

Mesozoic sequence stratigraphy and paleogeographic evolution of northeast Mexico

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ABSTRACT

The Monterrey-Saltito area of northeast Mexico is the juncture of two distinctly different Mexican tectono-stratigraphic provinces, the eastern Gulf of Mexico province and the western Pacific Mexico province, where Gulf of Mexico-driven versus Pacific-driven tectono-stratigraphic processes can be compared and contrasted. Each of these provinces are large subregions that have distinctive and separate tectonic evolutions, and different resulting stratigraphic packaging. They are characterized by distinctive structural belts and structural styles and basement. The different stratigraphies record a subregional response to the interaction of provincial tectonics (i.e., convergent versus divergent margins), eustatic changes in sea level, and sediment type and supply. The Monterrey-Saltito area contains elements related to both Gulf of Mexico passive-margin development (principally the stratigraphy) and Pacific-related convergent margin (arc) tectonism (chiefly the structure). Thus a complete understanding of the area is critical in linking together two somewhat disparate geologic provinces in Mexico.

In the Gulf of Mexico province, the tectonic evolution is dominated by passive-margin development associated with the opening of the Gulf of Mexico, overprinted by nonigneous Laramide orogenic effects. The stratigraphic evolution is dominated principally by eustasy in as far as thick regional accommodation cycles can be correlated throughout the Gulf of Mexico. I propose that the Middle Jurassic to Lower Cretaceous stratigraphy of northeast Mexico and the Gulf of Mexico area in general can be subdivided into four major, second-order depositional supersequences (~15 m.y. duration), defined as large regionally correlative, retrogradational to aggradational-progradational accommodation packages. Each supersequence exhibits systematic vertical stacking patterns and associated lateral facies shifts within subordinate third-order sequences (1–3 m.y. duration) and component lateral-vertical facies and systems tracts. The four supersequences are supersequence 1—upper Bathonian to lower Kimmeridgian (158.5–144 Ma); supersequence 2—lower Kimmeridgian to Berriasian (144–128.5 Ma); supersequence 3—Valanginian to lower Aptian (128.5–112 Ma); supersequence 4—lower Aptian to upper Albian (112–98 Ma). (Note that these ages are not certain.)

Second-order supersequence boundaries, condensed sections, transgressive surfaces, and second-order systems tracts have been identified in outcrops of the Sierra Madre Oriental, biostratigraphically dated, and correlated with the northern U.S. Gulf of Mexico stratigraphic section. The identification of these components is based on (1) gross shelf to basin relationships of onlapping and offlapping facies; (2) stacking

patterns of third-order sequences and their component high-frequency cycles; and (3) criteria for significant subaerial exposure and/or erosion of supersequence boundaries. Additional data are provided from regional seismic coverage and well-log cross sections in south Texas and extreme northeastern Mexico.

The stratigraphic evolution of the Late Jurassic through Early Cretaceous Gulf of Mexico passive margin is interpreted to have resulted from the superimposition of four second-order relative sea-level cycles atop a first-order long-term relative sea-level rise. This first-order relative rise likely reflects a global eustatic rise driven by long-term changes in mid-ocean ridge volume related to sea-floor spreading rates associated with the opening of the Gulf of Mexico and the Atlantic Ocean. These two different orders of eustasy operated in concert with underlying thermo-tectonic subsidence to produce systematic changes in accommodation from the base to the top of the Gulf Coast section. Such changes account for the overall shift from lowstand-dominated facies associations characteristic of the Middle to Upper Jurassic (redbeds, evaporites, marginal-marine siliciclastic rocks, and low-relief, shallow-marine high-energy carbonates), to highstand-dominated facies associations characteristic of the Lower Cretaceous (higher relief, shallow-marine carbonate platforms, deep-marine shales, and pelagic carbonates).

INTRODUCTION

This chapter addresses the paleogeographic and sequence stratigraphic evolution of the Mesozoic stratigraphy exposed in northeast Mexico. It is an outgrowth of my experience with the stratigraphy of the area, which stems from original field work and numerous field expeditions conducted over a span of 10 years (Goldhammer et al., 1991; C. A. Johnson et al., 1991). The principal area of concern is the Monterrey-Salttillo area in northeast Mexico, and includes the areas south, southeast, and east of the Coahuila block (Figs. 1 and 2). This area of Mexico, with its spectacular exposures of Mesozoic stratigraphy, is significant for the following reasons.

1. Sequence stratigraphic models and facies models derived from outcrop studies in northeast Mexico may be used to significantly enhance our understanding of equivalent-age stratigraphy in the onshore U.S. Gulf of Mexico, for example within the East Texas salt basin and in south Texas (Figs. 3). This is crucial in developing concept models in exploration and production of hydrocarbons (Goldhammer, 1998). Direct application of outcrop analogues to the United States subsurface can be made because the pre-Santonian (pre-Laramide) paleogeographic and stratigraphic evolutions of northeast Mexico and the U.S. Gulf Coast are fairly similar (e.g., Salvador, 1987, 1991a, 1991b, 1991c).

2. Sequence stratigraphic and facies models developed from northeast Mexico may also be utilized to enhance our understanding of other basins in Mexico (Fig. 3), including the neighboring Sabinas, La Popa, Parras, Burgos, Magascatzin, Tampico-Misantla basins, and the severely deformed equivalents in the Sierra Madre Oriental (e.g., Monterrey trough, Valles-San Luis Potosí platform-basin complex). These particular basins also had similar patterns of stratigraphic accumulation in response to Gulf of Mexico long-term accommodation cycles (Goldhammer et al., 1991) prior to the Laramide phase of deformation that affected the entire region.

3. Of particular importance to the Mexican hydrocarbon industry, northeast Mexico also serves as a useful early through middle Mesozoic (pre-Cenomanian) stratigraphic and facies analog for basins to the southeast, which include most of Mexico's significant petroleum provinces. These basins include the Tampico-Veracruz region, the Reforma-Campeche trend, the Macuspana basin, and the Chiapas trough. Taking into account the pre-Late Jurassic rifting and southerly migration of the Yucatan block, the genetic similarity between the southeast regions and northeast Mexico becomes even more apparent when one considers their original paleogeographic relationship prior to Yucatan migration (Fig. 3).

4. The area is essentially the juncture of two distinctly different tectono-stratigraphic provinces of Mexico, the eastern Gulf of Mexico province and the western Pacific Mexico province, and therefore allows one to compare and contrast Gulf of Mexico-driven versus Pacific-driven tectono-stratigraphic processes. The Monterrey-Salttillo area contains elements related to Gulf of Mexico passive-margin development (principally the stratigraphy) and to Pacific-related convergent margin (arc) tectonism (chiefly the structure). A complete understanding of the area is critical in linking together two somewhat disparate geologic provinces in Mexico.

The goals of this chapter are as follows. (1) I outline the tectono-stratigraphic development of the northeast Mexico by defining the present-day regional tectonic elements and by reviewing the tectonic evolution of the region within the context of the opening of the Gulf of Mexico. (2) I define the two major tectono-stratigraphic provinces mentioned here and illustrate their paleogeographic evolution by introducing a series of regional paleogeographic and facies maps. These maps place the stratigraphic and tectonic development of the Monterrey-Salttillo area in more regional context. (3) I review the Mesozoic stratigraphy of the area and summarize the chronostratigraphic rela-

tions. (4) I propose a regional sequence-stratigraphic framework that is built upon the identification and definition of four major second-order supersequences (each ~15 m.y. in duration). (5) I document principal facies relations and sequence stratigraphic interpretations with our field data, primarily photographs and measured sections.

REGIONAL SETTING

Northeast Mexico is essentially the juncture of two distinctly different Mexican tectono-stratigraphic provinces, the eastern Gulf of Mexico province and the western Pacific Mexico province, and therefore allows one to compare and contrast Gulf of Mexico versus Pacific tectono-stratigraphic processes. The Monterrey-Salttillo area contains elements related to both Gulf of Mexico passive-margin development (principally the stratigraphy) and to the

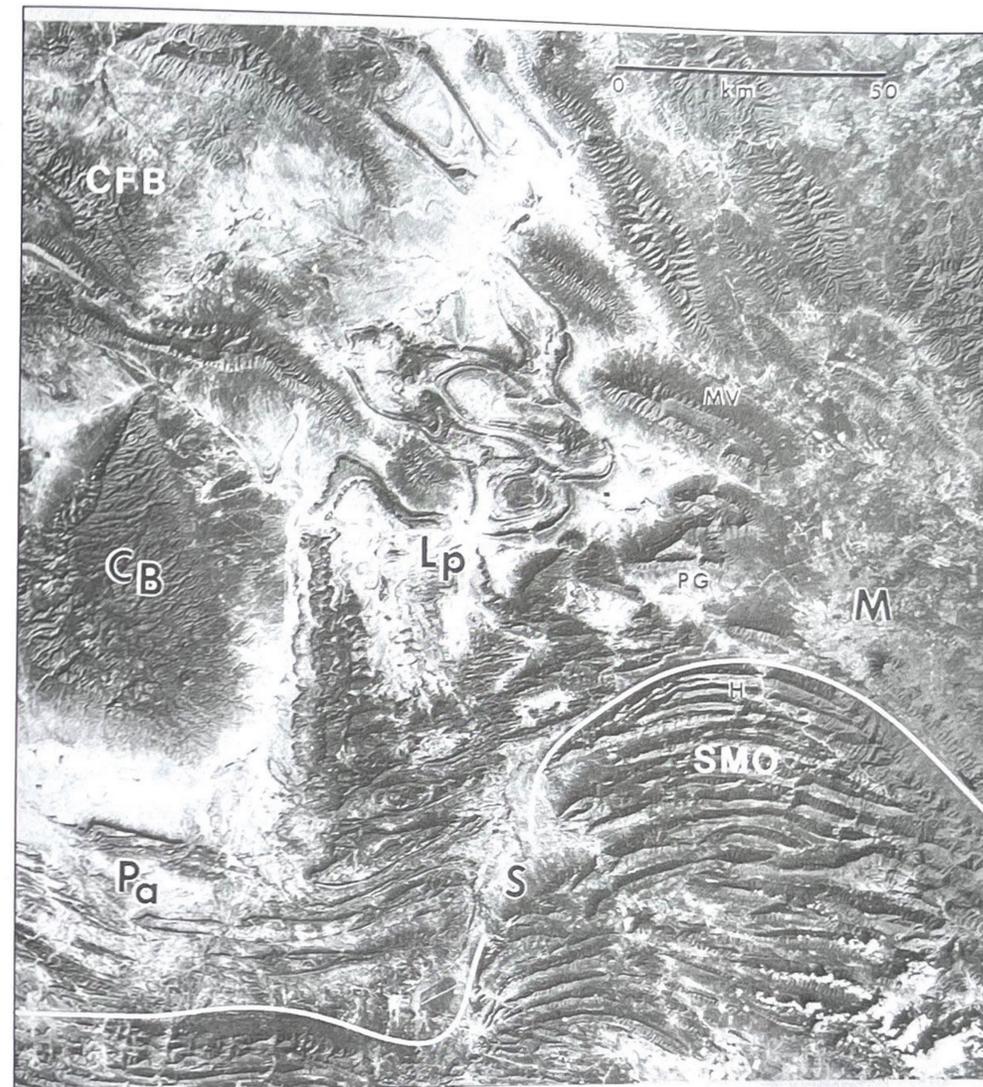


Figure 1. Enhanced Landsat image illustrating major tectonic provinces discussed in text. M—Monterrey, S—Salttillo, CB—Coahuila block, SMO—Sierra Madre Oriental fold belt, CFB—Coahuila folded belt, Pa—Parras basin, Lp—La Popa basin, MV—Potrero Minas Viejas, PG—Potrero García, H—Huasteca Canyon. Scale is in kilometers.

Pacific-related convergent margin (arc) tectonism (chiefly the structure). Therefore it is important to understand the regional tectono-stratigraphic evolution of both the western Pacific Mexico and the Gulf of Mexico provinces. These tectono-stratigraphic provinces are large subregions that have a distinctive and separate tectonic evolution, and different resulting stratigraphic packaging. They are characterized by distinctive structural belts, structural styles, and basement grain (de Cserna, 1989; Sedlock et al., 1993; Moran-Zenteno, 1994). The differing stratigraphies record a sub-regional response to the interaction of provincial tectonics (i.e., convergent versus divergent margins), eustatic changes in sea level, and sediment type and supply.

In northeast Mexico, the Coahuila block more or less separates the western Pacific Mexico province to the northwest and west from the Gulf of Mexico province to the northeast, east, and southeast (Fig. 3). In this chapter, the Gulf of Mexico province

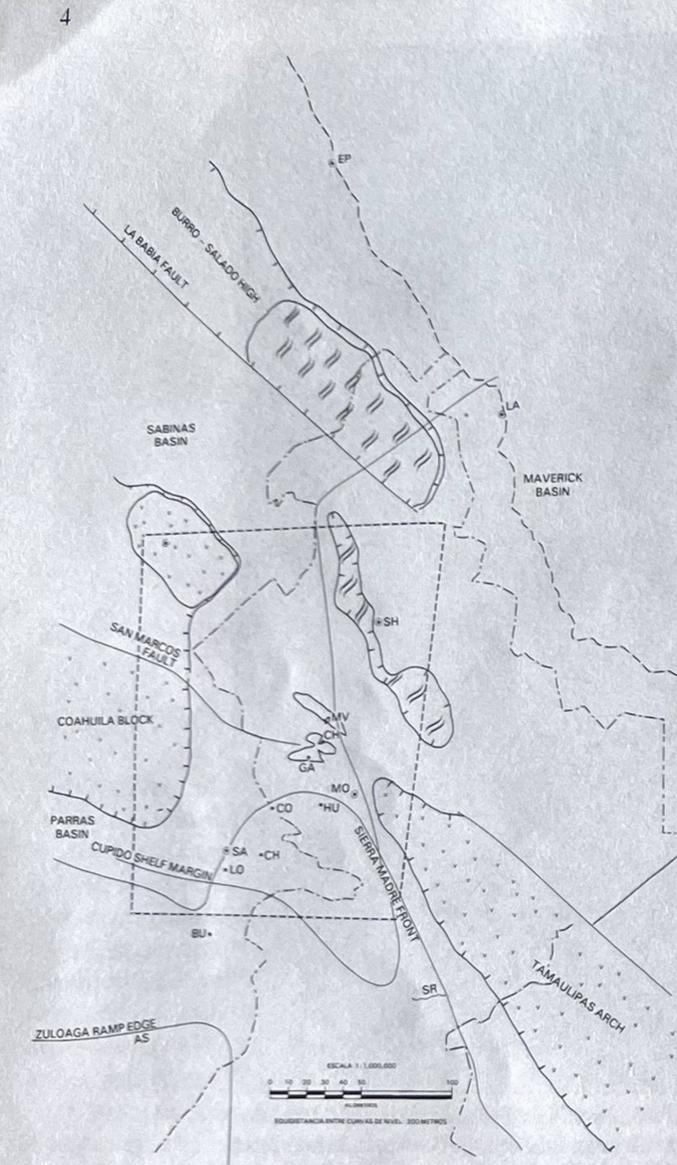


Figure 2. Regional tectonic elements of northeast Mexico (e.g., Tamaulipas arch; see Fig. 5) and location of Landsat image shown in Figure 1 (dashed outline of rectangle). Abbreviations for geographic localities are, from north to south: EP—Eagle Pass; LA—Laredo, Texas; SH—Sabinas Hidalgo; MV—Minas Viejas; CH—Potrero Chico; GA—Potrero García; MO—Monterrey; HU—Huasteca Canyon; CO—Cortinas Canyon; SA—Saltillo; CH—Los Chorros Canyon; LO—San Lorenzo Canyon; BU—Bunuelos; SR—Santa Rosa; AS—Astillero Canyon. Scale is in kilometers.

dominated by passive-margin development associated with the opening of the Gulf of Mexico, overprinted by nonigneous Laramide orogenic effects (Salvador, 1987, 1991a, 1991b, 1991c; Pindell, 1985, 1993; Ross and Scotese, 1988; Pindell et al., 1988; Pindell and Barrett, 1990; Bartok, 1993; Marton and Buffler, 1994). The stratigraphic evolution was dominated principally by eustasy (Todd and Mitchum, 1977; Vail et al., 1984; Haq et al., 1987; Scott et al., 1988; Goldhammer et al., 1991; Scott, 1993; Yurewicz et al., 1993; Lehmann, this volume); thick regional accommodation cycles can be correlated throughout the Gulf of Mexico (Salvador, 1991a, 1991b, 1991c; McFarlan and Menes, 1991; Sohl et al., 1991). For example, Goldhammer et al. (1991) proposed that the Middle Jurassic to Lower Cretaceous stratigraphy of the Gulf of Mexico province can be subdivided into four major, second-order depositional supersequences (~15 m.y. duration), that have regional significance for the Gulf of Mexico. The stratigraphic evolution of the Late Jurassic to Early Cretaceous Gulf of Mexico passive margin was interpreted by Goldhammer et al. (1991) to have resulted from the superimposition of four second-order relative sea-level cycles atop a first-order long-term relative sea-level rise. This first-order relative rise likely reflects a global eustatic rise (Vail et al., 1977) driven by long-term changes in mid-ocean ridge volume related to sea-floor spreading rates associated with the opening of the Gulf of Mexico and the Atlantic Ocean. These two different orders of eustasy operated in concert with underlying thermo-tectonic subsidence to produce systematic changes in accommodation from the base to the top of the Gulf Coast section. Such changes account for the overall shift from lowstand-dominated facies associations characteristic of the Middle to Upper Jurassic rocks (redbeds, evaporites, marginal-marine siliciclastic rocks, and low-relief, shallow-marine high-energy carbonates), to highstand-dominated facies associations characteristic of the Lower Cretaceous (higher relief, shallow-marine carbonate platforms, deep-marine shales, and pelagic carbonates).

The western Pacific Mexico province is distinct from the Gulf of Mexico province in that its style of basin evolution had little to do with Gulf of Mexico tectonic evolution (i.e., rift drift of the Yucatan block), but rather patterns of stratigraphic infill are primarily a function of tectonism related to Mesozoic Pacific tectonism and sediment supply, as opposed to the eustasy-dominated Gulf of Mexico (Cordoba, 1969; Cordoba et al., 1970, 1980; de Cserna, 1970, 1974, 1989; Sewald and Sundeen, 1971; Rangin and Cordoba, 1976; González-García, 1976; Tardy, 1977; Rangin, 1978, 1979; Gastil, 1983; Gastil et al., 1986; Dickinson, 1981; Tóvar Rodríguez, 1981; Roldan-Quintana, 1982; Servais et al., 1982, 1986; Brown and Handschy, 1983; Campa-Uranga and Coney, 1983; Cuévas-Pérez, 1983; Cuévas-Pérez et al., 1985; Marquez-Castaneda, 1984, cited in Moran-Zenteno, 1984; Cantú-Chapa et al., 1985; Campa-Uranga, 1985; Araujo-Mendieta and Arenas-Partida, 1986; González, 1989; Dickinson et al., 1986; Brown and Dyer, 1987; Limon, 1989; Pindell and Barrett, 1990; Sedlock et al., 1993; Moran-Zenteno, 1994; Grajales-Nishimura et al., 1992). Mesozoic subduction along the Pacific margin con-

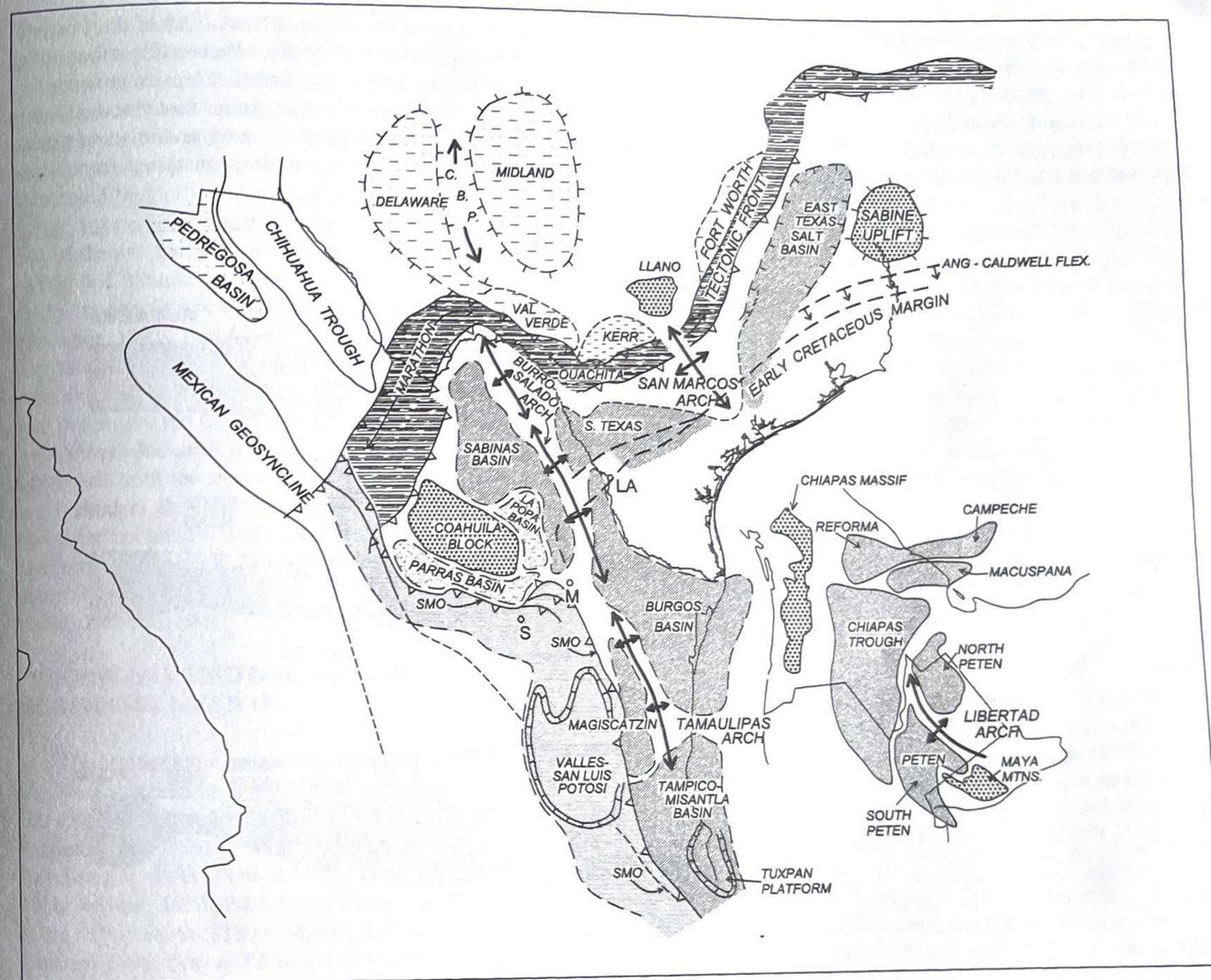


Figure 3. Regional basemap with basin outlines for general area discussed in this paper. Late Paleozoic foreland basins and uplifts include Pedregosa basin, Delaware basin, Central Basin platform, Midland basin, Val Verde basin, Kerr basin, and Fort Worth basin. These Late Paleozoic elements are bounded to south by late Paleozoic Marathon-Ouachita tectonic front. Eastern Gulf of Mexico province (GOM) contains following elements: Sabine uplift, East Texas salt basin, San Marcos arch, south Texas area, Sabinas basin, Burgos basin, Burro-Salado arch, Tamaulipas arch, Magiscatzin basin, Tampico-Misantla basin, Coahuila block, eastern Sierra Madre Oriental (SMO), Valles-San Luis Potosí, and Tamaulipas arch. Western Pacific Mexico province (WPM) includes: Chihuahua trough, Mexican geosyncline, and western Sierra Madre Oriental (SMO). Parras and La Popa basins are Late Cretaceous to early Tertiary foreland basins genetically related to both tectono-stratigraphic provinces. Yucatan elements shown include Chiapas massif, Reforma-Campeche trends, Macuspana basin, Chiapas trough, north and south Peten basins, Maya mountains, and Libertad arch. Yucatan block, which includes south-central Mexico (note outline of present-day coast), Yucatan Peninsula, and parts of Guatemala and Belize (note present-day country outlines), is shown in quasirestored predrift position relative to GOM elements to emphasize their genetic similarity (refer to text). LA—Laredo, Texas; M—Monterrey, Mexico; and S—Saltillo, Mexico.

controlled basin-specific styles of development in the western Pacific Mexico province, where facies development was strongly affected by adjacent arc-related tectonism and sediment supply. During the Mesozoic, the Pacific margin of Mexico was the site of a long-lived plutonic-volcanic arc complex, the Jurassic through Late Cretaceous Sinaloa arc, which was succeeded by the latest Cretaceous Alisitos arc (Tardy, 1977; Servais et al., 1982; Sedlock et al., 1993; Moran-Zenteno, 1994; Grajales-Nishimura et al., 1992). Mesozoic subduction along the Pacific margin con-

1986; Sedlock et al., 1993). The trench axis trended approximately north-northwest-south-southeast.

Johnson (1989), on the basis of ideas distilled from Tardy (1977), de Cserna (1979, 1989), Limon (1989), Cordoba et al. (1980), Dickinson (1981), Servais et al. (1982, 1986), and Araujo-Mendieta and Arenas-Partida (1986), summarized the tectonic development of the western Pacific Mexico province and its relationship to the Gulf of Mexico province (Fig. 4). Following the

6
creation of Pangea in the latest Paleozoic, the western Pacific Mexico province underwent two main tectonic cycles of backarc extension and backarc closure (partial to total) driven by Pacific-related subduction. According to Johnson's (1989) model, the first phase of backarc extension occurred in the Late Triassic to Middle Jurassic, forming the Chihuahua trough and northern Mexican

geosyncline, west of the Coahuila block. East of the Coahuila block, counterclockwise rotation of the Yucatan out of the Gulf of Mexico province tectonic evolution. In the latest Jurassic, partial closure and inversion of the preexisting backarc basin occurred, and in some places, thrusting (e.g., the Zacatecas-Guanajuato thrust front of de

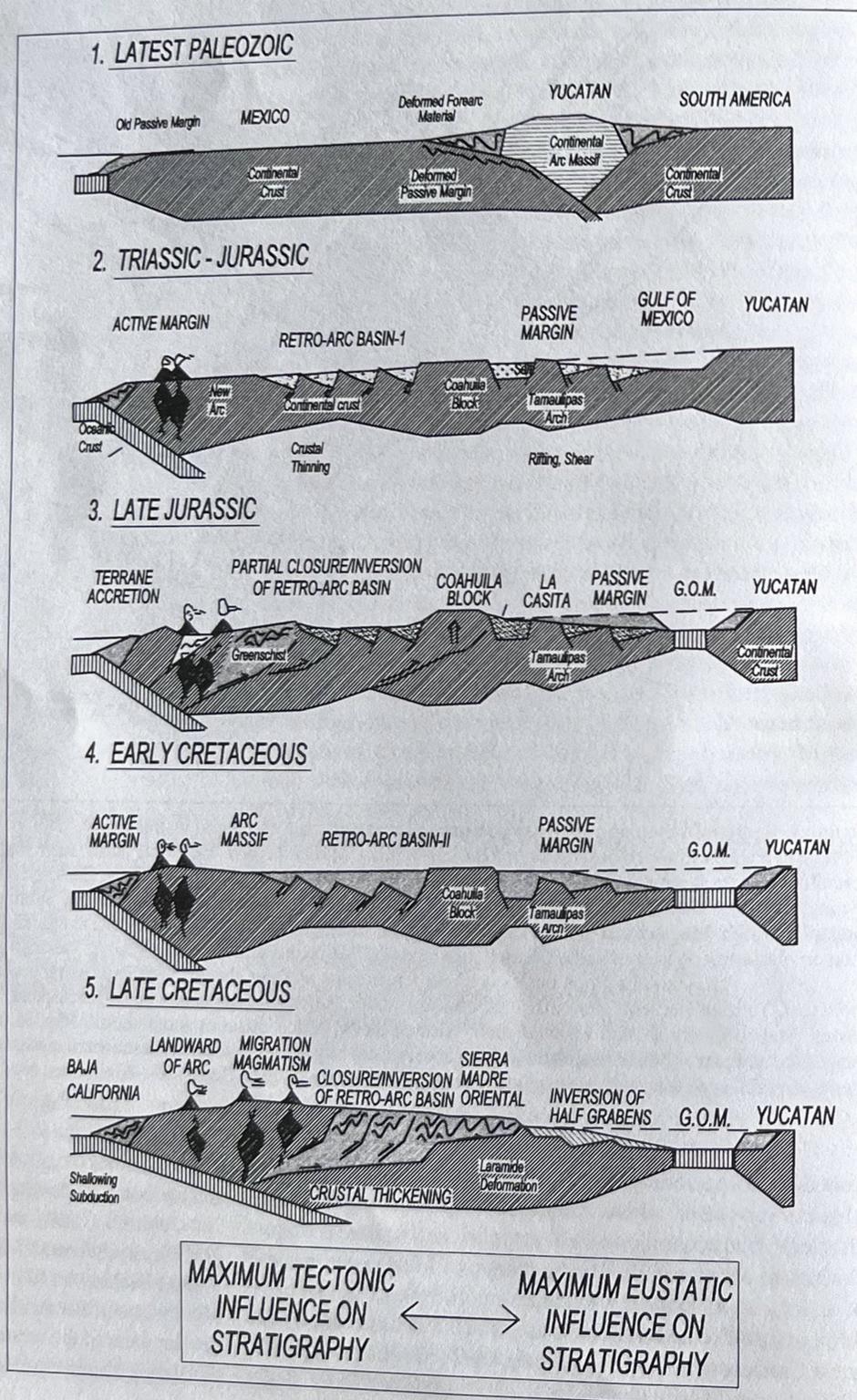


Figure 4. Tectonic model for evolution of western Pacific Mexico province (WPM) and eastern Gulf of Mexico (GOM) province in greater Mexico region. This schematic cross section traverses approximately west-east (from left to right) across northern Mexico. See to text for details.

Cserna, 1989). Johnson (1989) speculated that this event induced deep-seated uplift and reactivation of the Coahuila block, an idea supported by Araujo-Mendieta and Arenas-Partida (1986). Other than Coahuila block reactivation and local triggering of coarse clastic deposition proximal to the Coahuila block, the Gulf of Mexico province preserves little record of this event because it is dominated by Gulf of Mexico specific eustatic patterns. In the Early Cretaceous, the next phase of backarc extension occurred east of the arc and west of the Coahuila block (Fig. 4), rejuvenating the Chihuahua trough and northern Mexican geosyncline, which received thick deposits of volcanoclastic material (e.g., Dickinson, 1981). East of the Coahuila block the Gulf of Mexico province was undergoing passive-margin decelerating subsidence. In the Late Cretaceous, the western Pacific Mexico province underwent the Laramide phase of closure and inversion of the northern Mexican geosyncline and the Chihuahua trough, which had been the sites of Early to middle Cretaceous flysch deposition. In the latest Cretaceous, substantial uplift of the Alisitos arc coincided with regional east-directed uplift and contractional deformation, leading to the formation of the Sierra Madre Oriental fold belt (de Cserna, 1989; Sedlock et al., 1993; Moran-Zenteno, 1994).

PRESENT-DAY TECTONIC ELEMENTS OF NORTHEAST MEXICO

The stratigraphic and structural configuration of northeastern Mexico represents a complex tectonic evolution (Dickinson and Coney, 1980; López-Ramos, 1981; Padilla Sánchez, 1986; Salvador, 1987, 1991a, 1991b, 1991c; Pindell, 1985, 1993; Ross and Scotese, 1988; Pindell et al., 1988; Winker and Buffler, 1988; Wilson, 1990; Pindell and Barrett, 1990; C. A. Johnson et al., 1991; Bartok, 1993; Marton and Buffler, 1993; Moran-Zenteno, 1994; Gray and Johnson, 1995; Ye, 1997). It initiated in the Permian-Triassic with the Ouachita-Marathon orogenic event, followed closely by Late Triassic to Middle Jurassic rifting of Pangea, subsequent opening of the Gulf of Mexico, and passive-margin development through the Late Cretaceous. It culminated with Laramide foreland deformation through the early Tertiary. The structural grain of northeastern Mexico consists of Triassic to Liassic basement fault blocks, the development of which reflects in part late Paleozoic orogenic patterns of metamorphism and igneous intrusion (Wilson, 1990). These early Mesozoic fault blocks in turn controlled Late Jurassic and Cretaceous stratigraphic patterns (Wilson et al., 1984). In addition, these blocks strongly influenced Laramide structural patterns and foreland basin deposition (Charleston, 1981; Wilson, 1990; Johnson, 1989; C. A. Johnson et al., 1991; Soegaard et al., 1997).

Tectonic provinces

Present-day tectonic provinces with distinctive stratigraphic and structural characteristics are readily defined in the Monterrey-Salttillo area through analysis of Landsat images and

examination of regional geologic maps (Figs. 1 and 2; Humphrey, 1956; Murray, 1959; McBride et al., 1974; Charleston, 1981; Mitra-Salazar, 1981; Padilla Sánchez, 1982; Wilson, 1990; McKee et al., 1990; Goldhammer et al., 1991; C. A. Johnson et al., 1991).

Province 1. The Coahuila block (Figs. 1, 2, and 5) is characterized by a broad, southeast-plunging anticlinal dome that reflects low-intensity Laramide deformation of predominantly Cretaceous carbonates (Imlay, 1936; Charleston, 1981; Johnson, 1989; C. A. Johnson et al., 1991; Lehmann, this volume). This shallow, rigid basement block is held up primarily by Permian-Triassic granite to granodiorite intrusions (Wilson et al., 1984). These intrusions represent the roots of an island arc system which was created south of the Ouachita-Marathon orogenic belt by closure of Gondwana and North America and was stranded by subsequent rifting (Pindell and Dewey, 1982; Pindell, 1985; Wilson, 1990). Farther west, in the vicinity of Las Delicias, the block contains a thick (4000 m) Middle Pennsylvanian to Permian flysch and volcanoclastic succession (Wilson, 1990) that most likely represents the southern continuation of the Ouachita-Marathon orogenic trend (island arc assemblage). This trend was displaced to the southeast via left-lateral transform faulting associated with Late Triassic to Late Jurassic extension of northeastern Mexico during the opening of the Gulf of Mexico (Anderson and Schmidt, 1983; Wilson et al., 1984; Pindell, 1985). The block is bounded on the north by the San Marcos fault (Figs. 1, 2, and 5; Charleston, 1981), a left-lateral bounding structure of post-Paleozoic age, presumably active during Late Triassic to Late Jurassic extension and rifting of northeastern Mexico. The Coahuila block was a persistent Mesozoic basement high that had a strong influence on Upper Triassic through Cretaceous facies and stratigraphy. It contains no rift-related Upper Triassic siliciclastic rocks or Callovian evaporites (González-García, 1976; Padilla Sánchez, 1986; Wilson, 1990).

Province 2. The Sierra Madre Oriental fold and thrust belt is of Laramide age (Late Cretaceous to Eocene). The evolution of the fold belt and structural complexities have been discussed by numerous workers (e.g., de Cserna, 1956; Humphrey, 1956; Tardy et al., 1975; Padilla Sánchez, 1982; Campa-Uranga, 1985; Quinterro-Legoretta and Aranda-García, 1985; Suter, 1987; Aranda-García, 1991; Marret, 1995; Gray and Johnson, 1995). The belt is characterized by elongate anticlines that trend east-west (to the west) are arcuate, and curve to the south (farther east). The anticlines have very steep, vertical limbs, and some are overturned to the north (Figs. 1 and 2). Folds are arranged in a series of nappes and may be bounded by thrusts (Johnson, 1989). The deformed section consists of essentially the entire Upper Triassic to Cretaceous rift to passive-margin sequence. Major topics of debate and study include (1) the role of Callovian(?) salt as a basal detachment surface, (2) the contribution of preexisting rifted basement terrain to fold-belt geometry and structural style, (3) mechanisms of fold genesis (fault propagation versus fault-bend folding), (4) the presence of thrusting, (5) amount of lateral shortening, and (6) overburden above the fold belt (e.g., Prost et al., 1994; Gray and Johnson, 1995; Marrett, 1995). The eastward

R. K. Goldhammer

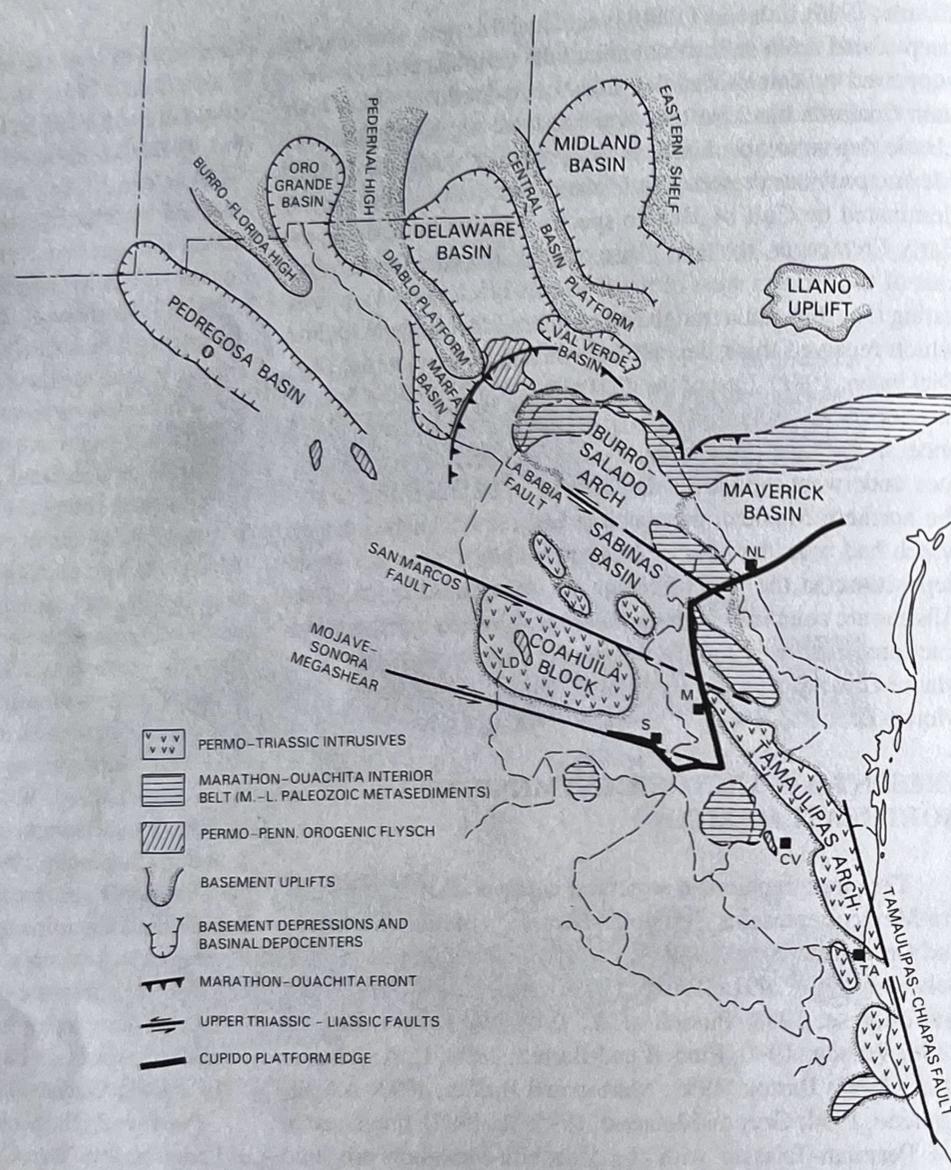


Figure 5. Detailed paleotectonic map of northeastern Mexico, southwest Texas, and southern New Mexico illustrating major tectonic features referred to in text. Abbreviations for Mexican cities: NL—Nuevo Laredo; TA—Tampico; CV—Ciudad Victoria; S—Saltillo; M—Monterrey. From Goldhammer et al. (1991). Mexican state outlines are also shown.

and northward advance of thrust sheets was perhaps facilitated by the occurrence of underlying thick Middle Jurassic (Callovia) salt, which was deposited in restricted rift-generated troughs (C. A. Johnson et al., 1991). One of these troughs was situated between the southeast margin of the Coahuila block and northwestern margin of the uplifted Tamaulipas arch (Monterrey trough, Fig. 3; Wilson et al., 1984).

Farther to the south within the fold and thrust belt, near Ciudad Victoria, displaced relicts of the Ouachita-Marathon orogenic belt crop out in the form of deformed Permian-Carboniferous metasedimentary rocks and lower Permian flysch (Fig. 5; Anderson and Schmidt, 1983; Pindell, 1985; Wilson, 1989). To explain these outcrops and other relicts of similar age in northeastern Mexico, Anderson and Schmidt (1983) postulated the existence of a major left-lateral transform fault of Late Triassic to Middle Jurassic age, the Mojave-Sonora megashear. This fault is hidden

beneath the deformed belt, but is believed to be located north of Ciudad Victoria and south of the Coahuila block (Fig. 5). Fault offset on the order of 800 km is postulated in order to restore these displaced Ouachita-Marathon relicts northwest to the orogenic front. This strike-slip fault and others of similar age and displacement to the north and east (e.g., the Torreon-Monterrey fault of de Cserna, 1970; the Rio Grande lineament of Pindell, 1985) are considered to have served as major intracontinental transform faults during the Late Triassic through Middle Jurassic attenuation of continental Mexico. These faults are essential in Pangaea reconstructions of the pre-rift Gulf of Mexico to avoid overlap of eastern Mexico with the South American plate (Anderson and Schmidt, 1983; Pindell, 1985). The megashear is considered to be a plate boundary between the early Mesozoic Yaqui plate to the south (Anderson and Schmidt, 1983; Pindell, 1985) and the North American plate to the north.

Province 3. The Coahuila folded belt is of Laramide age (Humphrey, 1956; Murray, 1959; McBride et al., 1974; Charleston, 1981; Mitra-Salazar, 1981; Padilla Sánchez, 1982) and consists of numerous isolated, northwest-southeast-oriented, elongated and tightly compressed anticlines separated by broad synclinal valleys (Figs. 1 and 2). Characteristic features of this belt are doubly-plunging, evaporite-cored, breached anticlines (Potreritos) that expose Callovian(?) evaporites through middle Cretaceous carbonates (Figs. 1 and 2). Due to the fact that intrusive effects of Middle Jurassic evaporites are observed in the anticline cores, many consider their origin partly due to evaporite diapirism (Murray, 1959; Weidie and Martínez, 1970; Laudon, 1984). The Coahuila folded belt contains important Mesozoic basement features that influenced sedimentation patterns (González-García, 1976; Padilla Sánchez, 1986; Wilson, 1990). These include (Figs. 1, 2, and 5): (1) a basement depression that marks the Mesozoic Sabinas basin, located north and northeast of the Coahuila block; (2) the northwest-southeast-trending Burro-Salado arch to the north; and (3) the northwest-southeast-trending Tamaulipas arch to the east. The Sabinas basin contains a thick (6000 m) section of Jurassic and Cretaceous strata, and developed initially as a rift-related trough between two basement highs, the fault-bounded Coahuila block to the south and the Burro-Salado arch to the northeast (González-García, 1973, 1976, 1979, 1984; Padilla Sánchez, 1978, 1986; Alfonso-Zwanziger, 1978; Eguilez de Antuñano and Aranda-García, 1983, 1984; Echanove, 1986). Within the Sabinas basin there are a few Permian-Triassic granite intrusive areas (e.g., the La Mula and Monclova uplifts; Jones et al., 1984; Wilson, 1990) that probably served as local basement highs (Fig. 5). Like the Coahuila intrusives, these also reflect the remnants of a Permian-Triassic island arc.

The Burro-Salado arch (Figs. 1, 2, and 5) contains basement of deformed late Paleozoic metasedimentary rocks presumed to have formed within the interior belt of the Ouachita-Marathon orogenic belt that developed south of the suture (Flawn et al., 1961; Wilson et al., 1984; Pindell, 1985). Handschy et al. (1987) suggested that the arch might be a piece of accreted Yucatan stranded during later rifting. The arch is bounded on its southwest border by a left-lateral fault, the La Babia fault (Charleston, 1981), which was most likely an active strike-slip fault during Late Triassic to Middle Jurassic continental rifting of northeastern Mexico. The Burro-Salado arch forms a slightly offset continuation of the northwest-trending Tamaulipas arch located to the southwest (Wilson, 1990). The Tamaulipas arch (San Carlos Island of Alfonso-Zwanziger, 1978) is supported by Permian-Triassic intrusive basement (remnants of the late Paleozoic island arc) and trends parallel to the Rio Grande southeast from Monterrey to Tampico (Wilson, 1990). It is bounded on the east by a major right-lateral fault, the Tamaulipas-Chiapas fault (Fig. 5; Pindell, 1985; Wilson, 1990). Pindell (1985) stated that the Tamaulipas trend and this bounding fault extend along the eastern Mexican margin from Tampico south past the Golden Lane high and offshore at Veracruz. The Arenque field at Tampico is located

on this structure. Pindell and Dewey (1982) and Pindell (1985) concluded that the major bounding fault on the east was a right-lateral transform fault between the Yucatan plate and the southwestern tip of the North American plate, that allowed migration of Yucatan away from the Texas-Louisiana margin during formation of the Gulf of Mexico. The linearity of the trend and the fact that the Tamaulipas arch was a basement high from the Late Triassic to Late Jurassic (Wilson et al., 1984) support a strike-slip interpretation (Pindell, 1985).

Province 4. Late Cretaceous foreland basins include the Parras and La Popa basins (Figs. 1, 2, and 5). The Parras basin is confined between the Coahuila block and the Sierra Madre front. The northern limit of this basin is marked by the San Marcos fault. The La Popa basin is north of the Parras basin and is flanked to the east and west by the Coahuila folded belt. These basins contain nearly 5000 m of Campanian to Maastriichtian shallow-marine and deltaic terrigenous siliciclastic rocks of the Difunta Group (Weidie and Murray, 1967; Laudon, 1975, 1984; McBride et al., 1974; Soegaard et al., 1997). The structures in the Parras basin are of Laramide age and are highly variable depending on proximity to the Sierra Madre front (Weidie and Murray, 1961; C. A. Johnson et al., 1991). South of the Coahuila block deformation is more intense, marked by highly elongate, northward overturned, tight folds and minor thrusting, with axes parallel to the Sierra Madre front. Farther north and east, the intensity of deformation decreases with distance from the frontal detachment, and structures are elongated open folds. Structures in the La Popa basin consist of broad domal uplifts, salt-involved domes and diapirs, and withdrawal synclines (Johnson, 1989).

MESOZOIC TECTONIC DEVELOPMENT OF NORTHEAST MEXICO

The Gulf of Mexico depicts a Mesozoic divergent margin basin formed through rifting and extension of Pangea, followed by breakup, sea-floor spreading, and migration of variously cooling and thermally subsiding tectonic plates (Ball and Harrison, 1969; Walper and Rowett, 1972; Dickinson and Coney, 1980; Pilger, 1981; Pindell and Dewey, 1982; Anderson and Schmidt, 1983; Buffler and Sawyer, 1985; Pindell, 1985, 1993; Salvador, 1987, 1991a; Pindell et al., 1988; Ross and Scotese, 1988; Pindell and Barrett, 1990; Marton and Buffler, 1994). The various proposed scenarios differ primarily in initial plate configurations (e.g., initial position of the Yucatan plate), plate motions (clockwise vs. counterclockwise rotation of Yucatan during breakup), the significance of major intracontinental transforms in Mexico, and the amount of attenuation of continental crust during rifting (e.g., cf. Buffler and Sawyer, 1985; Pindell, 1985). It is beyond the purpose and scope of this chapter to review or resynthesize the tectonic model for the Gulf of Mexico, but for the sake of placing northeast Mexico into a larger tectonic framework, a brief synopsis follows. Readers should refer to Pindell (1985) and Pindell and Barrett (1990, Plate 12).

Late Paleozoic reconstruction of Pangea

The structural pattern of basement blocks that was to influence later Mesozoic stratigraphy in northeastern Mexico largely reflects the effects of Late Mississippian to Early Permian, Ouachita-Marathon suturing of the North American, South American, and Yucatan plates (Salvador and Green, 1980; Pindell and Dewey, 1982; Wilson, 1990). Convergent orogeny was achieved with ocean closure during continent-continent collision, whereby Yucatan filled the gap between North America to the north and west and South America to the south (Pindell, 1985; Pindell and Barrett, 1990, and figures therein). Resultant accretionary complexes (e.g., Marathon-Ouachita terrains) are marked by metamorphosed and unmetamorphosed Permian-Carboniferous continental rise and slope sediments and orogenic flysch thrust up onto North American shelf sequences (Pindell and Dewey, 1982). Other complexes include displaced relicts located in northeastern Mexico (i.e., the Las Delicias and Ciudad Victoria localities mentioned here). The positions of these accretionary complexes (Figs. 3 and 5) and associated thrust-loaded foreland basins (e.g., the Val Verde, Marfa and Pedregosa basins located north and northwest of the Monterrey-Salttillo area) suggest southeast-dipping subduction of the North American plate (Pindell, 1985). The location of the suture zone in northeastern Mexico is believed to be between the Marathon belt and the zone of Permian-Triassic intrusive rocks that underlie the Coahuila block and southern Sabinas basin (Fig. 5). These granites and granodiorites are the remnant roots of an island arc system developed south of the continental suture (Pindell and Dewey, 1982; Pindell, 1985; Wilson, 1990).

Late Triassic to Callovian rift stage

Rifting and initial segmentation of Pangea (Pilger, 1981; Pindell, 1985; Buffler and Sawyer, 1985) is evidenced by attenuated basement in northeastern Mexico expressed as basement highs (Coahuila block, Burro-Salado arch, Tamaulipas arch) and lows (Sabinas and Magascatzin basins, the Monterrey trough). Basement features were often bounded by left-lateral, Late Triassic to Liassic strike-slip faults cutting across the strike of Permian-Triassic deformation and intrusion. Strike-slip faulting in conjunction with normal faulting generated rift grabens and half grabens that controlled the distribution of succeeding facies. Rift-related sedimentation and igneous activity accompanied this intracontinental block faulting (Pindell and Dewey, 1982; Wilson et al., 1984; Salvador, 1987; Salvador, 1991a, 1991b, 1991c; Wilson, 1990; Goldhammer et al., 1991). The rift sequence consists of a redbed sequence, the thickness of which (300 to 1000 m) is related to preservation in rift grabens (Upper Triassic to Middle Jurassic Huizachal Group), in addition to evaporites (to 1000 m thick), complemented by intrusive veins and dikes of rhyolitic to andesitic composition (Wilson et al., 1984; Salvador, 1987, 1991a, 1991b, 1991c; Wilson, 1990). The rifting stage lasted until the earliest Oxfordian; subsidence anal-

ysis (Goldhammer et al., 1991, Figs. 12 and 13) constrains the rift to drift transition at 150.5 Ma.

Counterclockwise rotation and southerly transport of the Yucatan block initiated about this time along the dextral, Tamaulipas-Chiapas transform (Pindell, 1985), and major intraplate motions occurred via left-lateral movement along the Mojave-Sonora megashear (Anderson and Schmidt, 1983), which trends along the southern edge of the Coahuila block (Fig. 5). Bajocian to Callovian movement along the megashear (and other intracontinental zones of left-lateral offset) involving displacements of several hundred kilometers allowed blocks of Cordilleran Mexico to migrate along with South America during initial breakup. This motion maintained an effective land bridge between North and South America until the Callovian, preventing any influx of Pacific seawater into rift basins. Pindell (1985) speculated that this sinistral movement in Mexico was driven by oblique subduction of the Kula-Farralon plate beneath the Yaqui and South American plates. This subduction zone, as evidenced by a calc-alkaline volcanic arc located to the northwest and west of northeastern Mexico, was persistent from Late Triassic through Late Jurassic time (Pindell and Dewey, 1982).

Upper Jurassic drift stage

Sea-floor spreading in the Gulf of Mexico began in the earliest Oxfordian (Buffler and Sawyer, 1985; Pindell, 1985) as the Yucatan block migrated essentially to the southern tip of the Tamaulipas arch. As motion along this fault ceased, the Tamaulipas arch subsided and was eventually overlapped by Upper Jurassic carbonates. To the west, southeastward transport of Mexican continental blocks along sinistral intracontinental transforms ceased during the Oxfordian; the Zuloaga Formation masks the megashear and is not offset by the fault zone (Pindell, 1985). Salt deposition in the Gulf of Mexico terminated as circulation of near-normal marine seawater was established. Pindell (1985) linked this early Gulf of Mexico freshening to the formation of a mid-oceanic ridge system, which split the Callovian salt basin into two separate salt provinces (i.e., the Louann and Campeche salt provinces; Buffler and Sawyer, 1985; Pindell, 1985; Salvador, 1987, 1991a, 1991b, 1991c). During the drift stage, spreading accounted for continued separation between the Texas Gulf of Mexico and Yucatan, which ceased during the Berriasian (Buffler and Sawyer, 1985; Pindell, 1985), at which point separation of North and South America was concentrated in the proto-Caribbean, where sea-floor spreading continued (Pindell and Barrett, 1990).

Deposition of Oxfordian strata above the breakup unconformity at 150.5 Ma was not controlled by primary rifting, but rather by differential subsidence between adjacent basement blocks within a thermally subsiding margin. For example, depositional patterns of Oxfordian and Kimmeridgian nearshore clastic facies (La Gloria Formation, discussed in the following) and offshore shoal-water carbonate facies (Zuloaga and San Andres Formations) were a direct function of proximity to base-

ment highs and topographic islands. The Tamaulipas arch in particular subsided into an irregular mosaic of islands which were surrounded by nearshore siliciclastic sediments and high-energy carbonate grainstones that grade offshore into lower energy, argillaceous micritic carbonates that mark basement lows (Wilson, 1990). Differential subsidence was also influenced in part by migration of underlying evaporite, analagous to the U.S. Gulf Coast (Pindell, 1985). This is confirmed in northeastern and eastern Mexico by consideration of regional Callovian to Kimmeridgian stratigraphic development and facies patterns, characterized by rapid lateral changes in facies complemented by abrupt variations in thickness (Salvador, 1987, 1991a, 1991b, 1991c; Wilson, 1990). Tithonian to Berriasian sedimentation primarily reflected a reduced influence of preexisting basement highs, with the exception of the Coahuila block in northeastern Mexico. Here, extensive clastic deposits (non-marine to nearshore marine La Casita Formation, discussed in the following) derived from the Coahuila block filled in remaining depositional lows, whereas offshore areas distal from the Coahuila block accumulated shales and deeper water carbonates (La Caja and Taraises Formations). At this time the Tamaulipas arch and Burro-Salado high had subsided and were no longer yielding exposed islands and only indirectly influencing facies distribution.

Cretaceous cooling stage

Horizontal plate motions associated with the opening of the Gulf of Mexico were completed by the Berriasian. At this time the northeastern Mexican passive-margin underwent continued decelerating tectonic subsidence and crustal cooling. Throughout most of this period extensive carbonate platforms with cumulative shelf thicknesses of about 2000 m developed around the entire Gulf of Mexico. This trend was punctuated by minor pulses of clastic sedimentation in the Sabinas basin in the Aptian (Patula Arkose; La Peña shale) and in the Maverick basin in the Albian (McKnight facies) related to second-order relative sea-level effects. In the larger scheme, however, terrigenous siliciclastic sedimentation was restricted to the arc systems bounding the Pacific realms (Pindell, 1985). The Coahuila block remained a basement high, but was no longer exposed and supplying siliciclastic sediments. Instead, it controlled the distribution and progradational patterns of carbonate facies (Wilson et al., 1984).

PALEOGEOGRAPHY AND STRATIGRAPHIC FRAMEWORK

In this section I review the stratigraphic and paleogeographic evolution of the northeast Mexico region by presenting a series of paleogeographic maps coupled with an integrated chronostratigraphic framework for the Mesozoic of both northeast Mexico and subsurface equivalents in the Texas Gulf Coast. The chronostratigraphic chart (Fig. 6) is modified from the version published by Goldhammer et al. (1991). In addition to the

44 sources originally cited by Goldhammer et al. (1991) used to construct the chart, the following additional references were incorporated in modifying it to its present state (Márquez, 1979; Scott et al., 1988; Salvador, 1991a, 1991b, 1991c; Salvador and Muñeton, 1991; McFarlan and Menes, 1991; Sohl et al., 1991; Wilson and Ward, 1993; Basáñez-Loyola et al., 1993; Cantú-Chapa, 1993; Scott and Warzeski, 1993, cited in Scott, 1993; Yurewicz et al., 1993; Scott, 1993; Marton and Buffler, 1994; Moran-Zenteno, 1994; Lehmann, this volume; Michalzik and Schumann, 1994; Kerans et al., 1995). The chronostratigraphic chart (Fig. 6) depicts formational stratigraphy, major facies relations, and the second-order sequence stratigraphic framework used in this study. As summarized herein, the Middle Jurassic to Lower Cretaceous stratigraphy of the Gulf of Mexico province can be subdivided into four major second-order depositional supersequences (~15 m.y. duration), that have regional significance. The chronostratigraphy is tied to the Haq et al. (1987) time scale; we emphasize that, throughout this chapter the ages of the sequences and their boundaries are uncertain.

Owing to the structural deformation within the Monterrey-Salttillo area, original large-scale stratigraphic geometries are lacking. However, in south Texas and in the East Texas salt basin, ample two-dimensional seismic coverage allows the visualization of essentially undisturbed stratigraphic architecture of age-equivalent strata and enables the reconstruction of original stratigraphic geometries and relations in northeast Mexico (e.g., Todd and Mitchum, 1977; Bebout and Loucks, 1977). Utilizing these age-equivalent subsurface analogs from the Texas Gulf Coast, one can schematically portray the predeformed general sequence architecture and facies relationships for northeast Mexico (Fig. 7). This schematic is based upon regional seismic data from south Texas and east Texas, and biostratigraphically constrained regional well-log cross sections from south Texas and extreme northeast Mexico (see Goldhammer et al., 1991, Figs. 31-37; see also regional cross sections in McFarlan and Menes, 1991).

An excellent example of such data is displayed in Figure 8, which shows a relatively undeformed regional seismic dip line from a two-dimensional survey in south Texas. This northwest-southeast-trending line is <24 km from the Texas-Mexico border and parallels the Rio Grande River. Figure 9 is a line drawing of the seismic data with the stratigraphic interpretation, constrained by unpublished biostratigraphic data and well-log control. The implications of this seismic section are discussed in full later, but it is introduced here to support the reconstructed stratigraphy proposed for northeast Mexico in Figure 7.

With the framework provided by Figures 6 and 7, I now investigate in some detail the Mesozoic stratigraphy and facies development of northeast Mexico principally by using a series of paleogeographic maps. These maps are based on a distillation of many of the literature sources cited earlier in the text, and those citations following. However, some unpublished subsurface data were incorporated, particularly for some of the Texas Gulf Coast portions of the maps; these data include unpublished gravity and magnetic data, seismic data, and well-log information. Many

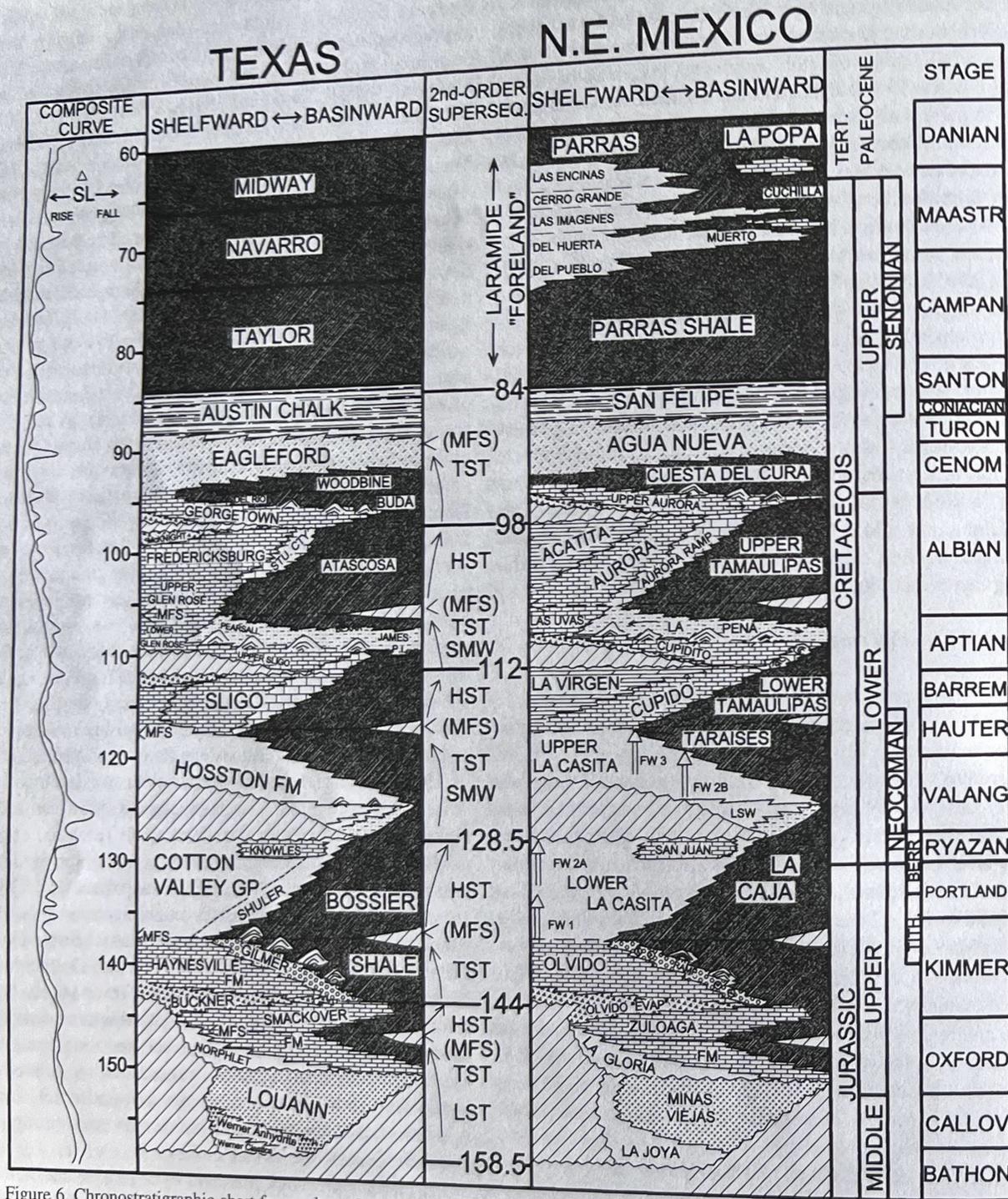


Figure 6. Chronostratigraphic chart for northeast Mexico and Texas Gulf Coast, modified from Goldhammer et al. (1991). Composite eustatic sea-level curve is from Haq et al. (1987). Second-order supersequences are defined in text. Abbreviations as follows: LST—lowstand wedge; SMW—shelf margin wedge. Second-order sequence boundary ages (e.g., 112) are approximations (ages are in Ma). Formation lithologies are discussed in text. Pinnacle reef and isolated carbonate buildups are depicted as small domes with internal concited by Fortunato and Ward (1982). See text for details.

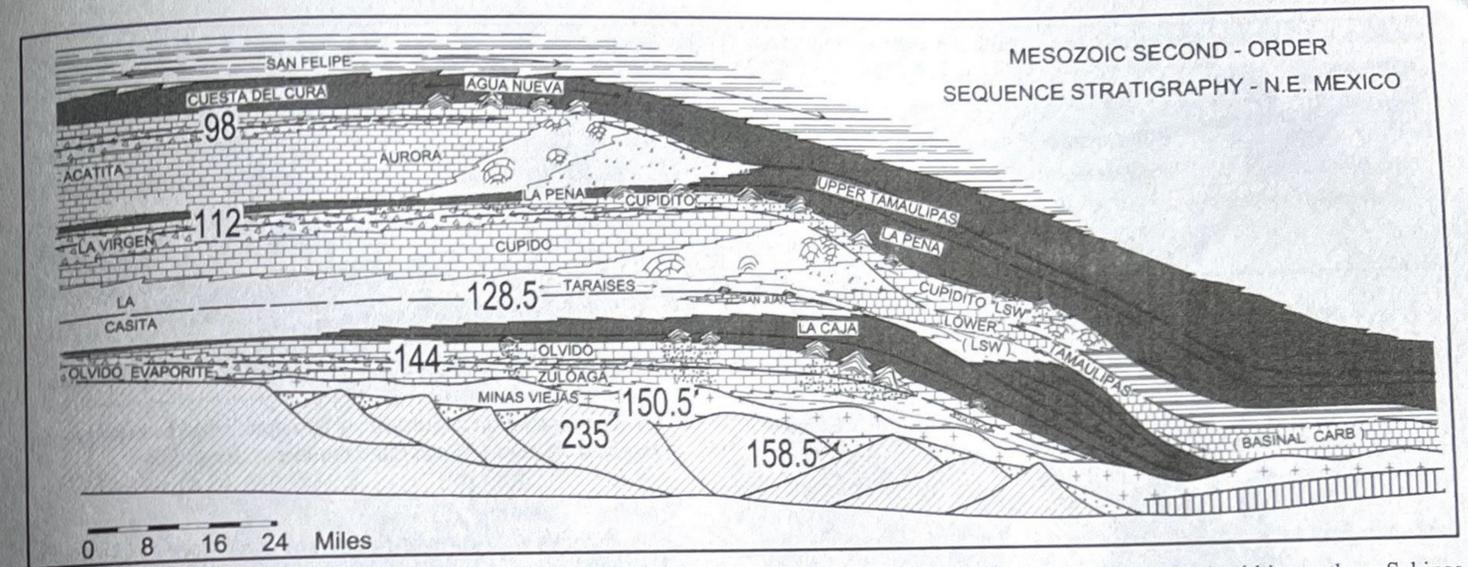


Figure 7. Schematic, dip-oriented regional restored cross section trending north-northwest to south-southeast (left to right) within southern Sabinas basin to south Texas area. Horizontal scale is approximate and no vertical scale is implied, although vertical thicknesses are relatively correct. Formational stratigraphy and lithologies are described in text. Major second-order supersequence boundaries are shown (approximate ages are in Ma). Major second-order supersequences are defined as large-scale basin-fill cycles marked by regionally correlative facies patterns of retrogradation and progradation. See text for details.

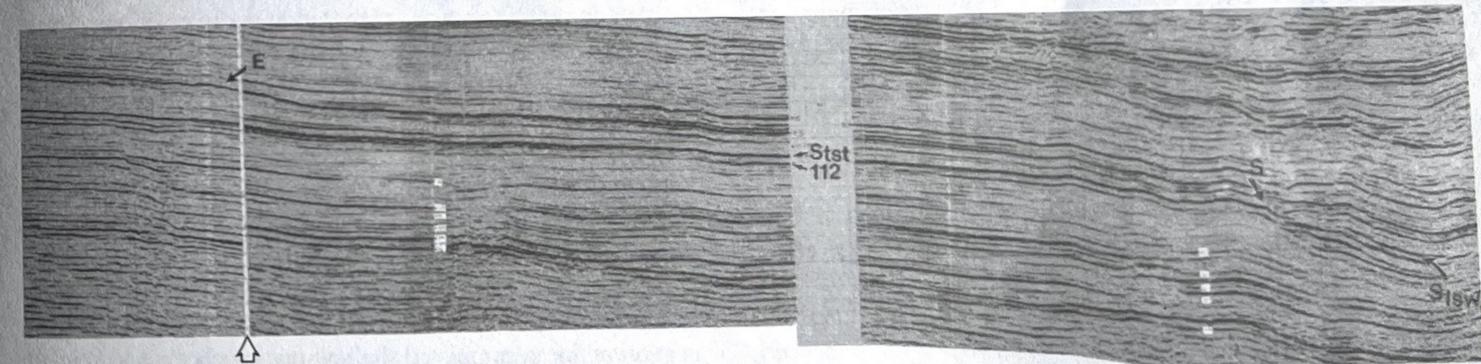


Figure 8. Regional two-dimensional seismic line from south Texas showing relatively undeformed dip-oriented stratigraphy. Northwest-southeast-trending line is <24 km from Texas-Mexico border and parallels Rio Grande River. In detail line consists of two closely spaced parallel lines spliced together. Splice is located right of E on line, accounting for lack of continuity in some reflectors in lower half of line across splice. Vertical scale is in two-way traveltime (0.10 intervals). Due to proprietary nature of this industry line, two-way traveltime and horizontal shot-point information are not shown. E shows location of Albian Edwards terminal shelf margin, S is Barremian-lower Aptian Sligo margin, Stst is top Sligo second-order transgressive systems tract of 98 Ma supersequence, 112 is 112 Ma supersequence boundary, and S1sw is Sligo second-order lowstand wedge. See line drawing in Figure 9.

authors have published Mesozoic paleogeographic reconstructions for portions of Mexico and the U.S. Gulf Coast over the past 50 yr, from Imlay (1936) to Salvador (1991a) and Moran-Zenteno (1994), and each has emphasized different aspects of the reconstruction. The primary goal of the maps presented here is to place the tectonic and sequence stratigraphic evolution of northeast Mexico in a more regional framework.

Late Triassic to Middle Jurassic (pre-Callovian)

In the Late Triassic to Middle Jurassic, the western Pacific Mexico and Gulf of Mexico provinces were characterized by a

complex pattern of basement highs and lows (Fig. 10). Mexican basement trends are based on published sources, whereas the Texas basement grain is simplified from more detailed, proprietary gravity and magnetic interpretation provided to the authors (J. Witte, 1997, personal commun.). Basement highs occurred in the form of (1) fault-bounded uplifted blocks composed of Permian-Triassic basement (e.g., the Coahuila block); (2) positive anticlinoria cored by Precambrian basement (e.g., Huizachal-Peregrina anticline; Woods et al., 1991); (3) regional north-northwest-south-southeast-trending anticlinal arches, cored by complex metamorphosed Paleozoic rocks (e.g., the Burro-Salado-Picachos trend); (4) regional north-northwest-south-south-

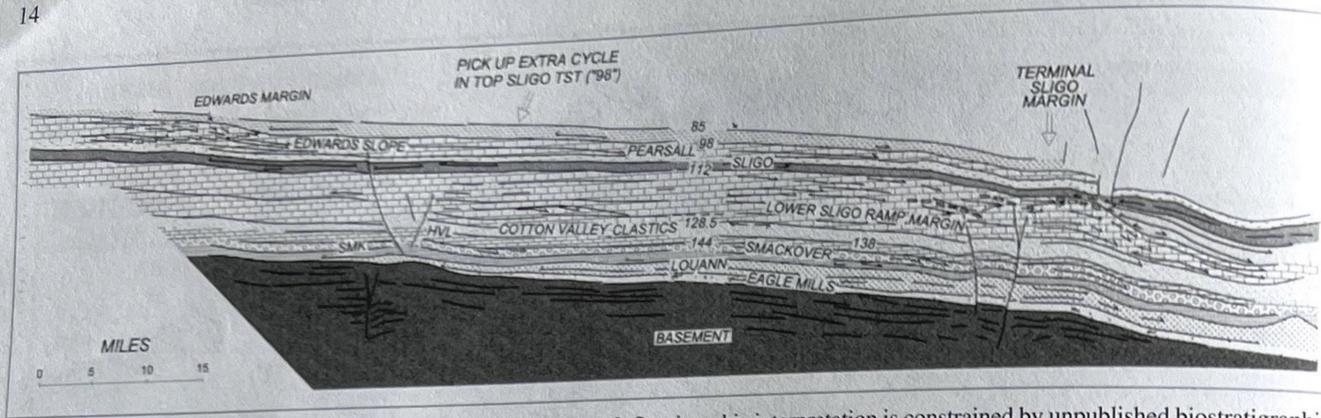


Figure 9. Line drawing of interpretation of seismic line shown in Figure 8. Stratigraphic interpretation is constrained by unpublished biostratigraphic data and industry well-log control. SMK refers to Smackover Formation, HVL is Haynesville, and 144 and other numbers refer to Ma.

east-trending anticlinal arches, cored by Permian-Triassic intrusives (e.g., the Tamaulipas arch; López-Ramos, 1972); and (5) broad, widespread positive areas such as the Llano uplift. Basement lows occurred as (1) fault-bounded rift grabens with synrift fill (e.g., redbed facies in the Huayacocotla anticlinorium; Salvador, 1991b); (2) regional north-northwest-south-southeast-trending lows or troughs (e.g., the Monterrey trough); or (3) irregularly shaped depressions bounded by smaller basement highs (e.g., the East Texas salt basin). The Chihuahua trough and incipient(?) Mexican geosyncline are interpreted to be backarc lows or extensional basins driven by Pacific arc effects. The basement lows northeast, east, and southeast of the Coahuila block are interpreted to owe their genesis to Gulf of Mexico rifting.

During this period, redbeds and associated volcanics accumulated within fault-bounded graben systems around the entire Gulf of Mexico (Stone, 1975; Todd and Mitchum, 1977; Salvador, 1987, 1991a, 1991b). In northeastern Mexico, these deposits compose the Huizachal Group, to which Mixon et al. (1959) assigned a Late Triassic age. Mixon et al. (1959) subdivided the Huizachal Group into the lower La Boca and upper La Joya formations (Fig. 6). The La Boca Formation (late Carnian to mid-Pliensbachian) correlates to the Eagle Mills Formation (Stone, 1975; Todd and Mitchum, 1977; Salvador, 1987, 1991a, 1991b), and consists of nonmarine redbeds, arkoses with volcanic flows, and igneous dikes and sills of rhyolite to andesite or diabase and/or basalt composition (Fig. 11A-D; Corpstein, 1974; Padilla Sánchez, 1982). The redbeds represent nonmarine alluvial fan, fluvial, and lacustrine depositional settings (Corpstein, 1974; Padilla Sánchez, 1982; Salvador, 1987, 1991a, 1991b; Michalzik, 1988). These deposits unconformably overlie late Paleozoic metasedimentary or Permian-Triassic granite basement. Thicknesses are on the order of 300 to 2000 m, but preservation is restricted to rift basins (Stone, 1975; Wilson, 1990).

The La Joya Formation (latest Bathonian to Callovian, Fig. 6; Bracken, 1984; Wilson, 1990) unconformably overlies the La Boca Formation, with an angular relationship preserved far south of Saltillo in Peregrina Canyon, west of Ciudad Victoria (Corpstein, 1974). The La Joya Formation (55–120 m thick) consists of lacustrine and coastal plain, nonmarine to marginal-marine

siliclastic rocks subordinate freshwater limestones (Corpstein, 1974; Padilla Sánchez, 1982; Michalzik, 1988). The redbeds include shales, siltstones, and coarser sandstones and conglomerates (volcanic and feldspathic litharenites; Bracken, 1984) that record continued infilling of areally restricted rift basins. The La Joya laps out onto basement highs and is in part coeval with the Callovian evaporites (Fig. 11, A, E, and F). The La Joya equates with the thin redbed section (restricted to updip positions; Stone, 1975) at the base of the Werner Anhydrite (Fig. 6).

Callovian to early Oxfordian

In the Callovian to early Oxfordian, the western Pacific Mexico province was bounded to the west by the San Andres-Sinaloa magmatic arc complex (Fig. 12; Tardy, 1977; Servais et al., 1982, 1986; Araujo-Mendieta and Arenas-Partida, 1986; Sedlock et al., 1993). West of the Aldama peninsula and Coahuila block, the Mexican geosyncline accumulated shallow-marine clastic and volcanoclastic sediments derived from the arc, whereas the Chihuahua trough was a restricted marine basin, perhaps in part evaporitic (Cordoba, 1969; Cordoba et al., 1970, 1980; de Cserna, 1970, 1979, 1989; Rangin and Cordoba, 1976; González-García, 1976; González, 1989; Tardy, 1977; Rangin, 1978, 1979; Gastil, 1983; Roldan-Quintana, 1982; Servais et al., 1982, 1986; Brown and Handschy, 1983; Cuévas-Pérez, 1983; Cuévas-Pérez et al., 1985; Marquez-Castaneda, 1984, in Moran-Zenteno, 1984; Cantú-Chapa et al., 1985; Campa-Uranga, 1985; Araujo-Mendieta and Arenas-Partida, 1986; Moran-Zenteno, 1994).

In the Gulf of Mexico province, widespread evaporite deposition occurred from the East Texas salt basin through south portions of the Sabinas basin and Monterrey trough (Figs. 6 and 12; González-García, 1976; Madrid, 1976; Zwanziger, 1979; Padilla Sánchez, 1986; Salvador, 1987, 1991a, 1991b; Moran-Zenteno, 1994). In the Monterrey-Saltillo area the Minas Viejas evaporite crops out as deformed masses of gypsum (Fig. 13, A and B; Weidie and Martinez, 1970; Laudon, 1984) that unconformably overlie the Huizachal redbeds and/or Paleozoic base-

ment (Fig. 6). The Minas Viejas is a marginal-marine deposit that marks the initial marine incursion into restricted, land-locked rift basins. The exact preformed thickness (~1000 m), lateral distribution, and depositional setting are unknown. The gypsum lithofacies probably represents the more landward fringe of these evaporite basins, with thick halite accumulating in basin centers.

The age and northern Gulf Coast equivalent of the Minas Viejas are somewhat problematic. Many workers (Humphrey, 1956; Weidie and Wolleben, 1969; Oivanki, 1974; Stone, 1975; Meyer and Ward, 1984; Wilson et al., 1984; Finneran, 1986; Winker and Buffler, 1988) consider the Minas Viejas to be equivalent to the Werner-Louann of the northern Gulf of Mexico (Fig.

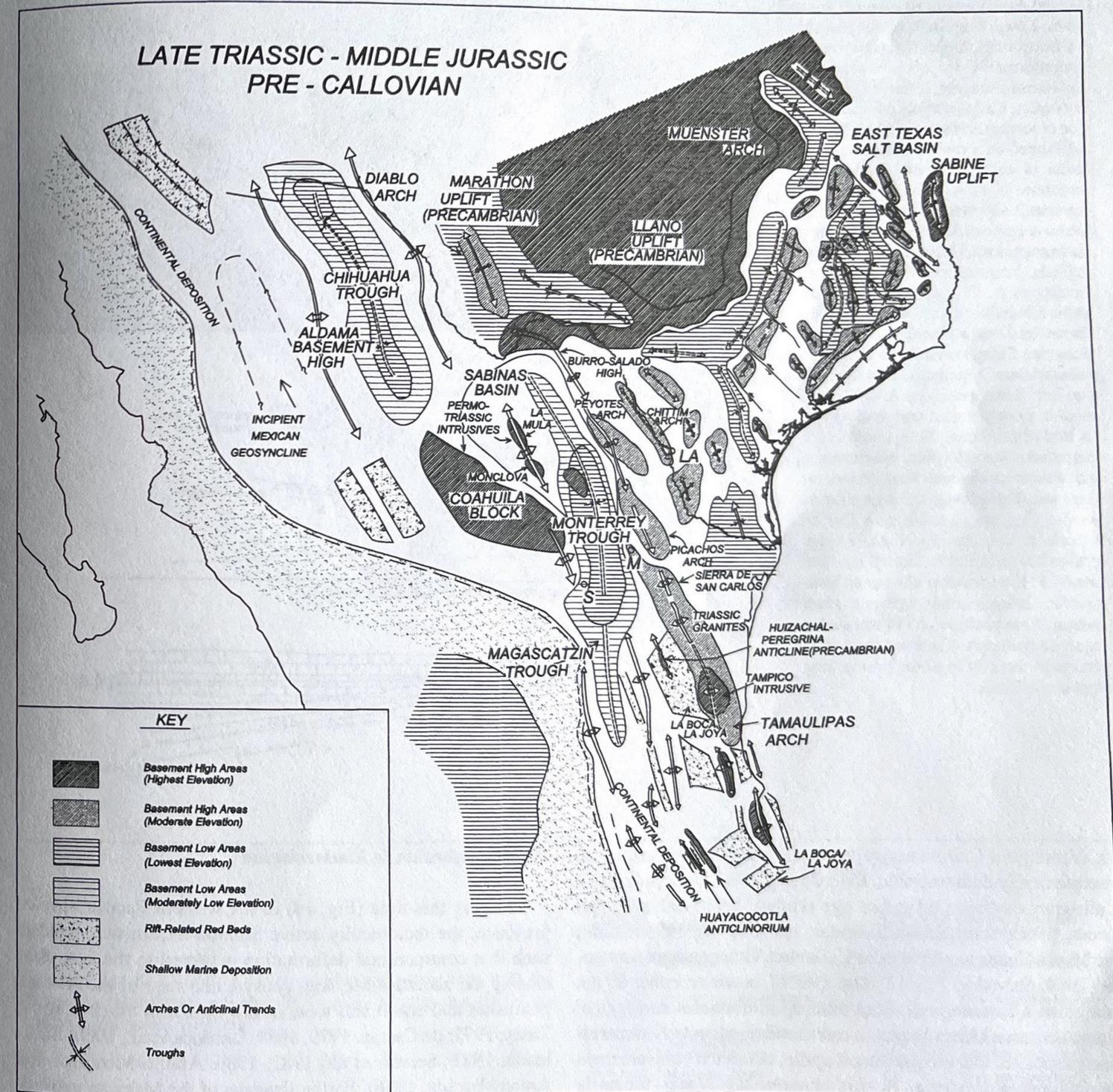
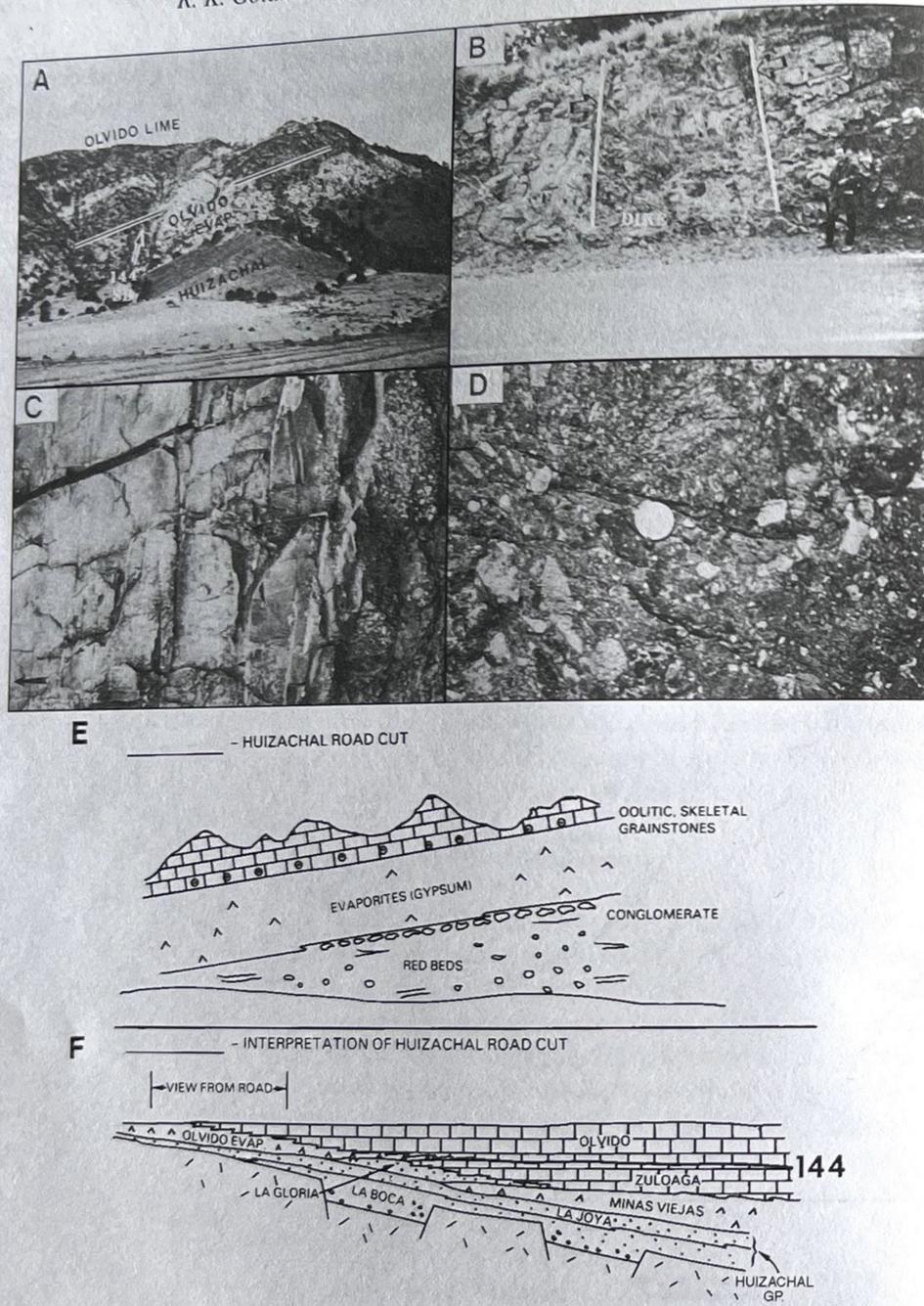


Figure 10. Late Triassic to Middle Jurassic (pre-Callovian) paleogeography. Texas and Mexico outlines are shown. M—Monterrey, Mexico; S—Saltillo, Mexico; LA—Laredo, Texas. Note that the key for this reconstruction is different than the key used in remaining paleogeographic maps. Tampico intrusive is a post-Early Cretaceous feature. Refer to text.

Figure 11. A: Panorama of Upper Triassic to Lower Jurassic Huizachal Group redbeds, overlain by Olvido evaporites (gypsum), in turn succeeded by the Olvido lime mudstone, just west of routes 58 and 61 intersection, state of Nuevo Leon. Lower redbeds here are probably La Boca rocks (Upper Triassic) overlain unconformably by conglomeratic La Joya strata (Jurassic). If this interpretation is correct, Callovian to Oxfordian portion of section is absent, presumably having lapped-out downdip. Kimmeridgian fauna in carbonate unit, Olvido lime mudstone (J. L. Wilson, 1989, personal commun.), supports this interpretation. B: Intrusive igneous dike (vertical, center of photograph) crosscutting La Boca arkosic redbeds. Person for scale ~2 m. Same locality as A. C: Fining-upward feldspathic litharenite in La Boca Group. Note channelized base with coarse pebble conglomerate fining upward into cross-bedded sandstone. Stratigraphic up direction is to left. Same locality as A. D: Coarse, angular, poorly sorted conglomerate of La Boca Formation. Note various rock fragments (metamorphic, sedimentary, and volcanic) derived from Paleozoic basement. This photograph was taken in Novillo Canyon, to south near Ciudad Victoria. E: Line drawing of stratigraphic relations observed at Huizachal road cut (see A). F: Line drawing illustrating stratigraphic interpretation inferred from roadcut. Note position of 144 Ma super-sequence boundary. Compare these relations with those of regional seismic line from south Texas.



6). Although a Callovian age for the Werner-Louann cannot be unequivocally demonstrated, the majority of evidence indicates a Callovian-earliest Oxfordian age (Imlay, 1980; Salvador and Green, 1980; Scott, 1984; Salvador, 1987, 1991a, 1991b). Thus the Minas Viejas would also be Callovian. Other authors (Longoria, 1984; Salvador, 1987, 1991a, 1991b), however, either do not recognize a Louann equivalent outcrop in northeastern Mexico, or use the term Minas Viejas to refer to Oxfordian to Kimmeridgian evaporites that are presumed updip, restricted equivalents to the Zuloaga Formation. In this chapter, the Minas Viejas is assigned a Callovian age (Louann equivalent) and the younger sequence of evaporites (Oxfordian to Kimmeridgian) is designated the Olvido evaporite (Buckner equivalent; Fig. 6).

Middle Oxfordian to Kimmeridgian

During this time (Fig. 14) in the western Pacific Mexico province, the tectonically active Sinaloa terrain was uplifted such that contractional deformation occurred to the east, thus closing the ancestral Mexican geosyncline west of the Aldama peninsula and south and west of the Coahuila block (Fig. 4; Tardy, 1977; de Cserna, 1979, 1989; Cordoba et al., 1980; Dickinson, 1981; Servais et al., 1982, 1986; Araujo-Mendieta and Arenas-Partida, 1986). Earlier deposits of the Mexican geosyncline were deformed along a north-south zone termed the Zacatecas-Guanajuato thrust front by de Cserna (1979). Within the Chihuahua trough, restricted shallow-marine carbonates (low

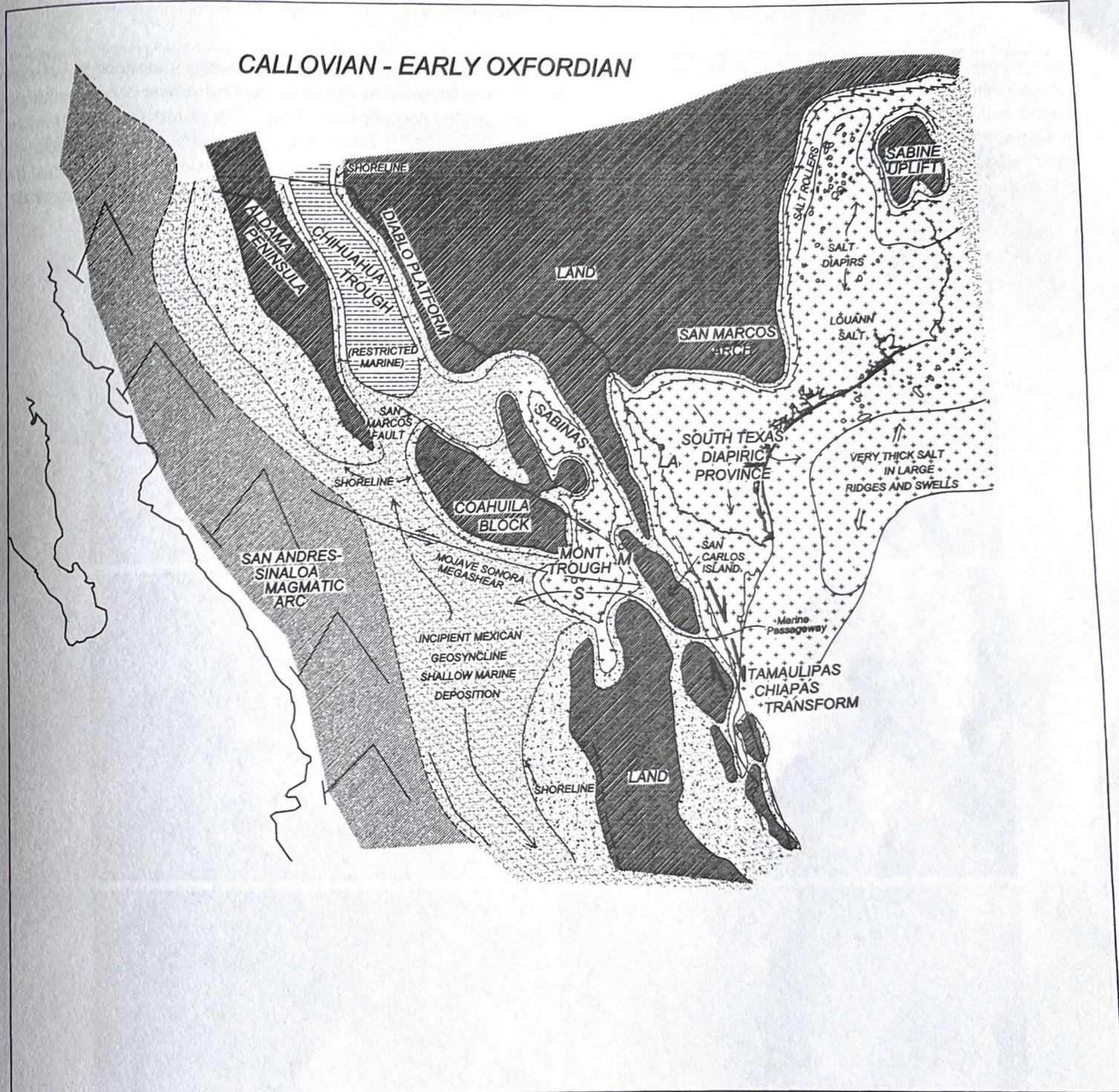
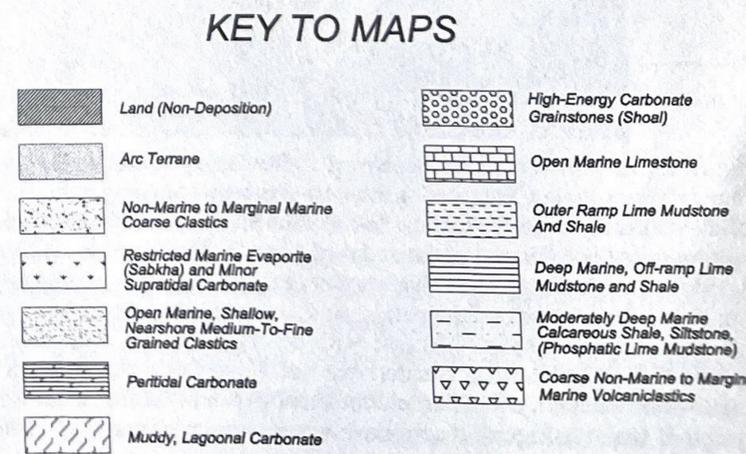


Figure 12. A: Key for all paleogeographic reconstructions with the exception of that shown in Figure 10. Map of Callovian to early Oxfordian paleogeography (see text).



energy, lagoonal) and fine-grained clastic sediments in the trough center were flanked by coarser grained shallow-marine clastic sediments (Cordoba, 1969; Cordoba et al., 1970, 1980; de Cserna, 1979; González, 1976; Tardy, 1977; Araujo-Mendieta and Arenas-Partida, 1986; Moran-Zenteno, 1994).

In the Gulf of Mexico province (Fig. 14), shallow-marine car-

bonate ramps with ramp-crest high-energy grainstone facies were flanked landward by nearshore marginal-marine clastic sediments and graded downdip into off-ramp deeper marine shales (González-García, 1976; Zwanziger, 1979; Padilla Sánchez, 1986; Salvador, 1987, 1991a, 1991b). In east Texas and south Texas, the classic Buckner to Smackover ramp system rimmed a regionally

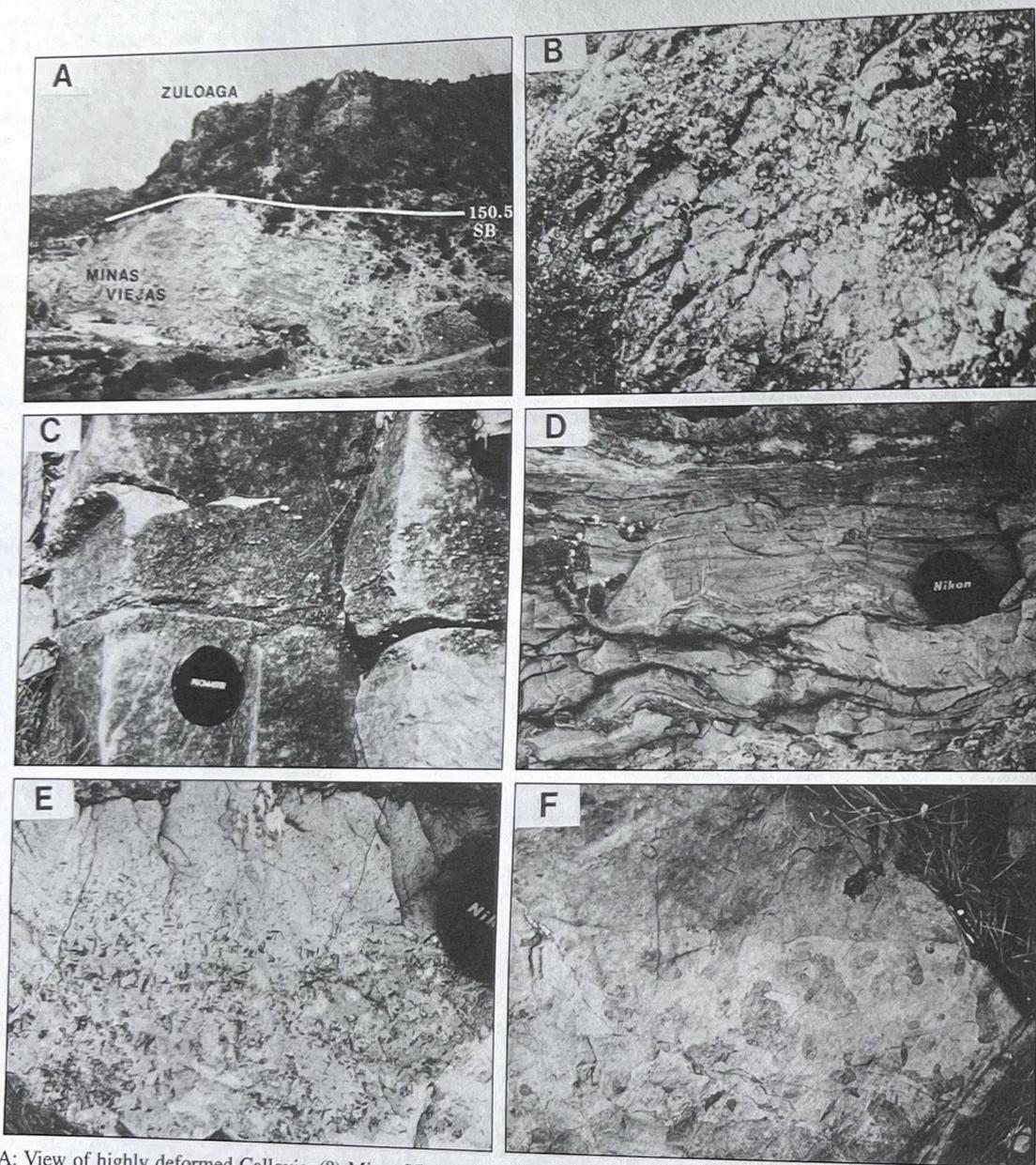


Figure 13. A: View of highly deformed Callovian(?) Minas Viejas gypsum and overlying Oxfordian(?) Zuloaga Formation exposed in core of Potrero Minas Viejas, breached northwest-southeast-trending anticline in state of Nuevo Leon. Boundary between two formations is interpreted as 150.5 Ma break-up unconformity. In this interpretation, evaporite is interpreted as Callovian to early Oxfordian. Note that some workers believe this evaporite to be Kimmeridgian, equivalent to Olvido facies. B: Close-up view of brecciated basal Zuloaga above contact. Brecciation interpreted as perhaps result of solution-collapse of underlying evaporite. C: Outcrop photograph of La Gloria facies composed of sandy carbonate grainstone millimeter-scale cryptalgal laminite with domal structures, indicative of peritidal deposition. This subfacies forms caps to peritidal cycles of Zuloaga-Olvido Formations. Section exposed along roadcut near Sierra Bunuelos along route 54 south of Saltillo. D: Outcrop photograph of millimeter-scale euhedral crystal molds of gypsum (calcite filled) in subtidal mudstone, Zuloaga Formation, Sierra Bunuelos. E: Outcrop photograph of bored hardground surface in outer ramp grainstones of Zuloaga Formation, Sierra Bunuelos, interpreted as subtidal cycle boundary.

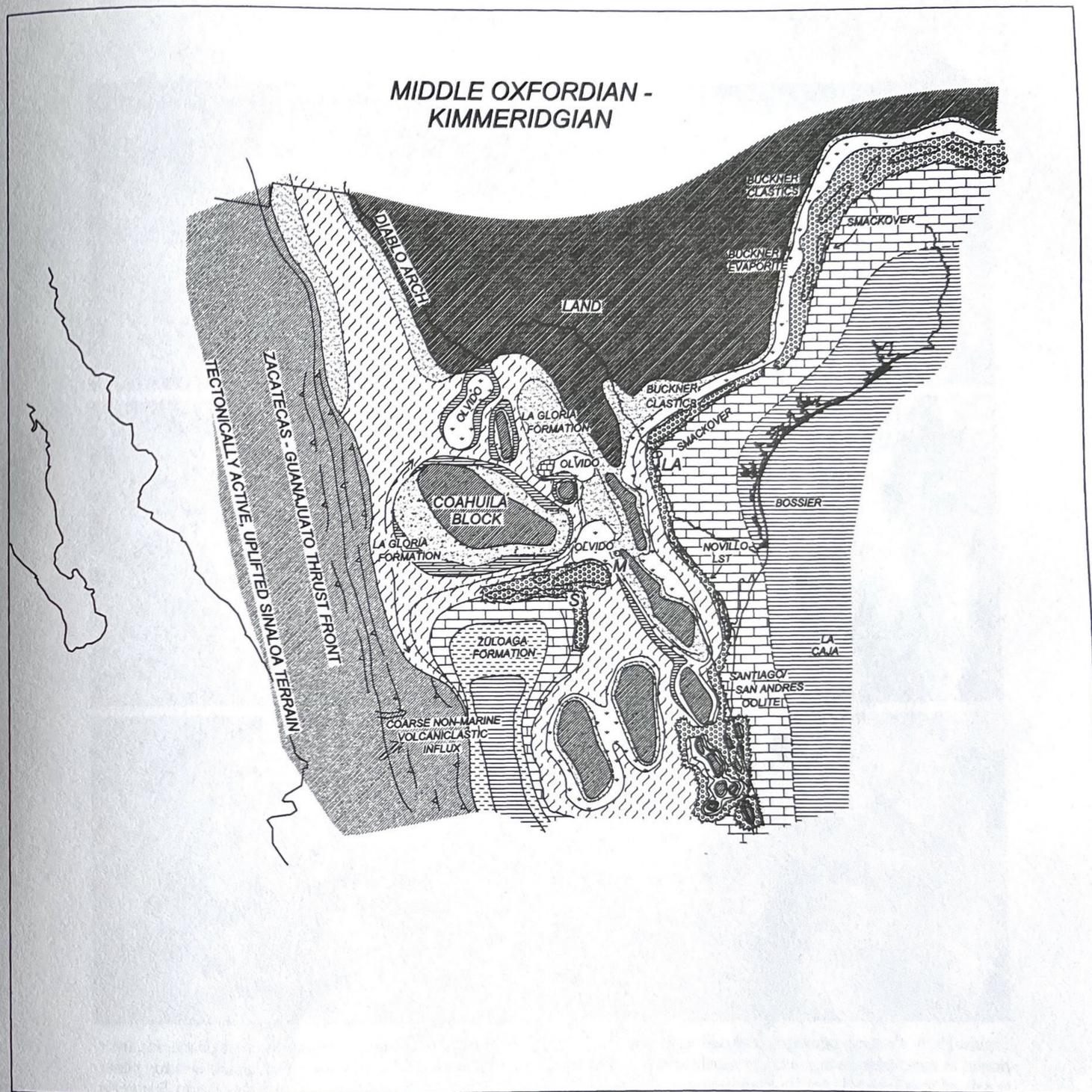


Figure 14. Middle Oxfordian to Kimmeridgian paleogeography (see text). See Figure 12A for key. Southernmost extension of Zuloaga Formation is partly speculative and may actually be largely coarse siliciclastics of Las Trancas Formation (turbiditic sands).

exposed land mass to the north (e.g., Budd and Loucks, 1981; Presley, 1984). In northeast Mexico and adjacent to the south, analogous carbonate ramp systems developed, nucleating on pre-existing, exposed land masses.

In northeast Mexico, the La Gloria Formation (Figs. 6 and 13C) is early Oxfordian in age (Imlay, 1936) and essentially represents the updip, transgressive clastic interval of the Zuloaga

Formation (Figs. 6 and 15; Imlay, 1936; Stone, 1975; Oivanki, 1974). It is the first prominent marine sand, overstepping the breakup unconformity at 150.5 Ma. It equates in part to the Norphlet Formation of the northern Gulf of Mexico (Wilson et al., 1984; Salvador, 1987, 1991a, 1991b) and forms a basinward-thinning wedge of fine to coarse, feldspathic quartz sandstones that lap onto exposed basement highs (Coahuila block, Tamauli-

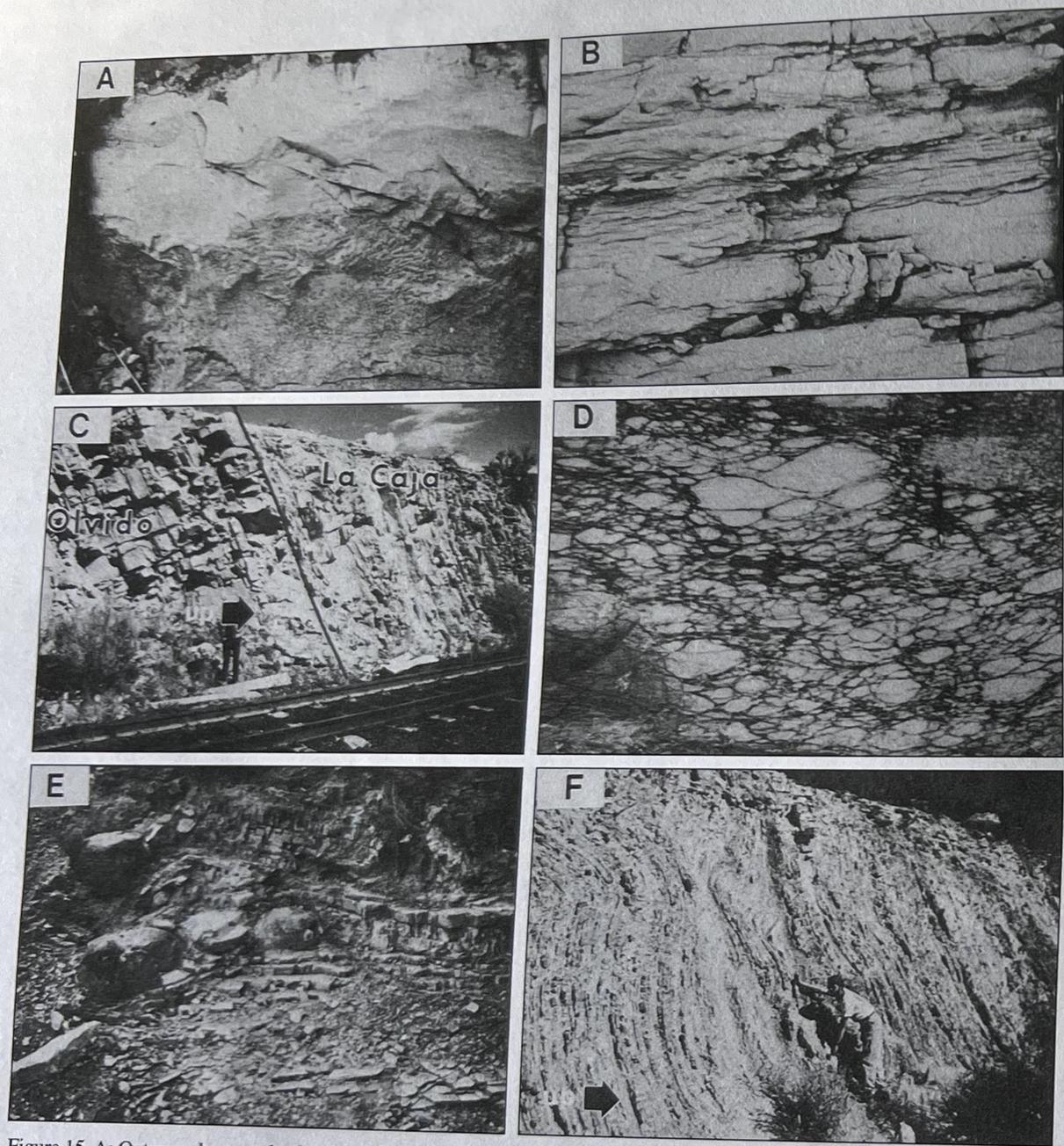


Figure 15. A: Outcrop photograph of oolitic, bioclastic (skeletal) grainstone within Zuloaga Formation, Sierra Bunuelos, interpreted as ramp-margin high-energy shoal facies. Field of view is ~40 cm in height. Pencil for scale on left. B: Outcrop photograph of thin-bedded, argillaceous peloid lime mudstone and wackestone within Zuloaga Formation, Sierra Bunuelos, representative of off-ramp facies. Pencil for scale. C: Stratigraphic contact between Olvido lime mudstone and clastic La Caja exposed along railroad cut east of Bunuelos roadcut. Arrow is stratigraphic up direction. Person for scale ~2 m. D: Outcrop photograph of deformed gypsum of Olvido evaporite unit. Chicken wire fabric is due to tectonic deformation. Located at small sulfur mine east of Bunuelos roadcut. E: Outcrop photograph of large concretions of phosphatic-rich carbonate mudstones to wackestones in thin-bedded calcareous siltstones and shales of La Caja Formation. This facies represents distal deep-water ramp starved sedimentation located south of high-energy ramp-crest shoal facies. Astillero Canyon is in state of Zacatecas, west of route 54. F: Outcrop photograph of thin-bedded, deformed calcareous siltstones and shales of La Caja Formation ~30 m above contact with top of Olvido carbonate. Arrow is stratigraphic up direction. Person for scale is ~2 m.

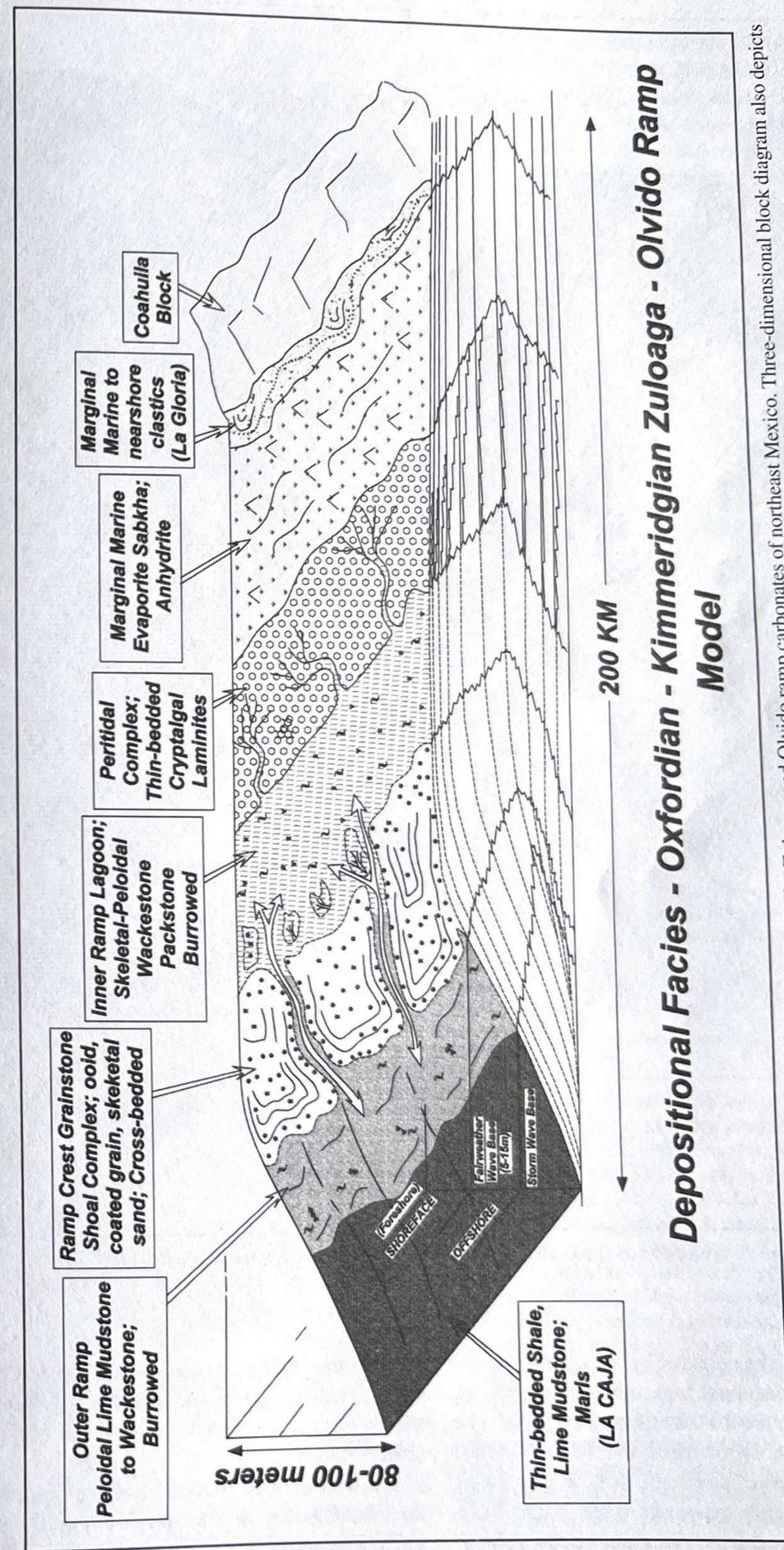


Figure 16. Schematic Oxfordian to Kimmeridgian depositional facies model for Zuloaga and Olvido ramp carbonates of northeast Mexico. Three-dimensional block diagram also depicts high-frequency stacking architecture of sequences within this system.

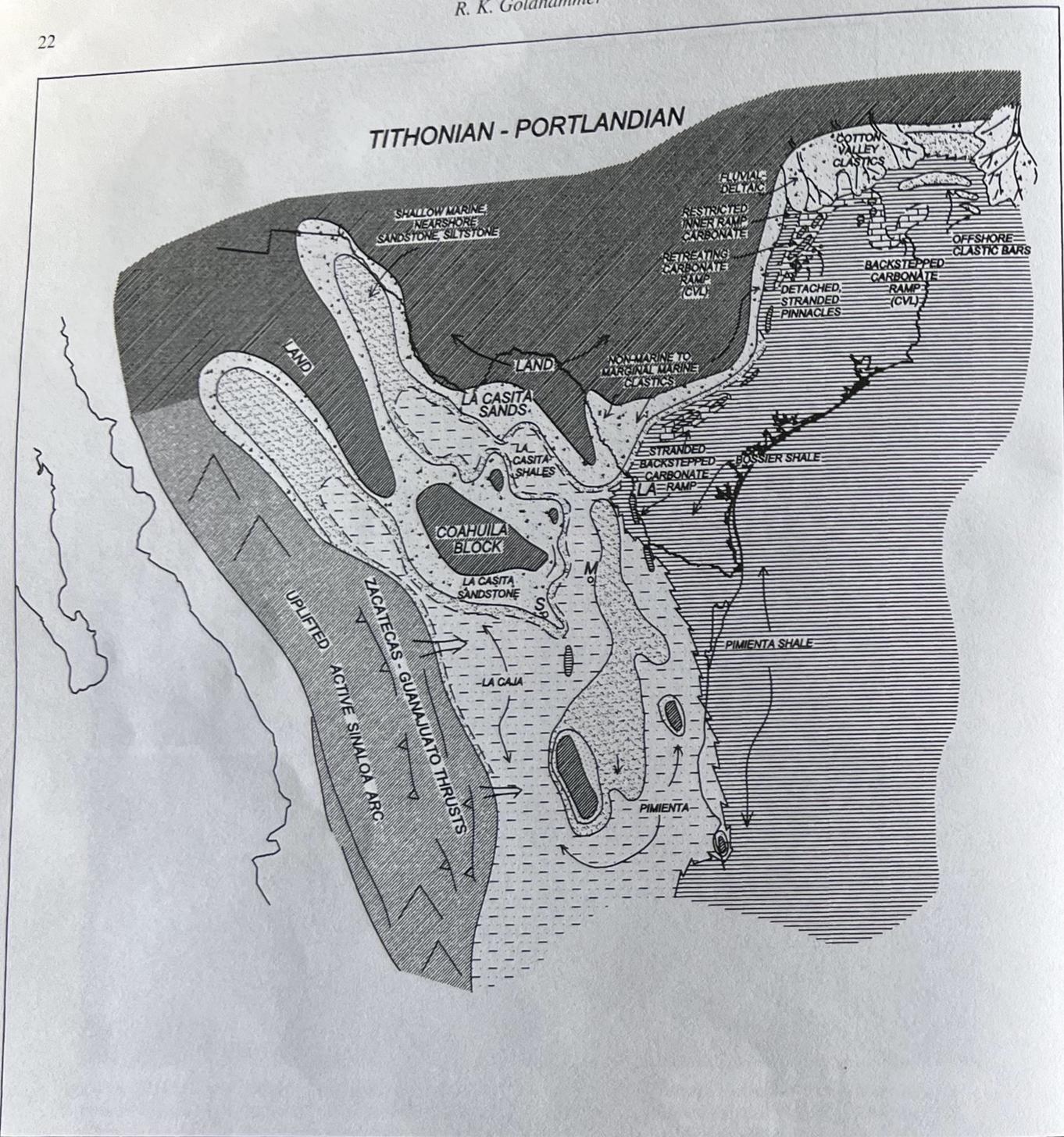


Figure 17. Tithonian to Portlandian paleogeography (see text). Symbols as in Figure 12A.

pas arch; Oivanki, 1974). Thicknesses are typically <50 to 100 m, but exceed 600 to 700 m proximal to basement blocks (e.g., southwest flank of the Coahuila block; Oivanki, 1974). The basal La Gloria unconformably overlies the Minas Viejas, Huizachal redbeds, or Paleozoic basement. It is in turn overstepped conformably by Zuloaga carbonates (Figs. 6 and 11F). Depositional environments range from marginal marine (playa)

to nearshore shallow marine, where detrital lithologies are intercalated with normal marine carbonates (Oivanki, 1974). Down dip, the La Gloria Formation grades into Zuloaga ramp carbonates (Fig. 16).

In northeast Mexico the Zuloaga Formation (Fig. 6) marks the establishment of open marine conditions (González-García, 1976; Zwanziger, 1979; Padilla Sánchez, 1986), with the transi-

tion from the rift to drift stage of passive-margin development. The Zuloaga is Oxfordian (Imlay, 1943) and is correlated with the Smackover Formation of the northern Gulf Coast (Fig. 6). Grain types and depositional facies are very similar to the Smackover Formation in south Texas (Stone, 1975; Budd and Loucks, 1981; Johnson, 1991). It unconformably overlies Huizachal redbeds or Minas Viejas evaporites. This transgressive carbonate formed an extensive low-angle, gently dipping ramp that nucleated proximal to exposed basement highs (Fig. 16; Oivanki, 1974; Johnson, 1991). Regional facies patterns and isopachs (Oivanki, 1974; Sandstrom, 1982; Meyer and Ward, 1984; Finneran, 1986; Johnson, 1991) suggest that the Coahuila block was a prominent topographic high, and that the Tamaulipas arch was a mosaic of islands forming an archipelago trending north-northwest-south-southeast (Fig. 14; Oivanki, 1974; Todd, 1972; Stone, 1975). Proximal siliciclastic sediments (La Gloria) rimmed the exposed islands, passing offshore into sabkha, tidal flat, and restricted lagoon environments of the inner ramp, in turn rimmed by extensive high-energy carbonate sand shoals at the ramp edge (Figs. 13, D-F; 15, A and B; Oivanki, 1974; Finneran, 1986; Johnson, 1991). Deeper, low-energy subtidal environments characterize the outer ramp (Meyer and Ward, 1984).

Antecedent topography resulted in marked lateral variations in thickness and depositional facies (Johnson, 1991). Depositional textures vary across the ramp profile, from muddy, peloidal mudstones to wackestones updip (peritidal to restricted lagoon), to ooid-pellet packstones and grainstones at the ramp edge (shoals), to mudstones and wackestones downdip (outer ramp; Fig. 16). In addition, evaporites (Ca sulfates) were an important component, as evidenced by numerous crystallopic molds, solution-collapse breccias, and intercalated layers of calcite-replaced anhydrite and/or gypsum (Oivanki, 1974; Michalzik, 1988; Johnson, 1991). Thicknesses vary from 150 to 500 m updip, to greater than 450 m downdip (Oivanki, 1974).

The Olvido Formation consists of a lower, early Kimmeridgian portion of evaporites (anhydrite, gypsum; Fig. 15D) and red shales, and an upper, Kimmeridgian unit of predominantly carbonate, but with varying admixtures of siliciclastic rocks depending on proximity to exposed paleohighs and clastic source areas (Figs. 6 and 7; Carrillo-Bravo, 1963; Todd, 1972; Padilla Sánchez, 1982; Salvador, 1987, 1991a, 1991b; Wilson, 1989). Following Goldhammer et al. (1991), the lower Olvido Formation is termed the Olvido evaporite and the upper Olvido is the Olvido lime mudstone (Fig. 6). Stone (1975) indicated that the Olvido evaporite correlates with the Buckner Anhydrite of the northern Gulf of Mexico, for which an early Kimmeridgian age has been determined (Stone, 1975; Todd and Mitchum, 1977; Salvador, 1987, 1991a, 1991b). The Olvido evaporite apparently conformably overlies the Zuloaga Formation, and is conformably overstepped by transgressive Kimmeridgian Olvido lime mudstone.

In the Monterrey-Salttillo area the Olvido evaporite is typically 20–50 m thick, and the Olvido lime mudstone varies from 100 to 200 m thick, but in the northern Sabinas basin, the evaporitic interval reaches a thickness of 100 to 300 m, and the overlying

Kimmeridgian carbonate is ~100 to 200 m in thick (Stone, 1975; González-García, 1976; Padilla Sánchez, 1986). This variation in thickness reflects differences in subsidence rates between the two areas. The Sabinas basin was an original basement low which subsided more relative to the shelfal regime flanking the southern side of the Coahuila block. The lower evaporitic Olvido presumably records deposition in a very restricted marginal-marine setting, implying a brief, but significant phase of regression in the overall Oxfordian to Kimmeridgian transgressive trend (González-García, 1976; Padilla Sánchez, 1986).

In the vicinity of Monterrey and Saltillo, the Olvido lime mudstone is similar to the underlying Zuloaga Formation in terms of grain types, depositional textures, carbonate facies, and cycle development, and is also interpreted to depict a carbonate ramp regime (Fig. 16). The Olvido lime mudstone correlates to the Kimmeridgian Haynesville Formation of south Texas, with which it is lithologically very similar (Stone, 1975), as well as other Kimmeridgian carbonates in the Gulf of Mexico (e.g., the Gilmer Limestone of east Texas; Ahr, 1981; Steffensen, 1982).

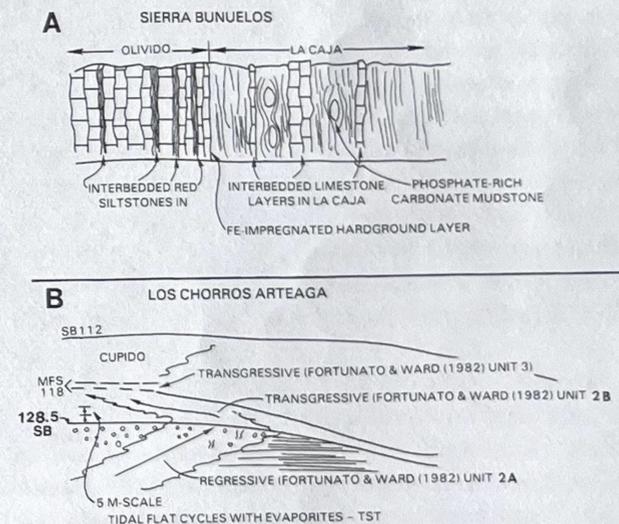


Figure 18. A: Stratigraphic relations exposed at top of Olvido lime mudstone and transition into La Caja Formation. Upper Olvido is principally cyclic grainstones with intercalated wave-rippled marine siltstones. Contact is sharp bored hardground surface stained red with Fe-oxide. Interspersed limestone layers in La Caja facies are composed of alloclastic (derived from updip ramp crest) grainstones that are downdip from retrograding Olvido ramp margin. Diagram is schematic and has no scale. B: Stratigraphic relations observable at Los Chorros anticline, east of Saltillo. Lower La Casita facies consist of progradational (regressive) coarse clastics (proximal fan delta facies) beneath interpreted 128.5 Ma supersequence boundary. Upper La Casita facies consists of upward-deepening facies and cycle-stacking motif depicting second-order transgressive systems tract of 112 Ma supersequence. La Casita facies change downdip into distal shales and siltstones of Taraises Formation, which thins updip where it approximates 118 Ma maximum flooding surface of 112 Ma supersequence. Above Taraises Formation, Cupido Formation comprises regionally upward-shallowing, basinward-prograding carbonate unit capped by 112 Ma unconformity. Diagram is schematic and has no scale.

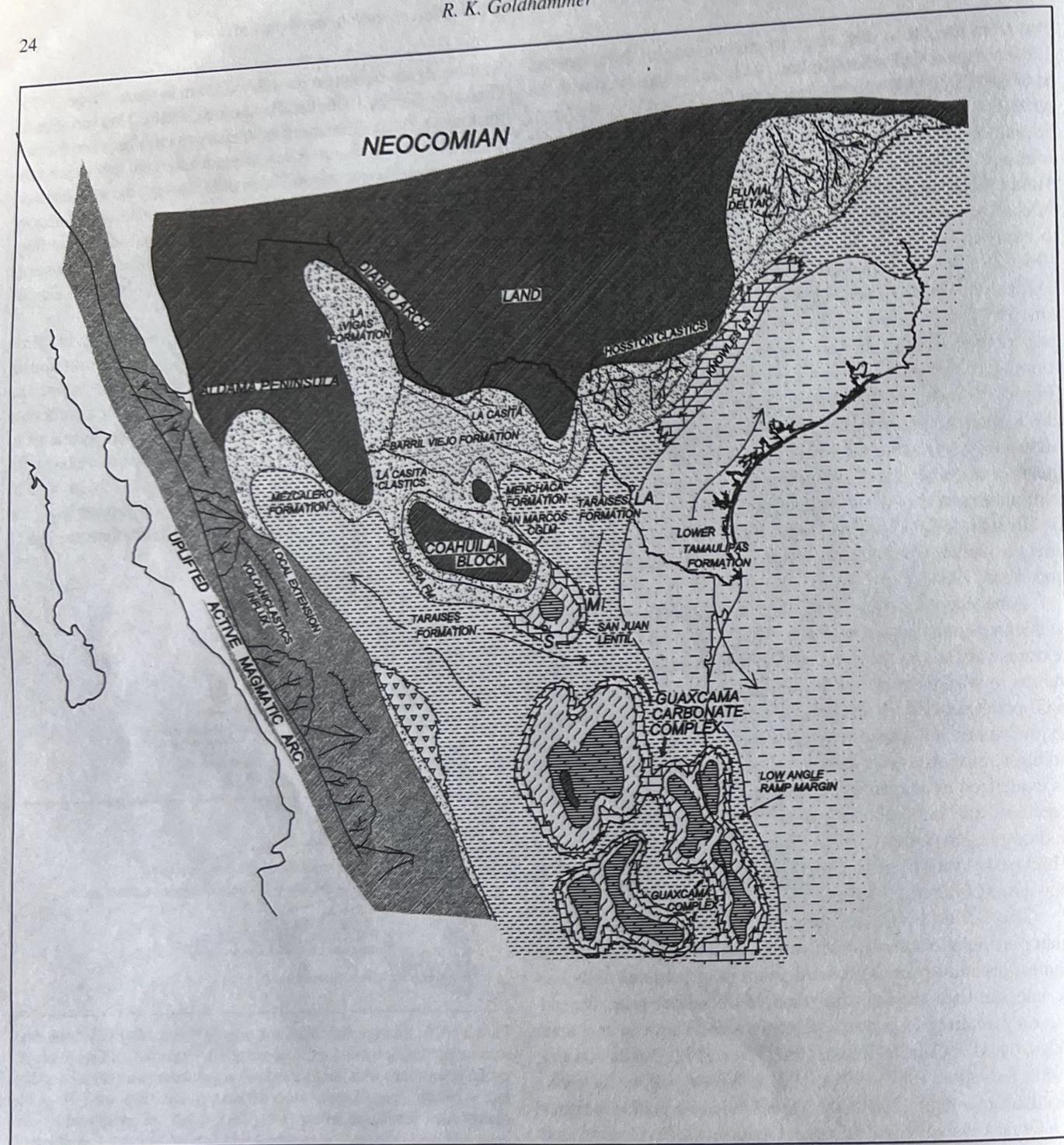


Figure 19. Neocomian paleogeography. Refer to text. Symbols as in Figure 12A. Much of detail within Guaxcama carbonate platform is speculative; little is known of it for this time interval.

For example, in the northern and western reaches of the Sabinas basin, clean carbonate packstones to grainstones full of ooids, hardened pellets, and oncolites predominate (Stone, 1975; Goldhammer et al., 1991, Figs. 31–35). To the south, in the Tampico-Misantla area, the Kimmeridgian section consists of a carbonate ramp system that nucleated on exposed basement highs along the Tamaulipas arch (Cantú-Chapa, 1992; Todd, 1972; González,

1977). Here, tidal flat facies with cryptalgal laminites grade offshore into thick (100 m) oolitic grainstones that mark the ramp edge (Todd, 1972). The underlying Oxfordian section consists largely of nearshore siliciclastics and carbonates, unlike the typical Zuloaga rocks to the north. These examples serve to illustrate the role that exposed basement highs played in controlling Oxfordian to Kimmeridgian thicknesses and facies evolution.

Tithonian to Portlandian

In the Tithonian to Portlandian, the Sinaloa arc was active in the western Pacific Mexico province and continued to influence eastward-propagating contractional deformation with thrusting at the leading edge (Fig. 17; Tardy, 1977; de Cserna, 1979, 1989; Córdoba et al., 1980; Dickinson, 1981; Servais et al., 1982, 1986; Araujo-Mendieta and Arenas-Partida, 1986). Late Jurassic inversion and total closure of the Mexican geosyncline was achieved west and southwest of the Coahuila block, whereas to the north, the Mexican geosyncline as well as the Chihuahua trough were sites of shallow-marine, largely volcanoclastic, clastic deposition, (Córdoba, 1969; Córdoba et al., 1970, 1980; de Cserna, 1979; González, 1976; Tardy, 1977; Araujo-Mendieta and Arenas-Partida, 1986; Moran-Zenteno, 1994).

In the Gulf of Mexico province, regional facies relationships are driven primarily by a major second-order gulf-wide transgression that caused antecedent carbonate ramp systems to be drowned and inundated with fine-grained marine clastics, such as the Bossier Shale in Texas (Figs. 6 and 7; Salvador, 1987, 1991a, 1991b). In the East Texas salt basin, gas-bearing pinnacle reefs and backstepped ooid shoal complexes developed on top of the retreating ramp systems (Goldhammer, 1998). Much of northeast Mexico was likewise inundated with fine-grained marine shales and siltstones of the La Caja and Pimienta Shale as deeper marine facies lapped onto preexisting basement highs (Figs. 15C and 17; González-García, 1976; Padilla Sánchez, 1986; Echanove, 1986). Despite this significant marine transgression, not all land areas were covered. The Coahuila block in particular may have been tectonically uplifted at this point (Fig. 4; Araujo-Mendieta and Arenas-Partida, 1986; Limon, 1989), as indicated by a significant influx of coarse, proximal clastics into areas proximal to the block, particularly within the Sabinas basin (González-García, 1976; Zwanziger, 1979; Padilla Sánchez, 1986; Aranda-García and Eguilez de Antuñano, 1983; Eguilez de Antuñano and Aranda-García, 1983, 1984; Echanove, 1986).

In northeast Mexico, the La Caja Formation is Kimmeridgian to middle Berriasian (Fig. 6) and consists of rhythmically bedded, thin calcareous shales, siltstones, and fine sandstones, and thin limestones toward the base (Fig. 15, E and F; Fortunato, 1982; Salvador, 1987, 1991a). Phosphatic beds and large concretions of phosphatic micrite with ammonites are conspicuous components. Thickness is variable, ranging from 25 to 150 m (Padilla Sánchez, 1982). The La Caja Formation is equivalent to the Bossier Shale of the northern Gulf of Mexico and records offshore, somewhat starved basinal depositional conditions. In south Texas, and elsewhere around the northern Gulf of Mexico, the Tithonian Bossier Shale overlies the underlying Kimmeridgian Haynesville Formation, as shown by seismic data and well-log pattern correlation (Stone, 1975; Goldhammer et al., 1991, Figs. 31–35). The La Caja Formation overlaps the Burro-Salado arch, and in the Tampico-Misantla area it overlaps the Tamaulipas arch (Cantú-Chapa, 1992; Todd, 1972; Stone, 1975; González, 1977). The Kimmeridgian portion of the La Caja

Formation is the deeper off-ramp basinal equivalent to the Olvido lime mudstone, and hence the formation boundary with the Olvido lime mudstone updip is a time-transgressive facies change (Fig. 18A). The Tithonian to middle Berriasian part is the deeper offshore equivalent to the updip La Casita Formation. Although the lower portion of La Casita Formation is Tithonian to Portlandian in age, it is discussed fully within the context of the Neocomian paleogeography in the following.

Neocomian

During the earliest Cretaceous (Fig. 19), in the western Pacific Mexico province, arc-related tectonism induced backarc extension within the Mexican geosyncline and rejuvenated subsidence within the Chihuahua trough (Fig. 4; Córdoba, 1969; Córdoba et al., 1970, 1980; DeFord and Haenggi, 1970; Seewald and Sundeen, 1971; González-García, 1976; González, 1989; Cantú-Chapa, 1976; Tardy, 1977; de Cserna, 1970, 1979, 1989; Dickinson, 1981; Tóvar Rodríguez, 1981; Roldan-Quintana, 1982; Servais et al., 1982, 1986; Cantú-Chapa et al., 1985; Araujo-Mendieta and Arenas-Partida, 1986; Brown and Dyer, 1987; Sedlock et al., 1993; Moran-Zenteno, 1994). Proximal marginal-marine to nonmarine volcanoclastic sediments (Mezcalero Formation) draped the upper reaches of the Mexican geosyncline flanking the exposed Aldama landmass (Fig. 19), whereas outer ramp, deeper water shales and lime mudstones accumulated in the central part of the Mexican geosyncline. In the Chihuahua trough, coarse proximal clastic material prograded southwest, flanking the Diablo arch in Texas, where it interfingered with slightly more open-marine clastic sediments within the northwestern reaches of the Sabinas basin (González-García, 1976; Zwanziger, 1979; Márquez, 1979; Padilla Sánchez, 1986).

In the Gulf of Mexico province, coarse, marginal-marine to shallow-marine clastic facies (Hosston Formation) with local carbonate accumulation (Knowles Formation; McFarlan and Menes, 1991) rimmed a large exposed landmass in Texas (Fig. 19), changing facies downdip into offshore shales and siltstones. This pattern of terrigenous influx was common all along the periphery of the Gulf of Mexico at that time (Stone, 1975; Todd and Mitchum, 1977; Salvador, 1987, 1991a, 1991b; see Goldhammer et al., 1991, Figs. 31–35). Within the Sabinas basin coarse marginal-marine to shallow-marine clastic sediments (Barril Viejo and La Casita Formations) accumulated north of the Coahuila block, passing downdip into finer grained, more open-marine facies of the Menchaca and Taraises Formations in the Burgos basin (González-García, 1976; Padilla Sánchez, 1986; Eguilez de Antuñano and Aranda-García, 1983, 1984; Echanove, 1986). To the south, in the Tampico-Misantla area, low-relief carbonate platforms were established on top of old basement high areas, forming a complex of aerially restricted platforms that together compose the Guaxcama carbonate complex (González, 1976, 1977; Enos, 1983; McFarlan and Menes, 1991). These low-relief banks attained thicknesses of as much as a few hundred meters during that time (McFarlan and Menes,

1991), and display a zoned lateral facies profile, from restricted peritidal carbonate (dolomites), to muddy, low-energy, lagoonal carbonate, to normal marine bank facies at their periphery. West and east of the Guaxcama complex, deeper marine outer ramp lime mudstone and shale facies rimmed the complex. To the east, lower Tamaulipas shales and deep-marine carbonates rimmed the entire Gulf of Mexico.

Locally, in northeast Mexico, the La Casita Formation (late Kimmeridgian to Hauterivian age; Fig. 6) represents a period of major clastic influx (Stone, 1975; Fortunato, 1982; Fortunato and Ward, 1982; Smith, 1987; Salvador, 1987, 1991a, 1991b; Michalzik and Schumann, 1994). The age and thickness (650–800 m) of the La Casita rocks vary geographically (Fig. 20), in part a function of proximity to the exposed Coahuila block, from which most of the detrital material was derived (Fortunato, 1982). The La Casita correlates with the Cotton Valley Group (Tithonian to Berriasian; nearshore Schuler and offshore Bossier Formations), as well as the overlying Hauterivian Hosston Formation (Stone, 1975; McFarlan and Stone, 1977; Todd and Mitchum, 1977; Salvador, 1987, 1991a). The apparent absence of any Valanginian strata in a shelfal position separating the Cotton Valley from the Hosston Formation (Fig. 6; Stone, 1975; Todd and Mitchum, 1977; McFarlan and Stone, 1977; Goldhammer et al., 1991) is of major significance in parts of the Gulf of Mexico. This unconformity at the top of the Cotton Valley is marked by extensive subaerial erosion in shelfal positions, and lowstand clastic wedges downdip of the Cotton Valley shelf margin (McFarlan and Stone, 1977; see Goldhammer et al., 1991, Figs. 35 and 36). Typically, in a basinward position the upper part of the Schuler Formation is characterized by an interval of limestones that thickens seaward (~20–30 m thick; Stone, 1975), the Cotton Valley Lime or Knowles Limestone (Mann and Thomas, 1964), that is essentially subjacent to the top Berriasian unconformity (Stone, 1975; Todd and Mitchum, 1977).

In the Monterrey-Salttillo area, the La Casita Formation has been subdivided into three regionally pervasive stratigraphic units that appear to correlate to the northern Gulf of Mexico section, both lithologically and biostratigraphically (Fortunato, 1982; Fortunato and Ward, 1982). The three units are interpreted to depict main stages in the progradation and retreat of an extensive fan-delta complex (Figs. 18B and 20). Unit 1 (137 to 148 m thick) of Fortunato and Ward (1982) consists of black carbonaceous mudstone and siltstone (Figs. 20 and 21C) with some burrow-mottling and scattered layers rich in oyster-like pelecypods. This unit, interpreted as a prodelta deposit on a deep subtidal shelf, equates to the lower Cotton Valley rocks and is probably Tithonian in age, although there are no biostratigraphic data to support this contention. Unit 2 (350 m thick) is predominantly fine- to coarse-grained sandstone (texturally and mineralogically immature arkose and lithic arkose) with many conglomerate intervals in the lower and upper parts (Figs. 20 and 21A; Fortunato and Ward, 1982). Burrow mottling, trough cross-bedding (Fig. 21D) and channeling are common features. Both coarsening-upward cycles (meter scale; mudstones and

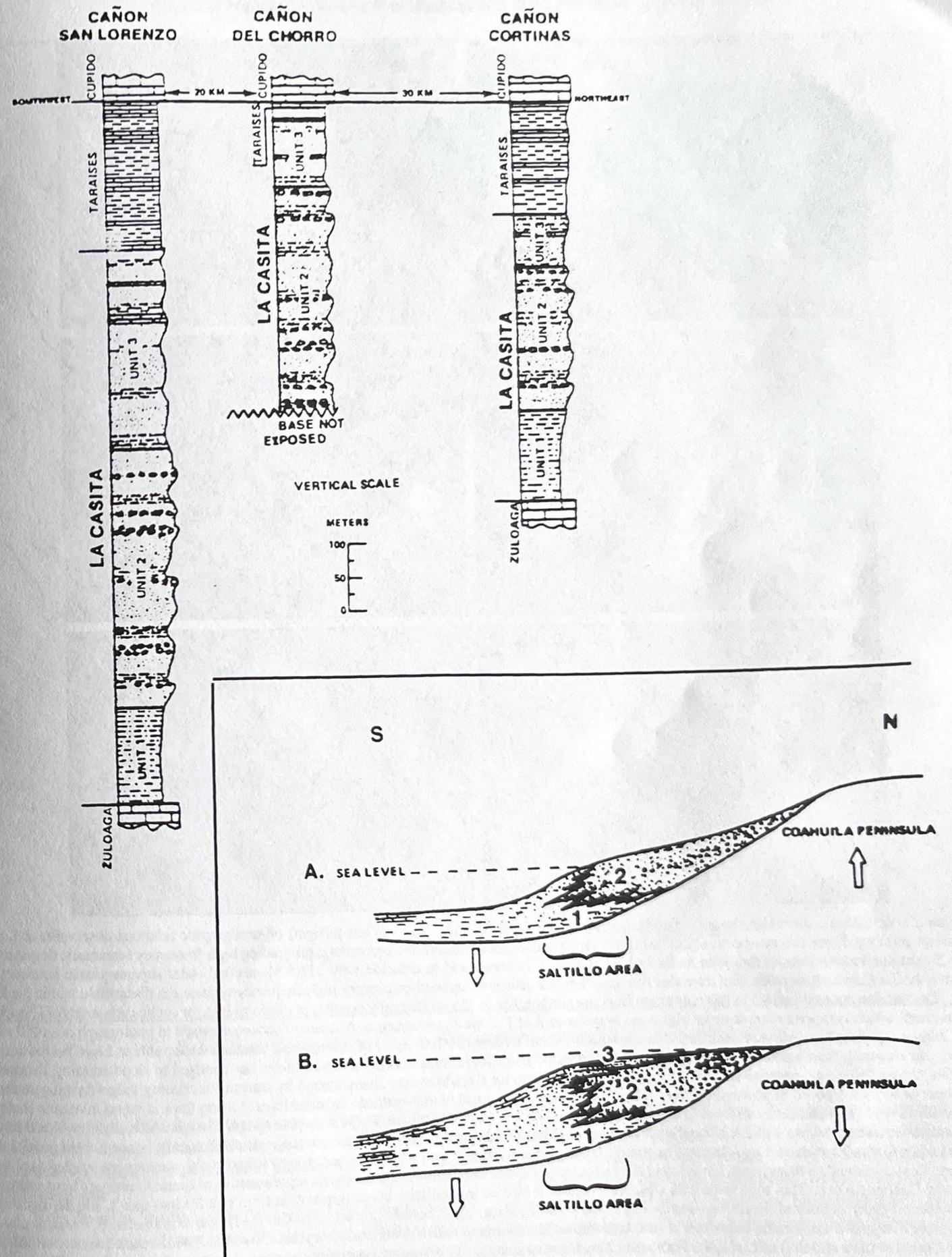
siltstones to coarse sandstone or conglomerate), and fining-upward cycles (meter scale; pebble conglomerate to medium sandstone) occur in the lower and upper parts.

In Cañon del Chorro, ~120 m from the top of unit 2, calcareous beds reveal a Kimmeridgian to Portlandian foraminiferal assemblage (Fortunato, 1982; 230 m from the base of the Cañon del Chorro measured section of Fortunato, 1982). Ammonites of Hauterivian to Valanginian age were found ~40 m above this by J. L. Wilson (270 m from the base of the Cañon del Chorro measured section of Fortunato, 1982). What this suggests is that the lower 230 m of unit 2 at this locality is Upper Jurassic and equivalent to the Cotton Valley rocks, and the remaining ~120 m is Lower Cretaceous and equivalent in part to the Hosston Formation, although additional biostratigraphic data are needed to confirm these correlations.

For the sake of clarity the Upper Jurassic portion of unit 2 is unit 2A and the Lower Cretaceous interval is unit 2B in Figure 6 (see also Fig. 18B). Units 2A and 2B represent lower alluvial-fan to shallow-marine deposition during the maximum seaward advance of the fan-delta complex (Fig. 20; Fortunato and Ward, 1982). Fining-upward cycles demarcate fluvial deposition on distal subaerial alluvial fans. Coarsening-upward cycles depict progradation of delta lobes in coastal and submarine-shelf environments. The overall nature of these coarse siliciclastics suggests rapid deposition of immature sediment in a fluvially dominated domain without substantial marine reworking.

Unit 3 (115–310 m thick) consists of siltstones and trough cross-bedded or burrowed sandstones intercalated with thin carbonates (Figs. 18B and 20). This upper unit of the La Casita at the Cañon del Chorro section (Fig. 6) is probably Hauterivian (on the basis of biostratigraphic control) and equates to the upper Hosston Formation of the U.S. Gulf Coast. The transition from unit 2 to 3 is marked by the first occurrence of micritic dolomite (Fig. 21F). The unit becomes generally finer grained, thinner bedded, and more calcareous upward, where it grades conformably into the Taraises Formation (Fig. 21B; Fortunato and Ward, 1982). A few dark marine shales are also prominent toward the top. This unit marks the waning of coarse siliciclastics and the

Figure 20. A: Generalized stratigraphic column of La Casita Formation at Cañon del Chorro (Los Chorros anticline), Cañon Cortinas, and Cañon San Lorenzo (see locations in Fig. 2). Datum is base of Cupido Formation. Thickness of San Lorenzo section may be too great owing to structural complications (from Fortunato and Ward, 1982). B: Schematic model for development of La Casita Formation in Monterrey-Salttillo area. (A) During Late Jurassic terrigenous sediment was shed seaward from uplifted southern Coahuila peninsula. Coarse-grained alluvial fan and shallow-marine deposits (unit 2) prograded seaward over finer grained prodelta and shallow-shelf sediment (unit 1), which accumulated following early to middle Kimmeridgian rise in relative sea level. (B) By earliest Cretaceous time terrigenous influx waned as southern end of Coahuila peninsula subsided, and finer grained shallow-marine sediment (unit 3) accumulated as fan delta retreated with late Valanginian to early Hauterivian rise in relative sea level (from Wilson et al., 1984).



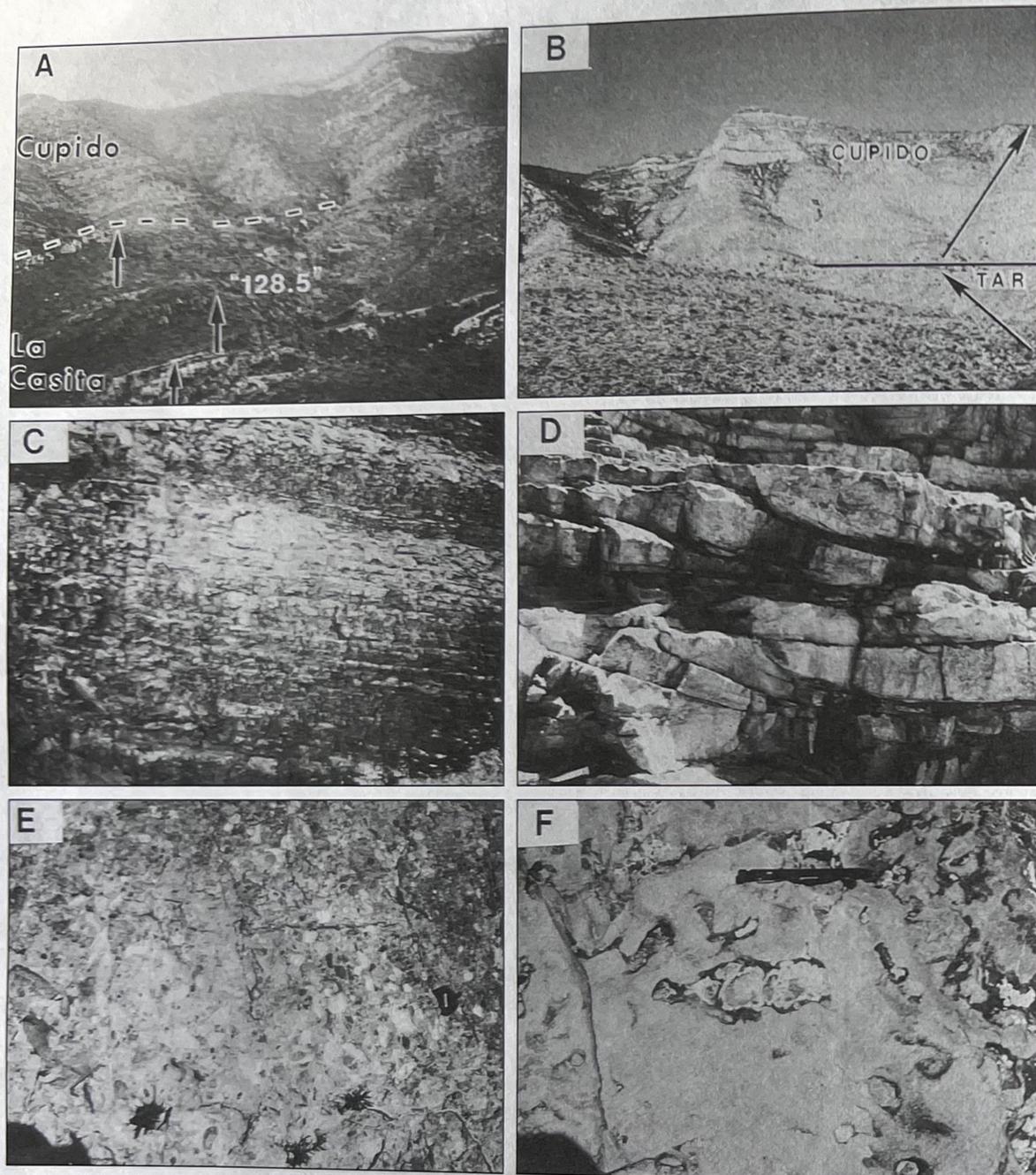


Figure 21. A: Oblique dip view trending north-northeast-south-southwest (viewed from left to right) of stratigraphic relations observable at Los Chorros anticline. From this perspective, La Casita Formation consists of three upward-coarsening, prograding high-frequency sequences. Sequence 128.5 contains most proximal fan-delta facies in La Casita, and is interpreted to coincide with 128.5 Ma second-order supersequence boundary. Above this La Casita retrogrades, and from this vantage point one additional upward-coarsening high-frequency sequence is discernible within back-formation, which comprise second-order highstand systems tract of 112 Ma supersequence. Amount of section exposed in photograph is ~1050 m. B: Oblique dip view trending north-northeast-south-southwest (viewed from left to right) of stratigraphic relations observable at Los Chorros anticline, just downdip (south-southwest) from previous photograph (A). Note coarse clastic La Casita facies has changed to slope-forming Taraises. Amount of section exposed in photograph is ~1200 m. C: Outcrop photograph of thin-bedded sandstone layers (20 cm thick at most) in marine shale, representative of pro-delta facies within lower La Casita Formation, Los Chorros Canyon. D: Outcrop photograph of sigmoidal trough cross-bedding facies of La Casita Formation, suggestive of tidal reworking. This outcrop is stratigraphically beneath most proximal marine fluvial-alluvial environments. Conglomeratic facies composed of immature clast assemblage representative of limited transport from nearby latest second-order highstand conditions within 128.5 Ma supersequence. Los Chorros Canyon. Lens cap is ~20 cm in diameter. E: Outcrop photograph of fine-grained dolomitic mudstone with calcite-replaced evaporite nodules in meter-scale cycles above 128.5 Ma supersequence boundary within lower portion of unit 3 of La Casita Formation, Los Chorros Canyon. This outcrop is stratigraphically ~7 m above that of photo in E.

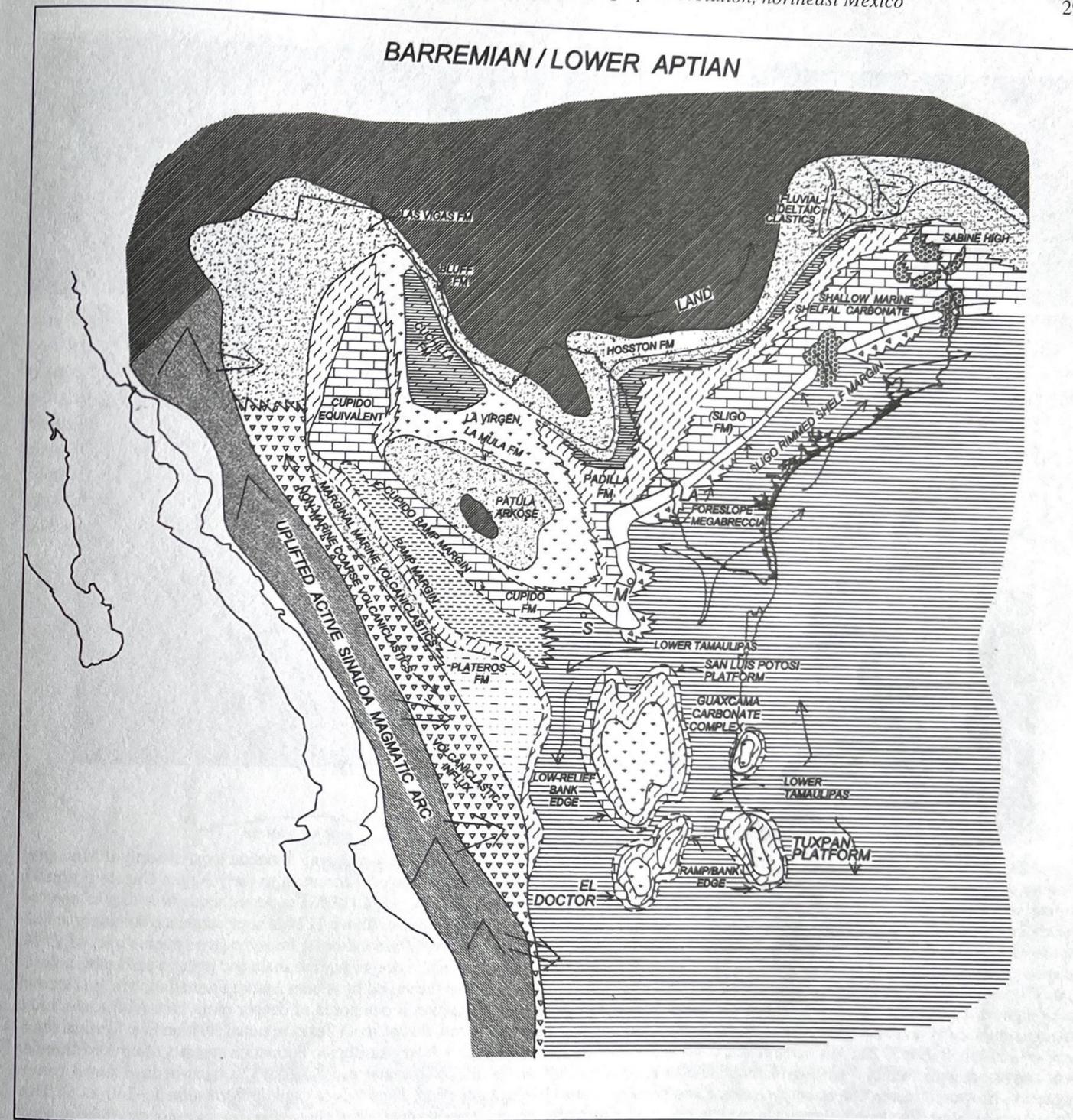


Figure 22. Barremian to lower Aptian paleogeography (see text). Symbols as in Figure 12A.

landward retreat of the fan-delta complex, accompanying a gulf-wide marine transgression. With diminished siliciclastic supply, carbonate production was initiated, yielding this mixed clastic-carbonate unit.

The Taraises Formation is the Lower Cretaceous (middle Berriasian through Hauterivian) deeper water, offshore facies equivalent to the middle and upper units of the La Casita Forma-

tion (Fig. 6; Smith, 1981; Blausler, 1981), and correlates with the basal Hosston Formation of the Gulf of Mexico (McFarlan and Stone, 1977; McFarlan and Menes, 1991). It conformably overlies the offshore La Caja Formation, where the distinction between the two units is based on biostratigraphic control (Blausler, 1981). The Taraises Formation, which thickens to the south and east (135–500 m thick) away from the main La Casita

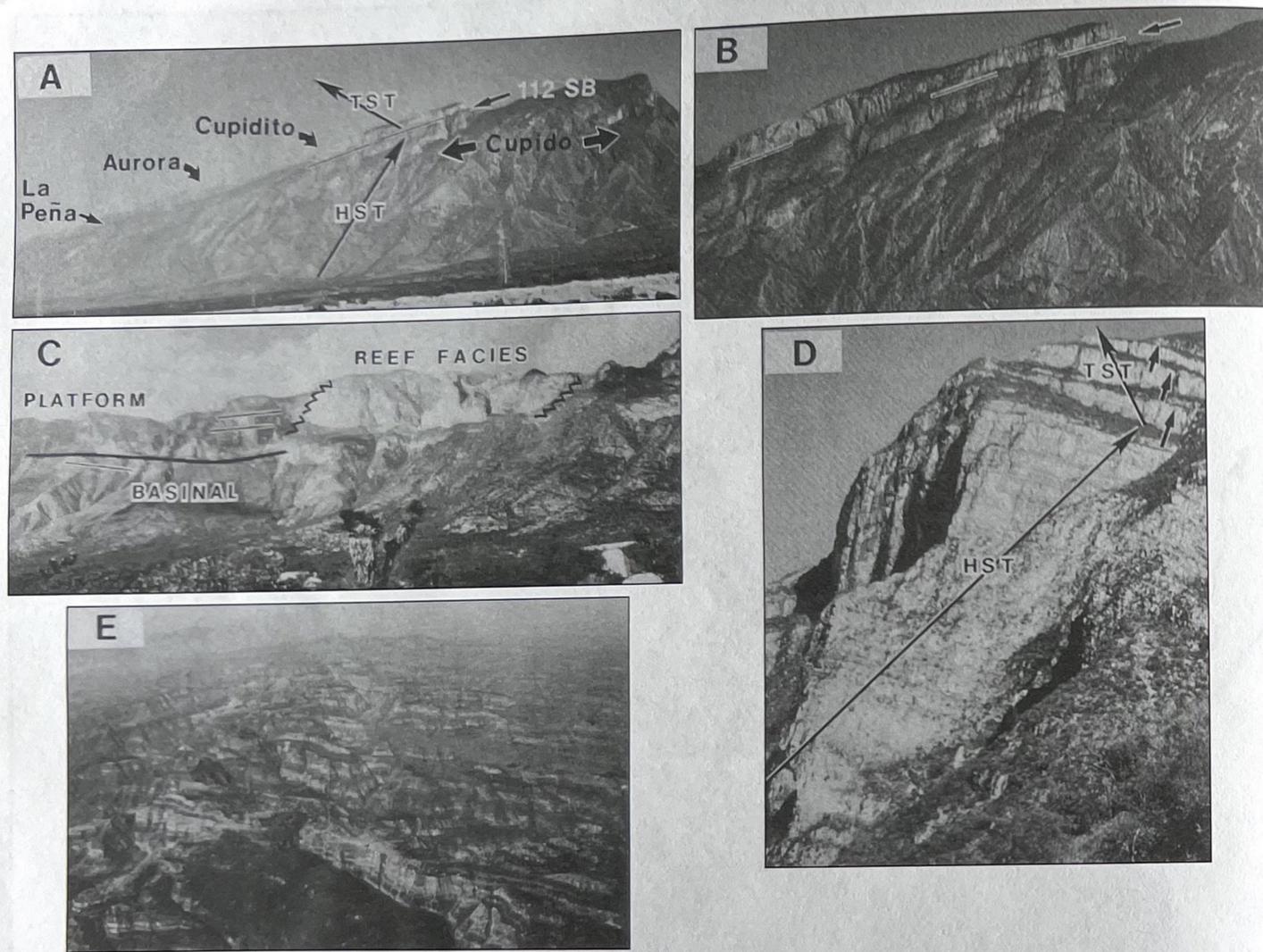


Figure 23. A: View of northwest flank of Potrero Minas Viejas (viewed from west), large doubly-plunging anticline located north of Monterrey. Despite structural rollover, Barremian through Albian stratigraphic relations are well displayed. Barremian to early Aptian Cupido Formation depicts second-order highstand progradation of 112 Ma supersequence. From this vantage point 112 Ma supersequence boundary is approximately located within recessive interval separating thinner beds below from thicker beds above. Above 112 Ma supersequence boundary, middle Aptian Cupido formation can be seen as more prominent ledge-forming unit indicative of second-order transgressive systems tract of 98 Ma supersequence. Cupido formation is overlain by time-transgressive late Aptian La Peña, a deeper marine shale and pelagic carbonate unit. La Peña Formation approximates interval of second-order maximum flooding. It in turn is succeeded by Albian Aurora Formation, which is second-order highstand systems tract of 98 Ma supersequence. In this position Aurora Formation is composed of deeper ramp lime mudstones and is paleogeographically downdip from Albian shelf margin. Compare this stratigraphy with that of south Texas regional seismic line. Vertical thickness is ~1350 m. B: Stratigraphic patterns discernible around 112 Ma supersequence boundary. Note that Cupido Formation consists of upward-thinning beds consistent with second-order highstand architecture, whereas Cupidito Formation displays more massive to thick-bedded stratal pattern suggestive of overall increase in accommodation above position of stratigraphic turnaround. Thickness of Cupidito formation is ~240 m. C: Two-dimensional oblique dip view of Barremian to early Aptian Cupido carbonate platform. In upper half of photo, there is upper sequence with in which massive Cupido reef or platform-margin facies changes updip (toward left) into ledge-forming medium to thin bedded platform interior facies. Lower half of photo shows recessive slope-forming beds of Cupido basinal equivalent (lower Tamaulipas), which belongs to older sequence. Upper sequence has prograded from left to right out over older sequence. General sense of progradation is to east-northeast. Photo is from interior of Potrero García, doubly-plunging, breached anticline. Approximate thickness of Cupido Formation here is 1020 m. D: Typical outcrop of large folds, flat-lying Cupido to Cupidito stratigraphy displays well-exposed stratal architecture. Note that highstand systems tract (HST) consists of thin- to medium-bedded platform interior cyclic carbonates. Turnaround point, interpreted to be 112 Ma supersequence boundary, is marked by change in vertical stacking architecture as expressed by changes in bed thickness. Exposed thickness of section is ~1050 m. Arrows within transgressive systems tract depict retrogradational fourth-order sequences in second-order backstep. E: Aerial view of ledge-forming Albian to Cenomanian basinal carbonates located northeast of Monterrey within Sierra de Picachos. This very thick section of Lower and Upper Tamaulipas clinal drape about Picachos arch.

depo-center, consists of rhythmic-bedded, black, cherty, pelagic lime mudstones and intercalated shales (Blauser, 1981). Fossils include coccoliths, nannoconids, calpionellids, and radiolaria. These pelagic lime mudstones accumulated in a deep offshore to basinal setting (400–500 m water depth) primarily associated with the La Casita retrogradation in the Hauterivian. The Taraises Formation laps out updip, where only a few meters of the formation separate the La Casita from overlying Cupido Formations (e.g., at Cañon del Chorro; Fortunato, 1982).

Locally a thin (20 m thick) limestone unit, the San Juan lentil, occurs within the upper portion of the La Caja Formation (Fig. 6). At Potrero Minas Viejas and Cañon Cortinas, this unit forms a persistent ridge in the La Caja shales and fine-grained siltstones. This normal open-marine limestone deposit loses its definition shelfward where the La Caja rocks change facies to the La Casita Formation. The lower part of this limestone lentil contains a Berriasian fauna (J. L. Wilson and R. L. Scott, 1989, personal commun.), which would equate the San Juan Formation with the Knowles Formation of the northern Gulf of Mexico.

Barremian to early Aptian

In the mid-Early Cretaceous, the previously distinct and separate Mexican geosyncline and Chihuahua trough lost their individual outlines and merged into one major depocenter northwest of the Coahuila block as the subsiding Aldama peninsula was overstepped by a regional sea-level highstand (Fig. 22; Cordoba, 1969; Cordoba et al., 1970, 1980; DeFord and Haenggi, 1970; Seewald and Sundeen, 1971; González-García, 1976; González, 1989; Cantú-Chapa, 1976; Tardy, 1977; de Cserna, 1970, 1979, 1989; Dickinson, 1981; Tóvar Rodríguez, 1981; Roldan-Quintana, 1982; Servais et al., 1982, 1986; Cantú-Chapa et al., 1985; Araujo-Mendieta and Arenas-Partida, 1986; Brown and Dyer, 1987; Sedlock et al., 1993; Moran-Zenteno, 1994). At this time this northwest-southeast-trending depocenter was bounded on the west by the Sinaloa magmatic arc. Proximal to the active arc system, coarse, nonmarine volcanoclastic sediments prograded eastward into what was previously the Mexican geosyncline. East of this volcanoclastic apron and west of the Coahuila block, marine facies accumulated as moderately deep marine carbonates and

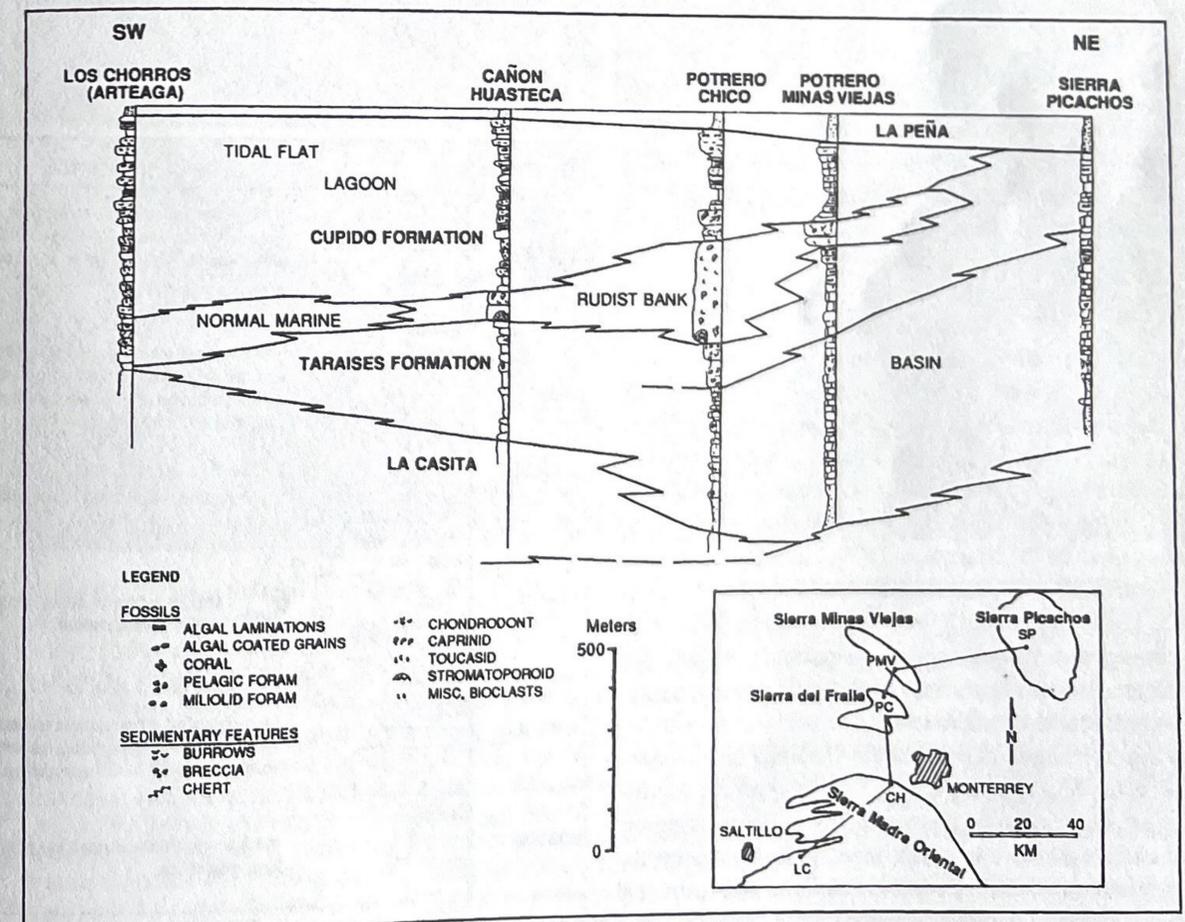


Figure 24. Reconstructed platform to basin cross section of Lower Cretaceous (Cupido to Taraises) shelf margin. Locations of sections are shown in inset. LC—Arteaga Los Chorros; HC—Cañon Huasteca; PC—Potrero Chico; MV—Potrero Minas Viejas; PI—Sierra de Picachos. Note backstepping La Casita (unit 3) and updip pinchout of Taraises indicative of late Viejas; PI—Sierra de Picachos. Note also overlapping, basinward thickening La Peña atop Cupido Valanginian to early Hauterivian rise in relative sea level. Note also overlapping, basinward-prograding carbonate package (from Wilson et al., 1984). Overall, Cupido Formation forms large basinward-prograding carbonate package

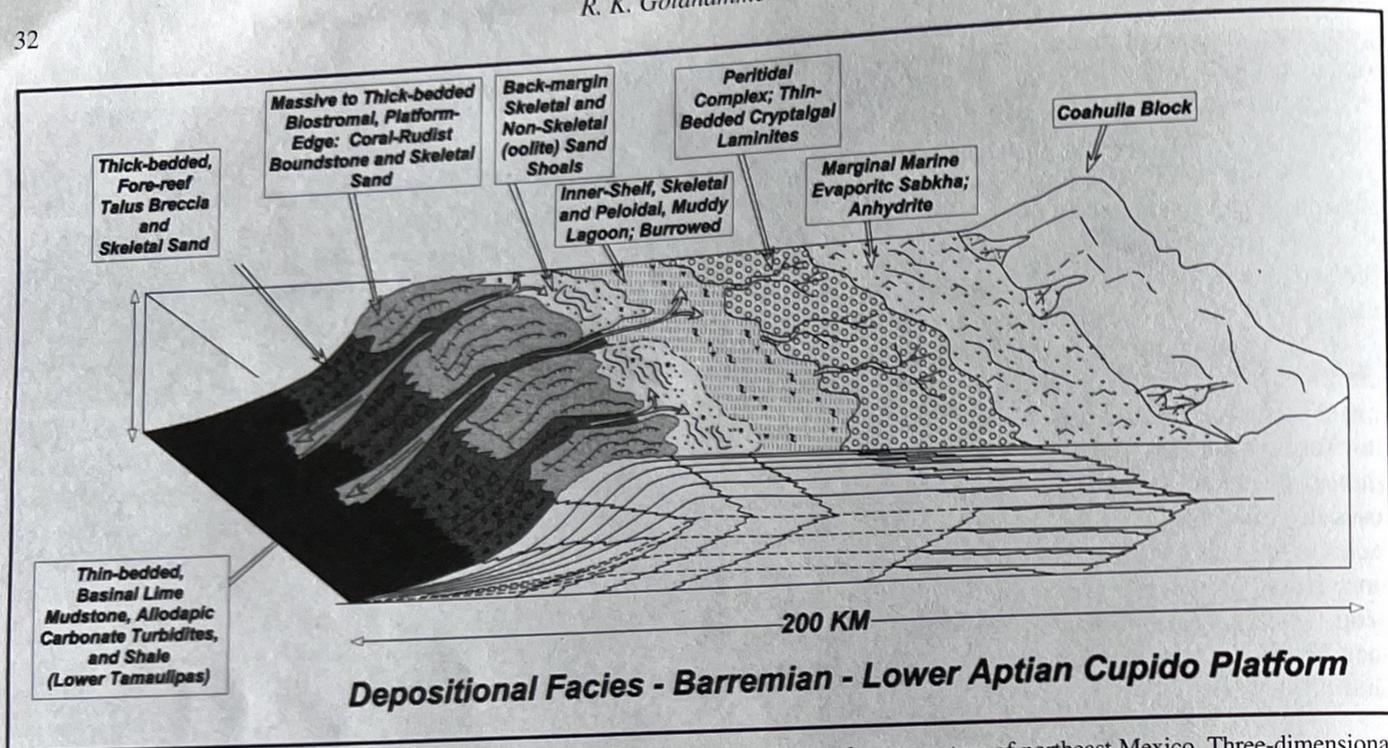


Figure 25. Schematic Barremian to lower Aptian depositional facies model for Cupido carbonate system of northeast Mexico. Three-dimensional block diagram also depicts high-frequency stacking architecture of sequences within this system.

calcareous shales formed a weakly developed low-angle carbonate ramp system. This north-northwest-south-southeast-striking carbonate ramp rimmed an elongate deeper marine trough in which fine-grained clastic-rich siltstones and lime mudstones accumulated (Cordoba, 1969; Cordoba et al., 1970, 1980; de Cserna, 1979; González, 1976; Tardy, 1977; Araujo-Mendieta and Arenas-Partida, 1986; Moran-Zenteno, 1994). In northernmost Chihuahua, coarse nonmarine to marginal-marine clastic sediments filled shallower updip portions of the Chihuahua trough and graded southeast into shallow-marine carbonate facies (Cuchilla Formation; Cordoba, 1969), which extended into the Sabinas basin (La Virgen and Padilla Formations; González-García, 1973, 1976, 1979, 1984; Padilla Sánchez, 1978, 1986; Alfonso-Zwanziger, 1978; Márquez, 1979; Aranda-García and Eguilez de Antuñano, 1983; Eguilez de Antuñano and Aranda-García, 1983, 1984; Echanove, 1986). Complicated facies patterns and consequent formational nomenclature reflect the interaction of arc-driven clastic influx and gulf-driven marine inundation and carbonate deposition.

To the north, northeast, and east of the Coahuila block, proximal, coarse-clastic rocks (Patula Arkose, La Mula) record continued stripping of the Coahuila basement high. These fringing clastic rocks change facies downdip, principally to the north, south, and east, into the restricted marine evaporite and restricted peritidal carbonate of the La Virgen Formation (Fig. 6; González-García, 1976; Zwanziger, 1979; Padilla Sánchez, 1986) that form the vast platform interior of the Cupido-Sligo carbonate platform. To the northwest in the Gulf of Mexico province, this enormous carbonate platform system maintains a low-relief, reef-rimmed

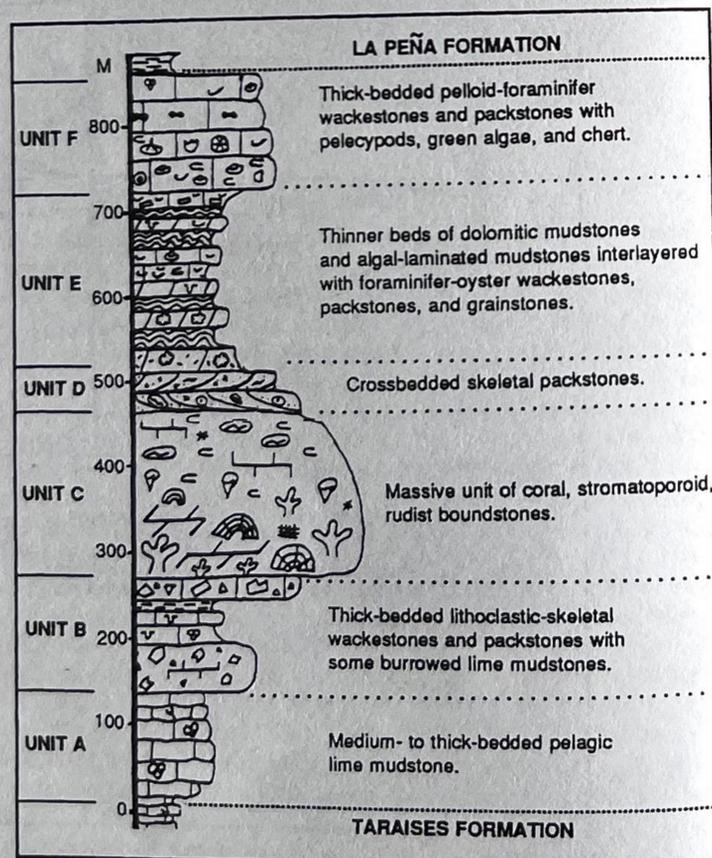


Figure 26. Idealized Cupido section containing six Cupido lithofacies as described by Conklin and Moore (1977; see also Selvius, 1982). Note that unit F and upper half of unit E are roughly equivalent to Cupidito formation of this paper.

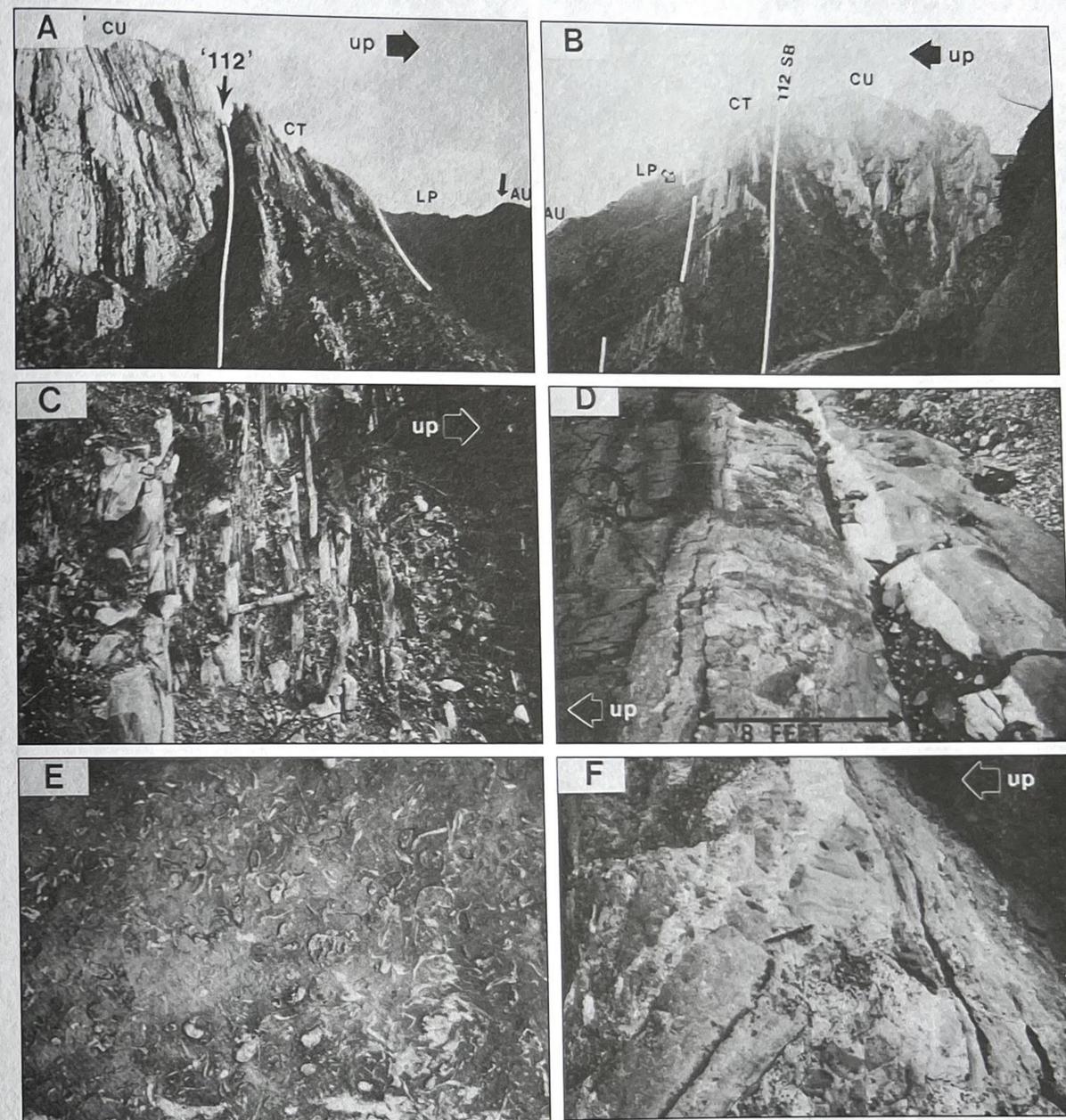


Figure 27. A: Lower Cretaceous carbonate strata (older units to left) at Potrero García, located northwest of Monterrey. View is of east wall just north of entrance. From left to right, units include Cupido (CU), Cupidito (CT), La Peña (LP), and Aurora (AU). 112 Ma supersequence boundary is marked by large arrow, and 107 Ma supersequence maximum flooding surface is marked by small arrow. Thickness of Cupidito formation is ~160 m. B: Lower Cretaceous stratigraphy at Potrero García. View is of west wall just north of entrance. From left to right, units include Cupido, Cupidito, La Peña, and Aurora. 112 Ma supersequence boundary (large arrow) is shown below. C: Outcrop photograph of upper contact of Cupidito formation with the La Peña Formation (beds are older to left), interpreted as major marine flooding surface atop transgressive Cupidito formation. La Peña rocks are argillaceous pelagic lime mudstone and shale. Hammer for scale is 0.3 m in length. Potrero García. D: Outcrop photograph of prominent solution-collapse breccia composed of centimeter- to meter-scale angular blocks of varying platform-interior Cupido lithofacies interpreted as regionally correlative 112 Ma supersequence boundary. Breccia is straddled by bedding-parallel, stratigraphically intact layers (older beds to right). Note shallowing-upward meter-scale peritidal cycle with bedded evaporite cap (now replaced by white calcite) beneath breccia. Potrero García. E: Outcrop photograph of requienid-caprinid packstone forming biostromal accumulation in upper part of transgressive Cupidito formation, Potrero García. F: Outcrop photograph of polymict stratigraphic breccia interpreted as 112 Ma supersequence boundary. Note extremely poor sorting of clasts, diversity of clast types (all identical to platform interior lithologies within Cupido), lack of evidence for transport, lack of grading, and internal sediment fill between clasts.

R. K. Goldhammer

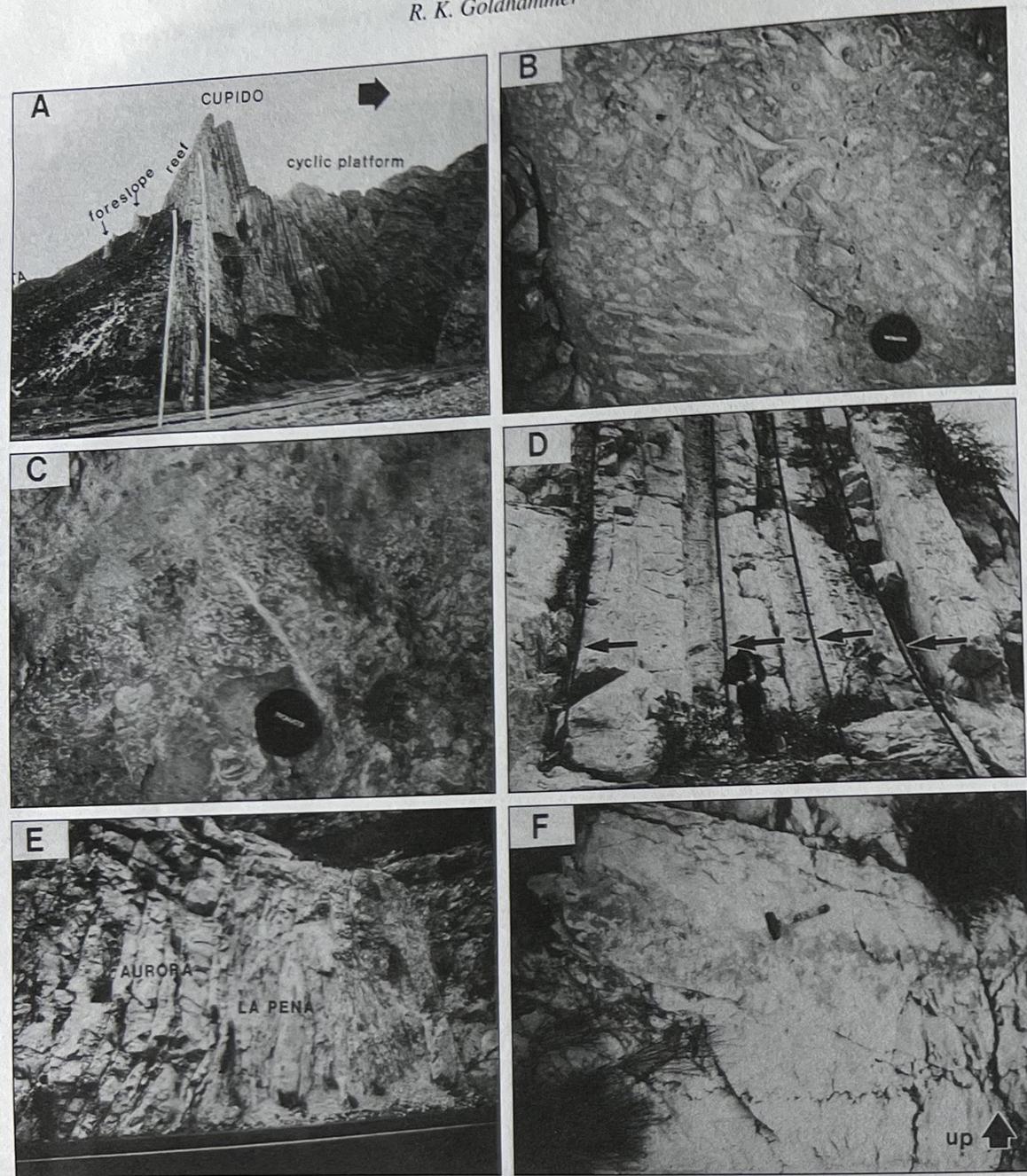


Figure 28. A: Taraisas through Cupido section at Huasteca Canyon, located southwest of Monterrey (see Fig. 2). From left to right, units include thin-bedded upper Taraisas pelagic carbonates (Ta), basinal and foreslope facies of Cupido Formation with thick lenses of lithoclastic debris flow (arrows), overlain by massive to thick bedded reef or biostromal facies (bounded on both sides by white lines), overlain by well-bedded cyclic platform interior strata. Stratigraphic up is to right. Vehicle for scale is in foreground (lower left). B: Outcrop photograph of Requienid-Caprinid biostromal zone representative of Cupido reef or platform margin, biostromal bank facies. From Potrero Chico, located north of Monterrey. C: Outcrop photograph of poorly sorted, foreslope debris bed with platform-margin derived clasts. Note that clast in center above lens cap contains corals. From Potrero García. Lens cap is ~20 cm in diameter. D: Outcrop photograph of Cupido cyclic platform interior at Huasteca Canyon. Beds are older to right. Five individual meter-scale, high-frequency (fifth-order) cycles are shown with cycle tops indicated by tops of arrows. Individual cycles are characterized by dark to light color alternations. Brown interval is largely vuggy, burrowed dolomitic mudstone (interpreted as transgressive part of meter-scale cycle) that grades into coarse, cross-stratified grainstones (white interval, interpreted as highstand or regressive part of meter-scale cycle). These cycles are subtidal cycles in that they lack peritidal capping facies or exposure surface. E: Outcrop photograph of near-vertical strata of Aurora Formation in contact with upper part of La Peña Formation (darker color), base of which is cut out by fault. Location is near southern end of Los Chorros Canyon on back limb of large anticline characteristic of Sierra Madre fold belt. F: Outcrop photograph of thick-bedded to massive Albian bioclastic wackestones to mudstones capped by darker (selectively dolomitized) subaqueous omission surfaces, which are burrowed firmgrounds and hardgrounds (at hammer). Location is near southern end of Los Chorros Canyon.

shelf margin (Figs. 8 and 9) with a myriad of platform interior shallow-marine facies (high-energy grainstone shoals, open shelf skeletal lime sands, muddy lagoonal carbonates, and restricted tidal flat facies; e.g., Bebout and Loucks, 1977; Loucks, 1977; Winker and Buffler, 1988; McFarlan and Menes, 1991). Seaward of the Sligo reef margin, foreslope aprons composed of platform-derived debris pass downdip into basinal lime mudstones and shales of the lower Tamaulipas Formation (Figs. 6 and 7). Coarse nonmarine to shallow-marine clastic rocks (Hosston Formation) interfingered with Sligo carbonates rim the exposed landmass of central Texas. Locally, high-energy grainstone complexes developed over older regional basement highs (e.g., Sabine high).

To the south in the Tampico-Misantla area and in the southern Sierra Madre Oriental, major carbonate platforms persisted, notably the Tuxpan, El Doctor, and San Luis Potosí platforms (Viniestra Osario and Castillo-Tejero, 1970; Enos, 1974, 1977, 1983; González, 1976, 1977; Carrasco-V, 1977; Viniestra Osario, 1981; Winker and Buffler, 1988; McFarlan and Menes, 1991; Wilson and Ward, 1993). According to these authors, these plat-

forms had moderately elevated rims that lacked the significant relief, which was to develop in the Albian. Not as much has been written about the facies development, diagenesis, and petroleum significance of these Lower Cretaceous platforms as compared to their younger mid-Cretaceous counterparts.

In northeast Mexico, the landscape of the Sierra Madre Oriental is dominated by the dramatic carbonate strata of the Cupido Formation (Fig. 23, A-E; 700-1200 m thick), which is Hauterivian to early Aptian in age (Fig. 6; McFarlan and Stone, 1977; Conklin and Moore, 1977; Wilson and Pialli, 1977; Goldhammer et al., 1991). The Cupido Formation is made up of a prograded, low-angle (low-relief) carbonate bank that steps up and over the underlying Taraisas Formation and the basinal equivalent to the Cupido Formation, the lower Tamaulipas Formation (Figs. 7, 23, C and E, and 24; McFarlan and Stone, 1977; Conklin and Moore, 1977; Wilson and Selvius, 1984). The Cupido Formation conformably overlies the La Casita or Taraisas Formations in updip positions (Smith, 1981; Wilson and Selvius, 1984). In downdip positions the contact between

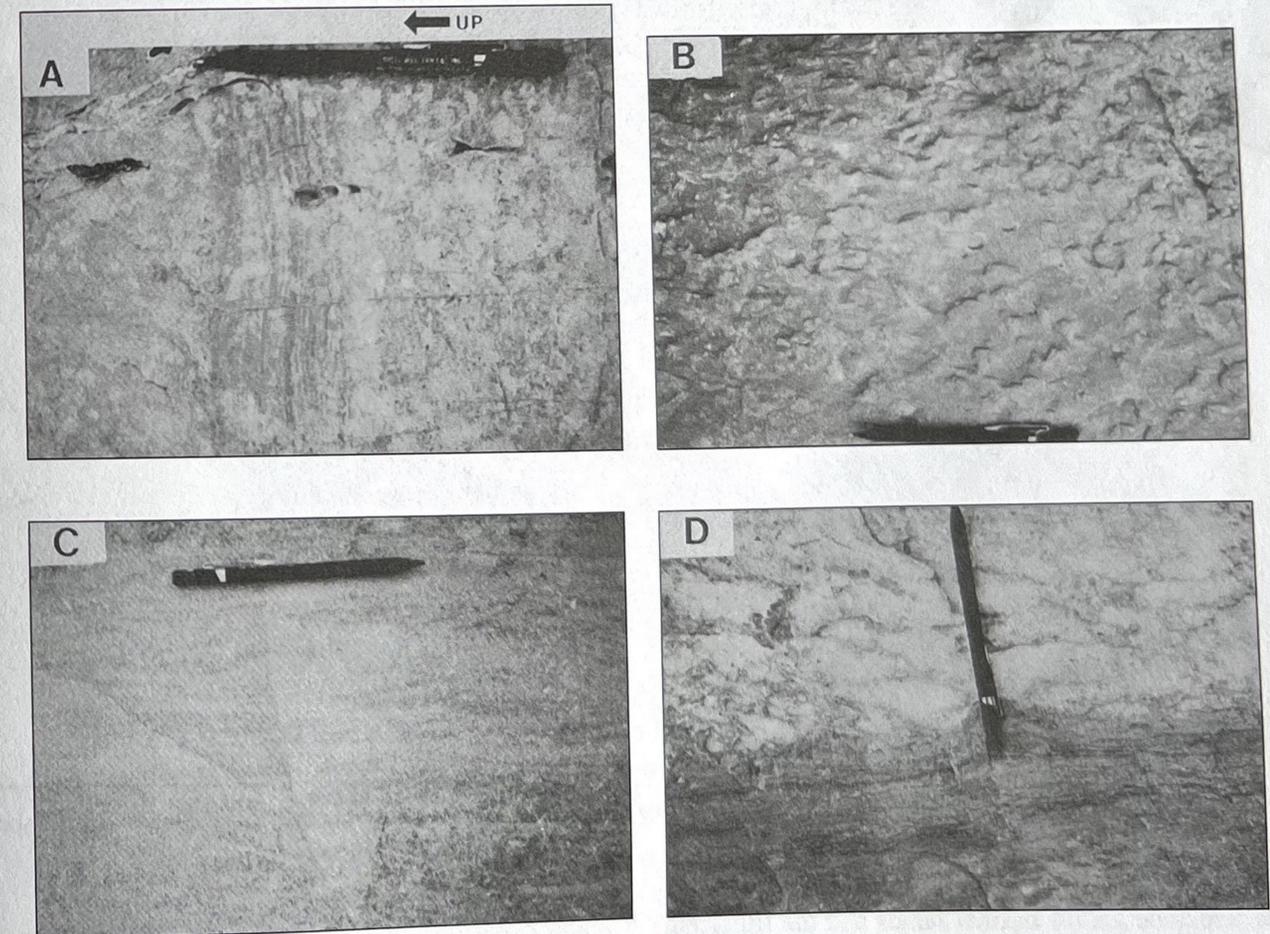


Figure 29. A: Outcrop photograph of cryptalgal laminitic cap indicative of peritidal deposition overlying burrowed subtidal wackestone, showing two facies types that compose a typical meter-scale peritidal, shallowing-upward cycle. Potrero García. B: Outcrop photograph of burrowed dolomitic, skeletal to peloidal wackestone that forms base of meter-scale peritidal cycle. Cycle base occurs within cycle that directly underlies major breccia interpreted as 112 Ma second-order supersequence boundary at Potrero García. C: Outcrop photograph of trough cross-stratified grainstone rich in ooids, which forms middle part of cycle discussed in B. Potrero García. D: Outcrop photograph of cryptalgal laminitic (peritidal facies) capped by bedded, mosaic evaporite (calcite replacement after anhydrite), forming cap to cycle discussed in Figure 27 (B and C). Potrero García.

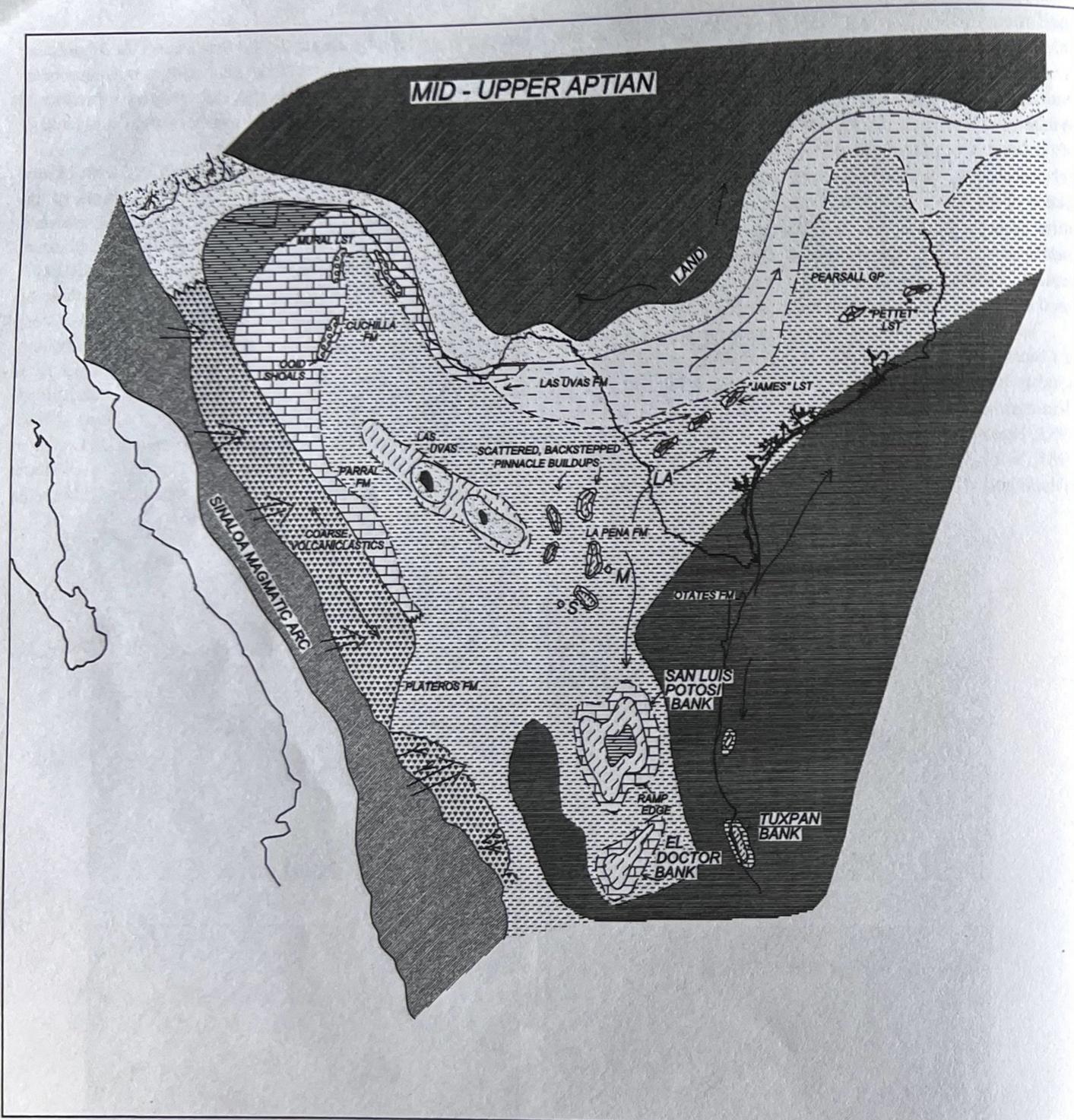


Figure 30. Middle to upper Aptian paleogeography (see text). Symbols as in Figure 12A. Note that orientation of El Doctor bank is speculative.

the Cupido foreslope and/or basinal facies and the subjacent lower Tamaulipas rocks is a time-transgressive facies boundary. The top of the Cupido Formation is marked by onlapping La Peña deeper water shales and argillaceous carbonates, which conformably drape the Cupido bank (Figs. 6-9 and 23, A and B; Tinker, 1982).

Shelf to basin depositional relief was <100 m at the end of

Cupido deposition (Tinker, 1982; Selvius, 1982). Behind the Cupido margin (which consisted of a biostromal facies), a paleotopographic, depositional high persisted in the form of high-energy carbonate sand shoals, as evidenced by isopach maps of the draping La Peña Shale (Tinker, 1982). The trend of the Cupido margin, essentially paralleling the outline of the Coahuila block, and the east to west direction of progradation clearly underscore

the influence of this positive feature in controlling Cupido facies development (Wilson, 1981; Wilson and Selvius, 1984). In contrast, the Cupido trend crosscuts the Burro-Salado arch to the northwest, indicating that this structure no longer affected depositional patterns (Wilson, 1981). The Burro-Salado arch was reactivated and uplifted by the Laramide orogeny (Fig.25).

A generalized platform to basin facies model developed by

previous workers (Eckdale et al., 1976; Conklin and Moore, 1977; Wilson and Piali, 1977; Wilson, 1981; Selvius, 1982; Wilson and Selvius, 1984) indicates that the Cupido Formation consists of essentially six lithofacies (units A to F of Conklin and Moore, 1977; lithofacies 1-6 of Selvius, 1982) that together compose one large-scale shallowing-upward package (Figs. 24, 26, and 27A). These are (1) thin-bedded, argillaceous pelagic,

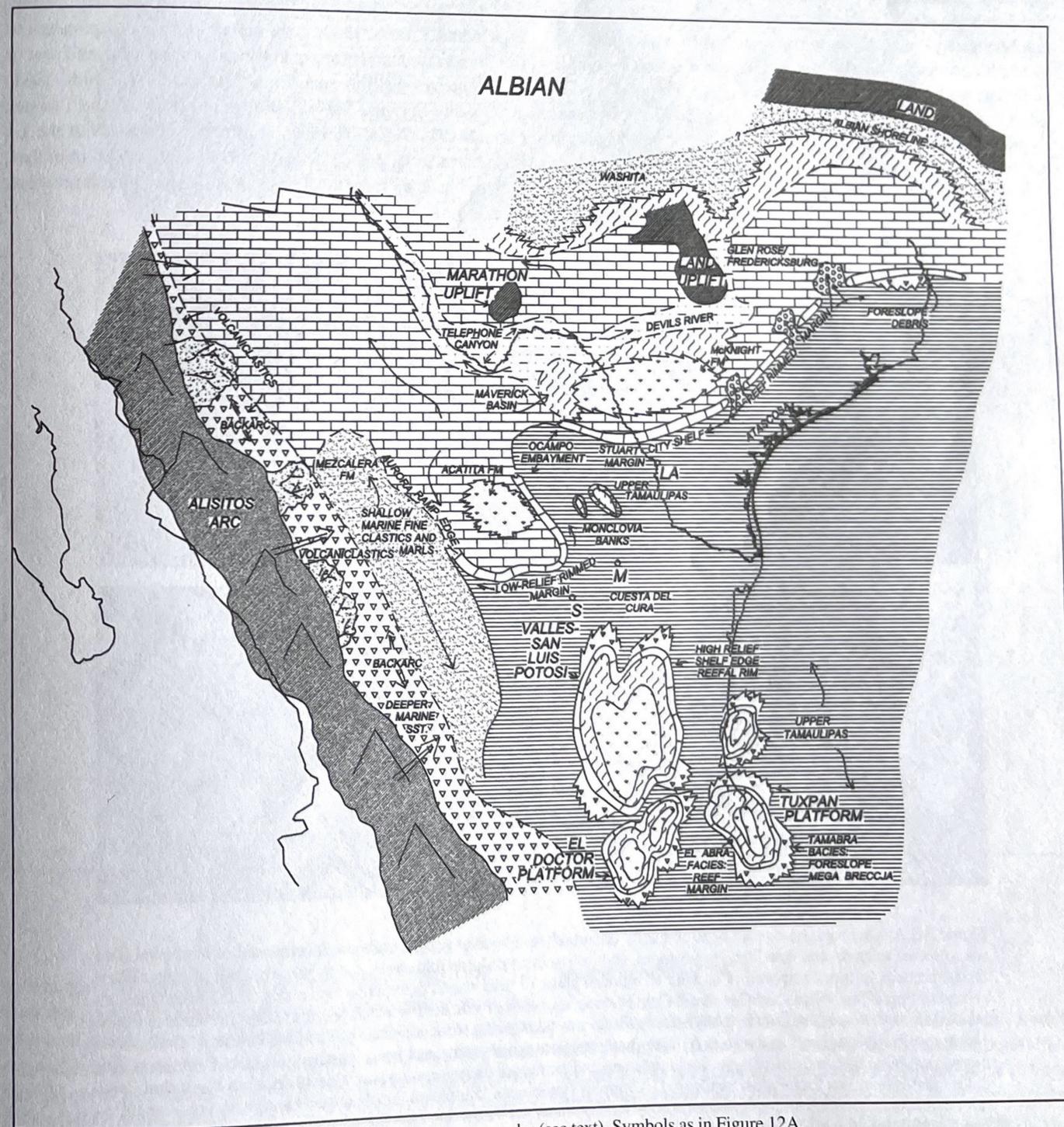


Figure 31. Albian paleogeography (see text). Symbols as in Figure 12A.

lime mudstones (basal environment—unit A, to 400 m thick in more basinward sections, e.g., Potrero Minas Viejas); (2) thick-bedded, intraclastic-bioclastic wackestones to packstones (ramp slope and fore-reef environments—unit B; Fig. 27C); (3) massive rudist and coral-dominated packstones, grainstones, and boundstones with stromatoporoids and marine cements (biostromal shelf margin—unit C, to 250 m thick, e.g., at Potrero Chico; Figs. 27B and 28); (4) crossbedded skeletal to peloidal, packstones to grainstones with ooids and oncolites (back-margin sand shoals—unit D; Fig. 29C); (5) thin-bedded, mudstones and packstones with cryptalgal laminites and evidence for evaporites (cyclic, peritidal platform interior—unit E, to 500 m thick at Los Chorros Arteaga; Figs. 27D and 29, A, B, and D); (6) medium-bedded, black, peloid-foram, wackestones to packstones with pelecypods and green algae (back-margin subtidal lagoon—unit F). In practical terms (i.e., in an interpretative sense), units 1 to 5 compose the large-scale prograding

and shallowing succession, and unit 6 depicts a relative deepening and initiation of retrogradation back over the Cupido bank (Figs. 6, 7, 8, 23, and 24). This transgressive unit is informally termed the Cupidito (Figs. 6, 7, 23, and 28, A and B; Wilson and Piali, 1977; Wilson, 1981) and its thickness varies laterally across the bank top from ~100 m near the Cupido margin (e.g., Potrero García and Potrero Chico) to only a few meters updip in platform interior positions (e.g., Huasteca Canyon, Los Chorros Arteaga).

The lower Tamaulipas (late Hauterivian to early Aptian, Figs. 6 and 7; Ross, 1981) is the downdip, basinal equivalent to the Cupido bank and crops out primarily to the south and east of the Monterrey-Salttillo area (Figs. 23C and 24A; Smith, 1981; Wilson and Selvius, 1984). Its lower contact with the Tareas Formation is conformable, as is its upper contact with the La Peña Formation (Ross, 1981). It consists of about 600 m of dark gray to black, thin- to medium-bedded, cherty lime mudstones

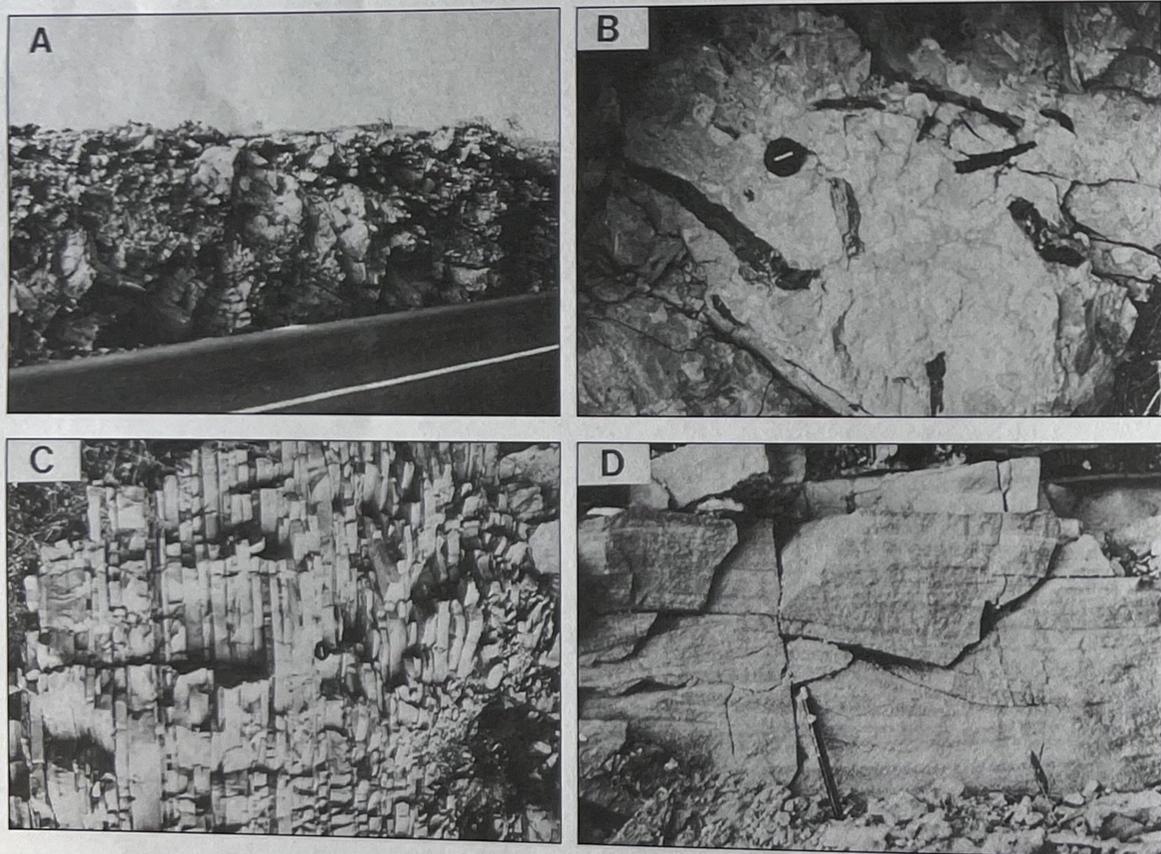


Figure 32. A: Outcrop photograph of tectonically disturbed, thin-bedded pelagic carbonates composed of laminated lime wackestones to cross-laminated lime grainstones, with soft-sediment slump folds truncated by massive layer of coarse lithoclastic breccia, in turn composed of angular to rounded clasts of deep-water, outer slope carbonates. These lithologies are typical of upper Tamaulipas and Cuesta del Cura Formations, off-platform, deep water facies equivalents to Albian to Cenomanian shallow-water San Luis Potosí platform. Photo was taken along roadcut in state of San Luis Potosí. B: Closer view photograph of even, thin beds of pelagic lime mudstone and laminated lime grainstones of Cuesta del Cura Formation. Note black chert layers. San Luis Potosí platform. C: Outcrop photograph of massive lithoclastic breccia shown in A. Note chertified clasts, poor sorting, and irregular shapes of clasts. D: Complex ripple cross-lamination (amalgamated hummocky cross-stratification), San Luis Potosí platform. Upper Tamaulipas Formation.

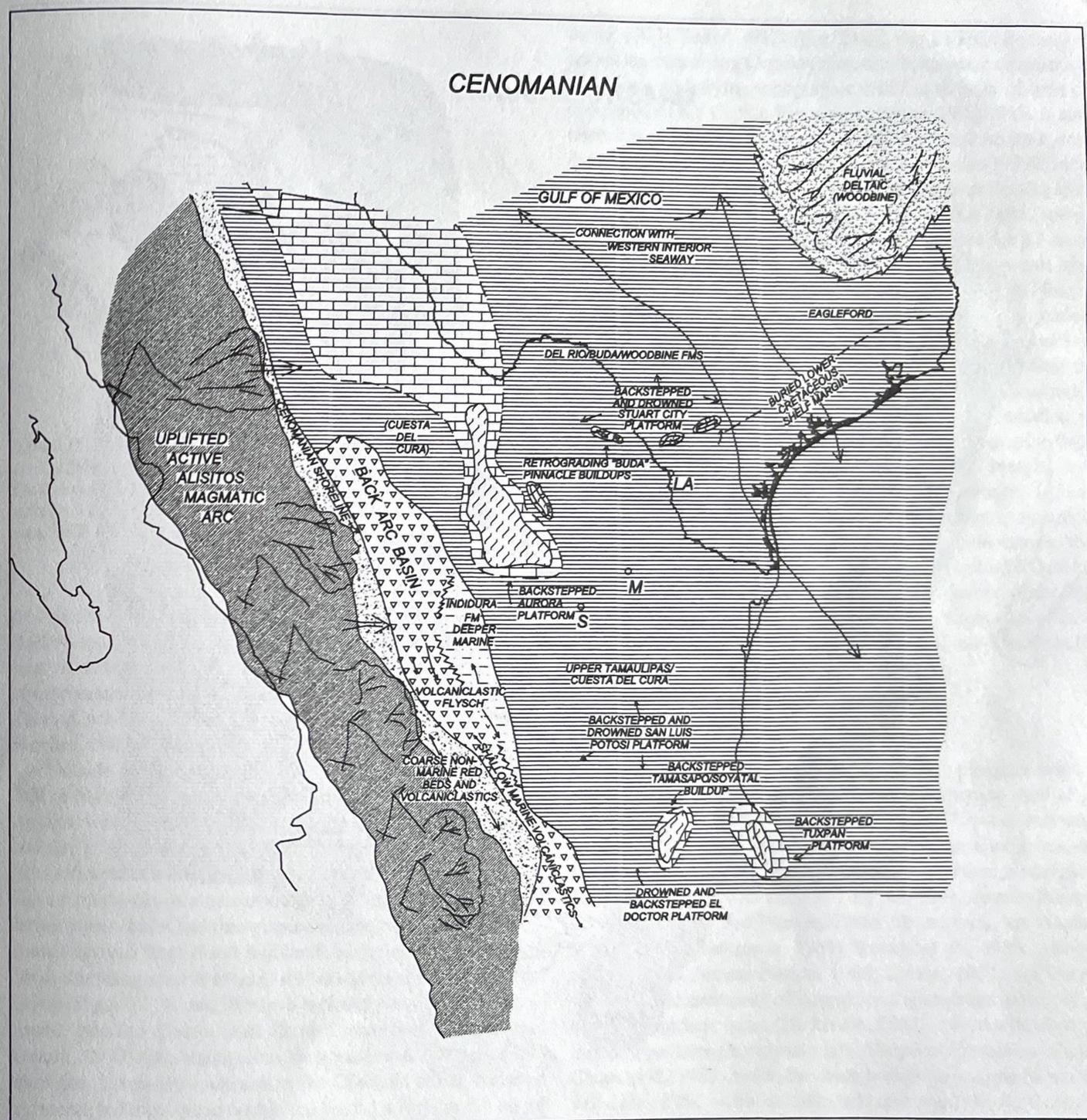


Figure 33. Cenomanian paleogeography (see text). Symbols as in Figure 12A.

to wackestones that display burrow mottling (Ross, 1981). It contains a pelagic fauna of radiolaria, nannoconids, coccoliths, and rare mollusks and echinoids (Ross, 1981). This pelagic deposit is interpreted to have accumulated in a dysaerobic, quiet basinal setting at depths between 50 and 150 m (Wilson, 1969; Byers, 1977; Ross, 1981).

Middle to late Aptian

During this time interval in the western Pacific Mexico province, the major facies trends outlined for the Barremian to early Aptian are fairly similar to those preserved in the middle to upper Aptian rocks (Fig. 30; DeFord and Haeggi, 1970; Seewald and Sundeen, 1971; González-García, 1976; González, 1989; Cantú-

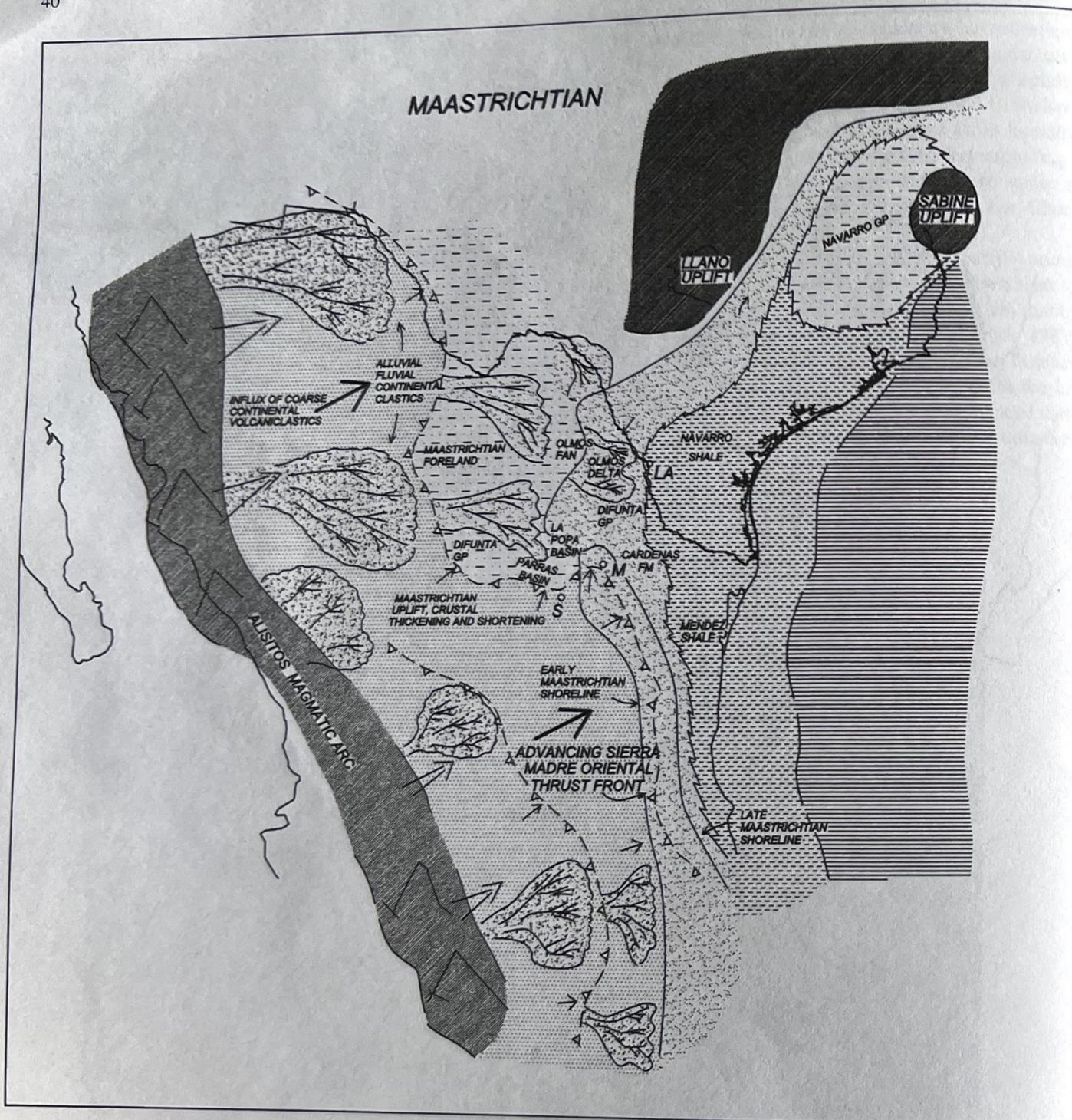


Figure 34. Maastrichtian paleogeography (see text). Symbols as in Figure 12A.

Chapa, 1976; Tardy, 1977; de Cserna, 1970, 1979, 1989; Dickinson, 1981; Roldan-Quintana, 1982; Cantú-Chapa et al., 1985; Araujo-Mendieta and Arenas-Partida, 1986; Brown and Dyer, 1987; Sedlock et al., 1993; Moran-Zenteno, 1994). Proximal to the Sinaloa arc, volcaniclastic sediments flanked the western edge of the western Pacific Mexico depocenter, changing facies to the south into deeper marine lime mudstones and shales of the

Plateros Formation, and to the north into shallow-water carbonates and offshore shales (Parral Formation; Cordoba, 1969; Cordoba et al., 1980; Tóvar Rodríguez, 1981; Cuévas-Pérez, 1983; Cuévas-Pérez et al., 1985; Limon, 1989; Servais et al., 1986). To the northwest in the expanded Chihuahua embayment, a fairly extensive carbonate platform with slope breccias and blocks (e.g., Mural Limestone, Scott and Warzeski, 1993, *in* Scott, 1993)

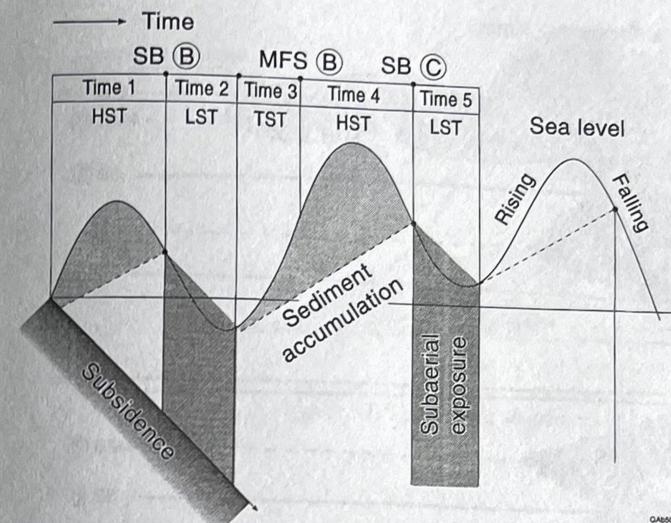


Figure 35. Schematic diagram illustrating interaction of eustatic sea-level, subsidence, and sediment accumulation in development of depositional sequences. SB—sequence boundary; MFS—maximum flooding surface; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract (see text).

existed downdip from shallow-marine clastics (Fig. 30). This shallow-marine carbonate ramp was marked by shoal development at its outer edge. To the southwest into the Sabinas basin, this carbonate system graded into outer ramp lime mudstones and shales (Cuchilla, La Peña; Fig. 6; González-García, 1976; Padilla Sánchez, 1986; Zenteno-Moran, 1994).

Outside of the western Pacific Mexico province, the entire Gulf of Mexico province from east Texas to Tampico underwent a major second-order marine transgression (e.g., Bebout and Loucks, 1977; Winker and Buffler, 1988; McFarlan and Menes, 1991) that effectively backstepped and/or drowned the older Sligo-Cupido-Guaxcama carbonate system, inundating it with deeper water shales and fine-grained terrigenous siliciclastic sediments derived from distal highlands to the north and west. In Texas this transgressive event is well documented by the Pearsall Group (Figs. 6, 7, 8, and 9) which includes some patches of carbonate buildup (James and Pettit Limestones; Bebout and Loucks, 1977) that managed to keep pace with this major sea-level rise. Likewise, southeast of the Coahuila block, scattered carbonate buildups occur within the basal La Peña at the top of the Cupidito rocks. The Coahuila block was nearly inundated and shallow submerged portions of the block became sites of restricted carbonate deposition (Las Uvas facies). To the south in the Tampico-Misantla area, the areal extent of the Tuxpan, El Doctor, and San Luis Potosí platforms diminished as they retrograded (McFarlan and Menes, 1991).

In the Monterrey-Salttillo area, the La Peña Formation (Figs. 23A, 27E, and 28, A, B, and C) is late Aptian (Fig. 6; Smith, 1981; Tinker, 1982) and correlates to the northern Gulf Aptian tripartite of the Pine Island Shale-James Limestone-Bexar Shale, which together constitute the Pearsall Group (McFarlan and

Stone, 1977; Tinker, 1982) (Fig. 24B). The La Peña Formation drapes the underlying Cupido Formation in apparent conformity, preserving underlying topographic relief at the end of time of deposition of the Cupido Formation (Tinker, 1982). This is also observed on high-resolution three-dimensional seismic data from south Texas. Biostratigraphic control of Tinker (1982) indicates progressive onlap of La Peña sediments over the Cupido unit of the Cupido Formation. The base of the La Peña Formation rises biostratigraphically from lower to upper Aptian in an east to west direction across the platform. In addition, this biostratigraphic control indicates that the top of the La Peña Formation is not an isochron, but rather a time-transgressive formation boundary with overlying Albian carbonates. The formation varies in thickness from a few meters to 200 m, depending on antecedent Cupido-lower Tamaulipas Formation depositional relief (Tinker, 1982). For example, the La Peña Formation is thinnest (a few meters) above the Cupido paleotopographic high (carbonate sand shoals) located behind the shelf margin, and thickens behind this above the Cupido back-margin lagoon facies (up to 150 m), perhaps because of differential compaction of subjacent lithologies. Out in front of the Cupido margin, the La Peña Formation thickens drastically into the basin (200 m; cf. Figs. 7 and 8). To the south and east, the deep basinal equivalent to the La Peña Formation, the Otates Formation, consists of thin-bedded dark, argillaceous cherty limestones and black shales (Tinker, 1982).

Albian

In the Albian, the western Pacific Mexico province was the site of an extensive shallow open-marine carbonate shelf (e.g., Finlay Limestone; DeFord and Haeggi, 1970) that extended northeast essentially uninterrupted through the East Texas salt basin and beyond (Fig. 31; Cordoba, 1969; Tóvar Rodríguez, 1981; Enos, 1983; McFarlan and Menes, 1991; Cantú-Chapa et al., 1985; Buffler and Winker, 1988). To the west, the Alisitos arc persisted (Dickinson, 1981; Servais et al., 1986; Araujo-Mendieta and Arenas-Partida, 1986; Limon, 1989) and coarse volcaniclastic sediments offlapped this high belt eastward, filling an Albian backarc basin (Dickinson, 1981). An area of shallow-marine nearshore clastic material (Mezcalera Formation; Cantú-Chapa et al., 1985) and to the south turbidites occupied a narrow belt east of the volcaniclastic belt and west of the Coahuila peninsula (Fig. 31). Southeast from Chihuahua the basin boundary with the northwestern reaches of the Sabinas basin is indistinguishable where shallow-marine carbonates of the Aurora Formation (Fig. 6) onlapped and rimmed the Coahuila block (Cantú-Chapa et al., 1985; Tóvar Rodríguez, 1981; González-García, 1976; Zwanziger, 1979; Padilla Sánchez, 1986; Wilson and Ward, 1993). The southeastern margin of the Sabinas basin formed an embayment (Ocampo embayment; Cantú-Chapa et al., 1985) separating Aurora carbonates of the Coahuila peninsula from the Glen Rose-Fredericksburg-Stuart City complex of south-central Texas (e.g., Wilson, 1975; Bebout and Loucks,

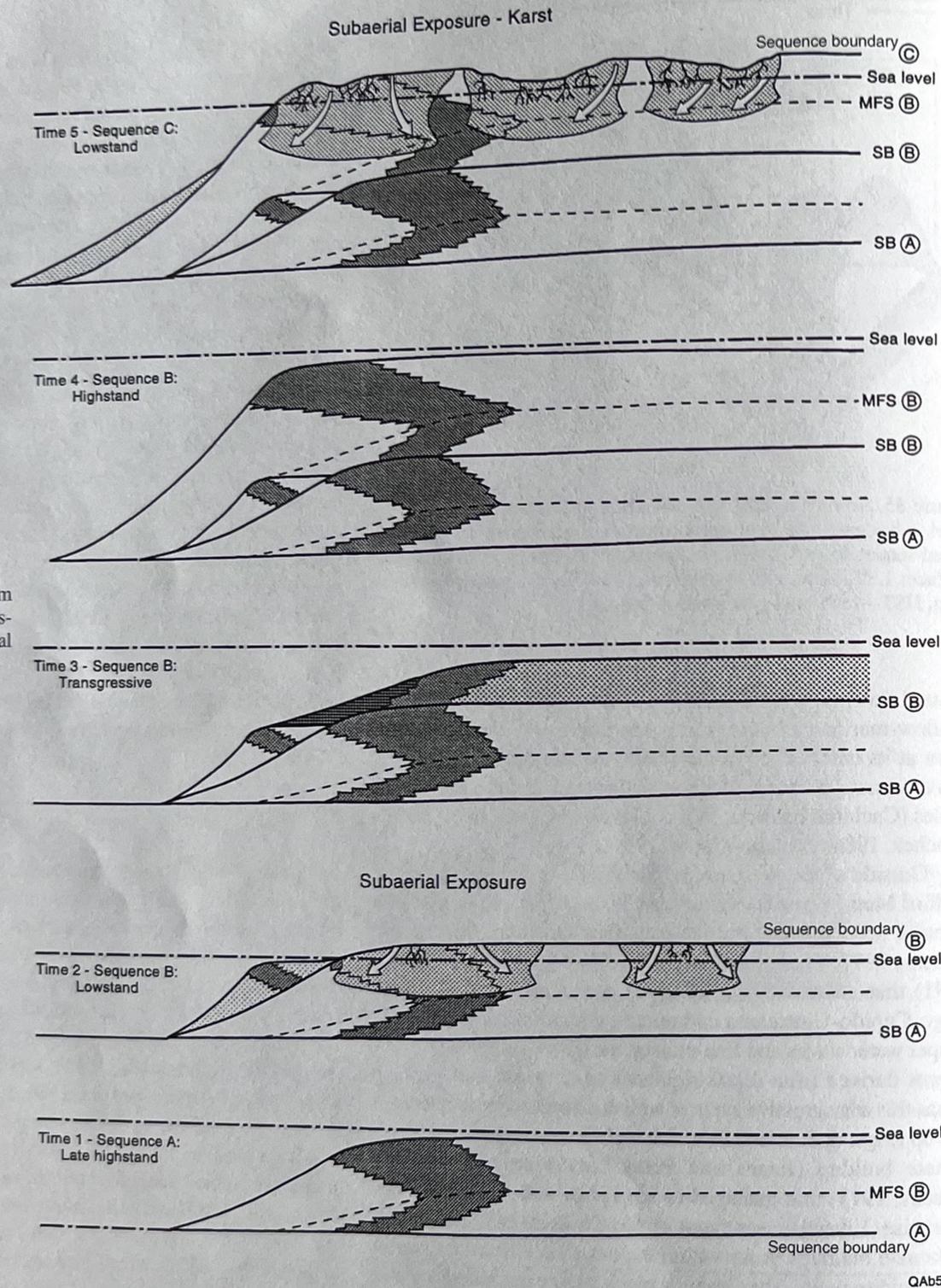


Figure 36. Schematic diagram illustrating evolution of systems tracts and depositional sequences (see text).

1977; Enos, 1983; Buffler and Winker, 1988; McFarlan and Menes, 1991).

To the northeast in Texas, this enormous carbonate system passed updip into nearshore clastics (Washita Group) and overstepped most of the previously exposed landmass of Texas, with the exception of small portions of the Llano and Marathon uplifts. The Stuart City-Edwards shelf margin in Texas formed a low-relief, reef-rimmed margin (e.g., Wilson, 1975) or ramp

margin (Kerans et al., 1995; Zahm, 1997), which was located updip from the underlying Sligo margin in south Texas (Figs. 8 and 9; Wooten and Dunaway, 1977; Winker and Buffler, 1988). South of the Coahuila block, the Tampico-Misantla area was the site of the classic Albian, high-relief, reef-rimmed platforms that have served as excellent petroleum reservoirs (Tuxpan, El Doctor, Valles-San Luis Potosí; Vinięra Osario and Castillo-Tejero, 1970; Enos, 1974, 1977, 1983; González, 1976, 1977;

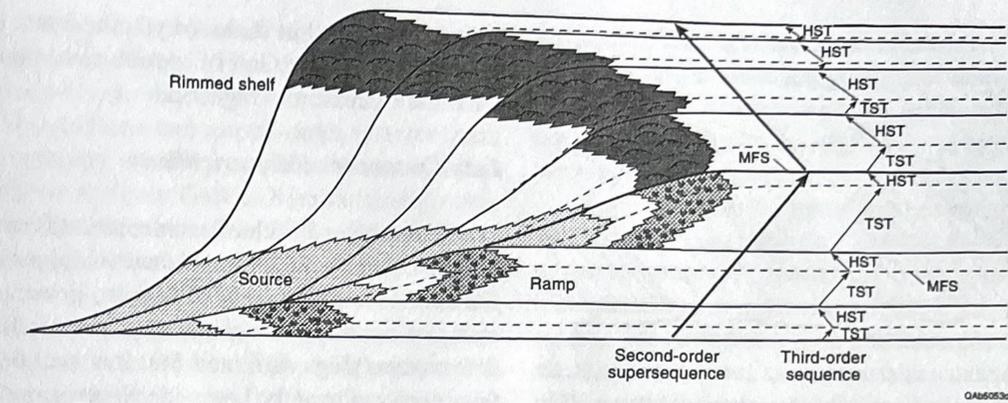


Figure 37. Third-order sequence architecture within second-order supersequence (see text).

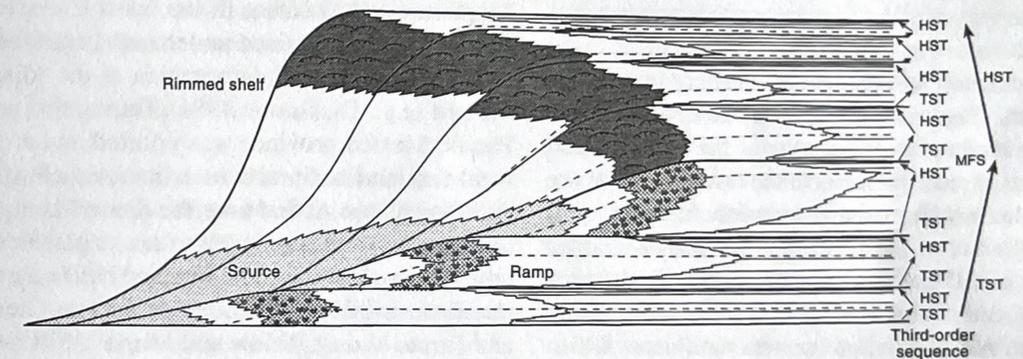


Figure 38. Composite fifth-order cyclic architecture within third-order sequences, which in turn are nested within second-order supersequence (see text).

Carrasco-V, 1977; Vinięra Osario, 1981; Winker and Buffler, 1988; McFarlan and Menes, 1991; Wilson and Ward, 1993). Down dip of the Albian rimmed shelf and isolated platforms, Upper Tamaulipas deep-marine shales and lime mudstones accumulated (Figs. 6 and 32, A, B, and D)

The Aurora Formation demarcates the second major phase of Cretaceous carbonate platform development in northeastern Mexico (Wilson, 1975; Smith, 1981). The Aurora Formation and its basal facies equivalent, the upper Tamaulipas facies, are Albian in age (Figs. 6, 7, and 27, E and F) and in contrast to the high-relief, steep-sided reef margins of the Valles platform to the south, Aurora carbonates were deposited on a gently dipping, low-angle carbonate ramp that rimmed the Coahuila block in the southern Sabinas basin (Smith, 1981). A prominent rudist bank facies marks the ramp edge, behind which 500 to 700 m of normal marine carbonates accumulated (Vinet, 1975). The Aurora Formation conformably overlies the La Peña Formation and is probably disconformable beneath the Cuesta del Cura Formation.

The upper Tamaulipas Formation (Albian; 100–200 m thick), which is the basal equivalent of the Aurora Formation, is also prominent in northeast Mexico exposures, and correlates with the Atascosa Formation in south Texas (Fig. 6; McFarlan and Stone, 1977; Smith, 1981; Ross, 1981). It crops out south and east of the

Aurora margin (Fig. 31) and conformably overlies the La Peña and underlies the Cuesta del Cura Formations (Smith, 1981). Here it consists of thin- and thick-bedded, cherty, dark pelagic mudstone to wackestone (Ross, 1981), interpreted as deep-water anoxic to dysaerobic off-ramp deposits. Toward the top, burrow-mottled fabrics are evidence of a slight shallowing. The top of the formation is marked by a prominent conglomerate bed a few meters thick that contains updip-derived cemented clasts of shallow-water Aurora lithologies (Ross, 1981).

Cenomanian

In the earliest Late Cretaceous, both the western Pacific Mexico and Gulf of Mexico provinces are inundated by a major superimposed first-order and second-order eustatic flooding event that connected the Gulf of Mexico with the Western Interior seaway of the Rocky Mountains (e.g., McFarlan and Menes, 1991). In the western Pacific Mexico province, the Alisitos arc was active and arc magmatism had migrated eastward as compared to the Albian (Tardy, 1977; de Cserna, 1979, 1989; Limon, 1989; Cordoba et al., 1980; Dickinson, 1981; Servais et al., 1982, 1986; Araujo-Mendieta and Arenas-Partida, 1986; Sedlock et al., 1993; Moran-Zenteno, 1994). East of the arc, a

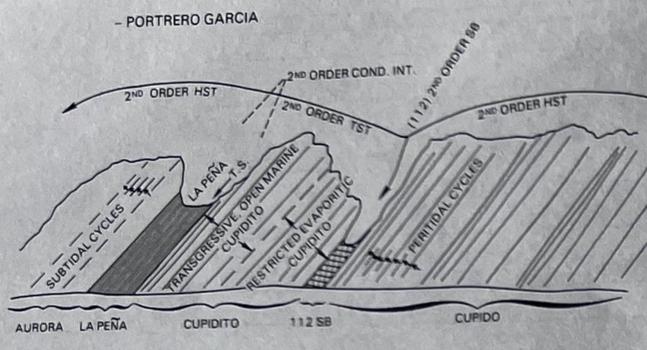


Figure 39. Drawing of interpreted stratigraphic relations at Potrero Garcia. HST—highstand systems tract; TST—transgressive systems tract; TS—transgressive surface; SB—sequence boundary. About 450 m of section are shown.

backarc basin persisted and was the site of a variety of volcanoclastic-related facies (Fig. 33), which passed eastward into deeper marine lime mudstones and shales of the Indidura and Cuesta del Cura Formations. To the north the last vestiges of the underlying Albian platform persisted in the northern extremes of the Chihuahua trough and to the south as calcareous turbidites (DeFord and Haeggi, 1970; Cordoba, 1969; Tóvar Rodríguez, 1981; Enos, 1983; Cantú-Chapa et al., 1985). This narrow band of shallow-marine carbonates linked up with thin latest Albian to early Cenomanian carbonates of the backstepped Aurora platform (Fig. 33). Locally in northeast Mexico and south Texas, a few pinnacle buildups of latest Albian to earliest Cenomanian age kept pace with the overall transgression in the region. These are small and isolated, yet prominent on two-dimensional regional seismic data in south Texas. To the southeast, the Albian platforms were backstepped and drowned.

In the Monterrey-Salttillo area, basinal facies are outcrops assigned to the Cuesta del Cura Formation, which is latest Albian to Cenomanian (Figs. 6 and 7; Enos, 1974; Smith, 1981; Ice, 1981) and consists of deep-water pelagic carbonates and shales that accumulated in front of elevated shallow-water, reef-rimmed middle Cretaceous platforms (Stuart City, Aurora, Valles platform, Fig. 32C). It equates to the Georgetown-Del Rio-Buda facies of south Texas (Smith, 1981). In exposures of northeast Mexico, it is composed of ~60 m of dark, thin- to medium-bedded, laminated lime wackestones to packstones intercalated with thin shales (rhythmites) and rare lithoclastic conglomerates (platform-derived megabreccias). Grain types include peloids, calcispheres, radiolaria, planktonic forams, echinoids, and sponge spicules (Ice, 1981). The upper formation contact is conformable (Ice, 1981).

The Indidura Formation (Cenomanian to Santonian) contains two members, the Agua Nueva and the San Felipe (Figs. 6 and 7), equivalent to the Eagleford Shale and Austin Chalk (Smith, 1981; Winker and Buffler, 1988; Ice, 1981). This package of deep-water pelagic deposits averages 300–400 m in thickness, and consists of pelagic lime mudstones to wackestones (radiolaria, globigerinids)

and intercalated thin shales (rhythmites) that essentially blanket the entire southwest Gulf of Mexico area, signifying the peak of the middle Cretaceous highstand.

Late Cretaceous (Maastrichtian)

From the end of the Cenomanian and throughout the Maastrichtian, paleogeographic and facies relations in both the western Pacific Mexico and Gulf of Mexico provinces are drastically changed as the result of the diachronous Laramide phase of deformation (Figs. 4, 6, and 34). It is well beyond the scope of this chapter to treat the Laramide phase in any detail (e.g., see, de Cserna, 1989; Sedlock et al., 1993; Moran-Zenteno, 1994), but for the sake of completeness it is summarized briefly, because it is responsible for the present day structural relations within the Monterrey-Salttillo area. In the latest Cretaceous, the western Pacific Mexico province underwent Laramide uplift and east-directed contractional deformation as the Alisitos arc migrated inboard (e.g., Dickinson, 1981). During this period the western Pacific Mexico province was uplifted and eroded, and despite local foreland basin accumulations, much of the record is an extended hiatus. At that time, the Sierra Madre Oriental fold belt developed and migrated west to east (e.g., Suter, 1987). In northeast Mexico, Maastrichtian foreland basins developed in front of the advancing Sierra Madre (e.g., Sabinas-Olmos area; La Popa and Parras basins; Weidie and Murray, 1967; González-García, 1976; Padilla Sánchez, 1986; Soegaard et al., 1997).

SECOND-ORDER SUPERSEQUENCE DEVELOPMENT

In northeast Mexico, the Triassic to middle Cretaceous section can be divided into two tectonic phases of passive-margin development: (1) rift stage (middle Carnian to early Oxfordian), 2400 m of rift-related continental to marginal-marine redbeds and evaporites; and (2) drift stage (early Oxfordian to Santonian), 3700 m of drift-related shallow-marine to deep-marine carbonates with subordinate clastic material (Goldhammer et al., 1991). Tectonic subsidence analysis indicates a thermal event at 150.5 Ma followed by typical exponential tectonic subsidence (~50% crustal thinning; Goldhammer et al., 1991). During the drift stage of passive-margin development, the stratigraphic evolution is interpreted to have been dominated principally by eustasy (Todd and Mitchum, 1977; Vail et al., 1984; Haq et al., 1987; Scott et al., 1988; Goldhammer et al., 1991; Scott, 1993; Yurewicz et al., 1993) for two reasons: (1) thick regional accommodation cycles of second-order supersequence development can be correlated throughout the Gulf of Mexico (Salvador, 1991a, 1991b, 1991c; McFarlan and Menes, 1991; Sohl et al., 1991); and (2) the rates of background tectonic subsidence are much too slow to account for the requisite accommodation space required to accumulate the thick supersequences.

With regard to the packaging of the drift-related stratigraphy, the Middle and Upper Jurassic through Lower Cretaceous stratigraphy has been subdivided into four major second-order

(i.e., 10–100 m.y. duration) depositional supersequences that have regional gulf-wide significance (Figs. 6–9; Goldhammer et al., 1991). Major second-order sequence boundaries, condensed sections, transgressive surfaces, and second-order systems tracts were identified in outcrops, dated by available biostratigraphy, and correlated with the northern Gulf of Mexico stratigraphic section (Figs. 6 and 7; Goldhammer et al., 1991). The identification of these components is based on: (1) gross shelf to basin relationships of onlapping and offlapping facies; (2) stacking patterns of third-order (1–10 m.y. duration) sequences and their component high-frequency (fourth- and fifth-order) cycles; and (3) in the case of sequence boundaries, criteria for significant subaerial exposure and/or erosion. Additional stratigraphic data came from regional seismic coverage in south Texas (e.g., Figs. 8 and 9) and regional well-log cross sections (see Goldhammer et al., 1991, Figs. 31–37; Stone, 1975; and McFarlan and Stone, 1977) in south Texas and extreme northeastern Mexico.

Generic sequence stratigraphic model

Here I review the basic model of the Mesozoic sequence stratigraphic interpretation of northeast Mexico (e.g., Sarg, 1988; Vail, 1987). In this review I concentrate on carbonate sequence models because most of the pre-Laramide Mesozoic stratigraphy in northeast Mexico is composed of carbonate. With modifications, the model outlined here can also be applied to siliciclastic systems. In the generic scheme, a depositional sequence, regardless of order, may be defined as a conformable succession of genetically related strata bounded by interregional unconformities or their correlative conformities (i.e., sequence boundaries). Initially the term sequence was typically linked to third-order changes in eustatic sea-level, but now sequence carries no time connotation and sequences originate via accommodation changes driven by relative sea-level changes (e.g., Kerans and Fitchen, 1995) and/or changes in sediment supply without relative changes in sea level (Schlager, 1993).

A sequence can be subdivided into component systems tracts defined as a linkage of contemporaneous depositional systems (i.e., shelf, slope, basin), which are three-dimensional assemblages of lithofacies (Vail et al., 1984; Van Wagoner et al., 1987; Sarg, 1988). Systems tracts, characterized by predictable large-scale geometry and facies associations, are defined objectively based on position within a sequence, the types of bounding surfaces (e.g., type 1 or type 2 sequence boundaries, maximum flooding surface), and the stacking patterns of higher frequency cycles.

As defined originally by the Exxon group, the lowstand systems tract (LST) is deposited during maximum sea-level lowstand, and may be characterized by nonmarine deposits on the shelf, and onlapping allochthonous to autochthonous deposits at the margin of a prograding highstand shelf margin. The transgressive systems tract (TST) is deposited when the rate of accommodation gain is greater than the rate of carbonate sedimentation. In two dimensions, stratal architecture of high-frequency cycles displays a retrogradational (backstepping) to aggradational stack-

ing pattern. The highstand systems tract (HST) is deposited when the rate of accommodation gain is less than the rate of carbonate sedimentation. In two dimensions, stratal architecture of high-frequency cycles displays an aggradational to progradational (backstepping) stacking pattern.

Figures 35 and 36 summarize the evolution of a second-order (i.e., duration ranging from 10 to 100 m.y.) carbonate sequence, or supersequence. Figure 35 illustrates changes in accommodation with time, as a function of the interplay of second-order eustasy and subsidence, for a reference point on top of a carbonate platform. Eustasy is portrayed as successive sinuform waves of rising and falling sea-level of equivalent duration, but different amplitude. Time proceeds from left to right (older to younger) on the diagram. Sediment accumulation is shown by a dashed line climbing from lower left to upper right during periods of third-order marine submergence. The light gray area beneath the sea-level curve and the sedimentation vector depicts water depth. When sea-level falls, it intersects the platform top, depicted by the dark-shaded phase of subaerial exposure. During this period, the platform merely subsides at the background rate.

Figure 36 shows the geometry and systems tract evolution of a hypothetical carbonate platform linked to the accommodation changes shown by Figure 35. Starting at the bottom of Figure 36, we proceed through five time slices, each of which is linked to a time slice in Figure 35.

Time 1. Relative sea level is located above the platform top, and we are in the late highstand systems tract of the underlying sequence A. Major facies tracts within the underlying sequence A display basinward progradation, due to systematic decline in second-order accommodation.

Time 2. Eustatic sea level has fallen beneath the top of the platform, exposing the platform top to subaerial diagenesis—the shaded areas with white arrows schematically show freshwater flow paths. A third-order sequence boundary is generated along the platform shown as a thicker dark line (sequence boundary B). Time 2 marks the lowstand systems tract of sequence B, and a hypothetical prograding autochthonous wedge of carbonate is shown perched down-dip from the previous shelf margin.

Time 3. Eustatic sea level rises, flooding the platform initiating carbonate deposition, and facies retrograde. Backstepping of facies belts reflects the notion that the rate of accommodation increase is greater than the rate of carbonate sedimentation. The maximum flooding surface (maximum flooding surface B; dashed line) occurs at the maximum point of facies retrogradation, theoretically coincident with the maximum rate of sea-level rise. Time 3 thus depicts the transgressive systems tract of sequence B.

Time 4. During time slice 4, the rate of eustatic rise declines, followed by a fall in sea level. Facies prograde seaward as the rate of carbonate sedimentation catches up with and outpaces the rate of creation of accommodation space. Time 4 thus marks the highstand systems tract of sequence B.

Time 5. At time 5, sea level falls beneath the top of the platform, subaerially exposing sequence B, beneath sequence boundary C (the sequence boundary of the next hypothetical sequence).

Onlapping the slope, an allochthonous megabreccia is schematically illustrated as the result of platform top or margin subaerial erosion. Time 5 illustrates lowstand conditions of sequence C.

This two-dimensional model is schematic, and depending on many factors—such as depositional profile, antecedent topography, compaction, windward-leeward effects, reef-rimmed margin versus sand-shoal margin—this scheme will vary. In humid climates, penetrative freshwater karstification will be more pronounced at sequence boundaries; in arid climates, less so. In arid climates, evaporites may form during lowstands in a restricted basin or within irregular depressions on the shelf. In mixed systems, siliciclastic sediments will tend to prograde out onto the carbonate platform and perhaps spill into the basin (cyclic and reciprocal sedimentation). The possible variations on the basic model are numerous, yet the model serves as a useful starting point.

As pointed out by numerous workers (e.g., Goldhammer et al., 1990, 1993; Kerans and Fitchen, 1995), relative fluctuations in sea level occur with different frequencies, yielding a hierarchy of relative sea-level changes based upon the inferred temporal duration of the relative sea-level cycle. These and other authors have demonstrated that composite relative sea-level changes, which combine the effects of third- (1–10 m.y. duration), fourth- (0.1–1 m.y. duration), and fifth-order (0.01–0.1 m.y. duration) eustatic cycles are of prime importance in determining both the depositional sequence scale (kilometer scale) and stratigraphic cycle scale (meter scale) stratigraphic packaging. It is this connection between composite sea-level changes and the stacking patterns of high-frequency cycles and sequences that is fundamental in interpreting low-frequency, second-order accommodation changes.

On the basis of the existence of composite relative sea-level cycles, Goldhammer et al. (1990) suggested that a hierarchy of stratigraphic forcing exists in which lower frequency sea-level cycles (e.g., second order) force the higher frequency sea-level cycles (e.g., third order) through composite interaction. The net effect produces systematic and predictable changes in accommodation space available for the deposition of individual cycles during the rising and falling stages of a relative low-frequency sea-level change. It is logical that in carbonate systems the hierarchy of stratigraphic forcing will result in organized vertical and lateral changes in stacking patterns (thickness, facies character, lateral geometry, and early diagenetic attributes) of high-frequency shallow-water carbonate cycles dictated by low-frequency, relative sea-level effects.

The stratigraphic hierarchy is scale invariant; i.e., the principle of superimposed orders of accommodation can be transmitted across all scales of stratigraphy. Extrapolation to the next stratigraphic scale (Fig. 37) illustrates the manner in which third-order sequences are grouped systematically to define second-order supersequences. This diagram shows a supersequence (800–1500 m thick) composed of second-order transgressive ramp sequences that evolve into second-order highstand rimmed shelf sequences. Note how the relative proportion of TST/HST components of the third-order sequences shifts systematically vertically through the

supersequence, from transgressive prone to symmetrical to highstand prone. In addition, the third-order sequences systematically thicken upward and then thin upward within a supersequence. Although the diagram is schematic, there are well-documented examples of this type of stratigraphic architecture.

Figure 38 shows the hierarchy expanded over three orders of magnitude and the resultant effect on the high-frequency cyclic architecture. The utility of high-frequency cycle stacking analysis in interpreting third-order sequence architecture and constraining definition of second-order sequences in the Mesozoic of northeast Mexico was extensively documented by Goldhammer et al. (1991). Much of the second-order sequence stratigraphic framework discussed in the following is based on that work, (see Goldhammer et al., 1991, for a full account).

Late Bathonian to early Kimmeridgian

Supersequence overview. This supersequence (Figs. 6 and 7) is dominated by second-order lowstand deposition (La Joya, Minas Viejas, Figs. 11 and 13A); the second-order transgressive surface at 150.5 Ma coincident with the regional breakup unconformity. The La Gloria and Zuloaga formations are largely transgressive, and the Olvido evaporite unit demarcates the second-order highstand containing the supersequence boundary at 144 Ma (Goldhammer et al., 1991; Figs. 6, 7, and 11, A and F). The Upper Triassic to Lower Jurassic La Boca and La Joya non-marine redbeds contain some volcanic material, and are areally restricted to rift basins, and unconformably overlie late Paleozoic basement. The Minas Viejas (gypsum, halite) is mostly deformed with a nonuniform distribution within the area, representing marginal-marine deposition prior to the second-order marine transgression. The La Gloria Formation consists of marine (shallow, nearshore) to marginal-marine (playa) siliciclastics located peripherally about margins of exposed Paleozoic land masses. The upper part of the La Gloria Formation is the nearshore, siliciclastic equivalent to the carbonate Zuloaga Formation, which consists of shallow-water, low-angle ramp deposits that grade downdip to outer ramp mudstones, changing facies to basinal shales and thin limestone beds of the La Caja Formation. The Olvido Formation consists of evaporitic deposits and associated marginal-marine clastics in the lower portion. The upper portion deepens upward overall into carbonates.

Second-order lowstand systems tract. The basal supersequence boundary at 158.5 Ma is a major unconformity (type 1 sequence boundary) and occurs as an angular unconformity between the La Boca and La Joya formations in outcrop (Peregrina Canyon, near Ciudad Victoria; Corpstein, 1974). It is defined seismically in south Texas by erosional truncation beneath the boundary on top of the underlying Eagle Mills Formation (La Boca), and by onlap of the Louann-Werner Formation against the underlying Eagle Mills and Paleozoic basement updip (Todd and Mitchum, 1977; Figs. 8 and 9). Well-log cross sections in northeastern Mexico and south Texas show the Callovian lowstand thinning updip and pinching out against basement highs or older

La Boca Formation (Stone, 1975; see Goldhammer et al., 1991, Figs. 33–35). Similar stratigraphic relations are observed in the age-equivalent section in east Texas and Louisiana (see Goldhammer et al., 1991, Figs. 31 and 32). On regional seismic data, the La Boca nonmarine redbeds and volcanic strata are areally restricted to rift basins, unconformably overlying late Paleozoic basement. The La Joya and Minas Viejas formations have a non-uniform distribution within the area, but step out over the La Boca Formation indicating marginal-marine deposition prior to the second-order marine transgression.

Second-order transgressive systems tract. The second-order transgressive surface marking the top of the lowstand is also an unconformity (marking a subsidiary third-order sequence boundary), and is observed in outcrop at two localities. At Potrero Minas Viejas, the contact between Minas Viejas gypsum and the Zuloaga Formation appears to be conformable, although there is considerable brecciation and disruption of the basal Zuloaga rocks, presumably due to Tertiary(?) evaporite dissolution (Fig. 13A). At Peregrina Canyon, the Zuloaga Formation onlaps the La Boca Formation (La Joya missing) in angular discordance (Corpstein, 1974). Seismically, the transgressive surface is characterized by onlap of Oxfordian strata against the underlying Callovian lowstand assemblage (Figs. 8 and 9; Todd and Mitchum, 1977). Basal reflectors can be traced updip beyond the subjacent Callovian onlap, where they terminate against basement or older Eagle Mills rocks (Figs. 8 and 9). These relationships are also present in well-log cross sections across the Gulf of Mexico (see Figs. 31–35; Stone, 1975), where the basal Norphlet (La Gloria) Formation thickens updip as it laps up and over Callovian strata, ultimately lapping out against basement. Downdip where the basal Norphlet Formation is very thin to missing, the basal Oxfordian carbonate is a transgressive dark, laminated carbonate mudstone that pinches out in a landward direction (see Goldhammer et al., 1991, Figs. 31–35; Stone, 1975; Todd and Mitchum, 1977).

The second-order transgressive systems tract is made up mostly of high-energy carbonate ramp deposits of the Zuloaga Formation and nearshore siliciclastics of the backstepping La Gloria Formation (Figs. 13, E and F, 14, A and B). In general, based on regional correlation to subsurface cross sections and seismic data to the north in Mexico and northeast in the Gulf of Mexico, the Zuloaga Formation is characterized by two or three largely aggradational, third-order sequences (average 80–100 m thick; ~2 m.y. duration) composed of stacked, high-frequency ramp cycles (fifth order) rich in shoal-water grainstones. At Sierra de Bunuelos, Goldhammer et al. (1991) measured and described a fairly complete Upper Jurassic section (375 m thick) incorporating the upper half of the Zuloaga Formation, Olvido evaporite, Olvido lime mudstone, and lower La Caja Formation (see Goldhammer et al., 1991, Fig. 45). Apparently, not all of the third-order sequences of the Zuloaga Formation composing this second-order transgressive systems tract are exposed in outcrops in the region (e.g., at Sierra de Bunuelos, Johnson, 1991; C. R. Johnson et al., 1991). The exposed rocks record the landward retrogradation of open ramp, open-ramp

shoal, open lagoon, inner-ramp shoal, inner lagoon, coastal lagoon, and sabkha depositional environments, producing an overall deepening-upward stacking architecture.

Second-order highstand systems tract. The second-order highstand systems tract at Sierra de Bunuelos consists of one (~100 m thick) third-order sequence (the 144 Ma sequence of Goldhammer et al., 1991, Figs. 45 and 46). The early TST of the 144 Ma sequence consists of upward-thickening subtidal, fifth-order cycles (cycles 8–12 in Fig. 46 of Goldhammer et al., 1991) with argillaceous, thin-bedded mudstone bases capped by shoal-water skeletal-oid packstones and grainstones. The remainder of the TST consists of amalgamated, thick, low-energy subtidal cycles composed of burrowed, peloidal lime mudstones to wackestones interpreted as an increase in third-order accommodation. Above this, the first few cycles of the early third-order HST of the 144 Ma sequence display thin-bedded argillaceous lime mudstones at their bases, capped by shoal-water, pellet-oid packstones to grainstones. These pass vertically into stacked, aggradational, coarsening-upward, subtidal grainstone cycles (average 3.3 m thick; cycles 4–13 in Fig. 46 of Goldhammer et al., 1991). These cycles are rich in pellets (*Favreina*), skeletal grains, composite grains, and ooids. The late third-order HST of the 144 Ma sequence is marked by the abrupt occurrence vertically in the section of a series of thin subtidal, pellet grainstone cycles (<1–1.3 m thick; cycles 14–17 in Fig. 46 of Goldhammer et al., 1991) that contain euhedral crystallatopic evaporite molds (after gypsum) at their tops. These in turn are overlain by thin (~0.5–0.65 m thick), restricted, peritidal cycles toward the top of the Oxfordian, just beneath the 144 Ma supersequence boundary. These cycles have replaced evaporite bases (calcitized gypsum?) and thick disrupted peritidal laminite caps. Lateral correlation (Johnson, 1991) demonstrates that they occur beneath the bedded gypsum deposits of the Olvido evaporite.

The 144 Ma third-order sequence boundary, which is coincident with the second-order supersequence boundary, is located within this reduced accommodation interval. In outcrop it is picked near the base of the Olvido evaporite, on top of a 3-m-thick peritidal, cryptalgal laminite full of centimeter-scale layers of replaced evaporite (cycle 19 at 118.5 m on Bunuelos section of Goldhammer et al., 1991). Such a thick laminite cap implies the development of substantial tidal flat complexes associated with maximum regression.

Early Kimmeridgian to Berriasian

Supersequence overview. Within this supersequence, the Olvido evaporite, Olvido lime mudstone, and basinal equivalent La Caja Formation compose the second-order transgressive systems tract; the second-order maximum flooding surface (MFS) is placed at the top of the Olvido lime mudstone (138 Ma; Figs. 6 and 7). The highstand part of the supersequence contains the lower two-thirds of the siliciclastic La Casita Formation, the upper portion of the La Caja Formation, and the lower portion of the Tarais Formation. The La Casita Formation in this super-

sequence consists of a basal unit of carbonaceous siltstone and mudstone (interpreted as deeper-water prodelta deposits), capped by an upper unit of coarse sandstones and pebble conglomerates (interpreted as an overall regressive, coarse-clastic, fan-delta system). The supersequence boundary occurs within this upper regressive interval, as reflected by the maximum seaward advance of the fan-delta system. The lower portion of the Taraises Formation is the deeper water offshore (basinal) equivalent to the La Casita Formation, consisting of argillaceous, rhythmic-bedded limestones and shales. The San Juan lentil is a persistent carbonate unit within the uppermost La Caja Formation to the lower part of the Taraises Formation and most likely depicts a third-order relative sea-level cycle in the overall second-order highstand.

Second-order lowstand systems tract. The basal supersequence boundary (144 Ma) is interpreted as a second-order type 2 sequence boundary (type 2 in the sense of Vail et al., 1984) because of a lack of evidence for prolonged subaerial exposure or erosion of the shelf. Above the supersequence boundary, at the Bunuelos locality, Goldhammer et al. (1991, Fig. 46, top of cycle 21) document a thin (<30 cm thick) laminated, stromatolitic gypsum layer that is at the base of the Olvido evaporite. This thin unit and <1 m of diagenetically altered, restricted, peloidal carbonate beneath it may, however, represent true sabkha deposition, or second-order lowstand deposition on the ramp top. The overlying Olvido evaporite contains tens to several tens of meters (locally) of evaporite and equivalent collapse breccia is present. Although deformed in outcrop (Bunuelos section), a progradational sabkha origin for the Olvido outcrops seems unlikely, based on the absence of interbedded peritidal carbonates or siliciclastic material, and the thickness of such a relatively homogeneous unit of gypsum. The bedded gypsum of the Olvido evaporite, containing a few intercalated thin carbonate beds of dolomitized ooid to peloid grainstone, is interpreted as a subaqueous deposit. The increasing marine character of this unit (compared to underlying laminites) signifies renewed slow increase in accommodation, which accompanied the ensuing transgression.

Second-order transgressive systems tract. Above this, four third-order sequences are recognized within the Olvido Formation, averaging ~70 m in thickness. The third-order sequences are defined by the vertical stacking patterns of higher frequency ramp cycles as outlined by Goldhammer et al. (1991) and discussed here (Fig. 38). The basal third-order sequence is rich in intercalated evaporites and solution-collapse breccias, whereas the overlying three sequences lack evaporites and are enriched in ramp-crest grainstone cycles. The third-order stacking architecture is representative of longer term second-order increase in accommodation. At Sierra de Bunuelos, the initial second-order flooding of the region above the transitional, restricted evaporite phase is documented where the Olvido evaporite passes vertically upward into thin, peritidal cycles that have restricted subtidal bases that shoal-upward into laminites or solution-collapse breccias (cycles 28–36 in Fig. 46 of Goldhammer et al., 1991). Above this are very thick (average 7–10 m thick) amalgamated, thick-bedded subtidal cycles (cycles 37 and 38 of Goldhammer

et al., 1991), that are rich in pellets, skeletal grains, and ooids, indicating a return to normal marine conditions associated with Kimmeridgian transgression. The retrogradational stacking pattern of these cycles and their thickness and grain content indicate significant ramp flooding over the region.

The remainder of the second-order HST at Sierra de Bunuelos, as documented by Goldhammer et al. (1991), contains three additional third-order ramp sequences (third-order sequences 2–4 within the Olvido lime mudstone; cycles 42–84 of Goldhammer et al., 1991). These third-order sequences generally consist of a fairly symmetrical facies and high-frequency cycle stacking arrangement. The lower portions of the sequences are marked by thin grainstone-based cycles with peritidal (cryptalgal laminite) caps that lack evaporites. Above this the sequences open up and are marked by thicker, stacked amalgamated grainstone-rich cycles, many of which have shaley, off-ramp facies at their base. In detail these cycles are thick (1–5 m thick), upward-coarsening, aggradational cycles with subtidal boundaries, often in the form of submarine hardgrounds. These cycles, rich in pellets (*Favreina*), composite grains, skeletal debris, and ooids, record initial ramp flooding and the establishment of shoal-water grainstone complexes. Shaley-based cycles are much thinner, and are composed of thin-bedded, argillaceous lime mudstone at the base, coarsening upward into burrowed peloid, skeletal packstone. These cycles are all subtidal cycles with hardground caps or sharp flooding surfaces. They represent significant deepening, perhaps beneath storm wave base, resulting in transgressive third-order cycle thinning and deposition of shaley material due to sediment starvation. The middle to upper parts of the sequences are marked by relatively thick, high-energy, upward-coarsening subtidal cycles full of mechanical cross-stratification. They are dominantly ooid grainstones with associated intraclasts and skeletal grains. These cycles depict a return to a ramp shoal complex within the overall third-order HST. The uppermost portions of the third-order sequences record late third-order HST progradation of updip peritidal cycles, which cap the sequences.

Toward the top of the Olvido lime mudstone at Sierra de Bunuelos, the uppermost section of carbonate is marked by three 0.30–1-m-thick cycles (cycles 81–83 of Goldhammer et al., 1991, Fig. 46), each composed of a normal marine, shoal-water subtidal base and a thin cycle cap (10–50 cm thick) of reddish siliciclastic siltstone. The siltstone caps display wavy bedding (centimeter-scale) with ripple cross-laminae, and hummocky cross-stratification suggestive of open-shelf deposition. This minor influx of open-shelf siliciclastic material toward the top of the Olvido Formation marks the initiation of the transition from carbonate ramp conditions to siliciclastic shelf deposition with the ensuing marine deepening recorded in the overlying La Caja and basal La Casita Formations.

The contact between the Olvido lime mudstone and the La Caja strata at Bunuelos is a sharp lithologic transition from shallow-water, normal-marine carbonate to fine-grained sandstones, siltstones, and shales (407.9 m on the Bunuelos section of Goldhammer et al., 1991; Figs. 15C and 18A). There is no evidence

for subaerial exposure at this surface. This surface is interpreted as a significant second-order flooding surface at Bunuelos, but the second-order MFS is somewhere above, within the La Caja Formation. In detail, the contact is a burrowed omission surface, with a network of centimeter-scale burrows infilled with carbonate sand on top of a sandy, skeletal-peloidal packstone. This marine flooding surface is immediately overlain by a 30-cm-thick transgressive lag of calcareous sandstone with gastropods and encrusting serpulid worm tubes. Above this the La Caja Formation deepens within 20 m from offshore subtidal siltstones and intercalated skeletal limestones to deeper marine, thinly bedded siltstones and dark shales (Fig. 15, E and F). These siltstones and shales contain phosphatic sand, concretions of phosphatic mudstone with ammonites, *Chondrites* burrow networks, and thin intervals of black shale. The intercalated limestone beds are interpreted as allodapic debris beds representing the downdip toes of updip time-equivalent retrogradational ramp carbonates.

Similar relationships are observed between the Olvido lime mudstone and the La Caja strata to the south at Astillero Canyon, a more basinal Zuloaga-Olvido locality (Meyer and Ward, 1984). This top of the Olvido Formation (Haynesville) flooding surface is present throughout the Gulf of Mexico, testifying to its regional significance (Goldhammer et al., 1991, Figs. 31–35; Stone, 1975; Todd and Mitchum, 1977). In the northern Gulf of Mexico, this surface is prominently delineated on seismic data by the strong onlap of Bossier Shale (La Caja) against the Haynesville Formation (Gilmer lime mudstone). In south Texas and northeastern Mexico, Stone (1975) demonstrated through pattern correlation, that this is a major flooding surface that reveals onlap of Tithonian shales (La Casita–La Caja) onto Kimmeridgian carbonates.

Second-order highstand systems tract. The second-order highstand systems tract is made up of the Tithonian to Berriasian La Casita Formation (Cotton Valley), which records the main progradational stage of a fan-delta complex nucleating around the Coahuila block (Fortunato and Ward, 1982). The San Juan lentil is a persistent carbonate unit within the upper part of the La Casita Formation, and most likely represents a third-order relative sea-level cycle in the overall second-order highstand. On the basis of Fortunato and Ward's (1982) work, the supersequence boundary (128.5 Ma) in the Monterrey-Salttillo area is placed at the top of the middle finer grained clastic interval of unit 2 (top of unit 2A), beneath the upper very coarse clastic section of unit 2 (unit 2B; Figs. 6, 18B, and 21A).

The supersequence boundary location is based on two lines of evidence. (1) Biostratigraphic control indicates that the top of unit 2A is Portlandian to Kimmeridgian. The next control point, located 35 m above this in unit 2B, indicates a Hauterivian to Valanginian age. Thus, the upper Berriasian, and perhaps part of the Valanginian, is essentially missing. This is consistent with the gulf-wide scenario in which a major type 1 unconformity overlies the Berriasian Cotton Valley Formation (see Goldhammer et al., 1991, Figs. 31–35; Stone, 1975; Todd and Mitchum, 1977; McFarlan and Stone, 1977; McFarlan and Menes, 1991). In the northern Gulf of Mexico, the entire Valanginian stage is absent

biostratigraphically in all shelfal positions, updip from the Cotton Valley shelf edge. Todd and Mitchum (1977, sequence K1.1) showed the Valanginian strata to be a basinally restricted, lowstand wedge in offshore West Africa, and speculated that a similar wedge would typify the Valanginian in the Gulf of Mexico. This has since been confirmed from regional seismic studies (Mitchum et al., 1977). (2) In outcrops at the Cañon del Chorro section, the lithologic transition from unit 2A to 2B is marked by a downward shift in facies from burrowed marine mudstones and fine-grained siltstones to coarse-grained cross-bedded sandstones with local conglomerates (Figs. 21, A and E). South Texas regional seismic data show that this supersequence boundary is marked by toplapping basinward-dipping clinofolds, as well as truncated reflectors beneath the boundary (Figs. 8 and 9). In addition, there is strong onlap of the Hosston Formation against this surface. Similar relationships have been observed from east Texas (Todd and Mitchum, 1977). Stone (1975) illustrated substantial stratal truncation of updip Cotton Valley Formation by way of pattern correlation on well-log cross sections along the Texas Gulf Coast (see Goldhammer et al., 1991, Figs. 31 and 32).

Late Valanginian to early Aptian

Supersequence overview. Within this supersequence, the upper part of the La Casita Formation consists of fine-grained clastic strata and thin carbonates, which are interpreted as transgressive marine deposits recording the waning input of clastic sediments and retreat of the fan-delta complex (Figs. 18B and 21A). This and the onlapping basinal equivalent of the upper portion of the Taraises depict the second-order TST with the second-order MFS (118 Ma) placed at the base of the overlying Cupido–Lower Tamaulipas carbonate package, which records the second-order HST (Figs. 6 and 7). The Cupido Formation comprises a shallow-water, low-angle ramp package that overall progrades basinward and shoals from basinal and/or fore-reef strata through peritidal cyclical laminites. The offshore, basinal equivalent to the Cupido Formation is the lower Tamaulipas Formation, a thick succession of pelagic lime mudstones. There are numerous well-developed higher frequency sequences within the Cupido–lower Tamaulipas package, and the supersequence is capped by a prominent evaporite-solution-collapse breccia (112 Ma) that separates the Cupido Formation from the transgressive Cupidito rocks.

Second-order lowstand systems tract. Above the lower supersequence boundary at Cañon del Chorro, about 100 m of unit 2B of the La Casita Formation (coarse nearshore marine sandstone and conglomerate) grade upward into transgressive unit 3 (Fig. 20). The presence of such coarse siliciclastic rocks above the supersequence boundary indicates that lowstand conditions persisted above the boundary as the result of extensive sedimentation proximal to the Coahuila block under conditions of minimum accommodation. Thus, despite the fact that this unit overlies the supersequence unconformity in an updip position, and hence strictly should fall within the transgressive systems tract, it could be considered a lowstand deposit perched updip on the shelf.

Second-order transgressive systems tract. The transition from unit 2B to unit 3 in outcrops, at the Cañon del Chorro is dramatic. The upper 33 m consists of seven stacked coarsening-upward siliciclastic cycles capped by conglomerates (representing progradation of individual fan lobes; Fortunato, 1982) that mark the final stages of the fan-delta complex (Fig. 21E). At this locality, a prominent flooding surface occurs as a sharp bedding plane separating coarse sandstones below (unit 2B) from fine-grained mudstones above (unit 3). Within 2 m of the uppermost cycle, unit 2B grades vertically into unit 3, which overall is finer grained, containing mixed carbonate and clastic lithologies with intervals of shale higher in the unit. The basal part of unit 3 contains five peritidal cycles (1–2 m thick) that mark the initial second-order transgression. They consist of: (1) dolomitic sandy mudstone at the base, burrowed with displacive evaporite nodules (replaced by calcite; Fig. 21F) overlain by (2) burrowed peloidal packstone, succeeded by (3) wavy to lenticular thin beds of siltstone and mudcracked laminated silty mudstone. The remainder of unit 3 deepens upward, becoming progressively more open marine in character. It is succeeded by 7 m of thin-bedded burrowed mudstones of the Taraises Formation (Figs. 18B and 21B). The second-order maximum flooding surface is placed within this thin, updip tongue of Taraises Formation that separates the La Casita rocks from the overlying Cupido rocks. Well-log cross sections from the Texas Gulf of Mexico also illustrate this overall second-order transgression for age-equivalent lower Hosston siliciclastic rocks (see Goldhammer et al., 1991, Figs. 36 and 37; McFarlan and Stone, 1977).

Second-order highstand systems tract. The Cupido Formation, and the coeval basinal lower Tamaulipas Formations, which together compose one major progradational package, constitute the second-order highstand of this supersequence (Figs. 6, 7, 18B, and 21, A and B). Like the Cupido Formation, the age-equivalent Sligo platform is recognized as the first of two gulf-wide cycles of major carbonate progradation (McFarlan and Stone, 1977; Bebout et al., 1981; Winker and Buffler, 1988; McFarlan and Menes, 1991). On seismic data, the Cupido-Sligo shelf margin is a prominent feature all along the Gulf of Mexico (Wooten and Dunaway, 1977; Bebout et al., 1981; Winker and Buffler, 1981; Figs. 8 and 9). Both seismic data and well-log cross sections (see Goldhammer et al., 1991, Figs. 36 and 37; McFarlan and Stone, 1977) illustrate the progradational character of the Cupido and Sligo Formations.

In outcrops in the Monterrey-Salttillo area, the Cupido Formation consists of several third-order depositional sequences (Goldhammer et al., 1991). These in turn are made up of higher frequency fourth-order depositional sequences, 25–75 m thick, which have calculated periodicities of ~500 k.y. (see Goldhammer et al., 1991, Fig. 48). These fourth-order sequences in turn contain multiple small-scale, fifth-order cycles (cycle periods averaging 40 k.y.; thickness of 0.3–8 m). The fourth-order sequences are recognized in outcrop by the vertical succession of facies and the cycle stacking patterns within a sequence (reviewed by Goldhammer et al., 1991). In addition, the distribution of evaporites and subaerial exposure features aids in sequence defini-

tion. Goldhammer et al. (1991, Fig. 48) measured in detail a 320-m-thick section at Potrero García (Figs. 28 and 39), which includes the upper portion of the Cupido, the Cupidito, and basal La Peña formations. This representative section is within lithofacies units 4 and 5 of Selvius (1982) as defined here (Fig. 26). At this locality, the upper 103.5 m of the Cupido Formation consists of two fourth-order sequences, the lower one about 57 m thick (cycles 1–18, Fig. 48 of Goldhammer et al., 1991), and the upper close to 39 m thick (cycles 19–30).

The lower sequence initiates on top of a thin-bedded, recessive interval containing thin (<1–2 m thick) peritidal cycles, marking minimum fourth-order accommodation. These are overlain by the fourth-order TST consisting of transgressive-skewed subtidal cycles. Cycles typical of this TST contain dark brown, burrowed-to-laminated peloidal wackestone to packstone shoaling upward into mechanically stratified ooid-skeletal grainstone (e.g., Fig. 27D). Individual cycles thicken from <1 to 7 m upward. As cycles thicken upward, the character of constituent subfacies shifts progressively from shallow and somewhat restricted to deeper subtidal and more open marine. This is evidenced by systematic shifts per successive cycle in such parameters as amount of grain-supported fabrics, ooid content, and faunal content (e.g., presence of small rudistids and requienid bivalves). About 50 m up from the base (45.6 m on Potrero García section; Fig. 48 of Goldhammer et al., 1991), subtidal cycles give way to peritidal cycles, marking the accommodation change to fourth-order highstand conditions. The remainder of the first sequence consists of six peritidal cycles (average 2.5 m thick), each capped by a peritidal laminite. These cycles contain little evidence for evaporites. The fourth-order sequence boundary is placed above the thickest laminite cap within the thinnest cycle, suggestive of a fourth-order accommodation minimum. This laminite cap contains more evidence for subaerial exposure (caliche-like fabrics) beyond that normally expected within the tidal-flat setting.

The second fourth-order sequence (39 m thick) begins with a few transgressive-skewed subtidal cycles (to 5 m thick) similar to those of the underlying sequence. These give way to 33 m of stacked peritidal cycles that progressively thin upward, from 7 m to 1 m, within the highstand part of the sequence. As they thin upward, they progressively display evidence for increasing restriction in the form of marine evaporites, which at the top of the sequence occur as discrete thin layers (several centimeters thick) of bedded evaporite (probable gypsum) replaced by calcite (e.g., at 96 m in the section; see Goldhammer et al., 1991, Fig. 48). These trends indicate that this upper fourth-order sequence is highly regressive in comparison to the underlying sequence. This is consistent with the fact that the upper sequence is much thinner than the underlying sequence. Together the two sequences mark the late second-order highstand of the Cupido supersequence, as they thin upward into the supersequence boundary (Figs. 28 and 39). Similar stratal relationships are seen at other localities (Figs. 23, A, B, and D). The actual physical second-order supersequence boundary in the field is essentially coincident with the upper

fourth-order sequence boundary and uppermost cycle boundary (at 103.5 m in the section of Goldhammer et al., 1991).

The supersequence boundary (112 Ma; Figs. 28 and 39) is marked by a spectacular 1–5-m-thick polymictic, clast-supported breccia that overlies a 0.67-m-thick bed of evaporite replaced by calcite (Fig. 28, D and F). This breccia has been physically traced along strike for many kilometers within Potrero García, where it forms a major recess (major notch in the skyline). It has also been found at the same stratigraphic horizon, i.e., separating the Cupido from the Cupidito formations, in several other localities (e.g., Fig. 23, A, B, and D), notably Canon San Lorenzo, which is located more than 100 km to the southwest. This breccia, which is interpreted as a karst solution breccia, contains large (centimeter to meter scale) angular (nontransported), poorly sorted clasts of typical peritidal Cupido lithologies that were lithified at the time of breccia formation. These include burrowed mudstone to packstone, ooid grainstones, cryptalgal laminites, rippled peloidal packstones, and clasts of calcitized evaporite. The matrix material is laminated and contains sand-sized lithoclasts and skeletal debris washed in from above. At Potrero García, the breccia is straddled by flat, stratigraphically intact beds, from both above and below, supporting a syndepositional origin for the breccia, as opposed to a later Tertiary age. In addition, relief along the upper surface of the breccia, measured in tens of centimeters, is filled by bedded calcitized evaporite (at 104 m in the section of Goldhammer et al., 1991) and cryptalgal laminite. The evaporite contains relict vertical growth structures outlined by millimeter-thick seams of grainstone, suggestive of subaqueous deposition of vertically oriented, centimeter-wide, palmate gypsum. Both the evaporite and overlying thin laminite thicken into topographic lows and thin onto highs, and locally out. Apparently, through restricted deposition in ponded lows, the irregular topography of the upper breccia surface was leveled out during the initial marine incursion back over the platform following subaerial exposure. The dissolution of the source rock (carbonate and evaporite?) responsible for the collapse in all likelihood resulted from leaching by near-surface waters undersaturated with soluble mineral phases, presumably linked to a fall in relative sea level.

On seismic data from south Texas, the second-order HST is marked by progradational geometries of the Sligo Formation with ill-defined toplapping clinoforms beneath the 112 Ma supersequence boundary. The 112 Ma sequence boundary appears as a discontinuous, somewhat chaotic reflector beneath the top of the Sligo carbonate (Figs. 8 and 9). The Cupido-Sligo supersequence boundary is further delineated by a prominent, basinally restricted wedge that onlaps the front of the margin, and downlaps the toe of slope (Figs. 8 and 9). This seismic feature is consistent with a type 1 interpretation of the supersequence boundary. Linked to the Cupido late second-order highstand is the basinward progradation of the Patula Arkose and La Virgen evaporite facies in the northern Sabinas Basin (Smith, 1981). These offlapping regressive deposits are truncated updip by the 112 Ma unconformity.

Early Aptian to late Albian

Supersequence overview. The Cupidito and La Peña formations mark the second-order transgressive systems tract, and the second-order maximum flooding surface is placed near the La Peña–Aurora Limestone contact (107 Ma). The Cupidito unit is a deepening-upward carbonate unit (shallow water, low-angle ramp) that grades from peritidal cyclic carbonates at the base through shoal-water subtidal carbonates toward the top. The upper contact with the La Peña Formation is gradational, and the La Peña consists of deep-water, transgressive, fine-grained siliciclastic shales, mudrocks, and thin-bedded argillaceous limestones. The Aurora–upper Tamaulipas carbonate package compose the second-order highstand systems tract; the Aurora represents shallow open shelf to ramp carbonate deposits that are overall aggradational to retrogradational. The pelagic lime mudstones of the upper Tamaulipas Formation make up the equivalent basinal strata. The upper supersequence boundary (98 Ma) is recognized from the basinward progradation of the McKnight evaporite in the Maverick basin, a nearshore to marginal-marine unit that records the second-order relative fall in sea level at the top of the Aurora–upper Tamaulipas formations. The overlying pelagic carbonates, the Cuesta del Cura, Agua Nueva, and San Felipe Formations, are all deep-marine basinal rhythmites. They reflect the overall, prolonged relative rise in sea level characteristic of the Early to middle Cretaceous. These deposits onlap updip and drape much of the underlying Mesozoic section.

Second-order lowstand systems tract. In outcrop in northeast Mexico the second-order LST is marked by the breccia just described. South Texas regional seismic data show a prominent lowstand wedge that persists as a basinally restricted onlapping package, which is only seen downdip of the terminal Cupido margin (Figs. 8 and 9). Well-log information tied to seismic data reveals that this wedge forms an upward-shallowing progradational package in an off-shelf lowstand position.

Second-order transgressive systems tract. At Potrero García (Figs. 28 and 39), the Cupidito and basal La Peña rocks are completely exposed (see Fig. 48 of Goldhammer et al., 1991). The Cupidito Formation consists of four (22–60 m thick) fourth-order depositional sequences, with numerous fifth-order cycles (Goldhammer et al., 1991). The fourth-order sequences have periodicities averaging 500 k.y.; there are four sequences representing about 2 m.y. of time (Goldhammer et al., 1991). Overall, these sequences progressively thicken upward from 24 to 60 m consistent with an overall increase in second-order accommodation (Figs. 28, A and B, and 39). Similar stratal relationships are seen throughout the Monterrey-Salttillo area (Fig. 23, A, B, and D). As they thicken upward, the character of subfacies changes from restricted shallow marine with evaporite and peritidal features in the lower sequence, to open marine, deeper subtidal with ooid grainstones and rudistid-requienid biostromes.

The first fourth-order sequence (22.5 m thick; cycles 31–42, Goldhammer et al., 1991, Fig. 48) contains 12 cycles (average 2–2.2 m/cycle; ~42 k.y./cycle; Goldhammer et al., 1991) that

systematically thicken upward away from the supersequence boundary (to 4.2 m thick) and sequentially thin upward into the next fourth-order boundary (as thin as 0.33–0.67 m beneath the boundary). Early transgressive and latest highstand cycles have peritidal, cryptalgal laminite caps, whereas cycles that make up the middle of this fourth-order sequence are subtidal cycles, defined by shoaling-upward subtidal subfacies patterns. The fourth-order sequence boundary is another solution-collapse breccia (1.5–2 m thick) that depicts a fourth-order relative sea-level drop in the overall long-term second-order rise (at 128.5 m in the section; Goldhammer et al., 1991, Fig. 48).

Above this, the second fourth-order sequence (40 m thick, cycles 43–54 of Goldhammer et al., 1991) is composed largely of aggradational stacks of thick-bedded, normal-marine, skeletal wackestone to packstone, characterized by extensive burrowing and a limited occurrence of Requienid bivalves. Cycles are difficult to define in this thick stack of amalgamated subtidal lithologies. Toward the top of this sequence, 5 well-defined cycles with packstone to grainstone caps thin upward from 3.3 to 1 m, signifying a decline in fourth-order accommodation. The uppermost 2 cycles are each capped by a 0.33-m-thick peritidal laminite cap. The uppermost laminite cap defines the upper fourth-order sequence boundary to the second sequence, as it caps the thinnest peritidal cycle (at 170 m in the section of Goldhammer et al., 1991).

The succeeding third fourth-order sequence (42 m thick; cycles 55–64 of Goldhammer et al., 1991) begins with four laminite-capped, peritidal cycles that progressively thicken upward from 1 to 5.3 m, signifying fourth-order accommodation increase. These cycles are succeeded in the middle of the sequence by thick-bedded, amalgamated subtidal cycles that contain significant amounts of rudists, in addition to the ambient normal-marine faunal assemblage. This fourth-order early highstand interval passes vertically into three late highstand peritidal cycles that thin upward into the fourth-order sequence boundary (at 210 m in the section of Goldhammer et al., 1991). The boundary is on top of stromatolitic laminites that cap the uppermost cycle (1.7 m thick), and is beneath a 1-m-thick calcitized bedded evaporite. These relations suggest a change in fourth-order accommodation from regressive peritidal conditions to transgressive, restricted evaporitic conditions.

The fourth and uppermost fourth-order sequence (60 m thick; cycles 65–78) is entirely transgressive and has no fourth-order relative decline in accommodation at the upper end of the sequence. Rather, it is composed of 14 aggradationally stacked subtidal cycles (average 4.2 m thick) that display little thickness variation. These cycles are composed of thick-bedded, cherty, open-marine carbonates, characterized by ooid grainstones and an abundance of bivalves. Beds rich in requienids and chondrodonts are more common in the lower half of the sequence, whereas rudistid-dominated biostromes are most prevalent toward the top (Fig. 28E). The top boundary of the uppermost cycle is a major marine flooding surface that effectively is the upper fourth-order sequence boundary (a conformable marine

boundary at 265 m in the section of Goldhammer et al., 1991; Fig. 28, A, B, and C). It separates thick-bedded, normal-marine packstone full of skeletal material and large *Thalassanoides* burrows below from overlying intercalated, thin-bedded (0.30–0.60 m thick) calcareous shales and deeper subtidal wackestones to packstones (Fig. 28C). Within about 6.5 m, the Cupidito formation gives way to very thin bedded (30 cm thick) intercalated shales and parallel-laminated, dark, cherty, peloidal limestones of the La Peña Formation. Thus the transition from the Cupidito formation into the La Peña Formation is in detail gradational.

South Texas seismic data show that the second-order TST is the thin interval above the 112 Ma boundary and the top of the Sligo Formation, which forms a prominent seismic reflector (Figs. 8 and 9). Updip from the terminal Sligo margin the TST thickens, and just downdip of the Edwards margin the top of the Sligo TST picks up an extra seismic reflector between the 112 Ma and the Sligo Formation top, interpreted as a retrogradational geometry during the second-order floodback. The top of the Sligo TST is a diachronous flooding surface and would constitute one of Schlager's (1989) drowning unconformities, overlapped by the flooding shales of the Pearsall Group. These relations indicate that in outcrop La Peña shales drape Cupido carbonates, suggesting termination of the Cupido Formation by drowning and/or siliciclastic pollution.

Second-order highstand systems tract. The Aurora–upper Tamaulipas carbonate package composes the second-order highstand systems tract (Figs. 23A, 28, A and B, and 39). The Aurora rocks depict shallow open shelf to ramp carbonate deposits that are overall aggradational to progradational. In northeastern Mexico and south Texas, the Aurora–Glen Rose–Stuart City trend retreats significantly landward (McFarlan and Stone, 1977; Wooten and Dunaway, 1977; Winker and Buffler, 1988). The upper supersequence boundary (98 Ma) is recognized from the basinward progradation of the McKnight evaporite in the Sabinas basin, a nearshore to marginal-marine unit that records the second-order relative fall in sea level at the top of the Aurora–upper Tamaulipas Formations. This supersequence boundary is a prominent gulf-wide unconformity recognized in the subsurface (McFarlan and Stone, 1977; Buffler and Sawyer, 1985; Winker and Buffler, 1988) and in outcrop (Smith, 1981) in northeastern Mexico and south Texas. This Middle Cretaceous unconformity marks the foundering and termination of the gulf-wide carbonate platform, and is considered by some (e.g., Schlager, 1989) to be a drowning unconformity, and by others (Vail et al., 1977) to be a lowstand unconformity resulting from a eustatic fall in sea level. The overlying pelagic carbonates consisting of the Cuesta del Cura, Agua Nueva, and San Felipe formations are all deep-marine basinal rhythmites. They reflect the overall prolonged relative rise in sea level characteristic of the Early to middle Cretaceous. These deposits overlap updip and drape much of the underlying Mesozoic section. On south Texas seismic sections, the second-order HST is well displayed, marked by the prograding and downlapping clinoforms of the Edwards margin and slope (Figs. 8 and 9).

SUMMARY

I have synthesized subsurface and outcrop data, both published and unpublished, in an attempt to provide a sequence stratigraphic framework for the Mesozoic paleogeographic and tectonic evolution of northeast Mexico. The Monterrey-Salttillo area is essentially the juncture of two distinctly different Mexican tectono-stratigraphic provinces, the eastern Gulf of Mexico province and the western Pacific Mexico province, and therefore allows us to compare and contrast Gulf of Mexico-driven versus Pacific-driven tectono-stratigraphic processes. Each of these tectono-stratigraphic provinces have a distinctive and separate tectonic evolution, and different resulting stratigraphic packaging. They are characterized by distinctive structural belts and structural styles and basement. The differing stratigraphies record a subregional response to the interaction of provincial tectonics (i.e., convergent versus divergent margins), eustatic changes in sea level, and sediment type and supply. As such, the Monterrey-Salttillo area contains elements related to both Gulf of Mexico passive-margin development (principally the stratigraphy) and the Pacific-related convergent margin (arc) tectonism (chiefly the structure). Thus a complete understanding of the area is critical in linking together two somewhat disparate geologic provinces in Mexico.

In the Gulf of Mexico province, the tectonic evolution is dominated by passive-margin development associated with the opening of the Gulf of Mexico, overprinted by nonigneous Laramide orogenic effects. The stratigraphic evolution is dominated principally by eustasy in as far as thick regional accommodation cycles can be correlated throughout the Gulf of Mexico. I propose that the Middle Jurassic to Lower Cretaceous stratigraphy of northeast Mexico and the Gulf of Mexico in general can be subdivided into four major second-order depositional supersequences (~15 m.y. duration), that have regional gulf-wide significance. The stratigraphic evolution of the Upper Jurassic to Lower Cretaceous Gulf of Mexico passive margin was interpreted by Goldhammer et al. (1991) to have resulted from the superimposition of four second-order relative sea-level cycles over a first-order long-term relative sea-level rise. This first-order relative rise likely reflects a global eustatic rise driven by long-term changes in mid-ocean ridge volume related to sea-floor spreading rates associated with the opening of the Gulf of Mexico and the Atlantic Ocean. These two different orders of eustasy operated in concert with underlying thermotectonic subsidence to produce systematic changes in accommodation from the base to the top of the Gulf Coast section. Such changes account for the overall shift from lowstand-dominated facies associations characteristic of the Middle to Late Jurassic (redbeds, evaporites, marginal-marine siliciclastic strata and low relief, shallow-marine, high-energy carbonates), to highstand-dominated facies associations characteristic of the Early Cretaceous (higher relief, shallow-marine carbonate platforms, deep-marine shales, and pelagic carbonates).

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