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Stratigraphic Evolution of Latest Cretaceous to Early Tertiary Difunta Foreland Basin in Northeast Mexico: Influence of Salt Withdrawal on Tectonically Induced Subsidence by the Sierra Madre Oriental Fold and Thrust Belt

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ABSTRACT

The latest Cretaceous to Eocene Difunta Group in the Parras, La Popa, and the southern part of the Sabinas Basins in the states of Coahuila and Nuevo León in northeast Mexico once occupied an extensive basin in the foreland to the Sierra Madre Oriental fold and thrust belt. The Difunta foreland basin records a complex history of initial Cretaceous deformation in the Sierra Madre Oriental and subsequent early Tertiary salt withdrawal in the region covered by the salt basin in the western part of the Gulf of Mexico.

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As a result of rapid facies transitions in the Difunta Group, stratigraphic correlation between the three structural basins is complex. Only one regionally extensive lithostratigraphic unit occurs in the Difunta Group, namely, the Maastrichtian Cañon del Tule Formation in the Parras Basin and the correlative Muerto Formation in La Popa Basin and the southern part of the Sabinas Basin. Detailed sedimentologic and sequence stratigraphic studies of the Cañon del Tule and Muerto formations have led to dramatic revisions in correlations in the Difunta Group. The Difunta Group is now subdivided into five informal "stratigraphic cycles" termed SC1, SC2, SC3, SC4, and SC5, each composed of marine mudstone and sandstone with overlying red fluvial mudstone.

Stratigraphic cycles SC1 to SC3 were deposited in the latest Cretaceous in response to tectonic loading by encroaching thrust sheets in the Sierra Madre Oriental. In the southeastern Parras Basin, near the Sierra Madre Oriental frontal zone, the foredeep fill is at least 3677 m thick, thinning to 922 m, 150 km (structurally unrestored) to the north in the southern Sabinas Basin. Sediment dispersal was from west to east along the axis of the Difunta foredeep with a dissected volcanic arc provenance presumed to be the Guerrero composite terrane. Exceptionally high subsidence rates of >1 m/1000 years caused sediment to be "trapped" in the southern part of the foredeep, adjacent to the thrust belt, preventing early deltaic complexes in SC1 and SC2 from prograding eastward. The contemporary Mendez shale in the Tampico-Misantla foredeep, which was connected to the Parras–La Popa Basins across the Monterrey salient, represents a starved, underfilled equivalent of the Difunta foredeep to the southeast. In the distal northern part of the Difunta foredeep, in northern La Popa and southern Sabinas Basins, stratigraphic cycles are characterized by forced regression caused by limited subsidence.

By the Paleocene and Eocene, thrusting in the Sierra Madre Oriental and accompanying foreland basin subsidence had ceased. In the region of the Parras Basin, no more sediment accumulated in the Difunta Group. In La Popa Basin and the southern part of the Sabinas Basin, which overlie the western extension of the Gulf of Mexico salt basin, growth of salt diapirs and associated salt withdrawal resulted in accumulation of more than 2300 m of sediment in structural "minibasins." Large volumes of volcaniclastic detritus continued to be supplied from the west, filling the salt minibasins with fluvial and shallow-marine sediment. These Tertiary sequences represent cycles SC4 and SC5 in the Difunta Group.

By the Paleocene, in the Tampico-Misantla portion of the Difunta foredeep, axially derived sands were deposited in the Chicontepec paleochannel. Only limited carbonate clastic input from the Sierra Madre Oriental highland was received in the Tampico-Misantla Basin in the Tertiary, and at no time did the Sierra Madre Oriental supply detritus to the Parras or La Popa Basins.

Some time after the Eocene, probably in the early Oligocene, the region covered by the Difunta foredeep was deformed, uplifted, and eroded, leading to the present outcrop pattern of structural basins and highs. This episode of uplift resulted in large volumes of sediment being deposited in the western Gulf of Mexico Basin and led to substantial progradation of the northeast Mexican continental margin and establishment of a large, early Oligocene depocenter.

INTRODUCTION

Uppermost Cretaceous to lower Tertiary sedimentary successions are exposed spectacularly in several structural basins north of the Sierra Madre Oriental fold and thrust belt between the cities of Torreon, Saltillo, Monterrey, and Monclova in the states of Coahuila and Nuevo León in northeast Mexico. These structural basins include the Parras, La Popa, and the southern part of the Sabinas Basins, covering more
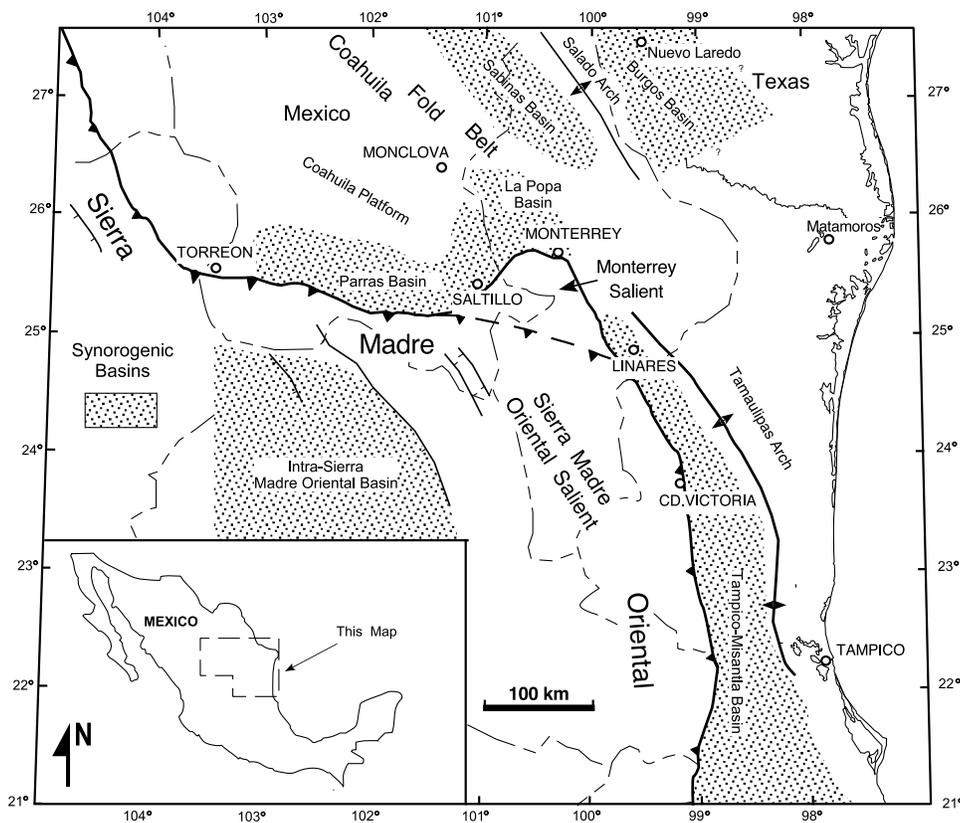
Figure 1. Regional geologic map of northeast Mexico illustrating location of Parras, La Popa, and Sabinas Basins.

sins analogous to those described in the Gulf of Mexico (e.g., Rowan, 1995; Prather et al., 1998) and therefore are unrelated to foreland basin subsidence.

This paper summarizes the revised stratigraphy of the Difunta Group, based on extensive field studies and diverse remote sensing data. Based on this revised stratigraphic framework, we discuss Late Cretaceous and early Tertiary tectonic evolution of foreland basins of the Sierra Madre Oriental of northeast Mexico.

than 25,000 km^2 (Figure 1). The basins are filled by uppermost Campanian to middle Eocene siliciclastic and lesser carbonate sedimentary rocks, which together make up the Difunta Group (McBride et al., 1974; Vega et al., 1989). Most striking are the several hundred meter–high sandstone cliffs outlining regional fold patterns that may be traced for hundreds of kilometers across the desert landscape of Coahuila and Nuevo León (Figure 2). Recent studies of the Sierra Madre Oriental propose that exposures of the Difunta Group are remnants of a once-extensive foreland basin filled by latest Cretaceous to early Tertiary strata (Freydier et al., 1996; Ye, 1997). The cumulative thickness of the Difunta Group is approximately 6000 m and is too great for the modest topographic relief of the adjacent Sierra Madre Oriental tectonic hinterland to be explained by topographic loading alone. Ye (1997) suggests that a subcrustal load from dense oceanic lithosphere from a remnant ocean basin contributed to tectonic loading in the adjacent foredeep, leading to exaggerated stratigraphic thicknesses in the Difunta Group.

Subsequent stratigraphic studies of the Difunta Group by Halik (1998) and Garrick (1999) indicate that foredeep subsidence was confined to the latest Cretaceous, and that more than 2300 m of Tertiary sediment accumulated in salt-withdrawal miniba-

GEOLOGIC SETTING OF THE DIFUNTA GROUP

The Parras Basin, La Popa Basin, and San Antonio Syncline in the southern part of the Sabinas Basin are located in the northeastern desert of Mexico directly north of the Sierra Madre Oriental between the cities of Torreon, Monclova, Saltillo, and Monterrey in the states of Coahuila and Nuevo León (Figures 1, and 3). The sedimentary fill of the three basins is referred to collectively as the Difunta Group, which has a composite stratigraphic thickness of more than 6000 m and an age of latest Cretaceous (latest Campanian) to early Eocene (Vega et al., 1989). Stratigraphic units in the Difunta Group were deformed during the latter stages of the Hidalgoan orogeny (Guzman and de Cserna, 1963), giving rise to large-scale folds. Sandstone units resistant to weathering and erosion in the Difunta Group have resulted in long, linear sandstone ridges or "Cuchilla" (knife ridges) which extend for hundreds of kilometers around the Parras, La Popa, and the southern part of the Sabinas Basins (Figure 2). Limestone "lentils" also provide dramatic topographic expression, although with lesser lateral extent (Laudon, 1984, 1996; Lawton et al., 2001). Topographic relief in the Parras, La Popa, and southern Sabinas Basins reaches about 900 m in places.
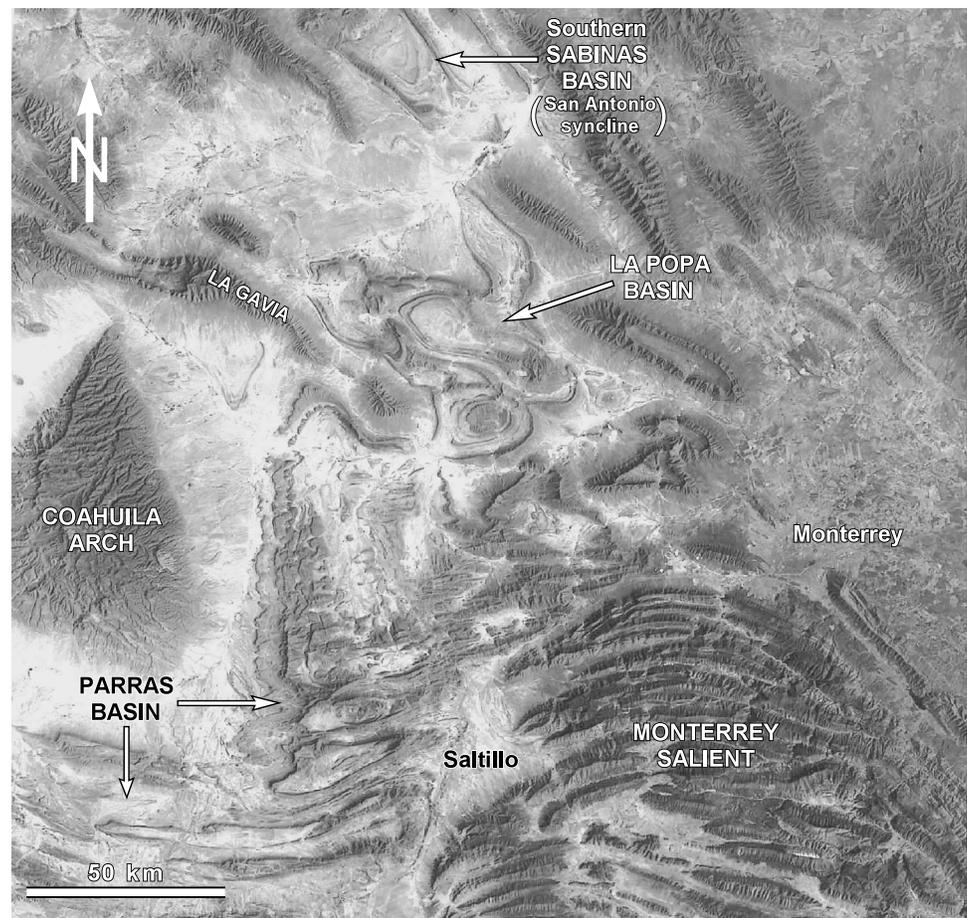
Figure 2. Multispectral (MSS) satellite scene of Parras, La Popa, and southern Sabinas Basins in northeast Mexico. The scene includes bands 754 in RGB in this gray-scale image.

Uplift of Lower Cretaceous carbonate rocks, which stratigraphically underlie the Difunta Group, occur as mountains with topographic relief of almost 3000 m between the three basins, as well as constituting the core of the Sierra Madre Oriental fold and thrust belt to the south (Warning, 1977). Between the Lower Cretaceous carbonate rocks and uppermost Cretaceous Difunta Group is the Santonian to Campanian Parras Shale (Figure 3). The Parras Shale is nearly 1000 m thick and is expressed as a flat, featureless valley between the Lower Cretaceous carbonate rocks and lowest sandstone ridges of the Difunta Group.

Regional Geology

Northern Mexico has been subdivided into three north-northwestward-trending provinces including (1) the Sierra Madre Occidental magmatic arc, covering most of northwest Mexico, (2) the Sierra Madre Oriental fold and thrust belt in north-central Mexico, and (3) the topographically subdued coastal plain to the east along the margin of the Gulf of Mexico Basin (de Cserna, 1989). The Sierra Madre Occidental magmatic arc is a result of eastward subduction by the Pacific Plate underneath Mexico, and it has been active from the Late Cretaceous to the present.

The Sierra Madre Oriental is a Late Cretaceous to early Tertiary fold and thrust belt, generally attributed to eastward subduction associated with the Sierra Madre Occidental magmatic arc (Suter, 1987; de Cserna, 1989; Hennings, 1994). Alternatively, Tardy et al. (1994), Freydier et al. (1996), and Ye (1997) have proposed that the Sierra Madre Oriental fold and thrust belt is a consequence of collision between eastern Mexico (southern Laurentia) and the Guerrero composite terrane, with westward subduction of oceanic lithosphere below the Guerrero composite terrane, leading to a suture between the two crustal blocks below the Sierra Madre fold and thrust belt. The basin that developed in the foreland to the north and east of the Sierra Madre Oriental has been referred to as the Difunta foredeep basin (Freydier et al., 1996). The Sierra Madre Oriental is considered part of the Laramide orogenic belt, but it is characterized by thin-skinned thrust faulting in addition to folding (Suter, 1987; Hennings, 1994). Near the city of Monterrey, the thrust belt forms a large salient or promontory, the "Monterrey salient" (Figures 1, and 2). North of the promontory, the foreland of the Sierra Madre Oriental is deformed by northwest-trending faults and folds that constitute the Coahuila fold belt (Charleston, 1981; González-Garcia, 1984). Moreover, this part of the deformational belt is underlain by the Gulf Coast Salt Basin, which profoundly affected folding north of the city of Monterrey (Gray et al., 1997; Giles and Lawton, 2002). The Difunta foredeep was partitioned by these structures in a similar fashion, but in a different structural style, to Laramide deformation
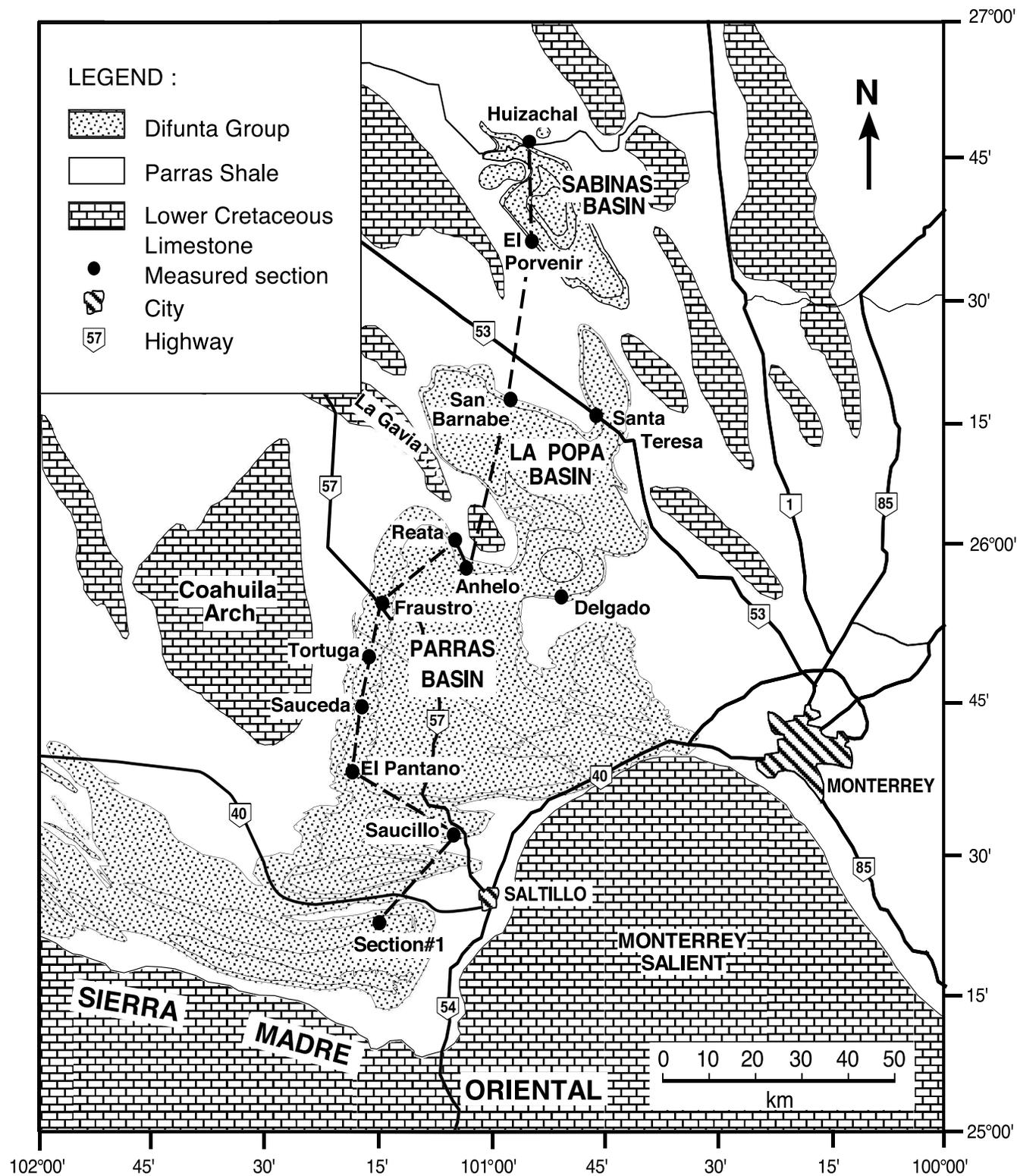
Figure 3. Detailed location map of eastern Parras Basin, La Popa Basin, and southern part of the Sabinas Basin.

of the Cretaceous foreland basin in the western interior of the United States of America (Oldow et al., 1989), so that the Parras, La Popa, and southern Sabinas structural basins are analogous to the San Juan, Powder River Basins, etc., of the western United States of America. Specifically, the northwest-trending La Gavia–Sierra Las Mitras anticline separates the Parras and La Popa Basins (Figure 4). Correlation of
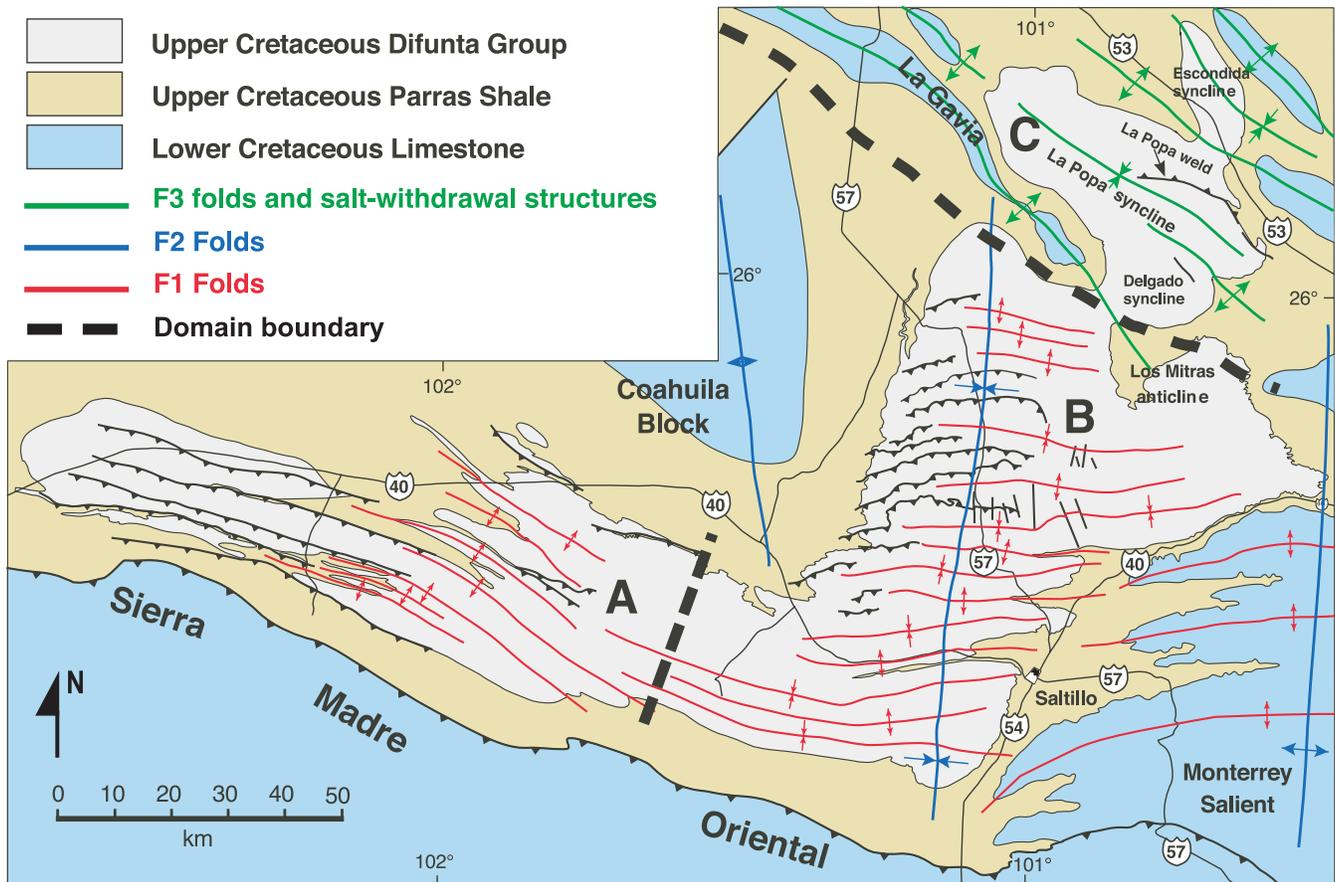
Figure 4. Map of Parras and La Popa Basins, emphasizing important structural elements affecting the Difunta Group succession. A, B, and C are structural domains defined by Weidie and Murray (1967) and discussed in the text. The boundary between domains B and C has been moved slightly northward, compared with the original definition of Weidie and Murray (1967), and coincides with the inferred boundary of the Gulf of Mexico Salt Basin.

stratigraphic units between the two basins and the degree to which the Parras and La Popa Basins evolved separately remain open to question (McBride et al., 1974).

Structure

The main structural trend in the Parras Basin is parallel to the structural grain in the Sierra Madre Oriental. Weidie and Murray (1967) subdivided the Parras and La Popa Basins into three domains, based on the changing structural style across the foreland (Figure 4). The western Parras Basin (domain A, Figure 4) consists of tight, overturned folds and numerous imbricated thrust sheets with as much as 1 km offset along faults. A central "transitional" domain B in the eastern Parras Basin is characterized by elongate, east-west-trending folds and lesser thrust faults with minimal offset (Figure 4). This transitional domain includes classical ramp-anticlinal structures (Dillman, 1985). The east-west-trend-

ing folds verge northward and are tight (interlimb angles < 20°) and upright. The folds have wavelengths of 7–9 km in the southern part of the central domain B and become open, with wavelengths of 3–4 km, as intensity of deformation decreases northward away from the thrust belt. The east-west-trending F1 folds are refolded by second-generation, north-south-oriented F2 folds leading to domes and basins, as a consequence of the noncoaxial interference folding (Figure 4). The F2 folds have interlimb angles of 150° and a half wavelength of approximately 60 km. The eastern Parras Basin represents an F2 syncline, whereas the Coahuila Arch and Monterrey Salient in Figure 3 are the adjacent anticlinal structures (Soegaard et al., 1997; Figure 4). Alternatively, the broad F2 folds may represent antecedent structures in the basement, such as the granite horst that underlies the Coahuila Arch (Charleston, 1981).

The third domain C of Weidie and Murray (1967; Figure 4), in the northernmost Parras Basin and La

Popa Basin, overlies the Gulf of Mexico Salt Basin (Gray et al., 1997). Here, F3 structures are defined by broad domal folds and circular basins (Figure 4). Several gypsum diapirs pierce the surface in the central La Popa Basin (Laudon, 1975, 1984, 1996; Giles and Lawton, 1999). Atoll-like isolated carbonate reefs developed above topographic highs created by the rising salt diapirs at the time of deposition of the Difunta Group in the latest Cretaceous to the early Paleocene. Garrison and McMillan (1999) and Giles and Lawton (1999) have demonstrated that salt diapirs were exposed on the sea floor at the time of reef growth by virtue of igneous xenolith blocks carried to the surface by the salt diapirs and incorporated as exotic blocks in the carbonate reefs.

Synclinal structures in domain C are commonly near circular in nature, such as the Delgado syncline in the southern La Popa Basin (Figures 2, 3, and 4). Thrust faults are absent in La Popa Basin; however, a steep fault exists in the northeastern part of the basin and is interpreted as a salt weld (Giles and Lawton, 1999).

Stratigraphic Framework

Weidie (1961) presented the first detailed geologic map of the Parras and La Popa Basins. He elevated the Difunta Formation, originally defined by Imlay (1936), to group status and subdivided the Difunta Group into seven formations. These seven formations were formalized by Murray et al. (1962). Weidie and Murray (1967) outlined stratigraphic relationships in the basin and summarized paleoenvironmental conditions during deposition. They argued that the basin was never very deep and did not form adjacent to an actively rising orogenic belt. Weidie and Murray (1967) interpreted the succession as fluviatile to brackish water deposits, with water depths never exceeding a few hundred feet.

Biostratigraphic data of McBride et al. (1974) and Laudon (1975) constrained the lower and upper limits of the Difunta Group as uppermost Campanian and lowermost Danian, respectively. The Campanian/Maastrichtian boundary is based on the transition from *Exogyra ponderosa* to *Exogyra costata* in the Cerro del Pueblo Formation in the eastern Parras Basin (McBride et al., 1974; Figure 5). On the basis of thick red-bed units and sandstone marker beds, McBride et al. (1974) subdivided the Difunta Group into seven formations in the Parras Basin and five formations in La Popa Basin (Laudon, 1975). The authors presented two possible scenarios for their lithostratigraphic correlation in the Difunta Group (Figure 5), but "truncated" the stratigraphy in their map between La Popa Basin, eastern Parras Basin, and western Parras Basin by using different stratigraphic terminology among the three areas.

Vega et al. (1989) and Vega and Perrilliat (1992, 1995) have provided a biostratigraphic correlation for the Difunta Group between the Parras and La Popa Basins and the San Antonio syncline (southern part of the Sabinas Basin) and indicate that existing correlation schemes by McBride et al. (1974) are incorrect. Most significant is the recognition that the upper half of the Difunta Group in La Popa Basin is Paleocene and Eocene in age and, therefore, younger than the Difunta Group sediments in the Parras Basin, which are Campanian and Maastrichtian in age (Figure 5).

Halik (1998) employed an informal scheme of "stratigraphic cycles" (SC) in an extensive remapping program of the eastern Parras Basin, La Popa Basin, and the southern part of the Sabinas Basin. He used both facies analysis and sequence stratigraphic principles in concert with biostratigraphic data of McBride et al. (1974), Vega et al. (1989), and Vega and Perrilliat (1992, 1995) in order to extend correlation beyond lateral facies transitions. Geologic mapping was extended away from 10 regional stratigraphic control sections, using a full range of remote sensing data including satellite imagery, airborne photography panoramas, and aerial photographs. Existing geologic maps by McBride et al. (1974) for the entire Parras and La Popa Basins and Dillman (1985) for the southeastern Parras Basin were used in compiling the final geologic map, which is constructed in a registered ArcInfo GIS (Figure 6). Halik (1998) recognized five stratigraphic cycles— SC1, SC2, SC3, SC4, and SC5— and related these directly to earlier stratigraphic schemes of McBride et al. (1974) and Vega et al. (1989). Further biostratigraphic work by Vega et al. (1999) near the town of Fraustro in the northeastern Parras Basin has placed the Cretaceous-Tertiary boundary in Las Encinas Formation. These results, in conjunction with the most recent remapping in La Popa Basin by Lawton et al. (2001), have led to refinement of the original stratigraphy of Vega et al. (1989) for the Difunta Group (Figure 5).

SEQUENCE STRATIGRAPHY OF DIFUNTA GROUP

The Difunta Group is characterized by thick (>100 m), laterally continuous, shallow-marine
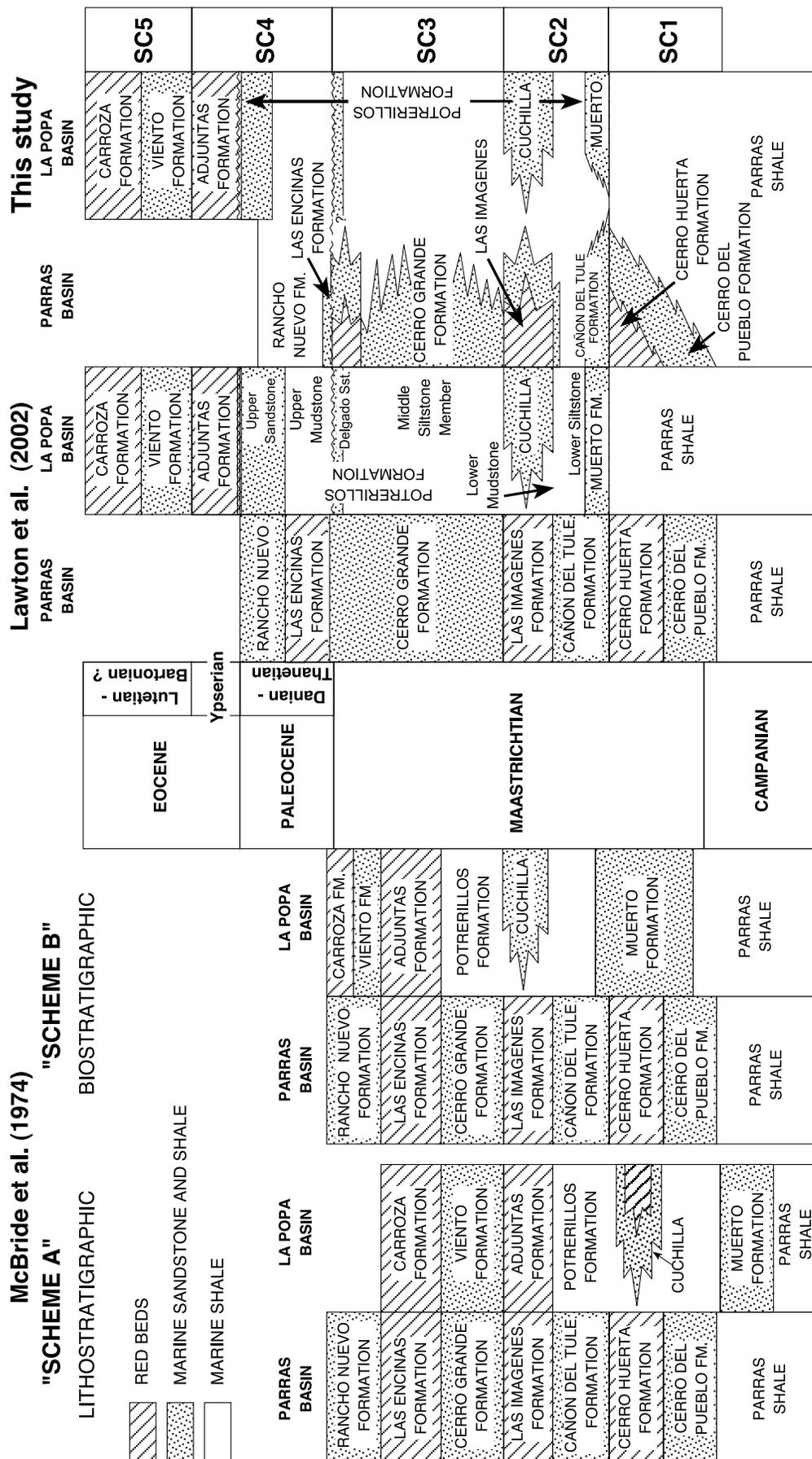
Figure 5. Comparison between various stratigraphic schemes for the Difunta Group between the Parras and La Popa Basins. The southern part of the Sabinas Basin is not included in the comparison but is equivalent to La Popa Basin stratigraphy in "This study."
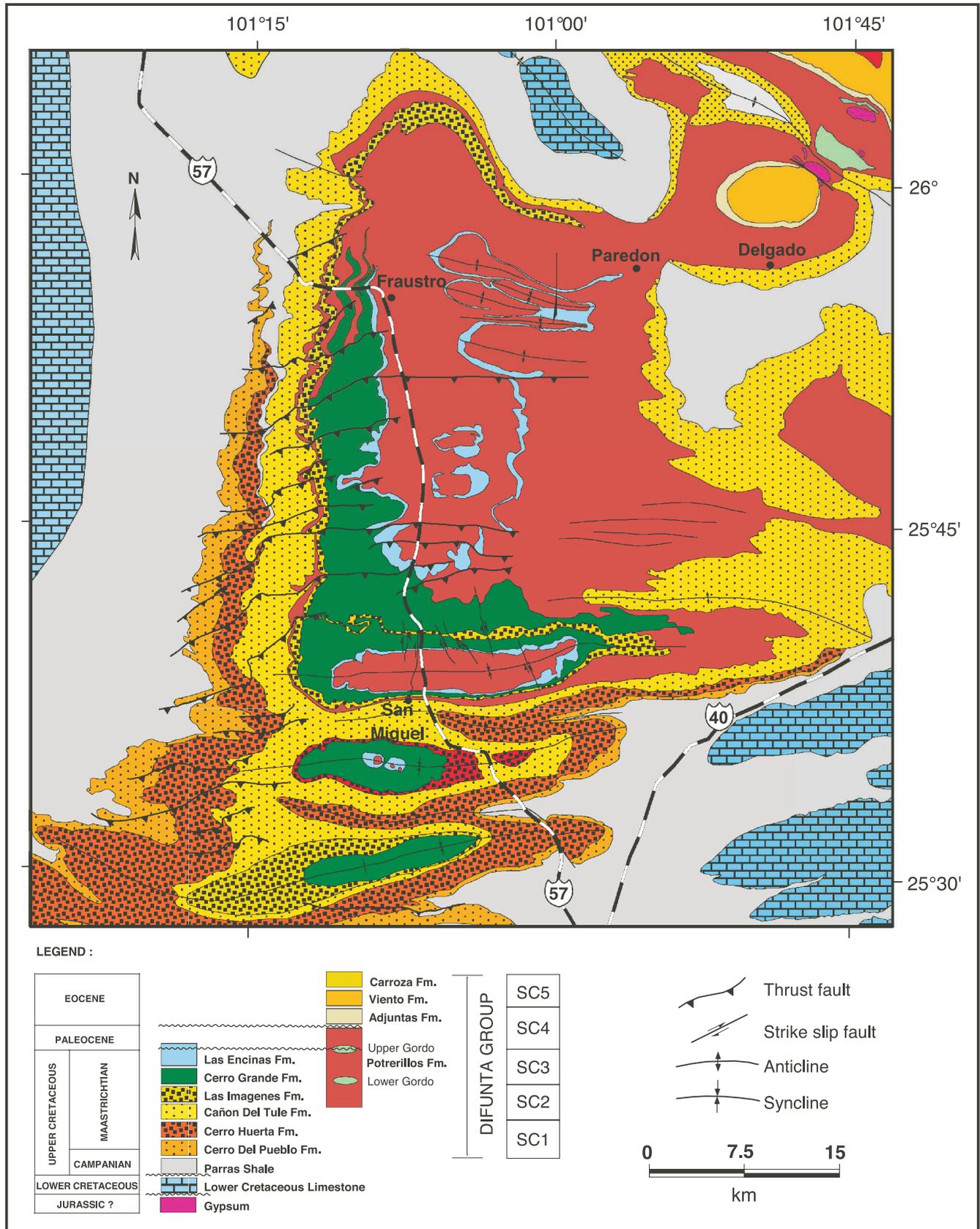
Figure 6. Detailed geologic map of eastern Parras Basin and southwestern La Popa Basin illustrating the stratigraphic relationship between the two basins (after Halik, 1998).
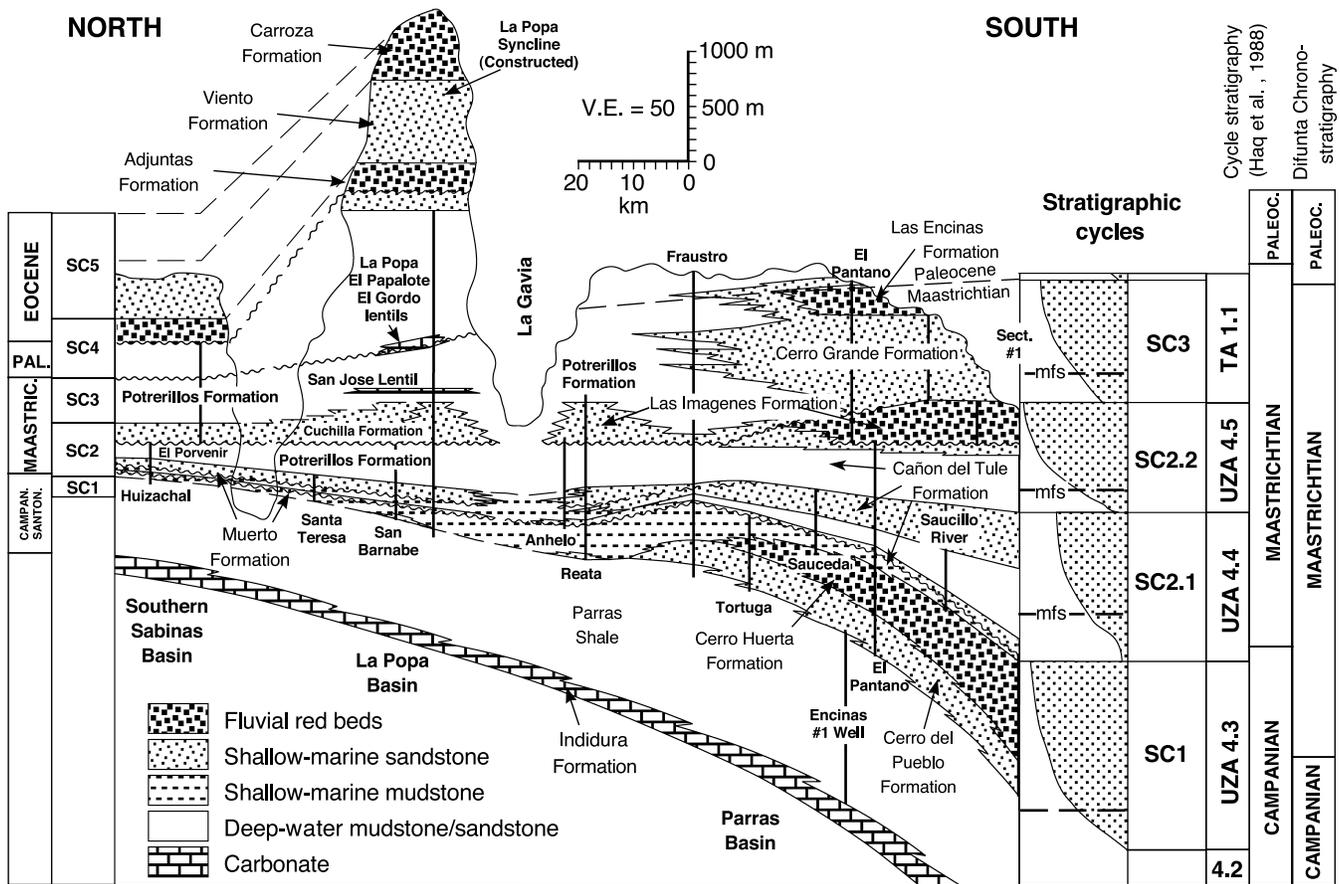
Figure 7. Revised stratigraphy of Parras, La Popa, and southern Sabinas Basins. The Campanian-Maastrichtian boundary is after McBride et al. (1974). All other biochronologic data are from Vega et al. (1989, 1999). Datum for the cross section is at the base of Las Imagenes–Cuchilla Tongue. The location and stratigraphic extent of measured sections is shown. Section #1 is from McBride et al. (1974), and the section from La Popa syncline is based on measured sections from McBride et al. (1974) and Laudon (1975). Structural shortening, particularly in the southern part of the Parras Basin, is not removed. mfs = maximum-flooding surface. See Figure 3 for geographic location of sections.

sandstone successions and associated overlying red mudstone intervals of fluvial affinity that are separated by intervening gray marine mudstone and siltstone intervals. A total of three such couplets exist in the Cretaceous (Maastrichtian) part of the Difunta Group. Marine sandstone units and, in some cases, correlative mudstone intervals can be traced across the entire Parras, La Popa, and southern Sabinas Basin area (Figures 3, and 6). By contrast, the Paleocene and Eocene stratigraphic intervals are restricted to structural basins in the La Popa Basin and the southern part of the Sabinas Basins, both of which overlie the Gulf Coast Salt Basin.

Cretaceous Part of Difunta Group: Foreland Basin Phase

The oldest of the three stratigraphic cycles, SC1, includes the upper part of the Parras Shale, the Cerro del Pueblo Formation, and the Cerro Huerta Formation of McBride et al. (1974) in the Parras Basin. Cycle SC1 occurs exclusively in the Parras Shale in La Popa Basin. Cycle SC2 is subdivided into two subcycles, SC2.1 and SC2.2 (Figure 7). Subcycle SC2.1 includes the "lower sandstone member," the "mudstone member," and the "sandstone and mudstone member" of the Cañon del Tule Formation, following terminology of McBride et al. (1974) in the Parras Basin. In La Popa Basin, SC2.1 consists of the Muerto Formation. Subcycle SC2.2 contains the "upper mudstone member" of the Cañon del Tule Formation and red beds of Las Imagenes Formation of McBride et al. (1974), whereas in La Popa Basin, subcycle SC2.2 consists of the "lower mudstone member" and the lower part of the "middle siltstone member" of the Potrerillos Formation, including the Cuchilla Tongue. Finally, SC3 includes

the Cerro Grande Formation and red beds of Las Encinas Formation of McBride et al. (1974) in the Parras Basin, which correlate with the top of the Cuchilla Tongue to the top of the ''Delgado sandstone member'' of the Potrerillos Formation in La Popa Basin (Lawton et al., 2001; Figure 5).

Parras Shale, Cerro Del Pueblo and Cerro Huerta Formations (SC1)

The Parras Shale consists of dark-gray to black calcareous fissile-marine mudstone with thin beds of calcareous fine-grained sandstone and siltstone. The entire Parras Shale is more than 700 m thick. Contacts with both the underlying Indidura Formation and overlying Difunta Group are conformable and gradational (Figure 7). The lower boundary is marked by a gradational contact between deep-water gray calcareous mudstone of the Indidura Formation. The Parras Shale coarsens gradually upward into the sandstone-prone Cerro del Pueblo Formation in the basal Difunta Group (Ye, 1997). The transition zone is commonly well-bedded and relatively unfossiliferous, with the thickness of the transition zone varying from 6 to 15 m, but it may be as thick as 90 m (Laudon, 1975; Ye, 1997).

The Cerro del Pueblo Formation is a nonred-bed sequence which overlies the Parras Shale and is overlain, in turn, by red mudstone and subordinate sandstone of the Cerro Huerta Formation. At the small settlement of El Pantano is an exceptionally well-exposed and representative section through the entire Cerro del Pueblo Formation (Figure 7). At El Pantano, the Cerro del Pueblo Formation is 378 m thick but thins north and eastward before pinching out into marine mudstone, where sandstone beds cross Mexico Highway 57 west of the town of Fraustro (Figures 6, and 8a). The Cerro del Pueblo Formation is composed predominantly of sandstone, mudstone, siltstone, and rare limestone in the form of oyster banks. The lower part of the Cerro del Pueblo Formation is marked by a 90 m-thick sandstone unit containing intervening shale breaks and burrows. The sandstone unit overlies siltstone and mudstone of the Parras Shale and consists primarily of amalgamated hummocky cross-stratification deposited in an upper-shoreface setting (Ye, 1997). Intervening deeper-water mudstone intervals represent minor flooding events and delineate five parasequences in this 90 m-thick parasequence set.

Above the sandstone unit is an 18 m-thick, intensely burrowed mudstone interval with numerous oyster beds and glauconitic sandstone (Figure 7). This mudstone and fossiliferous interval accumulated in a lagoonal setting. Above the mudstone and oyster-bearing interval is a second amalgamated, hummocky cross-stratified interval of upper-shoreface deposits. The upper part of the Cerro del Pueblo Formation consists of predominantly gray marine mudstone alternating with fine sandstone beds. This sequence is interpreted as a lagoonal and lower-coastal-plain succession. The top of the formation is placed at the base of the lowermost red or green shale in the overlying Cerro Huerta Formation (McBride et al., 1974).

The Cerro Huerta Formation consists of predominantly red and green mudstone interbedded with greenish to reddish siltstone and fine- to very-fine-grained lenticular fluvial channel sandstone bodies. The channel sandstone units are 0.3 to 10 m thick, with average thicknesses of 1 to 3 m. The sandstone bodies have abrupt bases with mudstone intraclast conglomerate layers and reworked calcareous nodules along their base (Laudon, 1975). Petrified wood, plant debris, charophytes, dinosaur remains, and the world's oldest banana plant are present in the Cerro Huerta Formation (Hernandez, 1992; Hernandez and Kirkland, 1993). The contact with the underlying Cerro del Pueblo Formation is conformable and gradational. The upper boundary with the overlying Cañon del Tule Formation is also gradational and defined by the last occurrence of red mudstone. The Cerro Huerta Formation pinches out to the north and east and thickens to the south and west with a maximum thickness of 978 m near Saltillo (Murray et al., 1962; McBride et al., 1974; Halik, 1998; Figures 7, and 8a). At El Pantano, the Cerro Huerta Formation is 384 m thick.

Because of the red color of the thick mudstone units, fossil evidence, and ubiquitous fluvial-channel sandstone units, the Cerro Huerta Formation is interpreted as an alluvial succession. The lateral proximity to coastal deposits of the Cerro del Pueblo Formation suggests that the fluvial mudstone accumulated in a delta plain and flanking coastal-marine environment (McBride et al., 1974).

Interpretation of SC1

The upper Parras Shale, shallow-marine sediments of the Cerro del Pueblo Formation, and fluvial red beds of the Cerro Huerta Formation represent an overall prograding succession. A sequence boundary should occur either at the base of the Cerro Huerta Formation (Type 1 sequence boundary; Van Wagoner, 1995) or in the Cerro Huerta Formation (Type 2
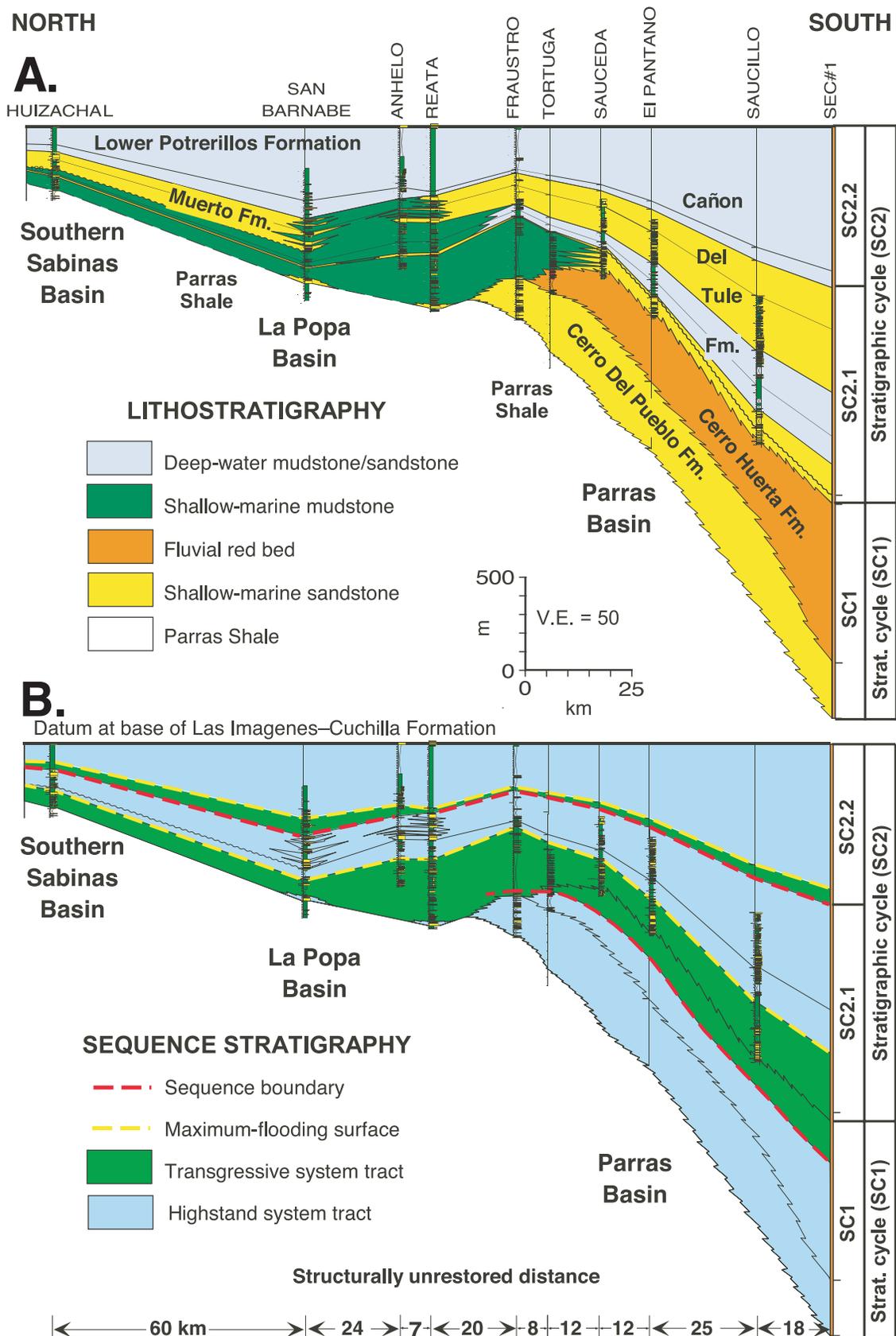
Figure 8. (A) North-south cross section of lithostratigraphy in cycles SC1 and SC2 in eastern Parras Basin, La Popa Basin, and southern part of the Sabinas Basin. (B) Sequence stratigraphic interpretation of same transect as (A). See Figure 3 for location of cross section.
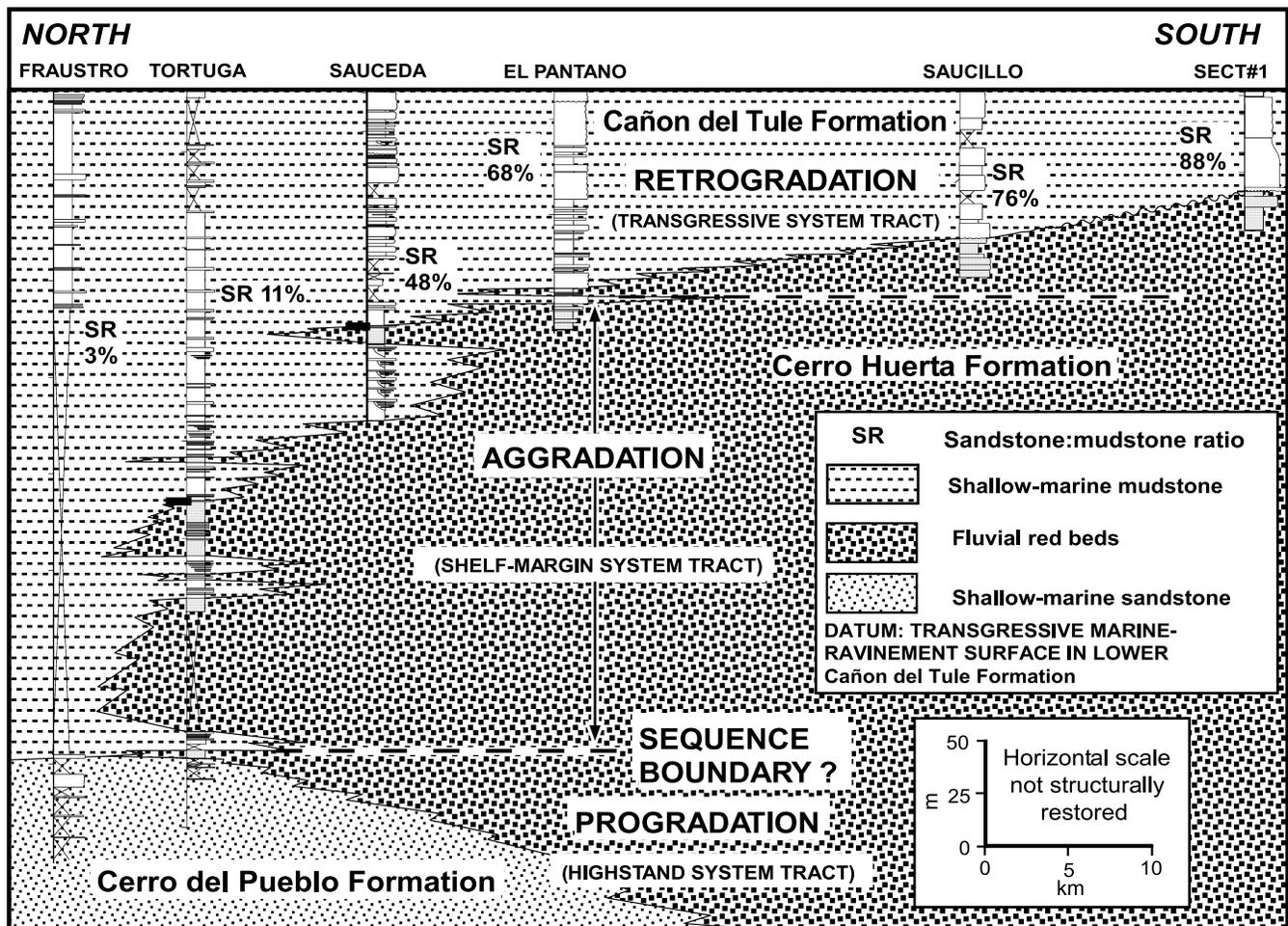
Figure 9. North-south stratigraphic cross section of transition between Cerro del Pueblo–Cerro Huerta highstand deposits of cycle SC1 and transgressive systems tract of the lower Cañon del Tule Formation in stratigraphic cycle SC2.1. The section is "hung" on the transgressive marine-ravinement surface located in the upper part of the "lower sandstone member" of the Cañon del Tule Formation in the lower part of SC2.1. See Figure 3 for location of the section along the western escarpment of the eastern Parras Basin.

sequence boundary; Van Wagoner et al., 1988; Posamentier and Allen, 1993). The transition between the Cerro del Pueblo marine sediments and overlying Cerro Huerta fluvial deposits is gradational, with fossil-bearing gray marine siltstone units interfingering with red fluvial mudstone. Nowhere along the transect in Figure 8a do fluvial-channel sandstone beds cut into marine sediments of the Cerro del Pueblo Formation. Consequently, a Type 1 sequence boundary is not present in SC1.

Type 2 sequence boundaries are more subtle and difficult to identify in foreland basins, according to Posamentier and Allen (1993). The sequence boundary lacks erosion and, in the proximal portion of the basin fill, occurs wholly in the alluvial deposits. Based on stacking patterns of regressive-transgressive fluvial and shallow-marine cycles or parasequences, the Type 2 sequence boundary should occur at the transition from overall progradation to retrogradation. In SC1, depositional trends are from progradation to aggradation and finally to retrogradation (Figure 9). Using criteria of Van Wagoner et al. (1988), the sequence boundary should be located between the progradational highstand deposits and the aggradational "shelf-margin" systems tract. However, this transition is poorly defined, and a discrete surface cannot be identified in the Cerro Huerta fluvial deposits (Figure 8b).

It is important to note that the upper part of the Cerro Huerta fluvial red beds belongs to the aggradational shelf-margin systems tract and transgressive systems tract (Figure 8b). Thus, the boundary

Figure 10. Stratigraphic summary of cycles SC1 and SC2 of the Difunta Group in the Parras Basin. *Coahuilites sheltoni* is an endemic ammonite of uppermost lower Maastrichtian age that was collected from the top of the Cañon del Tule Formation by Juan C. Bermudez (the University of Texas at Austin) and identified by Keith Young. Together, the Cerro del Pueblo, Cerro Huerta, and Cañon del Tule Formations are 1839 m thick at El Pantano (where the section is most complete) and accumulated over a mere 1.9 Ma, giving an average accumulation rate of 0.97 m per 1000 years (absolute time scale based on Gradstein et al., 1996).

FORMATION		THICKNESS (m)		CYCLE STRATIGRAPHY	STAGES
Las Imagenes		60–130		SC2.2	UPPER MAASTRICHTIAN
Cañon del Tule	upper mudstone member	273-1808	141–763		* 69.4 Ma (Not formal boundary)
	lower sandstone and mudstone mbr.		106–522	SC2	* *Coahuilites sheltoni*
	lower mudstone member		0–351	SC2.1	LOWER MAASTRICHTIAN
	lower sandstone member		25–172		
Cerro Huerta		0–920		SC1	
Cerro del Pueblo		0–378			*Exogyra costata*
Parras Shale		ca. 700			71.3 ± 0.5 Ma — *Exogyra ponderosa* — CAMPANIAN

Informal substage boundary is 69.4 Ma
* *Coahuilites sheltoni* is an endemic ammonite
  of uppermost lower Maastrichtian age
  (Keith Young, personal communication)

Duration: 1.9 Ma
Thickness: 1839 meters
Sedimentation rate: 97 cm/1000 years

between SC1 and SC2, at the contact between the Cerro Huerta fluvial red beds and Cañon del Tule marine sediments, does not coincide with a sequence boundary, nor does it have sequence stratigraphic significance (Figure 8b). However, the boundary is of lithostratigraphic importance and is therefore used for the purpose of mapping.

Lower Cañon Del Tule Formation (SC2.1)

Overlying the fluvial red beds of the Cerro Huerta Formation in stratigraphic cycle SC1 in the southeastern Parras Basin are shallow-marine sedimentary rocks of the Cañon del Tule Formation in stratigraphic cycle SC2 (Figures 6, and 7). The type section of the Cañon del Tule Formation is 1808 m thick at the Saucillo River section (Figures 3, and 7) where McBride et al. (1974) subdivide the formation into (1) a "lower sandstone member," (2) a "lower (mudstone) member," (3) an "(upper) sandstone and mudstone member," and (4) an "upper (mudstone) member." The three lower members belong to stratigraphic subcycle SC2.1, whereas the "upper sandstone member" is part of stratigraphic subcycle SC2.2 (Figure 10). This stratigraphy can be traced from the type locality in the south-central Parras Basin northward along the western escarpment of the eastern Parras Basin to the section at Tortuga. In the north-easternmost Parras Basin, from Fraustro and northward, the "lower mudstone member" pinches out and the "lower sandstone member" and "upper sandstone and mudstone member" merge into a single, thick, sandstone-dominated succession. This sandstone-rich sequence encompasses stratigraphic cycle SC2.1 and is correlative with the Muerto Formation of Laudon (1975) in La Popa Basin (Figure 7).

From the type locality at Saucillo River, 35 km northward to Tortuga, the contact between the "lower sandstone member" and underlying Cerro Huerta red beds is clearly gradational, with oyster-bearing, shallow-marine sediments and fluvial red beds interfingering over more than 50 m of stratigraphic section (Figure 9). The lower part of the "lower sandstone member" exhibits a progressive decrease in sandstone-to-mudstone ratio northward from Section #1 of McBride et al. (1974) (Section #1 in Figure 9) to the section at Fraustro.

This zone of transition is subdivided into (1) a distal facies association, (2) a medial facies association, and (3) a proximal facies association. (1) In the distal facies association at Fraustro and Tortuga, mudstone makes up more than 90% of the section with centimeter- and decimeter-scale, fine-grained sandstone beds constituting less than 10% of the rock. Sandstone beds display excellent wave-ripple
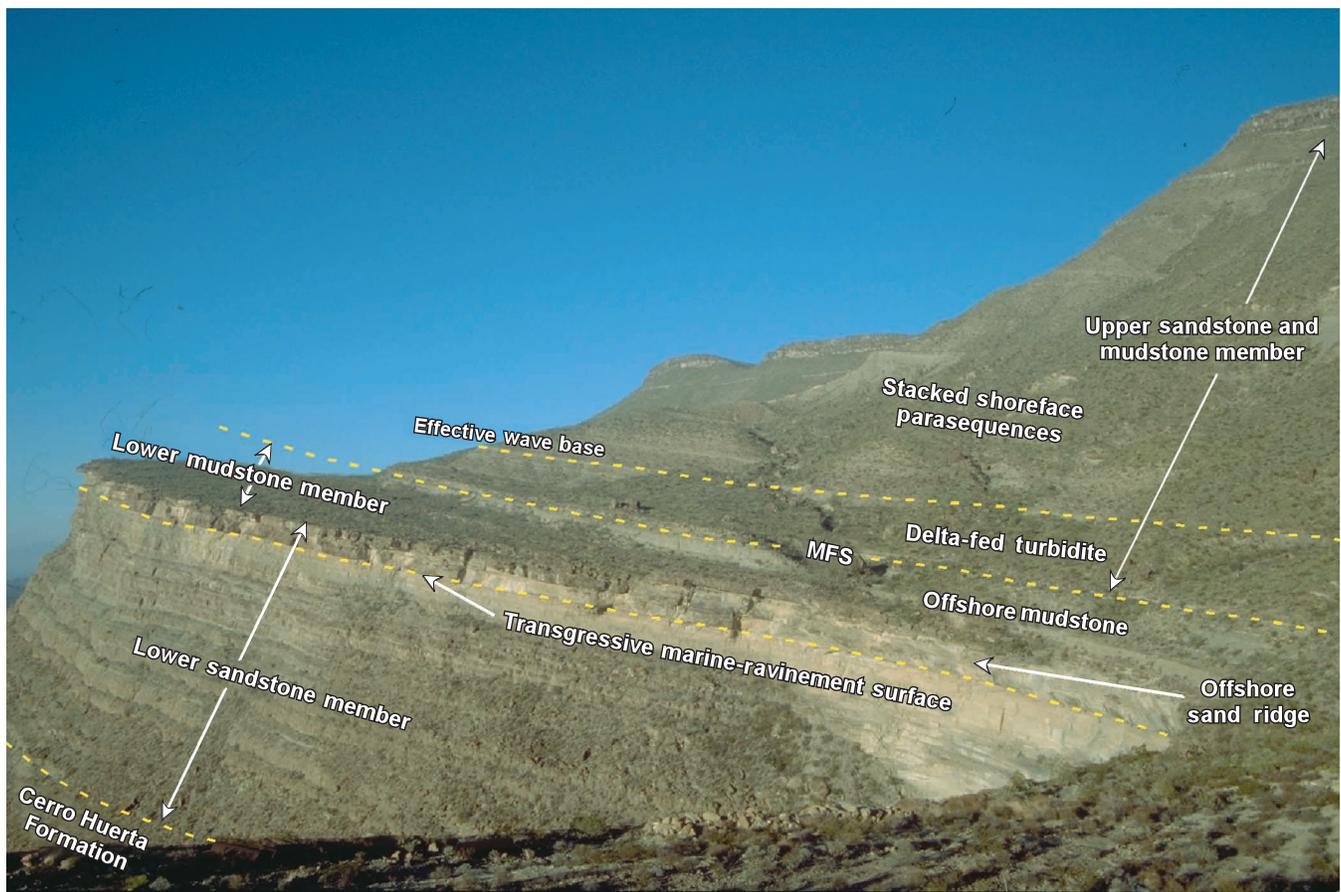
Figure 11. Field photograph of ''lower sandstone member'' of the Cañon del Tule Formation at El Pantano. The lower 99 m of the ''lower sandstone member'' consists of interlayered sandstone and mudstone, with sandstone comprising 68% of the section (Figure 9). The upper 23 m of the ''lower sandstone member'' is a distinct ridge of sandstone. The sharp ledge at the base of this sandstone coincides with an erosional lower contact and is interpreted as a transgressive marine-ravinement surface. In the background, above the sandstone ridge, is the ''lower mudstone member'' and the overlying ''upper sandstone and mudstone member'' of McBride et al. (1974). Together, the three members represent the entire SC2.1. See Figure 12 for section covered by photograph.

caps with ripple spacing of less than 5 cm and often less than 3 cm. Bedding planes also exhibit abundant feeding trails on the upper surface. Neither at Fraustro nor at Tortuga are stratigraphic cycles apparent in the marine sedimentary section in the form of systematic changes of bed thickness or facies arrangement. Rare whole fossils, including a large ammonite, are scattered throughout the section.

(2) The medial facies association at Sauceda and El Pantano consists of between ~50% and ~70% sandstone (Figure 9). The sandstone-to-mudstone ratio in this medial facies association is difficult to estimate because of extensive bioturbation and homogenization of the sediment. Most bedding is poorly developed. Upper and lower contacts are diffuse and irregular between sandstone, siltstone, and mudstone units as a consequence of biogenic activ-

ity. Fragments of oysters occur throughout this lower part of the Cañon del Tule Formation.

(3) The proximal facies association is composed of 76% and 88% sandstone at the Saucillo River section and at Section #1, respectively (Figure 9). Individual sandstone beds may be several meters thick, with only thin, discontinuous, intervening mudstone layers. Sandstone units lack bioturbation but are either massive or parallel laminated. At both Saucillo River and Section #1 are well-developed ball and pillow structures.
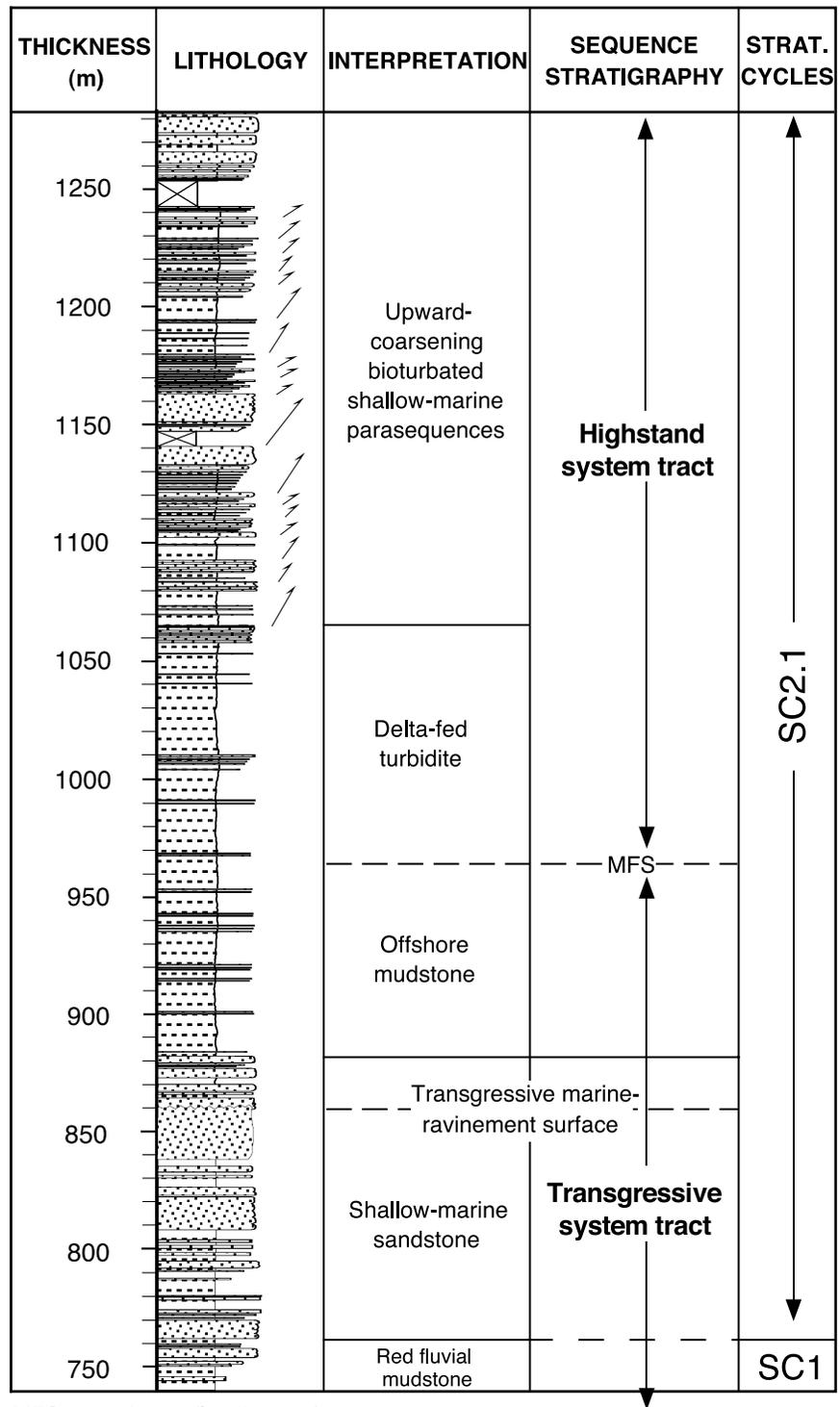
In the upper part of the ''lower sandstone member'' of the Cañon del Tule Formation is a 5- to 25-m-thick sandstone unit which forms a prominent ridge along the western escarpment of the eastern Parras Basin (Figure 11). This sandstone is in sharp contact with the underlying marine mudstone-sandstone

Figure 12. Stratigraphic column of SC2.1 at El Pantano, illustrating facies associations in the foredeep proximal to the Sierra Madre Oriental fold and thrust belt. Deeper-water facies, including the offshore mudstone and delta-fed turbidite section, are present only in the southern part of the foredeep and give way to shallow-marine sandstone sections in the north. See Figure 11 for outcrop covered by the section.

MFS = maximum-flooding surface

unit described above. The upper contact of the ridge-forming sandstone is gradational, with a thick succession of mudstone that constitutes the "lower mudstone member" of McBride et al. (1974) (Figures 8a, and 9). The sandstone is fine grained and contains abundant skeletal debris. No intact or, even, large fossil fragments are preserved in the sandstone. Primary sedimentary structures include parallel lamination and hummocky cross-stratification. Mudstone layers of as much as 50 cm in thickness are intensely burrowed.

Overlying the "lower sandstone member" of McBride et al. (1974) in the Cañon del Tule Formation is the "lower mudstone member" (Figures 7, and 10). The "lower mudstone member" is 140 m thick at Saucillo River (McBride et al., 1974) but pinches out to 40 km to the north near Fraustro (Figures 7 and 8a). The upper contact with the overlying "upper sandstone and mudstone member" is gradational, with mudstone giving way to interlayered mudstone and sandstone turbidite beds.

The proportion of sandstone in the "upper sandstone and mudstone member" of the Cañon de Tule Formation (Upper SC2.1) increases upward through the section (Figures 11, and 12). The lower part of the "upper sandstone and mudstone member" consists of centimeter-to decimeter-scale Ta-d Bouma-sequence sandstone beds which give way upward into upward-coarsening parasequences of wave-rippled and hummocky cross-

stratified sandstone. The upper parasequences are intensely bioturbated; consequently, primary sedimentary structures, and even bedding, are difficult to discern. The upper part of the "upper sandstone and mudstone member" consists of amalgamated massive, parallel-laminated and hummocky cross-stratified sandstone.
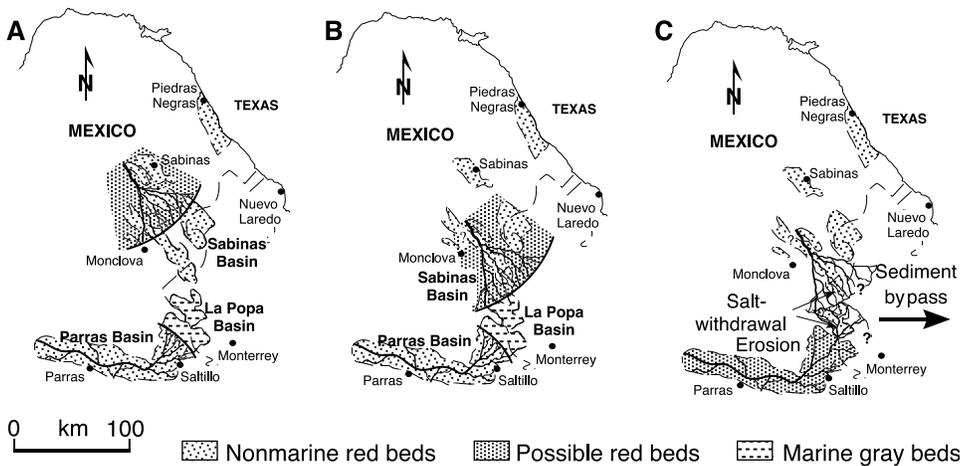
Figure 13. Paleogeographic maps for Parras, La Popa, and Sabinas basins illustrating the distribution of fluvial red beds with time in the Difunta Group. (A) Maximum regression for early Maastrichtian Cerro Huerta Formation in Parras Basin and for Muzquiz member of the Escondito Formation in Sabinas Basin. (B) Maximum regression for middle Maastrichtian Las Imagenes Formation in Parras Basin and Cuchilla Tongue in northwestern La Popa Basin. (C) Salt-withdrawal minibasin stage during early Eocene Adjuntas Formation in La Popa Basin when most sediment bypassed the study area.

Interpretation of SC2.1

The transition from fluvial red beds in the Cerro Huerta Formation (SC1) to shallow-marine sandstone and mudstone in the lower Cañon del Tule Formation (lower SC2.1) is clearly transgressive. The lower SC2.1 ("lower sandstone member" and "lower mudstone member" of McBride et al., 1974) is interpreted as a retrogradational succession belonging to a transgressive systems tract (Figure 8b). The upper SC2.1 ("upper sandstone and mudstone member" of McBride et al., 1974) consists of progradational turbidites and shoreface deposits that accumulated during a highstand event (Figure 8b).

The "lower sandstone member" of the Cañon del Tule Formation constitutes most of the transgressive systems tract. Below the prominent sandstone ridge, in the upper part of the "lower sandstone member," the amount of sandstone decreases gradually northward (Figure 9). Van Wagoner et al. (1988) and Gardner (1995) use stacking of upward-thinning parasequences to characterize this type of retrogradational succession. However, nowhere in the section is there a systematic cyclicity revealing retrogradation (e.g., Figures 11 and 12). In the mudstone-rich northern sections at Fraustro and Tortuga, thin sandstone beds with closely spaced, straight-crested wave ripples indicate a low-energy coastline during the onset of transgression. Whole fossils in this part of the section also suggest low-energy conditions. The mudstone-rich distal sections are interpreted as having accumulated in lagoonal and marshy environments marginal to the large eastward-prograding Cerro Huerta delta complex to the south (Figure 13a). Outward building of small rivers into these low-energy

marine settings is preserved as thin mudstone red beds in the marine mudstone succession (Figure 9). Important to note, by the interfingering and gradational transition between fluvial deposits and marine sediments, is the lack of clearly defined surfaces separating the terrestrial and marine successions in the north.

Farther south, closer to the source of sediment input, stratigraphic sections at Sauceda, El Pantano, and Saucillo River are richer in sandstone (Figures 9 and 11). As in the north, these three sections do not exhibit clearly defined retrogradational stacking of parasequences as a consequence of the transgression. Both at El Pantano and Saucillo River, the contact is gradational between the fluvial red beds and marine sandstone units (Figure 9). In the south, the transition is more abrupt and occurs over less than 10 m of section, whereas in the north, the transition spans more than 50 m of section. The sandstone-rich sections at El Pantano and Saucillo River also are interpreted as having accumulated along a low-energy coastline because of the paucity of high-energy sedimentary structures and ubiquitous bioturbation of sandstone units.

The first clearly defined sequence-stratigraphic surface in SC2.1 is in the upper part of the "lower sandstone member" of McBride et al. (1974), where the 5- to 25-m-thick sandstone ridge is in sharp contact with the underlying low-energy transgressive coastal mudstone and sandstone deposits (Figure 11). This discrete surface is traced across the entire Parras Basin into La Popa Basin. Sediments immediately above the surface are devoid of mudstone and/or bioturbation and are dominated by upper

flow-regime sedimentary structures, such as hummocky cross-stratification and planar lamination. The sandstone "ridge" is interpreted as intensely reworked shelf sandstone in which low sedimentation rates during marine transgression resulted in extensive reworking by marine processes (Nummedal and Swift, 1987). The surface at the base of the sandstone ridge represents a transgressive marine-ravinement surface, and sandstone bodies above the surface are interpreted as transgressive sandstone ridges similar to those described for the Shannon Sandstone in Wyoming (Gaynor and Swift, 1988) and the Tocito Sandstone in the San Juan Basin in New Mexico (Nummedal and Molenaar, 1995).

The shelf-sandstone ridges in the "lower sandstone member" of the Cañon del Tule Formation grade upward into mudstone of the overlying "lower mudstone member." At El Pantano, Saucillo River, and Sauceda, three to four upward-thinning parasequences define the transition between the two members. This parasequence set is 73 m thick in the south at Saucillo River and thins northward to 17 m at Sauceda. The overlying "lower mudstone member" is 153 m thick in the south at Saucillo River; it thins progressively northward to 83 m at El Pantano and 21 m at Sauceda before pinching out altogether at Fraustro (Figures 7 and 8a). The "lower mudstone member" represents the culmination of the marine transgression and is bounded at the top by a marine maximum-flooding surface (Figure 8b).

The maximum-flooding surface is overlain by upward-thickening and upward-coarsening turbidite cycles and overlying shoreface parasequences that constitute the upper "sandstone and mudstone member" of the Cañon del Tule Formation (Figures 8a, 11 and 12). This overall upward-shallowing succession represents renewed influx of siliciclastic sediment as a consequence of sedimentation rates exceeding the rate of relative sea-level rise. In sequence stratigraphic terminology, the "sandstone and mudstone member" represents a highstand systems tract (Figure 8b). The turbidite deposits in the lower part of the highstand systems tract are not related to lowstand sedimentation but are rather considered as delta-fed turbidites deposited during regression of SC2.1.

Upper Cañon Del Tule and Las Imagenes Formation (SC2.2)

Above the "sandstone and mudstone member" in the upper part of the Cañon del Tule Formation in the Parras Basin is the "upper mudstone member." In La Popa Basin, the "lower siltstone member" and "lower mudstone member" of the Potrerillos Formation are lateral equivalents of the "upper mudstone member" of the Cañon del Tule Formation but here overlie the thick succession of sandstone in the Muerto Formation (Figure 5). The transition between the "sandstone and mudstone member" and the "upper mudstone member" in the Parras Basin and the Muerto Formation and "lower siltstone member" in La Popa Basin is generally gradational. This transition is poorly exposed in the southern Parras Basin, but spectacular shale outcrops occur along steep cliffs in the northern Parras Basin at Reata and Anhelo, at San Barnabe in the northern La Popa Basin, and at Huizachal in the southern part of the Sabinas Basin (Figure 3). The transition is defined as a single parasequence at Reata and Huizachal, whereas four upward-thinning parasequences occur at San Barnabe. Above this transition zone, the "upper mudstone member" of the Cañon del Tule Formation and "lower mudstone member" of the Potrerillos Formation consist of monotonous dark-gray marine mudstone. The mudstone is as much as 400 m thick in the southern Parras Basin and between 180 and 200 m thick in the northern Parras Basin and La Popa Basin, respectively (Figures 7 and 8a).

In La Popa Basin, several carbonate "lentils" occur in the "lower mudstone member" of the Potrerillos Formation and include the lower portion of El Gordo, El Papalote, and La Popa carbonate lentils (Lawton et al., 2001; Figure 14). The lower La Gorda lentil is ~100 m thick, whereas the lower part of El Papalote carbonate lentil is 11 m thick (Hunnicutt, 1998). Both El Papalote and El Gordo carbonate lentils are closely related to gypsum diapirs in time and space, whereas La Popa lentil is associated with a salt-weld fault (Laudon, 1996; Giles and Lawton, 1999; Lawton et al., 2001). In the vicinity of El Papalote and La Popa carbonate lentils, the stratigraphy in the Potrerillos Formation is complex, with several intraformational unconformities extending away from the diapirs into the Potrerillos Formation, where the unconformities are traced into their conformable equivalents (Lawton et al., 2001; Giles and Lawton, 2002).

In sections from Sauceda and southward, the uppermost part of the "upper mudstone member" grades upward into upward-coarsening and upward-thickening sandstone beds. In places, these beds are rich in oyster fragments and are clearly shallow
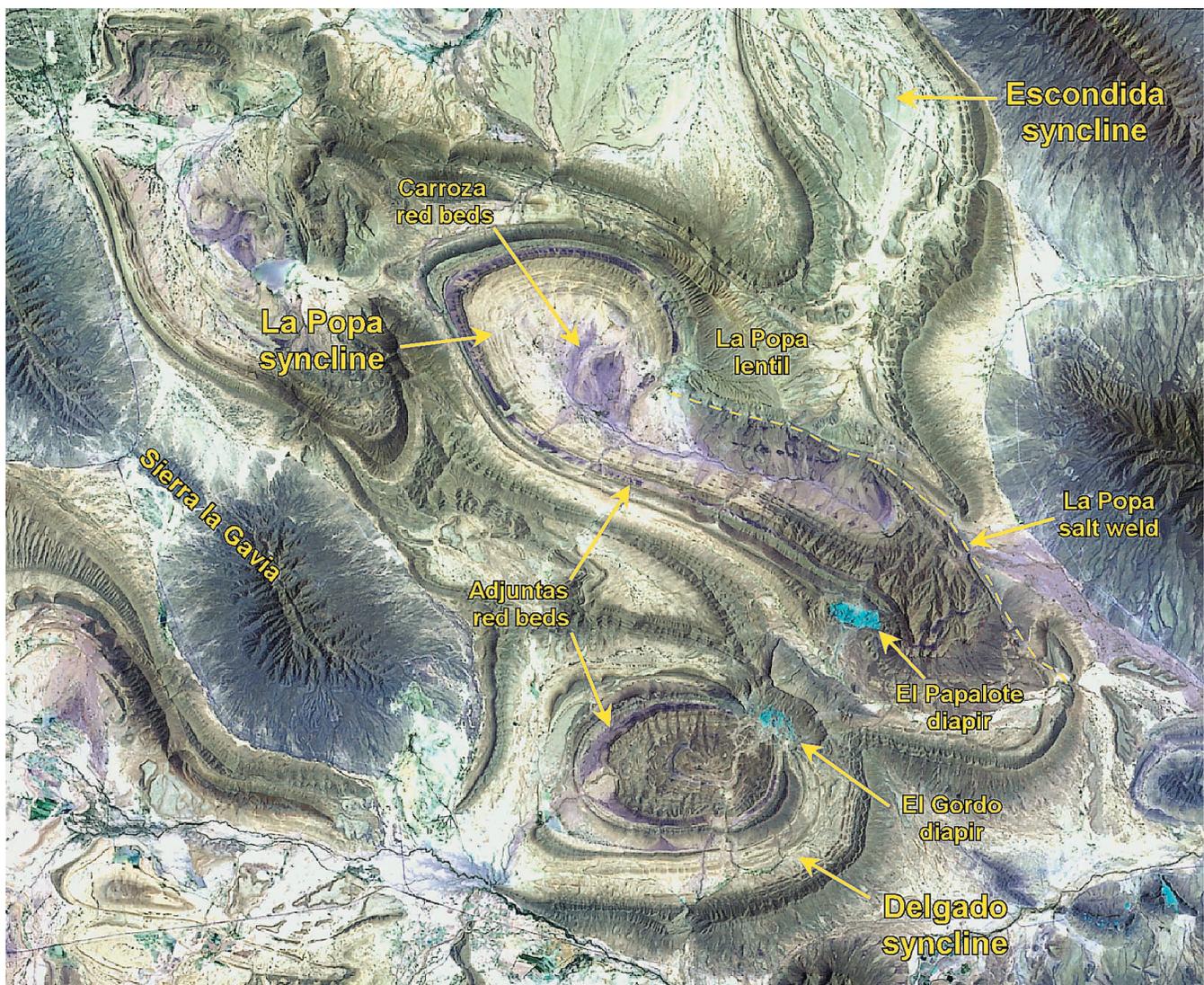
Figure 14. Partial thematic (TM) satellite scene of La Popa Basin with bands 7, 5, and 1 in RGB which emphasizes Eocene fluvial red bed sequences (burgundy) of the Adjuntas Formation in the upper SC4 and Carroza Formation in SC5, in addition to diapirs composed of Jurassic gypsum (pale blue).

marine in origin. Above the marine sandstone interval in the uppermost Cañon del Tule Formation are fluvial mudstone red beds of Las Imagenes Formation (McBride et al., 1974; Ye, 1997). Las Imagenes Formation defines the top of stratigraphic subcycle SC2.2 (Figure 7).

In the northern Parras Basin, north of the section at Sauceda and across La Popa Basin and the southern part of the Sabinas Basin, fluvial red beds are not present in Las Imagenes–Cuchilla Tongue (Ye, 1997). Rather, the succession consists of oyster-bearing, amalgamated, hummocky cross-stratified and cross-bedded sandstone units in a sandstone body that varies in thicknesses of between 60 and 130 m. This

thick sandstone unit has an erosional lower boundary with ubiquitous well-developed gutter casts along the base (Ye, 1997).

Interpretation of SC2.2

Stratigraphic subcycle SC2.2, consisting of the upper Cañon del Tule and Las Imagenes Formations, represents a retrogradational and overlying progradational succession. The single parasequence that overlies SC2.1 at Reata and Huizachal and the four upward-thinning parasequences at San Barnabe and Anhelo represent retrogradation during deposition of a transgressive systems tract. In addition to a retrogradational parasequence set, the transgressive

systems tract contains considerable shallow-marine fauna, including whole oysters. The transgressive systems tract is between 45 and 84 m thick and is capped by a marine maximum-flooding surface (Figure 8b). The maximum-flooding surface and overlying highstand systems tract consist of thick, monotonous, dark-gray mudstone devoid of shallow-marine fossils.

The highstand systems tract is capped by prograding fluvial-deltaic sediments of Las Imagenes Formation in the south and forced-regressive shoreface deposits of Las Imagenes Formation and the Cuchilla Tongue in the northern Parras, La Popa, and southern Sabinas Basins (Ye, 1997; Halik, 1998). The base of the forced-regressive shoreface deposit is sharp and erosional and is used as the basinwide datum for the Difunta Group in Figure 7. This sequence boundary is traced along the base of the Cuchilla Tongue and Las Imagenes Formation north of Fraustro and southward up through shoreface deposits to the top of red fluvial mudstone deposits of Las Imagenes Formation south of the section at Sauceda (Figure 7). This stratigraphic framework is analogous to the forced-regressive sequences described by Posamentier et al. (1992) in the Cretaceous foredeep basin of western Canada.

Cerro Grande and Las Encinas Formations (SC3)

The Cerro Grande Formation is a thick succession of relatively homogeneous fine-grained sandstone to coarse siltstone that occurs in the southern and western parts of the Parras Basin. The sandstone gives way to more distal fine siltstone and mudstone of the ''middle siltstone member'' of the Potrerillos Formation in the northeastern Parras Basin (Figures 5 and 6). The type section for the Cerro Grande Formation is 4 km southwest of the small town of San Miguel on the north side of Cerro Grande and approximately 5 km west of Mexico State Highway 57 (Figure 6). Here, the Cerro Grande Formation is 792 m thick (Ye, 1997).

South of the section at El Pantano, a 7- to 15-m-thick shoreface sandstone unit in the basal Cerro Grande Formation is in abrupt contact with underlying red fluvial and coastal-plain mudstone of Las Imagenes Formation. This marine sandstone is capped by a pebble conglomerate with rounded, varicolored chert clasts at this southern location (Ye, 1997). The base of the lower sandstone is interpreted as a transgressive marine-ravinement surface, and it defines the base of stratigraphic cycle SC3 in the

southern Parras Basin. At this southern location, the transgressive marine-ravinement surface directly overlies the sequence boundary of the forced regression above Las Imagenes Formation (Figure 7).

In the southern part of the Parras Basin, the basal transgressive sandstone of the Cerro Grande Formation passes upward into a succession of thinly bedded, intensely burrowed, muddy siltstone, siltstone, and sandstone. The mud-rich succession is as much as 150 m thick and thins southward and westward (Crawley, 1975), forming the marine transgressive systems tract in the lower part of cycle SC3. In the northern part of the Parras Basin and in the western half of La Popa Basin, upward thinning of bedding and decrease in sandstone occurs above Las Imagenes Formation and the Cuchilla Tongue, respectively, through a thickness of 15 to 20 m. This represents the transgressive systems tract in the lower SC3 in the northern, distal part of the Difunta foredeep.

Overlying the maximum-flooding surface, above the transgressive systems tract, are highstand deposits of cycle SC3 (Figure 7). In the southern part of the Parras Basin, south of the Fraustro section, the highstand deposits constitute the main part of the Cerro Grande Formation and consist of a thinly bedded, interlayered sandstone and mudstone of prodelta to lower delta-front affinity with abundant ball-and-pillow structures (Ye, 1997). The uppermost part of the Cerro Grande Formation typically consists of thick upper delta-front/shoreface sandstone, which is overlain by the delta plain/coastal plain red and gray mudstone, siltstone, and sandstone of Las Encinas Formation (Figure 7). The succession of the upper Cerro Grande and Las Encinas Formations represents an overall upward-shallowing sequence characterized by the lower delta-front (and prodelta?) association passing upward into upper delta-front and delta-plain sediments. In the eastern Parras Basin and north of the Fraustro section, marine sandstone intervals of the Cerro Grande and Las Encinas highstand deposits interfinger with and taper out into more distal basinal marine mudstone and siltstone of the ''middle siltstone member'' of the Potrerillos Formation (Halik, 1998; Figure 6). In La Popa Basin, a laterally persistent sandstone occurs at the top of the ''middle siltstone member'' and is defined as the ''Delgado sandstone member'' by Lawton et al. (2001). The type section of the ''Delgado sandstone member'' is in the Delgado syncline, approximately 500 m west of El Gordo diapir, where the sandstone is 11 m thick. The sandstone consists of hummocky and swaley cross-stratification and

contains ophiomorpha trace fossils (Lawton et al., 2001). The ''Delgado sandstone member'' thins to a few beds of very fine-grained sandstone, both toward El Gordo and El Papalote diapirs.

Lawton et al. (2001) have clearly established that the top of the ''Delgado sandstone member'' of the Potrerillos Formation in La Popa Basin coincides with the Cretaceous-Tertiary boundary based on the presence of *Cimomia haltomi* at the very base of the overlying ''upper mudstone member'' of the Potrerillos Formation (Figure 5). Ostreids in the upper part of Las Encinas Formation at Fraustro have been identified as Paleocene in age (Vega et al., 1999), thus confirming the correlation between Las Encinas Formation in the Parras Basin with the ''Delgado sandstone member'' of the Potrerillos Formation in La Popa Basin.

Discussion of Foreland Basin Phase

The Cretaceous portion of the Difunta Group is characterized by marked asymmetry with a thickness of more than 3677 m in the southeastern part of the Parras Basin near the Sierra Madre Oriental tectonic front and thinning to 922 m, 150 km (structurally unrestored) to the north in the southern part of the Sabinas Basin (Figure 7). This asymmetry indicates differential subsidence at the time of deposition and is attributed to tectonic loading by the Sierra Madre Oriental fold and thrust belt in the south.

The origin of stratigraphic cycles SC1, SC2.1, SC2.2, and SC3 appear to be controlled primarily by tectonism rather than eustatic effects. The clearest example of a tectonic signal in the foredeep, apart from the asymmetry of the basin fill, is the drowning of SC1. In the southern part of the Parras Basin, at Saucillo River, more than 350 m of deep-water mudstone and subordinate turbidite beds overlie transgressive sandstone units above the Cerro Huerta red beds (Figures 7 and 8a). This deep-water drowning phase can be traced northward almost 60 km to the section at Fraustro before pinching out between two thick, shallow-marine sandstone complexes. Localized drowning in the south, adjacent to the Sierra Madre Oriental frontal zone, clearly cannot be attributed to a global sea-level rise.

Increased accommodation space is also evident in shallower-water facies assemblages in the southern part of the foredeep. In the upper part of highstand deposits in stratigraphic subcycle SC2.1 are at least 19 gradually upward-coarsening parasequences with thicknesses ranging from just a few meters to 20 m (Figure 12). The correlative section at Huizachal in the northernmost part of the San Antonio syncline in the southern part of the Sabinas Basin (Figure 3) is three times thinner than at El Pantano (Halik, 1998). At Huizachal, without exception, sandstone bodies consist of hummocky cross-stratified, forced-regressive shoreface sandstone with large gutter casts along the erosive base (Figure 15). Ye (1997) documented similar gradational transitions between upward-shallowing offshore mudstone-to-shoreface sequences in the south where accommodation space was maximized to erosively based, forced-regressive shoreface sequences in the north where subsidence rates in the foredeep were minimized. The primary example given by Ye (1997) in the Difunta Group is Las Imagenes Formation, with its gradational base in the southern part of the Parras Basin, whereas the lower contact is erosional from Fraustro in the northern Parras Basin and northward into La Popa Basin and the correlative Cuchilla Tongue (Figure 7).

The overall architecture of the Cretaceous cycles reflects progressive infilling of the basin as forced-regressive sequences are progressively better developed up through the section with erosional sequence boundaries extending farther south in the upper part of the Cretaceous portion of the Difunta foredeep fill (Ye, 1997; Figure 7).

Progressive infilling of the basin also is revealed by paleogeographic maps for the various stratigraphic cycles in the Difunta Group (Figure 13). During stratigraphic cycle SC1, high subsidence rates in the south trapped fluvial-deltaic sediments in the southwest and prevented them from building eastward (Figure 13a). Based on biochronologic data in Figure 10 for stratigraphic cycles SC1 and SC2, 1839 m of sediment accumulated at El Pantano over only 1.9 Ma, yielding an average accumulation rate of 0.97 m/1000 years. At the southernmost sections in the basin, average subsidence rates at the same time were at least 1.63 m/1000 years.

During stratigraphic cycle SC2, fluvial sediments of Las Imagenes Formation prograded into the northeastern Parras Basin and shallow-marine equivalents, including the Cuchilla Tongue, extended into the eastern La Popa Basin (Ye, 1997; Figure 13b). Although paleogeographic maps are not constructed for SC3, the entire region covered by the Parras and La Popa Basins was characterized either by fluvial or shallow-marine environments, and deeper-water mudstone facies would not return in the Difunta Group from the time of cycle SC3 and later.

Figure 15. Hummocky cross-stratified, forced-regressive, upper-shoreface sandstone deposits directly overlying lower-shoreface to offshore transition heterolithic deposits in the upper part of SC2.1 at Huizachal. Note large gutter casts at base of sandstone body attesting to erosive base. See Figure 7 for location of the section. HCS = hummocky cross-stratification.

Tertiary Part of Difunta Group: Salt-withdrawal Basin Phase

Apart from modest amounts of Paleocene sediment in the northeastern part of the Parras Basin (Las Encinas and Rancho Nuevo Formations) no Tertiary-age sediment is preserved in the Parras Basin. We argue here that, after the Cretaceous period, almost no more sediment accumulated in the Difunta foredeep in the region covered by the Parras Basin, proximal to the Sierra Madre Oriental tectonic front. By contrast, in the Delgado, La Popa, and Escondida synclines in La Popa Basin (Figures 4 and 14) and in the San Antonio syncline in the southern part of the Sabinas Basin, more than 650 m of Paleocene strata and at least 1660 m of Eocene strata were deposited (Figures 2 and 7).

Upper Potrerillos Formation and Adjuntas Formation (SC4)

Above the uppermost Maastrichtian ''Delgado sandstone member'' of the Potrerillos Formation are the ''upper mudstone member'' and the ''upper sandstone member'' of the Potrerillos Formation (Figure 5). Together these two members have a combined thickness of 653 m in La Popa syncline (McBride et al., 1974) and 615 m in the southern

part of the Delgado syncline (Garrick, 1999). Unconformably overlying the ''Delgado sandstone member'' is a thin, lenticular conglomerate composed of oysters, bivalves, and cobbles of chert, limestone, and metaigneous rocks (Lawton et al., 2001). Vega et al. (1989), Vega and Perrilliat (1995), and Vega et al. (1999) describe the Paleocene nautiloid *Cimomia haltomi* in the lowermost mudstone of the ''upper mudstone member.'' *Venericardia (Baluchicardia) francescae* is present in the central part of the ''upper mudstone member,'' further supporting a Paleocene age for this upper portion of the Potrerillos Formation.

In the lower part of the ''upper mudstone member'' are a number of isolated but locally thick limestone lentils, including the upper five lentils at El Papalote diapir (Giles and Lawton, 2002), the upper El Gordo lentil at El Gordo diapir, and La Popa lentil north of La Popa salt weld (Lawton et al., 2001; Figure 14). The carbonate lentils all consist of shallow-marine, subtidal deposits which grade laterally into correlative calciturbidites and debris flows derived from the carbonate accumulations (Lawton et al., 2001). The upper El Gordo lentil is cored by sponge and coral boundstone near El Gordo diapir and is flanked by sponge and red algal packstone turbidites

and forereef debris. La Popa lentil is as much as 350 m thick with a similar core of sponge and coral boundstone flanked by beds of strombolitic packstone with interbeds of allodaptic grainstone (Lawton et al., 2001). At El Papalote diapir, the reef core is not well preserved, but Giles and Lawton (2002) describe more than 240 m of forereef deposits that accumulated adjacent to an atoll-like carbonate reef that developed above the rising diapir. They outline five separate halokinetic sequences that, together with igneous basement blocks transported to the surface by the rising diapir, have yielded a detailed history of synkinematic evolution between the carbonate reefs and salt diapirs in La Popa Basin (Garrison and McMillan, 1999; Giles and Lawton, 2002).

Gradationally overlying the ''upper mudstone member'' in which the carbonate lentils occur is the ''upper sandstone member'' of the Potrerillos Formation. The ''upper sandstone member'' is, in turn, overlain by red beds of the Adjuntas Formation (Figure 7). The ''upper sandstone member'' is 275 m thick at its type section east of El Papalote diapir (McBride et al., 1974) and consists of hummocky cross-stratified, very fine to fine-grained sandstone in the lower part, with fine- to medium-grained planar tabular cross beds in the upper part (Lawton et al., 2001).

The Adjuntas Formation is composed of primarily red mudstone and siltstone with lenticular bodies of fine- to medium-grained sandstone. The red beds contain horizons with calcareous nodules that Lawton et al. (2001) interpret as paleosols. At the base of the Adjuntas Formation is an olive-green interval of alternating siltstone and mudstone that contains diverse brackish water fauna, indicating an estuarine or marginal-marine setting (Vega and Perrilliat, 1992). The gastropod *Turritellamortoni*, a lower Eocene index fossil reported from the Kinkaid Formation in Alabama, and the bivalve *Venericardiaplanicosta*, a lower Eocene index fossil reported in the Paris Basin in France, are both present in the lower Adjuntas Formation (Vega and Perrilliat, 1989). The fresh-water snail *Melanatriaipresiana* also occurs in the green shale units in the lower Adjuntas Formation, as does the fresh-water gastropod *Melanatria* (genus) (Vega et al., 1989).

Cycle SC4 extends from the top of the ''Delgado sandstone member'' in the Potrerillos Formation to the top of the Adjuntas red beds in La Popa Basin. Cycle SC4 includes the upper part of Las Encinas Formation and all of the Rancho Nuevo Formation of McBride et al. (1974), or the Paleocene ''upper mudstone and sandstone members'' of the Potrerillos Formation in the northernmost and easternmost Parras Basin (Figure 5). Vega et al. (1999) have determined that a significant unconformity exists at the Cretaceous-Tertiary boundary between our SC3 and SC4 stratigraphic cycles. Lawton et al. (2001) interpret this boundary as a significant sequence boundary.

Viento Formation and Carroza Formations (SC5)

The Viento and Carroza Formations constitute the two youngest lithostratigraphic units in the Difunta Group. The Viento Formation is more the 836 m thick in the Delgado syncline (Garrick, 1999) and 737 m thick in La Popa syncline directly to the north (McBride et al., 1974) and consists exclusively of shallow-marine siliciclastic sediment. The marine succession is dominated by medium-grained sandstone, although numerous granular-pebble horizons exist throughout the Viento Formation. Marine fossils, including bivalves and oysters, are ubiquitous throughout the Viento succession.

Overlying the Viento Formation in La Popa and Escondida synclines in La Popa Basin and San Antonio syncline to the north in the southern part of the Sabinas Basin is the dominantly red mudstone unit of the Carroza Formation. In La Popa syncline, more than 658 m of sediment make up the Carroza Formation without exposing the top of the succession. Apart from red mudstone and subordinate siltstone are rare 3- to 9-m-thick medium-grained sandstone units with channel geometries. No fossils are reported from the Carroza Formation, although fragments of wood are abundant (McBride et al., 1974).

Neither the Viento nor Carroza formations in La Popa Basin have been dated. However, based on fossils reported from the underlying Adjuntas Formation, the Viento and Carroza Formations must be middle Eocene in age or younger. Together, marine mudstone, sandstone, and conglomerate units of the Viento Formation and red mudstone deposits of Carroza Formation constitute the fifth and final stratigraphic cycle, SC5, in the Difunta Group (Figures 5, 6 and 7).

Provenance Data for Difunta Group

One of the key issues regarding the tectonic setting of the Difunta Group is the provenance to the Cretaceous foredeep and to the Tertiary section of the Difunta Group. Arney (1998) studied the composition of 52 medium-grained sandstone samples

Figure 16. (A) Q-F-L ternary diagram for the Difunta Group using provenance discrimination fields after Dickinson et al. (1983). Open circles represent framework grain compositions of medium-grained sandstone samples from SC1 and SC2 from Arney (1998). Black triangles are from SC3 after Garrick (1999). Black squares are for Tertiary samples from SC4 and SC5 in Delgado syncline in La Popa Basin and are after Garrick (1999). (B). Qp-Lv-Ls ternary diagram for the Difunta Group using provenance discrimination fields after Dickinson and Suczek (1979). Open circles represent the composition of the lithic portion of framework grains of medium-grained sandstone samples from SC1 and SC2 from Arney (1998). Black triangles are from SC3 after Garrick (1999). Black squares are for Tertiary samples from SC4 and SC5 in Delgado syncline in La Popa Basin and are after Garrick (1999).
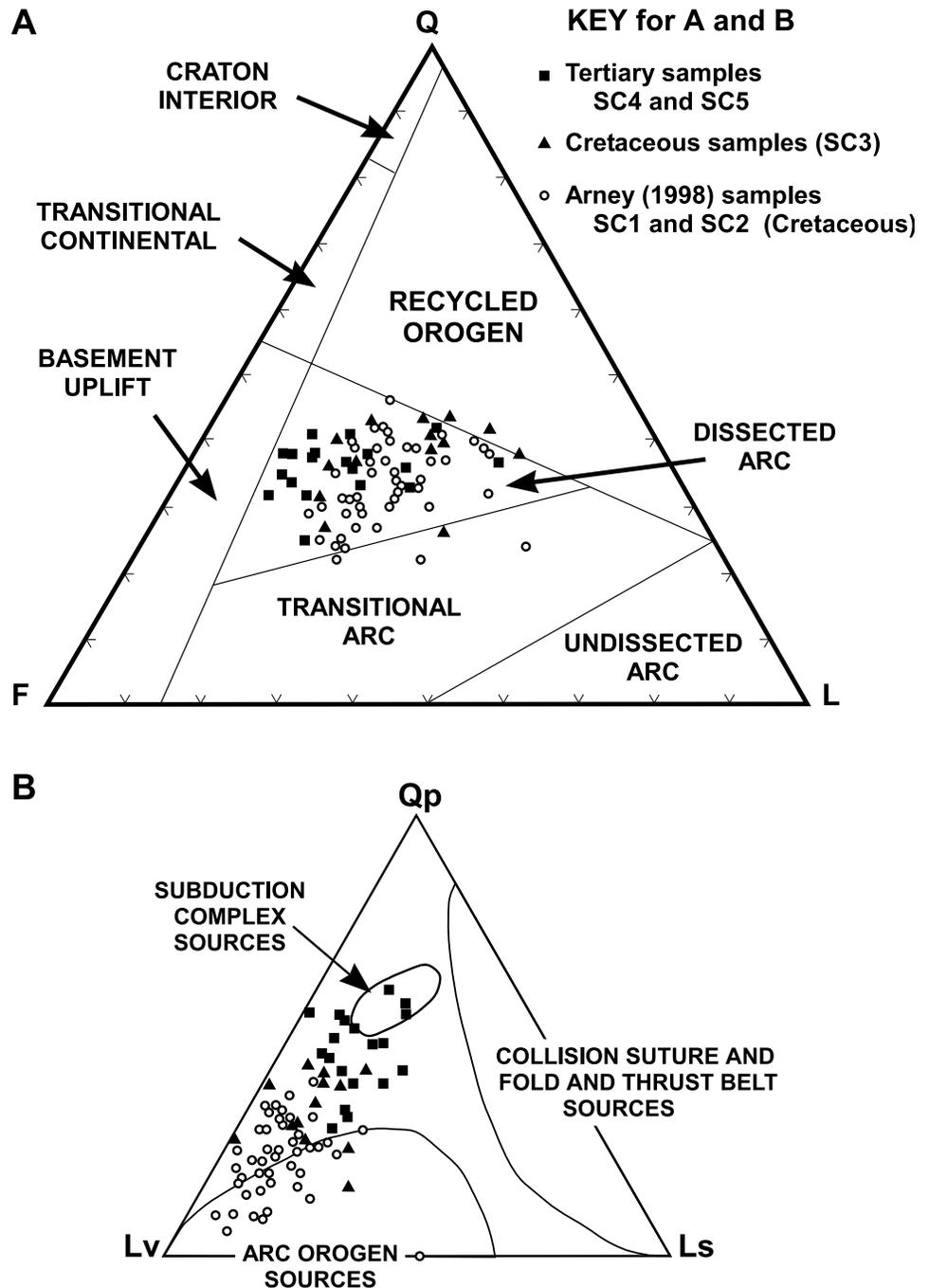
from SC1 and SC2 stratigraphic cycles in the lower part of the Difunta Group across both the Parras and La Popa Basins. The sandstones are volcanic lithic arenites interpreted as having been sourced from a dissected volcanic arc (Tardy and Maury, 1973; McBride et al., 1975; Figure 16). Arney (1998) concluded that arc volcanism and uplift along the western margin of Mexico during latest Cretaceous time (Damon et al., 1981) associated with accretion of the Guerrero composite terrane to the west (Tardy et al., 1994) was the primary source of detritus for the Difunta Group. Sandstone samples are devoid of carbonate lithic grains; consequently, the Sierra Madre Oriental directly south of the Parras and La Popa Basins, which primarily consist of Lower Cretaceous carbonate rocks, did not constitute a source for the Difunta Group in the study area.

In order to establish the degree to which the Sierra Madre Oriental orogenic belt supplied detritus in the latter stages of the Difunta Group history, Garrick (1999) analyzed 33 samples of medium-grained sandstone from stratigraphic cycles SC3 and, in particular, SC4 and SC5 in the Delgado syncline in the southern La Popa Basin. He found that sandstones in the upper part of the Difunta Group are indistinguishable from sandstones studied by Arney (1998) in the lower part of the group (Figure 16) and

concluded that the Sierra Madre Oriental orogenic belt never supplied detritus to the foredeep in the vicinity of the Parras and La Popa Basins. Rather, it is assumed that large rivers transported voluminous amounts of sediment from the far west near the Guerrero arc and deposited the axially derived sediment in the western Parras Basin initially, and subsequently across the entire Difunta foredeep (also McBride, 1985; Figure 13).

Interpretation of Tertiary Sedimentary Sequences SC4 and SC5

Determining the origin of the Tertiary sedimentary successions in the relatively small structural basins (synclines) of La Popa Basin is conjectural with the present data coverage. Two issues are central to resolving the origin of the Tertiary basins. These include (1) the mechanism for generating accommodation space and (2) the source of sediment. Several important observations can be made leading to indirect evidence for the structural basins:

1) Tertiary sequences are intimately related to diapiric structures.
2) Tertiary sequences occur only in circular or semicircular synclinal structures and are absent from all other areas covered by the Difunta Group.
3) Despite limited lateral extent of the structural basins (<15 km in diameter), more than 2300 m of Tertiary sediment has accumulated in La Popa syncline, and in excess of 1750 m was deposited in the Delgado syncline.
4) Sediment source for the Difunta Group remained constant through the Cretaceous and Tertiary with a provenance located to the far west in a Late Cretaceous magmatic arc.

In order to consider the two Tertiary stratigraphic cycles SC4 and SC5 as part of the Difunta foredeep basin fill, rejuvenated activity in the Sierra Madre Oriental is required in which the locus of subsidence is moved northward to La Popa Basin. Such rejuvenation should be accompanied by a drowning phase in the very latest Cretaceous to earliest Tertiary, coeval with deposition of the "upper mudstone member" and "upper sandstone member" of the Potrerillos Formation. Moreover, a contribution of clastic material from the Sierra Madre Oriental, in the form of Carbonate detritus, is expected.

Based on faunal assemblage, fine-grained sediment of the upper mudstone member of the Potrerillos Formation is assumed to have been deposited in relatively shallow water without evidence of a drowning phase. Shallow-marine and terrestrial sedimentation persisted throughout the Paleocene and Eocene in La Popa Basin.

Garrick (1999) showed that the upper part of the Difunta Group consists of volcanic lithic arenites that are indistinguishable compositionally from sandstones in the Cretaceous lower part of the section (Figure 16). Consequently, a rising Sierra Madre Oriental highland to the south through continued thrusting in Tertiary time is rejected.

The subsidence mechanism envisaged for the Delgado and La Popa synclines was driven by salt withdrawal, similar to minibasins along the continental slope in the northern Gulf of Mexico Basin offshore Texas and Louisiana (Peel et al., 1995; Weimer et al., 1998, Prather et al., 1998). One of the primary sources of evidence for identifying salt withdrawal in creating minibasins is through seismic profiling of a thick basin fill that onlaps steep (almost vertical) basin margins bordered by rising salt stocks and diapirs. At present, no seismic data exist for these onshore basins. Giles and Lawton (1999, 2002) do provide a detailed account of the relationship between diapiric growth and accompanying sedimentation in La Popa syncline and interpret the structure as a salt-withdrawal minibasin.

Although the subsidence mechanism for La Popa salt-withdrawal minibasins appears similar to that of the minibasin province along the northern Gulf of Mexico Basin, it should be noted that Tertiary sedimentation in La Popa Basin was exclusively shallow marine and terrestrial in nature, whereas salt-withdrawal minibasins in the Gulf of Mexico are filled with deep-water sediment gravity flows.

The timing of salt movement is somewhat unclear. Giles and Lawton (1999, 2002) and Lawton et al. (2001) indicate that carbonate lentils in the Maastrichtian "lower mudstone member" of the Potrerillos Formation are related to salt movement and that halokinesis may have been initiated as early as the late Aptian. Based on the stratigraphy in the Difunta Group, we argue here that the main episode of salt-induced subsidence in La Popa Basin was from the Paleocene to middle Eocene, when thick sequences of sediment accumulated in the Delgado, La Popa, Escondida, and San Antonio synclines. The Cretaceous portion of the carbonate lentils around El Gordo and El Papalote diapirs in La Popa Basin are relatively thin compared with the thick Paleocene portion of the carbonate lentils, further suggesting
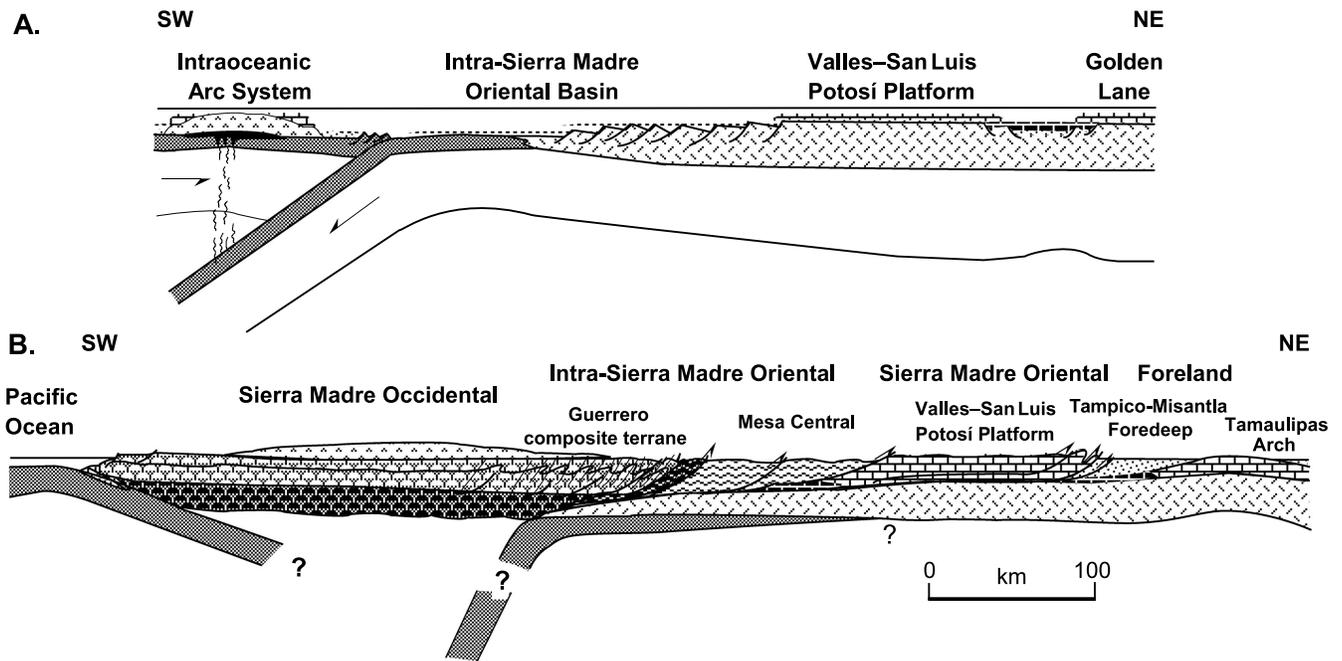
Figure 17. (A) Southwest-northeast schematic cross section through central Mexico showing Albian paleogeography and tectonic framework. (B) Same cross section as in (A) showing tectonic relationship between the Sierra Madre Oriental fold and thrust belt, peripheral foreland basin, and intra-Sierra Madre Oriental at the end of the Cretaceous (after Ye, 1997).

that the main episode of salt movement was in early Tertiary time.

DEFORMATION AND EROSION OF THE FOREDEEP: REGIONAL IMPLICATIONS

The present outcrop pattern in and surrounding the area of the Parras, La Popa, and southern Sabinas Basins is as much a result of deformation and erosion of the foreland basin as it is sedimentation. Anticline-syncline pairs and associated thrust faults in the southwestern Parras Basin and corresponding elongate dome and basin structures in the southeastern Parras Basin parallel the Sierra Madre Oriental fold and thrust belt directly to the south (Figure 4). These are the earliest structures in the Parras Basin and are related to convergence in the Sierra Madre Oriental fold and thrust belt. This convergence was initially manifested as differential subsidence in the Difunta foredeep; it started at least by the time of deposition of SC1 in the Campanian and may already have been initiated during drowning of the Indidura carbonates in the late Coniacian to early Santonian (Ye, 1997; Figure 7). Convergence must have persisted at least into the earliest Paleocene, which is the age of the youngest sediments

deformed by F1 folding. Ye (1997) and Freydier et al. (1996) argue that this early phase of convergence is related to westward subduction of oceanic lithosphere to a marginal ocean basin separating the Guerrero composite terrane from the North American continent to the northeast (Figure 17). This deformation culminated with closure of the marginal basin and collision between the Guerrero composite terrane and North America in the latest Cretaceous, when the foredeep was most active (Figure 17).

The Coahuila Arch, eastern Parras Basin, and Monterrey Salient are illustrated as a large anticline-syncline-anticline structure in Figure 4 and are F2 folds with a wavelength of more than 100 km. The Monterrey Salient and syncline defining the eastern Parras Basin are northward plunging. We propose herein that the Difunta Group originally extended across the Lower Cretaceous rocks of the Monterrey Salient, greatly increasing the areal extent of the original Difunta foredeep. Immediately northwest of Saltillo, in the southeasternmost Parras Basin, are numerous flute casts at the base of the delta-fed turbidite sands in subcycle SC2.1, with a transport direction due east, directly toward the Monterrey Salient. Since flute casts are indicators of paleoslope, the paleoflow orientation in SC2.1 implies that the Monterrey Salient was *not* a positive feature in the

early history of the Difunta foredeep. Moreover, Difunta-type strata exist in the core of large synclinal folds in the salient south of Monterrey suggesting that the Difunta Group originally extended across the Monterrey Salient, thereby connecting the Parras Basin with the Tampico-Misantla Basin to the southeast (Francisco Vega, personal communication, 2002 ; Figure 1). This connection is supported by deposition of the early Paleocene Chicontepec "flysch" in the Tampico-Misantla Basin that received large volumes of volcanic lithic detritus from the northwest (Bitter, 1986, 1993). We argue that the Tampico-Misantla foredeep was starved of coarse-grained detritus during the latest Cretaceous as the deep-water Mendez shale accumulated. Only after the axially derived sediment from the west had filled the Parras Basin during SC1–SC3 cycles, did the coarser volcaniclastic detritus described by Bitter (1993) make it into the Tampico-Misantla Basin as the Chicontepec "flysch."

The contention of Late Cretaceous, tectonically-induced subsidence in the Tampico-Misantla foredeep is supported by the existence of a flexural bulge immediately east of the basin along the Tamaulipas Arch and Golden Lane, which we propose resulted from loading of thrust sheets in the Sierra Madre Oriental. Several lines of evidence support this hypothesis of flexural arching east of the Tampico-Misantla foredeep, and they are critical for understanding development of the giant Golden Lane oil fields. These lines of evidence include:

1) Early to Late Cretaceous rudist atoll-reefs developed over the Gold Lane (Wilson, 1987), suggesting a paleohigh, in contrast to the deep-water sediments accumulating in the adjacent foredeep immediately to the west.
2) On the crest of the Golden Lane atoll is an unconformity between upper Lower to Upper Cretaceous and Eocene strata in the north and Oligocene strata in the south (Viniegra and Castillo-Tejero, 1970; Wilson, 1987). Below this unconformity is extensive karsting in which caves became filled with Oligocene mudstone, suggesting flexural uplift of the Gold Lane in the Late Cretaceous to Paleocene. This uplift was coeval with deposition of "flysch" and "molasse" sequences in the adjacent Tampico-Misantla foreland basin (Busch and Govela, 1978; Suter, 1984, 1987; Bitter, 1986).
3) Flysch and molasse sequences (Chicontepec and Tantoyuca Formations) in the Tampico-Misantla

foredeep basin significantly thin toward the arch, and paleocurrent indicators in the Chicontepec Formation suggest axial transport of sediment to the south and southeast (Bitter, 1986, 1993; Wilson, 1987), also implying a paleohigh separating the foredeep basin on the west and the western deep gulf to the east.
4) Isostatic gravity data indicate that a gravity high coincides with the Tamaulipas Arch and Golden Lane uplift, contrasting with gravity lows along the Tampico-Misantla foredeep to the west (Ye, 1997). These gravity data also favor broad flexural upwarping of the crust around the Tamaulipas Arch and Golden Lane, rather than a shallow-level crustal fold or blind thrust.

The present outcrop pattern of the Difunta Group and surrounding Lower Cretaceous carbonate sequences is considered to be a result of subsequent deformation, uplift, and erosion. Wholesale deformation of the foredeep either coincided with or postdated development of salt-withdrawal basins in La Popa Basin in the middle to late Eocene. Giles and Lawton (1999) quote a regional study by Gary Gray at Exxon Production Research in Houston, Texas, on apatite fission track cooling ages of 31 Ma from both the Difunta Group and surrounding Lower Cretaceous carbonate successions. This uniform, early Oligocene cooling age coincides with a period of dramatic progradation of the entire continental shelf along the northeast coast of Mexico (Galloway et al., 2000), suggesting that vast amounts of sediment were being uplifted and eroded to the west in the area presently covered by the Difunta Group.

SUMMARY

Based on a regional remapping program of the Parras and La Popa Basins, stratigraphic correlation in the Difunta Group has been dramatically revised. The Difunta Group accumulated during two distinct stages of basin formation. In the latest Cretaceous, foreland basin subsidence accommodated more than 3700 m of sediment adjacent to the encroaching Sierra Madre Oriental fold and thrust belt. The foredeep fill thinned northward to just 922 m, more than 150 km (structurally unrestored) to the north in the southern part of the Sabinas Basin.

Sediment in the foredeep was axially derived with a volcanic source in the present region of the Sierra Madre Occidental and was supplied by rivers flowing

eastward. Three stratigraphic cycles constitute the foredeep phase. During rapid subsidence in the early history of the foredeep, (SC1) fluvial sediments were restricted to the southwestern portion of the basin and eastward progradation was limited. Successive cycles prograded ever farther eastward as basin infilling proceeded and subsidence rates diminished. Parasequences in the south, where accommodation space was greatest, had gradational lower contacts, whereas coastal deposits in the northern part of the foredeep exist as forced-regressive sequences because of limited accommodation space.

The second phase in the evolution of the Difunta Group was the accumulation of more than 2300 m of alluvial, coastal-plain and shallow-marine sediment in small salt-withdrawal basins in La Popa Basin during the Paleocene and Eocene. These circular and semicircular basins are flanked either by gypsiferous diapirs or salt welds, which are intimately related to development of these small structural basins.

Present outcrop patterns of the Difunta Group in the Parras and La Popa Basins reflect noncoaxial polyphase folding and subordinate faulting of the basin fill. Uplift and erosion of the Difunta Group in the Parras, La Popa, and southern Sabinas Basins occurred in the latest Eocene and early Oligocene and are manifested as a major depocenter along the margin of the coast of northeast Mexico.

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