidence of karst in the offshore Tampico area is more difficult to demonstrate; true karstic fabrics are often not apparent in the few cores taken through the basinal sediments, although karstic systems admittedly are notoriously "hit and miss." The Neocomian sediments beneath the major end-Santonian break are often unusually microporous (e.g., in the Nayade-1 well and in the Tamaulipas Constituciones field) (Horbury, personal observation). Chalky porosity may be caused by long-term emergence, as is development of microporosity in Thamama Formation (Early Cretaceous) reservoirs in Abu Dhabi and Saudi Arabia (Budd, 1989). Rapid uplift may have favored physical erosion over chemical processes such as those involved in the development of mature karstic systems.

Entry of clastic sediments, particularly in carbonate basins, almost certainly requires some form of subaerial exposure of the basin margin. This is particularly true along the ECM when clastic systems are clearly sourced from the east, as where the Eocene-age part of the Chicontepec Formation, and the Tantoyuca Formation, pass westward into deep-water shales. Carrillo (1980) also suggests that fluvial processes may have had a major role in the erosion (if not the infill) of the features he describes.

Identification of Sequence Boundaries as Major Tectono-stratigraphic Events

Many workers note or imply that the later Mesozoic and early Paleogene history of the Gulf of Mexico basin is relatively passive (e.g., Enos, 1983; Salvador, 1991; Galloway et al., 1991) which is true for the U.S. and Yucatán margins. However, pure "Vailian-type" eustatic mechanisms of sequence development and normal passive-margin sedimentary processes have insufficient amplitude of sea-level change, or are too slow, to explain the whole range of observed stratigraphic features, their geometries, and scale of development.

Features that we take to indicate tectono-stratigraphic reorganization of the basin include (1) major erosional unconformities, (2) shelf systems present in basin center settings that would have been hundreds of meters deep, (3) sequence boundaries developed on slope and basinal sediments, (4) sudden appearance of coarse clastic sediment in carbonate systems, (5) development of paleohighs that then show long-lived onlap, (6) significant switches in input directions of clastic sedimentary systems, and (7) association of events with igneous rocks. In addition, initiation and drowning of carbonate platforms may be, in part, a result of such reorganization.

The following events we consider to be strong evidence for active changes in base level as a result of tectonic forcing:

- In the Jurassic: Hettangian, late Pliensbachian–early Aalenian, mid Bathonian, end-Oxfordian, middle- and end-Kimmeridgian, and end-Tithonian events.
- In the Cretaceous: middle Cenomanian, end-Santonian, and end-Maastrichtian events.
- In the Paleogene: latest Paleocene, early–middle Eocene, middle Oligocene, and early–middle Miocene events.

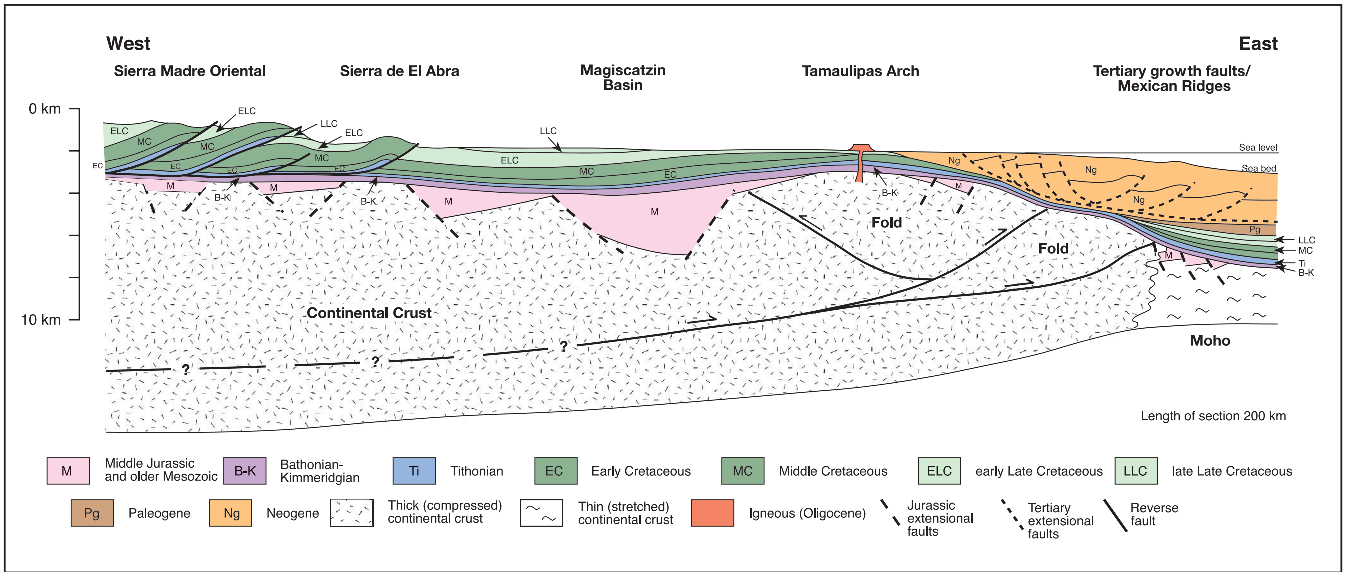


Figure 39. **West-east cross section through the Tampico area, showing the geometry of the inner, Sierra Madre Oriental deformation and the presence of a second, outer zone of deformation expressed as monoclinal folding at the edge of thick continental crust. The outer zone controls many of the sequence boundaries discussed in this paper.**

- Minor events include: end-Callovian, middle Oxfordian, middle Aptian, middle Paleocene, and intra–late Eocene events.

Data quality and the large scale of the subject matter means that while some events and phenomena are well understood, others remain less certain and require further work, for example the precise origin of the Tamabra Formation of Poza Rica and the significance of its meteoric diagenesis. In addition, the role of complete Gulf of Mexico evaporitic drawdown, as proposed by Wilson (1993, 2003) needs to be further examined as a possible cause of at least some of the major sea-level falls as observed in the Mexican data presented here.

Origin of Large-scale Deformation Events

We propose that active Pacific plate-margin processes in western Mexico resulted in an "Andean" style of plate-margin deformation that translated laterally into the western part of the Gulf of Mexico basin rather than onto stable continental crust. As a result, strong regional and local uplift, folding, tilting, and erosion are noted along the Gulf Coast, particularly in association with the MOP (Figure 5A). Only one degree of tilting on the western limb 200 km long (as in Figure 39) would result in 3.5 km of uplift on this broad-wavelength structure. Figure 24 suggests a typical pre–late Oligocene configuration with gentle westerly dip in the underlying strata.

Early–Middle and some Late Jurassic deformation appears to have been related to sinistral strike-slip along the Mojave-Sonora megashear and, ultimately, connected to sinistral movement along the Pacific margin of North America (Anderson and Schmidt, 1983; Pindell and Kennan, 2001). Late Jurassic processes also relate to the onset of the opening of the Central Atlantic and Yucatán rotation during the Bathonian; in the Oxfordian-Kimmeridgian most of Mexico was in a transtensional to back-arc setting (Pindell and Kennan, 2001). The passage of Yucatán along the ECM provides another source of shear, in this case dextral; it is notable that evidence of deformation ceases for a period once Yucatán comes to rest. Typical responses are local inversion of Middle Jurassic and older half-graben, e.g., in the Jurel area. Basement highs, by contrast, are affected only by chance development of thick-skinned deformation, e.g., easterly verging faults at the end of the Kimmeridgian that cut basement in the Arenque area, and otherwise respond to regional uplift. Such processes may require more direct compression than simple shear. Other possible responses include onset of halite deposition in the Gulf of Mexico in response to mild orogenesis, e.g., in the Teziutlán area, thereby restricting the marine connection to the Pacific (Imlay et al., 1948).

Later Jurassic uplift and erosion along the ECM can be correlated with evidence of mild orogenesis along the Pacific margin (Erben, 1956b), itself marked by development of greenschist-grade metamorphism (159–145 Ma), major uplift resulting in unconformities, erosion down into basement gneiss, and development of base-Neocomian conglomerates (Meneses et al., 1994). Late Jurassic orogenesis is thought to be related to an eastward shift in the location of the Pacific margin volcanic arc system, as evidenced by the development of altered, slightly metamorphic andesite-dacite pillow lavas, tuffs, and agglomerates interbedded with sandstones, limestones, and shales containing a Tithonian ammonite fauna, at Ixtapan de la Sal approximately 90 km southwest of Mexico City (Campa et al., 1974). This event resulted in thermal uplift and crustal thickening (Vélez, 1990; Meneses et al., 1994). Indeed, it is hard to see how such an event could fail to have an impact on the Gulf of Mexico margin. Back-arc extension lasted until the end of the Cretaceous in western Mexico (Pindell and Kennan, 2001).

The Pacific margin flipped from being sinistral to dextral during the Aptian because of strong westward plate acceleration at this time, initiating the "Sevier" orogenesis along the entire western margin of the Americas, including Mexico (Pindell and Kennan, 2001). At the same time, the Kula/Caribbean intra-oceanic spreading center developed tangentially to the Pacific coast of Mexico (Pindell and Kennan, 2001); this was to catalyze breakup of the Pacific continental margin. The first widespread compressional event on the Gulf margin caused the development of the major middle-Cenomanian unconformity, the breakup of the large platform systems, and deposition of the Tamabra Formation reefs, although the development of the Cupidito lowstand wedge could have been a precursor. This is accompanied by uplift, with exposure and erosion not only of the Albian–Cenomanian platforms but also of older rocks, including basement metamorphics in the Taxco area (De Cserna et al., 1978). There was also intrusion of granites and metamorphism, as well as elevation of the magmatic arc above sea level for the first time (Meneses et al., 1994; Schaaf et al., 1995). Onset of flyschoid clastic deposition (Mexcala and Yucunama Formations) began in southwestern Mexico in the late Cenomanian (Meneses et al., 1994; Hernández et al., 1997; Aguilera et al., 2001). Sedlock et al. (1993) and Pindell and Kennan (2001) suggest that by the Campanian, the northwest migration of Baja California had begun, as well as the southeast migration of Chortis. This must have resulted in shortening of the distance between the Pacific margin and Gulf of Mexico. By the end of the Cretaceous, the Pacific subduction margin had changed from being one of tangential to one of perpendicular collision (Pindell and Kennan, 2001), again making for more effective transmittal of stress toward the east. This may explain why many authors working on a variety of basins across Mexico, including De Cserna (1989) and Meneses et al. (1994), suggest that that compressional deformation started as a western zone in the late Cenomanian and propagated eastward. Deformation became more thick-skinned through time and culminated in the Sierra Madre Oriental event of middle Eocene age. We would argue that, from the outset, there was an immediate and direct impact on the MOP by a deeper, thick-skinned component; the major Cretaceous break in the MOP appears to be end-Santonian, with a lower-intensity event at the end of the Cretaceous. In the Paleogene, the MOP was a site of both erosion (e.g., the Cañon Bejuco–La Laja; Carrillo, 1980) as well as onlap onto its flanks (Figures 2 and 23C), such that unconformities tended to increase in magnitude toward the hinge line of the MOP (e.g., Figure 36). The uplifted MOP acted as a sediment source area in the Paleogene, for example, for the early Eocene portion of the Chicontepec Formation and also for the late Eocene Tantoyuca Formation.

Thick-skinned deformation reached a climax in the middle Eocene and resulted in formation of the Sierra Madre Oriental fold and thrust belt (Figure 39) (Eguiluz et al., 2000). De Cserna (1989) showed that the orogenic events that affected the Sierra Madre Oriental have much in common with, and may have the same origin as, age-equivalent events (Sevier and Laramide orogenies of Campanian–early Eocene age) in the southwestern and northeastern Rocky Mountains (as described by Cross, 1986). The Sevier orogeny ended in the Late Cretaceous, and was primarily involved with thin-skin folding and thrusting of Paleozoic and Mesozoic rocks over relatively undeformed Precambrian basement. The Laramide orogeny (generally to the northeast of Sevier orogenic structures) involved thrust-bound basement uplifts and basement-involved asymmetric anticlines. It is attributed to the onset of subduction of the Farallon plate beneath North America in the middle Eocene, which is analogous to processes occurring at present in the Andean subduction zone (Dewey and Bird, 1970; Suárez et al., 1983). Middle Oligocene uplift and erosion may be largely a reactivation of the middle Eocene event, the last and most "outboard" expression of the Sierra Madre Oriental deformation. The Chiapaneco event of the middle Miocene relates to the movement and maximum shortening in the

Chortis block as it traveled southeast and cleared the Yucatán promontory (Pindell and Kennan, 2001).

Controls on Small-scale Deformation

Studies of individual basins generally have looked to subregional mechanisms to explain the association of erosion and uplift. Pérez (1992) supposed that uplift in the Burgos Basin could be due to several factors, namely, basement (made buoyant as a result of Mesozoic and/or Cenozoic granite intrusion), flexural uplift along the margin of a Cenozoic depocenter (isostatic loading effects), epeirogenic uplift, inversion of older basins of Jurassic age, or simple horizontal compression. Although all of these mechanisms have validity, we suggest that each basin along the Gulf Coast now can be considered with respect to both the Sierra Madre Oriental and the MOP deformation. In simple terms, the Burgos, Veracruz, Southeastern and deep-water Gulf of Mexico Basins have similar characteristics; they largely sit in front of the MOP and show propagation of thin-skinned deformation that originates on the front of the MOP. The Tamaulipas Arch and areas of offshore Tampico and northern Veracruz, passing into the Jalapa/Santa Ana Uplift and possibly the Chiapas Massif, represent the hinge line of the MOP, on which there was strong regional elevation and local inversion of older Mesozoic basins at different times. The western flank of the MOP is best illustrated by the basin systems developed between Poza Rica and Tampico; this flank shows less evidence of inversion and regional uplift than seen to the east. Crossing the MOP and the Sierra Madre Oriental are zones of west-southwest–north-northeast-oriented dislocation (e.g., along the Conchos River and bounding the San Carlos Island to the north) that probably served as transfer faults. Wilson (1990) recognized such orientations in the Poza Rica area and noted that they are probably related to variations in pre-Jurassic basement type. They divide the MOP into zones with slightly different responses to compression, e.g., the Tamaulipas High versus the Ebano-Panuco area to the south of the Río Panuco lineament (line A-A′ in Figure 2). Deformation events, then, had different expressions, dependent on local geology. For example, the Corvina-Arenque-Jurel area (1) suffered major basin inversion in the ?Bathonian, (2) suffered basin inversion and possible regional uplift at the end of the Oxfordian and middle Kimmeridgian, (3) was locally thrust-uplifted and suffered local basin inversion again at the end of the Kimmeridgian, (4) suffered local basin inversion again at the end of the Tithonian, and (5) subsequently had major regional uplift and erosion at the end of the Santonian (and possibly Maastrichtian). The area was then regionally re-uplifted prior to tilting to the east and final flooding, possibly during the late Paleocene and middle Eocene and certainly during the middle Oligocene. With each event, unconformities and condensed stratigraphies developed.

Salt Basins

In the salt basins, compression was not expressed by deep-seated, thick-skinned intrabasinal compression, but rather by thick-skinned compression of the basin margins. This resulted in long-distance, thin-skinned propagation of folds and thrusts that detach on salt, which led, in turn, to development and later erosion of small, subaerially emergent paleohighs and local seeding of carbonate platforms. Sometimes salt mobilization (evacuation) associated with increased input of clastics into the basin accelerated growth faulting (Pérez, 1992), but sediment input and salt mobilization were dependent on external forcing and probably were not the sole initiators of growth faulting. This is because growth faults occur in many areas without underlying salt; in such areas, growth faults are already documented as being related to increases in dip gradient of the Mesozoic (Pérez, 1992). It often appears that new families of growth faults were initiated in front of the folded zone for each phase of compression on the salt basin margins. These extensional structures often detach in shales rather than salt. Stacked, normal, listric-fault systems often developed in this way. For example, in Burgos basin margin folding/tilting occurred at the end of the Cretaceous, during the middle Eocene, middle Oligocene, and Miocene; each event is associated with development of a slightly younger, outboard normal-fault system (see Figure 7). Mobilization of the salt itself then caused development of a host of other features (e.g., Pérez, 1992).

Cenozoic compressive deformation on the Gulf of Mexico Basin floor has been related to a relatively passive-margin structural setting, with deformation a result of both salt tectonics and sediment loading/gravity tectonics, as is true for the U.S. Gulf of Mexico. This is the case for both the Mexican Ridges (Buffler et al., 1979) and Perdido Foldbelt (Blickwede and Queffelec, 1988). However, the evidence for lateral compression and periodic tilting of the Mesozoic homocline may be an additional factor in initiation of these structures, since deformation has been shown to be related to initiation of the updip extensional systems to these compressive systems.

One consequence of this work is to recognize that the Veracruz Basin has much more in common tectono-stratigraphically with the salt basins to the southeast than it does with the Eastern Mesozoic Basin. This supports Viniegra's (1981) view that this is essentially a salt basin at depth, and it is further supported by the work of Imlay et al. (1948), who show salt springs beneath the Papaloapan fold and thrust belt.

Economic Implications

Juxtaposition of Pacific margin tectonics and Gulf of Mexico (Tethyan) stratigraphy has had enormous implications for the development of hydrocarbon systems.

Reservoir

''Highland'' karstification of the Tuxpan platform started as early as the middle Cenomanian and continued intermittently as late as the middle Oligocene, accounting for some of the world's highest-ever recorded production rates (Viniegra and Castillo, 1970). Uplift along the MOP possibly was responsible for the entire platform standing out of the water as an elevated ''mesita'' with approximately 1–2 km of relief. Such a model also could explain the development of the Tamabra Formation as a platform margin that suffered intensive meteoric diagenesis, by combining and rationalizing the models of Coogan et al. (1972) and Enos (1988). Similarly, Miranda (2000) notes that many of the breccias in southeastern Mexico could be attributed to platform seeding and platform uplift followed by karstification during the middle and Late Cretaceous; we make the same observations concerning platform development and karstification in the Veracruz Basin. The development of breccias, which have accounted for approximately 90% of Mexico's oil production in the last ten years, is attributed presently either to slope processes (e.g., Angeles et al., 1994) or to meteorite impact (Grajales et al., 2000). The possibility of an early, karstic origin has not been considered seriously because of a perceived lack of a mechanism allowing uplift in the Southeast Basin. Our work demonstrates that such a mechanism, namely middle–Late Cretaceous compression, existed in the basin, and consequently a karstic origin of breccia reservoirs should be taken more seriously as an option. A karstic model has ramifications for timing of porosity development, reservoir layering, and the ability to predict development of fracture systems that are very different from current ''deep-water'' depositional models for the breccia systems.

Jurassic reservoir quality can be explained in part by the basin setting, with microporous reservoirs tending to be developed in the forced regressive systems, while highstand oolites on paleohighs are usually karstified and possess lower but more effective porosities.

Siliciclastic reservoirs clearly respond to the active margin; many of the plays in the Burgos Basin are related to input of sandstones following compression and uplift of basin margins. The changing dip in the middle Oligocene also is of critical importance in that it enabled large-scale coarse clastic systems to bypass the MOP and enter the deep-water Gulf of Mexico adjacent to the ECM. This is contrary to models that have the ECM cut by eastward-debauching submarine paleocanyons throughout the Paleogene.

Trap

Early mild compressional structures resulted both in seeding of carbonate platforms, which may form stratigraphic traps, as well as placing the reservoir in an ideal structural position for later thrust reactivation that uplifted them into tighter anticlinal traps.

Karstic topography along the Golden Lane has been understood for a long time (Viniegra and Castillo, 1970) and is a classic example of an unconformity-bounded stratigraphic trap. Lesser-known Neocomian chalky limestone reservoirs in the Tampico area also often are stratigraphically trapped, e.g., the Nayade-1 discovery (González, 1999) in the form of ''buried hill–type'' play sealed beneath the Méndez Breccia and Neogene shales.

Changing of regional dips and trap orientation in the middle Oligocene resulted in a complex interplay of cementation and charge, both of which affected reservoir quality. The Arenque oolite bank at the time of early migration of low API oil was westerly dipping, and a stratigraphic trap developed with a low API oil charge on its eastern flank (Horbury et al., 1996). This regional dip changed to easterly and the trap changed to a combination structural-stratigraphic type during the Neogene, as indicated by uniform emplacement of lighter and later oils across the whole structure, but often into poorer-quality reservoir that had suffered cementation in the Paleogene water leg (Horbury et al., 1996).

The middle Miocene (Chiapaneco) event clearly is of great importance because of its role in the formation of the major hydrocarbon traps in southeastern Mexico (Miranda, 1997). However, recognition that many older traps have been hidden by such younger and stronger events suggests that searches for paleotraps in some basins will improve play fairway assessment— as for example, in the middle Eocene (Sierra Madre Oriental) structures in the Southeast Basin.

Source Rock and Seal

These appear to be less dependent on the tectonostratigraphic history of the basin and more dependent on Tethys-wide eustatic processes, such as sea-level maxima in the middle Tithonian and global oceanic anoxic events in the Aptian and Turonian. The only exception may be where the MOP barred coarse clastics from entering a depocenter in the Gulf of Mexico bordering the ECM during the Paleogene.

Other Comments

The strong homoclinal dip of Neogene age across the entire shelf area has made it difficult to interpret many older events. This probably was the reason that original models of submarine paleocanyon development were aligned to the Neogene slope (e.g., Carrillo, 1980). Both the Sierra Madre Oriental and Chiapaneco events have such a strong structural overprint that they largely mask all earlier phases of compressive deformation, trap, and reservoir formation. The advent of workstations that allow flattening and examination of paleotopographies will aid the understanding of stratigraphic geometries and also the search for reservoirs and traps in this area, with its complex structural and stratigraphic history.

CONCLUSIONS

1) Post-Triassic deformation along the Mexican part of the Gulf of Mexico relates primarily to Pacific plate-margin processes. These events are analogous to the Laramide and Sevier orogenies recorded in the U.S. Rocky Mountains. In addition to documented Sierra Madre Oriental and Chiapaneco structures, deformation also takes place along a very long, monoclinal fold and thrust belt (Monoclinal Outer Paleohigh) that runs approximately parallel and is situated to the east of the Sierra Madre Oriental, and is broken up by transfer faults that usually run west-southwest–east-northeast.
2) Full documentation of regional structure development has identified many events that may result in structural traps that predate early oil charge.
3) Two types of Kimmeridgian shelf development (lowstand and highstand systems tracts) are recognized to be a consequence of forcing of sequence stratigraphies, and they have different paleogeographic distributions and different reservoir characteristics.
4) Inversion and uplift in the Late Jurassic resulted in development of major angular unconformities that allow karstic porosity to be developed in deep-water carbonates as well as shelf carbonates. However, karstic fabrics are often absent in carbonates deposited as lowstand wedges, probably because sea level had already ''touched bottom'' and much of what was subsequently deposited reflects deposition during a slow transgression.
5) The upper part of the Tamabra Formation in the Poza Rica area is tentatively reinterpreted as a forced regressive wedge, analogous with the Cupidito Formation of the Sabinas Basin.
6) Late Cretaceous thrust-related uplift explains breakup of the extensive middle Cretaceous platforms, as well as initiation of localized carbonate platform systems in and above basinal sediments. These early structures were sited ideally for reactivation in younger traps with stronger relief.
7) Regional and thrust-controlled uplift of Late Cretaceous to Neogene age associated with large amounts of erosion is important in order to understand depth and lateral extent of karstification, fracturing, brecciation, and peneplanation of Cretaceous sediments.
8) Progradation of Cenozoic clastic sedimentary systems show strong relationship to development of the MOP along much of the coastal area of Veracruz and Tamaulipas, in that coarse clastic sediments often were shed westward by the MOP in the Paleogene. Clastics with a westerly sediment source did not cross the MOP until the late Oligocene.
9) Many features described as paleocanyons or paleocanals of Cenozoic age can be reinterpreted wholly or in part as zones of localized uplift and erosion, rather than as pure cut-and-fill structures.
10) The importance of restoring the margin to its paleodip geometry needs to be emphasized, since many critical features have been missed or misinterpreted as a result of strong Paleogene–Neogene-age folding and strong Neogene-age down-to-the-Gulf tilting.

ACKNOWLEDGMENTS

First we would like to thank Pemex Exploration and Production for permission to publish this work, which is a by-product of various PEP-funded projects over a period of nine years. In particular, the permission of Adán Oviedo and Arturo Soto is gratefully acknowledged. Although this work is based on data from the Tampico and Veracruz offices of Pemex, many people in other Pemex offices have contributed in different ways to this work, through participation in projects, advice, and discussion at various times. Their names are too numerous to mention but this work is in many ways thanks to them and their generosity. Specifically, people who have helped us develop our regional understanding, in preparation of this manuscript, and in discussion of the topics within who require special thanks (but no blame for the contents or conclusions) are (in Mexico): Guillermo Pérez-Cruz, Noemi Aguilera, Ulises Hernández, Conrad Sabino, José Hernández, Daniel Velez, Alfredo Mahrx, Jaime Patiño, Juan Duran, Aurelio Garza, and Juan Rico. In the United Kingdom, we would like to thank Mike Simmons (Cambridge Arctic Shelf Project, now at Neftex Ltd.) for his opinion of critical biostratigraphic data, and in the United States, Steve Cossey for advice on characteristics of submarine canyon systems. Many of the concepts here resulted from original concepts discussed with Mark Shann in 1992–1996, for which the senior author would like to give due credit. Many thanks need to go to John Scott and Rowland Benbrook who drafted many of the figures, often at short notice. We would also like to thank James Lee Wilson and Charles Winker for thoughtful reviews of the manuscript, and lastly, to Neil Pickard for a final checking of the manuscript prior to publication.

REFERENCES CITED

Adatte, T., W. Stinnesbeck, and J. Remane, 1994, The Jurassic-Cretaceous boundary in northeastern Mexico: Confrontation and correlation by microfacies, clay mineral mineralogy, calpionellids and ammonites: Geobios, Mémoire Spécial 17, p. 37–56.

Aguilera-F. N., U. Hernández-R., P. A. Allison, 2001, Biostratigraphy and environmental changes across the Cenomanian-Turonian boundary, southern Mexico: Journal of South American Earth Sciences, v. 14, p. 237–255.

Alfonso-Z, J. W., 1978, Geología regional del sistema sedimentario Cupido: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 30, p. 1–56.

Ambrose, W. A., et al., 2001. Structural and stratigraphic controls on regional Miocene and Pliocene gas plays in the Macuspana Basin, Southeastern Mexico: Abstracts, Asociación Mexicana de Geólogos Petroleros and AAPG Joint Conference, 2001, Veracruz (unedited, unpaginated).

Anderson, T. H., and V. A. Schmidt, 1983, The evolution of Middle America and the Gulf of Mexico-Caribbean Sea region during Mesozoic time: Geological Society of America Bulletin, v. 94, p. 941–966.

Angeles-A., F., and A. Cantú-C., 2001, Subsurface Upper Jurassic stratigraphy in the Campeche Shelf, Gulf of Mexico, *in* C. Bartolini, R. T. Buffler, and A. Cantú-Chapa, eds., The western Gulf of Mexico Basin: Tectonics, sedimentary basins, and petroleum systems: AAPG Memoir 75, p. 343–352.

Angeles-A., F., J. Reyes, J. Quezada-M., and J. Meneses, 1994, Tectonic evolution, structural styles and oil habitat in Campeche Sound, México: Transactions of the Gulf Coast Association of Geological Societies, v. 44, p. 53–62.

Back, W., and B. B. Hanshaw, 1970, Comparison of chemical hydrology of the carbonate peninsula of Florida and Yucatan: Journal of Hydrology, v. 10, p. 330–368.

Barnetche, A., and L. V. Illing, 1956, The Tamabra Limestone of the Poza Rica oil field: 20th Congreso Geológico Internacional, México, Monograph, 38 p.

Basáñez-L., M. A., R. Fernández-T., and A. C. Rosales-D, 1993, Cretaceous platform of Valles-San Luis Potosí, northeastern central Mexico, *in* J. A. Simo, R. W. Scott, and J. P. Masse, eds., Cretaceous carbonate platforms: AAPG Memoir 56, p. 51–59.

Blickwede, J. J., 2001, The Nazas Formation: A detailed look at the early Mesozoic convergent margin along the western rim of the Gulf of Mexico Basin, *in* C. Bartolini, R. T. Buffler, and A. Cantú-Chapa, eds., The western Gulf of Mexico Basin: Tectonics, sedimentary basins, and petroleum systems. AAPG Memoir 75, p. 317–342.

Blickwede, J. J., and T. A. Queffelec, 1988, Perdido foldbelt; a new deep water frontier in the western Gulf of Mexico: AAPG Bulletin, v. 72, p. 163.

Bloomfield, K., and L. Cepeda-D., 1973, Oligocene alkaline igneous activity in NE Mexico: Geological Magazine, v. 11, p. 551–555.

Bonet, F., 1956, Zonificación microfaunísticas de las calizas Cretácicas del este de México: 20th Congreso Geológico Internacional, México, Monograph, 102 p.

Brito-B., A., F. Sánchez-L., J. Patiño-R., J. R. Román-R., 1999, El sistema petrolífero y la reactivación exploratoria en la porción marina de la plataforma de Tuxpan, México: Abstracts, Joint Asociación Mexicana de Geólogos Petroleros/AAPG Conference, Veracruz, (unedited, unpaginated).

Budd, D. A., 1989, Micro-rhombic calcite and microporosity in limestones: A geochemical study of the Lower Cretaceous Thamama Group, U.A.E.: Sedimentary Geology, v. 63, p. 293–311.

Buffler, R. T., F. J. Shaub, J. S. Watkins, and J. L. Worzel, 1979, Anatomy of the Mexican Ridges, southwestern Gulf of Mexico, *in* J. S. Watkins, L. Montadert, and P. W. Dickerson, eds., Geological and geophysical investigations of continental margins: AAPG Memoir 29, p. 319–327.

Burckhardt, C., 1930, Étudé Synthétique sur le Mésozoïque mexicain, Premiére Partie: Mémoires Société Paléontologique Suisse 49, p. 1–123.

Burkhart, B., 1983, Neogene North American Caribbean plate boundary across northern Central America: Offset along the Polochic Fault: Tectonophysics, v. 99, p. 251–270.

Busch, D. A., and S. Govela-A, 1978, Stratigraphy and structure of Chicontepec turbidites, southeastern Tampico-Misantla basin, Mexico: AAPG Bulletin, v. 62, p. 235–246.

Campa, M. F., F. Campos, R. Flores, and R. Oviedo, 1974, La secuencia Mesozoica volcánico-sedimentaria metamorfizada de Ixtapan de la Sal, Mex.-Teloloapan, Gro.: Boletín de la Sociedad Geológica Mexicana, v. 35, p. 7–28.

Cantú-C., A., 1969, Estratigrafia del Jurásico Medio-Superior del subsuelo de Poza Rica, Ver. (Area de Soledad-Miquetla): Revista del Instituto Mexicano del Petróleo, v. 1, no. 1, p. 3–9.

Cantú-C., A., 1971, La Serie Huasteca (Jurásico Medio-Superior) del Centro-Este de Mexico: Revista del Instituto Mexicano del Petróleo, v. 3, no. 2, p. 17–40.

Cantú-C., A., 1977, Las amonitas del Jurásico Superior del pozo Chac 1, Norte de Campeche (Golfo de México): Revista del Instituto Mexicano del Petróleo, v. 9, no. 2, p. 8–39.

Cantú-C., A., 1979, Bioestratigrafía de la Serie Huasteca (Jurásico Medio y Superior) en el subsuelo de Poza Rica, Ver.: Revista del Instituto Mexicano del Petróleo, v. 11, no. 2, p. 14–24.

Cantú-C., A., 1982, The Jurassic-Cretaceous Boundary in the subsurface of Eastern Mexico: Journal of Petroleum Geology, v. 4, p. 311–318.

Cantú-C., A., 1992, The Jurassic Huasteca Series in the subsurface of Poza Rica, Eastern Mexico: Journal of Petroleum Geology, v. 15, p. 259–282.

Cantú-C., A., 1996, ''¿Que hacer con las calpionelas del límite Jurásico-Cretácico?'': Revista Española de Micropaleontología, v. 28, p. 57–65.

Cantú-C., A., 2001a, Paleocanyons in the subsurface of Eastern Mexico: Facts and uncertainties, *in* C. Bartolini, R. T. Buffler, and A. Cantú-Chapa, eds., The western Gulf of Mexico Basin: Tectonics, sedimentary basins, and petroleum systems: AAPG Memoir 75, p. 421–430.

Cantú-C., A., 2001b, Mexico as the Western Margin of Pangea based on biogeographic evidence from the Permian to the Lower Jurassic, *in* C. Bartolini, R. T. Buffler, and A. Cantú-Chapa, eds., The western Gulf of Mexico Basin: Tectonics, sedimentary basins, and petroleum systems: AAPG Memoir 75, p. 1–27.

Carrillo-B., J., 1961, Geologia del Anticlinorio Huizachal-Peregrina al N-W de Ciudad Victoria, Tams.: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 13, p. 1–98.

Carrillo-B., J., 1980, Paleocañones terciarias en la planice costera del Golfo de México: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 32, p. 27–55.

Chapin, C. E., 1979, Evolution of the Rio Grande Rift— A summary, *in* R. E. Riecker, ed., Rio Grande Rift: Tectonics and magmatism: American Geophysical Union, p. 1–5.

Cohen, Z., 1976, Early Cretaceous buried canyon: Influence on accumulation of hydrocarbons in Helez Oil Field, Israel: AAPG Bulletin, v. 60, no. 1, p. 108–114.

Coogan, A. H., D. G. Bebout, and C. Maggio, 1972, Depositional environments and geological history of Golden Lane and Poza Rica trends, Mexico, an alternative view: AAPG Bulletin, v. 56, p. 1419–1447.

Cosmo, C. A., A. Palhares, H. D. Rangel, B. Wolff, and A. M. F. de Figueiredo, 1991, Lagoa Parda Field— Brazil, *in* N. H. Foster and E. A. Beaumont, eds., Stratigraphic traps II, Treatise of petroleum geology, Atlas of oil and gas fields: Tulsa, Oklahoma, AAPG, p. 349–360.

Cross, T. A., 1986, Tectonic controls of foreland basin subsidence and Laramide style of deformation, western United States, *in* P. A. Allen and P. Homewood, eds., Foreland basins: International Association of Sedimentologists Special Publication No. 8: Oxford, U. K., Blackwell Scientific Publications, p. 15–40.

Cruz-H., P., R. Verdugo-V., and R. Bárcenas-P., 1977, Origin and distribution of Tertiary conglomerates, Veracruz Basin, México: AAPG Bulletin, v. 61, p. 207–216.

De Cserna, Z., 1956, Tectónica de la Sierra Madre Oriental de México, entre Torreón y Monterrey, México, D.F.: 20th Congreso Geológico Internacional, México, Monograph, 87 p.

De Cserna, Z., 1989, An outline of the geology of Mexico, *in* A. W. Bally, ed., The Geology of North America— an overview: Geological Society of America, Decade of North American Geology, v. A, p. 233–264.

De Cserna, Z., M. Palacios-N., and J. Pantoja-A., 1978, Relaciones facies de rocas Cretácicas en el noroeste de Guerrero y en áreas colindantes de México y Michoacán: Universidad Nacional Autónomo de México, Instituto de Geología, Revista, v. 2, no. 1, p. 8–18.

Dewey, J. F., and J. M. Bird, 1970, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647.

Dickinson, W. R., 1981, Plate tectonic evolution of the Southern Cordillera, *in* W. R. Dickinson and W. D. Payne, eds., Relations of tectonics to ore deposits in the Southern Cordillera: Arizona Geological Society Digest, v. 14, p. 113–135.

Eguiluz de A., S., M. Aranda-G., and R. Marrett, R., 2000, Tectónica de la Sierra Madre Oriental, México: Boletin de la Sociedad Geologica Mexicana, v. 53, p. 1–26.

Enos, P., 1977, Tamabra limestone of the Poza Rica trend, Cretaceous, Mexico, *in* H. E. Cook and P. Enos, eds., Deep water carbonate environments: Society for Sedimentary Geology (SEPM) Special Publication 25, p. 273–314.

Enos, P., 1983, Late Mesozoic palaeogeography of Mexico, *in* M. W. Reynolds and E. W. Dolly, eds., Mesozoic palaeogeography of West-Central United States: Rocky Mountain Section, Society for Sedimentary Geology (SEPM), Palaeogeography Symposium no. 2, p. 133–157.

Enos, P., 1985, Cretaceous debris reservoirs, Poza Rica Field, Veracruz, Mexico, *in* P. O. Roehl and P. W. Choquette, eds., Carbonate petroleum reservoirs: New York, Springer-Verlag, p. 457–469.

Enos, P., 1988, Evolution of pore space in the Poza Rica trend (mid-Cretaceous), Mexico: Sedimentology, v. 35, p. 287–325.

Enos, P., and B. P. Stephens, 1993, Mid-Cretaceous basin margin carbonates, east-central Mexico: Sedimentology, v. 40, p. 539–556.

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

Erben, H. K., 1956b, El Jurásico Medio y Calloviano de México: 20th Congreso Geológico Internacional México, Monograph, 140 p.

Esteban, M., and C. F. Klappa, 1983, Subaerial exposure environment, *in* P. A. Scholle, D. G. Bebout, and C. H. Moore, eds., Carbonate depositional environments: AAPG Memoir 33, p. 1–54.

Galicia-B., J. G., 1997, Estratigrafía de secuencias y potencial de hidrocarburos del Jurásico Superior en la región de Cd. Valles, S.L.P.: Revista Ingeniería Petrolera de la Asociación de los Ingenieros Petroleros de México, v. 37, p. 38–47.

Galloway, W. E., 1989, Genetic stratigraphic sequence in basin analysis II: Application to the northeast Gulf of Mexico Cenozoic basins: AAPG Bulletin, v. 73, p. 143–154.

Galloway, W. E., D. G. Bebout, W. L. Fischer, J. B. Dunlap Jr., R. Cabrera-C., J. E. Lugo-R., and T. M. Scott, 1991, Cenozoic, *in* A. Salvador, ed., The Gulf of Mexico: Geological Society of America, Decade of North American Geology, v. J, p. 245–324.

Goldhammer, R. K., P. A. Dunn, and L. A. Hardie, 1990, Depositional cycles, composite sea-level changes, cycles stacking patterns, and the hierarchy of stratigraphic forcing: Examples from Alpine Triassic carbonates: Geological Society of America Bulletin, v. 102, p. 535–562.

Goldhammer, R. K., 1999, Mesozoic sequence stratigraphy and paleogeographic evolution of northeast Mexico, *in* C. Bartolini, J. L. Wilson, and T. F. Lawton, eds., Mesozoic sedimentary and tectonic history of North-Central Mexico: Geological Society of America Special Paper 340, p. 1–58.

González-G., R., 1970, La Formación Huehuetepec, nueva unidad litoestratigráfica del Jurásico de Poza Rica: Revista Ingeniería Petrolera de la Asociacion de Ingenieros Petroleros de México, v. 10, p. 5–22.

González-G., R., and N. Holguín-Q., 1992, Las rocas generadoras de México: Boletin de la Asociación Mexicana de Geólogos Petroleros, v. 42, p. 9–23.

González-P., F., 1999, Posibilidades petroliferas en el area marina frente a Tampico: Revista Ingeniería Petrolera de la Asociacion de Ingenieros Petroleros de Mexico, v. 39 p. 39–49.

Grajales-N., J. M., E. Cedillo-P., C. Rosales-D., D. Morán-Z., W. Alvarez, P. Claeys, J. Ruíz-M., J. García-H., P. Padilla-A., and A. Sánchez-R., 2000, Chicxulub impact: The origin of reservoir and seal facies in the southeastern Mexico oil fields: Geology, v. 28, p. 307–310.

Grajales-N., J. M., E. Cedillo-P., C. Rosales-D., D. Morán-Z., W. Alvarez, P. Claeys, J. Ruíz-M., J. García-H., P. Padilla-A., and A. Sánchez-R., 2001, Chicxulub impact: The origin of reservoir and seal facies in the southeastern Mexico oil fields: Reply: Geology, v. 29, p. 95–96.

Gray, G. G., R. J. Pottorf, D. A. Yurewicz, K. I. Mahon, D. R. Pevear, and R. J. Chuchla, 2001, Thermal and chronological record of syn- to post-Laramide burial and exhumation, Sierra Madre Oriental, Mexico, *in* C. Bartolini, R. T. Buffler, and A. Cantú-Chapa, eds., The western Gulf of Mexico Basin: Tectonics, sedimentary basins, and petroleum systems: AAPG Memoir 75, p. 159–181.

Heim, A., 1940, The front ranges of Sierra Madres Oriental, Mexico, from Ciudad Victoria to Tamazunchale: Eclogae Geologicae Helvetiae, v. 33, no. 2, p. 313–362.

Hernández-R., U., N. Aguilera-F., M. Martínez-M., J. Barceló-D., 1997, Guerrero-Morelos Platform drowning at the Cenomanian Turonian boundary, Huitziltepec area, Guerrero State, southern Mexico: Cretaceous Research, v. 18, p. 661–686.

Hernández-M., J. J., 2000, Interpretation and distribution of depositional systems: Oligocene Frío Depisode in the subsurface of the Burgos Basin, Northeastern Mexico: Master's thesis, University of Texas at Austin, 102 p.

Horbury, A. D., J.-L. Celestino-U., N. Oxtoby, A. Soto-C., and S. Johnson, 1996, Diagenesis y evolución de la porosidad en el campo petrolifero Arenque, costa afuera de Tampico, Tamaulipas, México: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 45, p. 58–80

Imlay, R. W., 1937, Lower Neocomian fossils from the Miquihuana Region, Mexico: Journal of Paleontology, v. 11, no. 7, p. 554–557.

Imlay, R. W., 1943, Jurassic formations of the Gulf Region: AAPG Bulletin, v. 27, p. 1407–1544.

Imlay, R. W., 1952, Correlation of the Jurassic Formations of North America, exclusive of Canada: Geological Society of America Bulletin, v. 63, p. 953–992.

Imlay, R. W., E. Cepeda, M. Álvarez Jr., and T. Díaz, 1948, Stratigraphic relations of certain Jurassic formations in Eastern Mexico: AAPG Bulletin, v. 32, p. 1750–1761.

Kuenen, P. H., 1963, Marine geology: New York, John Wiley and Sons, 568 p.

Lehmann, C., D. A. Osleger, and I. Montañez, 2000, Sequence stratigraphy of Lower Cretaceous (Barremian-Albian) carbonate platforms of Northeastern Mexico: Regional and global correlations: Journal of Sedimentary Research, v. 70, no. 2, p. 373–391.

Longman, M. W., 1980, Carbonate diagenetic textures from nearsurface diagenetic environments: AAPG Bulletin, v. 64, p. 461–487.

Longoria, J. F., 1993, La terrenoestratigrafía: un ensayo de metodología para el análisis de terrenos con un ejemplo en México: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 43, p. 30–48.

Longoria, J. F., and J. M. Grajales-N., 1993, Field trip guide to selected KT boundary localities in Tamaulipas and Nuevo León, Northeastern Mexico: Revista de la Sociedad Mexicana de Paleontología, v. 6, pt. 2, p. 73–85.

López-O., J. G., G. Keller, and W. Stinnesbeck, 1995, El Limite Cretácico-Terciairo en el noreste de México: Memorias del 5th Congreso Nacional de Paleontología, México, 23 p.

López-R., E., 1982, Geología de México, v. 3, 3rd ed., 454 p.

Loucks, R. G., 1999, Paleocave carbonate reservoirs: Origins, burial-depth modifications, spatial complexity and reservoir implications: AAPG Bulletin, v. 83, p. 1795–1834.

Lutterell, E. P., 1977, Carbonate facies distribution and diagnoses associated with volcanic cones— Anacacho Limestone (Upper Cretaceous), Elaine Field, Dimmit County, Texas; Cretaceous Carbonates of Texas and Mexico: Applications to Subsurface Exploration: Bureau of Economic Geology, The University of Texas at Austin, Report of Investigations No. 89, p. 260–285.

Meneses-R, J. J., M. E. Monroy-A., and J. C. Gomez-C., 1994, Bosque paleogeografico y tectonico del sur de México durante el Mesozoico: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 44, p. 18–45.

Meneses-R., J. J., J. Rodríguez-F., J. Toriz-G., R. Banda-H., R. Hernández de la Fuente, and V. Valdivieso-R., 1997, Geologic field trip to the Zongolica fold and thrust belt: AAPG/Asociación Mexicana Géologos Petroleros, International Research Symposium Guidebook, 103 p.

Minero, C. J., 1988, Sedimentation and diagenesis along an island-sheltered platform margin, El Abra Formation, Cretaceous of Mexico, *in* N. P. James and P. W. Choquette, eds., Paleokarst: Berlin and New York, Springer-Verlag, p. 385–405.

Minero, C. J., 1991, Sedimentation and diagenesis along open and island-protected windward carbonate platform margins of the Cretaceous El Abra Formation, Mexico: Sedimentary Geology, v. 71, p. 261–288.

Miranda-C., E., 1997, Estructuras compresivas y su potencial petrolero en las cuencas sedimentarias del sureste Mexicano: Revista Ingeniería Petrolera de la Asociacion de Ingenieros Petroleros de México, v. 37, no. 2, p. 55–61.

Miranda-C., E., 2000, Contribución al estudio sobre el origen y distribución de las brechas Cretácicas del area Reforma-Comalcalco-Sen.: Abstracts, III Conferencia Latina de Geofisica, Veracruz, México (unedited, unpaginated).

Miranda-C., E., A. Ruíz-O., T. Castillo-R., M. Mata-J., L. Granado-C., and C. Marín-S., 1999, Análisis estructural-estratigráfico e importancia económica del extremo SW de la cuenca de Macuspana (proyecto Reforma): Abstracts, Asociacion de Ingenieros Petroleros de México Annual Conference, Merida (unedited, unpaginated).

Mixon, R. B., 1958, The Jurassic formations of the Ciudad Victoria region, Tamaulipas Mexico: Master's thesis, Louisiana State University, Baton Rouge, 70 p.

Mixon, R. B., G. E. Murray, and T. Díaz-G., 1959, Age and correlation of Huizachal Group (Mesozoic), State of Tamaulipas, Mexico: AAPG Bulletin, v. 43, p. 757–771.

Monreal, R., and J. F. Longoria, 1999, A revision of the Upper Jurassic and Lower Cretaceous stratigraphic nomenclature for the Chihuahua trough, north-central Mexico: Implications for lithocorrelations, *in* C. Bartolini, J. L. Wilson, and T. F. Lawton, eds., Mesozoic sedimentary and tectonic history of North-Central Mexico: Geological Society of America Special Paper No. 340, p. 69–92.

Montanari, S., P. Claeys, F. Asaro, J. Bermúdez, and J. Smit, 1994, Preliminary stratigraphy and Iridium and other geochemical anomalies across the KT Boundary in the Bochil Section (Chiapas, Southeastern Mexico), *in* New developments regarding the KT event and other catastrophes in earth history: Lunar and Planetary Institute, LPI Contribution No. 825, p. 84–85.

Muir, J. M., 1936, Geology of the Tampico Region, Mexico: Tulsa, Oklahoma, AAPG, 280 p.

Müllerried, F. K. G., 1946, Geología del Estado de Nuevo León: Universidad de Nuevo León, Anales del Instituto de Investigaciones Cientifica, v. 1, no. 2, p. 52–54.

Ortuño-M., E., 1999, Tithoniano formación productora de hidrocarburos en la Sonda de Campeche: Revista Ingeniería Petrolera de la Asociación de los Inginieros Petroleros de México, v. 39, p. 29–36.

Padilla y Sánchez, R. J., 1982, Geologic evolution of the Sierra Madre Oriental between Linares, Concepción del Oro, Saltillo and Monterrey, México: Ph.D. dissertation, University of Texas at Austin, 217 p.

Padilla y Sánchez, R. J., 1985, Las estructuras de la Curvatura de Monterrey, Estados de Coahuila, Nuevo Leon, Zacatecas y San Luis Potosí: Universiadad Nacional. Autónomo de México, Instituto de Geología, Revista, v. 6, no. 1, p. 1–20.

Pemex Exploración y Producción, 2000, Las reservas de hidrocarburos de México: Los principales campos de petróleo y gas de México, v. II, México, D.F.

Pérez-C., G. A., 1992, Geologic evolution of the Burgos

Basin, northeastern Mexico: Ph.D. dissertation, Rice University, Houston, Texas, 209 p.
Pindell, J., 1985, Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and Proto-Caribbean: Tectonics, v. 4, p. 1–39.
Pindell, J. L., and J. F. Dewey, 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179–211.
Pindell, J. L., and L. J. Kennan, 2001, Kinematic evolution of the Gulf of Mexico and Caribbean: Proceedings of Gulf Coast Section, Society for Sedimentary Geology (SEPM) Foundation, 21st Annual Research Conference, Petroleum Systems of Deep-Water Basins, p. 193–220.
Quezada-M., J. M., 1983, Las formaciones San Ricardo y Jericó del Jurásico Medio-Cretácico Inferior en el SE de México: Boletín de la Asociación Mexicana Geologos Petroleros, v. 35, p. 37–64.
Quezada-M., J. M., 1990, El Cretácico Medio-Superior y el límite Cretácico Superior-Terciario Inferior en la Sierra de Chiapas: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 39, no. 1, p. 3–98.
Remane, J., W. Stinnesbeck, and T. Adatte, 1999, What to do with Cantu Chapa's (1996) definition of the Jurassic-Cretaceous Boundary?: Revista Española de Micropaleontología, v. 31, no. 1, p. 149–154.
Rockwell, D. W., and A. G. Rojas, 1953, Coordination of seismic and geologic data in Poza Rica-Golden Lane area, Mexico: AAPG Bulletin, v. 37, p. 2551–2565.
Rodrígeuz-U., M. A., J. Patiño-R., M. A. Quintero-A., and A. R. Gómez-G., 2000, Interpretación geológica-geofísica en el área fronteriza del Golfo de México: Abstracts, III Conferencia Latina de Geofisica, Veracruz, México (unedited, unpaginated).
Ross, C. A., and C. R. Scotese, 1988, A hierachical tectonic model of the Gulf of Mexico and Caribbean region: Tectonophysics, v. 155, p. 139–168.
Salvador, A., 1987, Late Triassic-Jurassic paleogeography and origin of the Gulf of Mexico Basin: AAPG Bulletin, v. 71, p. 419–451.
Salvador, A., 1991, Origin and development of the Gulf of Mexico Basin, in A. Salvador, ed., The Gulf of Mexico Basin: Geological Society of America, Decade of North American Geology, v. J, p. 389–444.
Sánchez-M, R., 1979, Geología petrolera de la Sierra de Chiapas: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 31, p. 67–97.
Sánchez-R., M. A., and P. Salmerón-U., 1996, El Paleogeno de México: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 45, p. 39–57.
Santiago-A, J., and A. Baro, 1990, Mexico's giant gields, 1978–1988 decade, *in* M. T. Halbouty, ed., Giant oil and gas fields of the decade 1978–1988: AAPG Memoir 54, p. 73–99.
Sawyer, D. S., R. T. Buffler, and R. H. Pilger, 1991, The crust under the Gulf of Mexico Basin, *in* A. Salvador, ed., The Gulf of Mexico Basin: Geological Society of America, Decade of North American Geology, v. J, p. 53–72.
Schaaf, P., Z. D. J. Moran, B. M. de S. Hernández, P. G. N. Solis, G. Tolson, and H. Koehler, 1995, Paleogene continental margin truncation in southwestern Mexico; geochemical evidence: Tectonics, v. 14, p. 1339–1350.
Schlager, W., J. A. Austin Jr., W. Corso, C. L. McNulty, E. Fluegel, O. Renz, and J. C. Steinmetz, 1984, Early Cretaceous platform reentrant and escarpment erosion in the Bahamas: Geology, v. 12, p. 147–150.
Sedlock, R. L., G. F. Ortega, and R. C. Speed, 1993, Tectonostratigraphic terranes and tectonic evolution of Mexico: Geological Society of America Special Paper 278, 153 p.
Smit, J., A. Montanari, N. H. M. Suinburne, W. Alvarez, A. Hildebrand, S. V. Margolis, P. Claeys, W. Lowerie, and F. Asaro, 1992, Tektite-bearing, deep-water clastic unit at the Cretaceous-Tertiary boundary in Northeastern Mexico: Geology, v. 20, p. 99–103.
Smith, B. A., 1986, Upper Cretaceous stratigraphy and the mid-Cenomanian unconformity of east-central Mexico: Ph.D. dissertation, University of Texas at Austin, 190 p.
Sotomayor-C., A., 1954, Distribución y causas de la porosidad en las calizas del Cretácico Medio en la región de Tampico-Poza Rica: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 6, p. 157–206.
Stabler, C., 1972, Secuencia de una trampa estratigráfica en el Jurásico Superior: Campo Tamaulipas-Constituciones: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 24, p. 165–197.
Stinnesbeck, W., G. Keller, and T. Adatte, 2001, Chicxulub impact: The origin of reservoir and seal facies in the southeastern Mexico oil fields: Comment: Geology, v. 29, p. 94–95.
Suárez, G., P. Molnar, and B. C. Burchfiel, 1983, Seismicity, fault plane solution, depth of faulting and active tectonics of the Andes of Peru, Ecuador and southern Colombia: Journal of Geophysical Research, v. 88, p. 10,403–10,428.
Tardy, M., 1980, Contribution a l'etude geologique de la Sierra Madre Orientale de Mexique: Mémoire de Thése de Doctorat d'Etat, Université Pierre et Marie Curie de Paris, 259 p.
Trejo, M., 1975, Tintinidos Mesozoicos de México: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 27, no. 10–12, p. 329–449.
Trujillo-A., A., A. Orozco-D., and L. Ramirez-C., 2000, Análisis sismico aplicado a los sedimentos del Oligoceno en la porción NE de la cuenca de Tampico-Misantla: Abstracts, III Conferencia Latina de Geofisica, Veracruz, México (unedited, unpaginated).
Vélez, D., 1990, La Cuenca de Guerrero: Ejemplo de deformación por transcurrencia en el Sur de México: Revista Ingeniería Petrolera de la Asociación de los Inginieros Petroleros de México, v. 30, p. 25–35.
Viniegra-O., F., 1965, Geologia del Macizo de Teziutlan y de la Cuenca Cenozoica de Veracruz: Boletín Asociación

Mexicana de Geólogos Petroleros, v. 17, nos. 7–12, p. 101–163.

Viniegra-O., F., 1981, Great Carbonate Bank of Yucatán, southern Mexico: Journal of Petroleum Geology, v. 3, pt. 3, p. 247–278.

Viniegra-O., F., and C. Castillo-T., 1970, Golden Lane fields, Veracruz, Mexico: AAPG Memoir 14, p. 309–325.

Williams-R., C. T., 2001, Geological controls on reservoir performance in two gas fields, Southeast Mexico: Master's thesis, Colorado School of Mines, Golden, 82 p.

Williams-R., C. T., and N. F. Hurley, 2001, Geologic controls on reservoir performance in Muspac and Catedral gas fields, southeastern Mexico, *in* C. Bartolini, R. T. Buffler, and A. Cantú-Chapa, eds., The western Gulf of Mexico Basin: Tectonics, sedimentary basins, and petroleum systems. AAPG Memoir 75, p. 443–472.

Wilson, H. H., 1987, The structural evolution of the Golden Lane, Tampico embayment, Mexico: Journal of Petroleum Geology, v. 10, p. 5–40.

Wilson, H. H., 1993, The age of salt in the Gulf of Mexico basin: Journal of Petroleum Geology, v. 16, p. 125–152.

Wilson, H. H., 2003, Extensional evolution of the Gulf of Mexico basin and the deposition of Tertiary evaporites: Journal of Petroleum Geology, v. 26, p. 403–428.

Wilson, J. L., 1990, Basement structural controls on Mesozoic carbonate facies in northeastern Mexico—a review, *in* M. E. Tucker, J. L. Wilson, P. D. Crevello, J. F. Sarg, and J. F. Read, eds., Carbonate platforms, facies, sequences, and evolution: International Association of Sedimentologists Special Publication 9, p. 235–256.

Wilson, J. L., and W. C. Ward, 1993, Early Cretaceous carbonate platforms of Northeastern and East-Central Mexico, *in* J. A. Simo, R. W. Scott, and J. P. Masse, eds., Cretaceous carbonate platforms: AAPG Memoir 56, p. 35–49.

Winker, C. D., and R. Buffler, 1988, Paleogeographic evolution of early deep-water Gulf of Mexico and margins, Jurassic to Middle Cretaceous (Comanchean): AAPG Bulletin, v. 72, p. 318–346.