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THE NATURE OF LIMESTONE-SILICICLASTIC "CYCLES" IN MIDDLE AND UPPER PENNSYLVANIAN STRATA, TEJANO CANYON, SANDIA MOUNTAINS, NEW MEXICO

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Abstract—Middle and Upper Pennsylvanian strata exposed in roadcuts on the east flank of the Sandia Mountains, New Mexico, consist of intimately interbedded limestone and siliciclastic facies that do not alternate in a repeated fashion and are not strictly described as cyclic. Nonetheless, facies analysis, with an emphasis on outcrop and petrographic characteristics of thin beds, permits designation of transgressive-regressive facies alternations that are arguably related to glacioeustasy recorded globally in strata of this age. The complexity of the transgressive-regressive cycles, leading to their nonrepetitive facies sequences, is determined by variations in the clastic facies and associated erosion surfaces. Limestone facies typically form upward-shallowing successions, similar to those described from many localities. Each such succession is commonly overlain by marine and/or nonmarine clastic facies that differ considerably from one transgressive-regressive cycle to the next. Erosion prior to deposition of most clastic facies removed variable amounts of underlying limestone adding to the nonrepetitive facies character. Variations in clastic facies relate to how delta distributary channels and related delta-front/delta-plain environments responded to sea-level change, and lateral variability of facies inherent in these environments. Strong asymmetry of most cycles, well-developed ravinement surfaces with paired sandstone and grainstone lag deposits, interpreted storm beds, and rarity of tidal indicators are all suggestive of deposition in a wave-dominated setting. Most transitions from limestone to clastic facies involve subaerial erosion or weathering surfaces and/or evidence of extensive, early meteoric diagenesis of subtidal limestone facies. The lack of intertidal limestone facies implies that carbonate sedimentation did not fill all available accommodation space prior to exposure. Nonmarine clastic facies are, in almost all cases, found resting directly on erosion surfaces cut on limestone and only rarely are found overlying progradational marine clastic rocks. These relationships require relative sea-level change, rather than autogenic mechanisms, to account for transgressive-regressive cycles. Roadcut exposures in Tejano Canyon provide insights into limestone-clastic "cycles" that are rarely appreciated on natural outcrops of such facies in northern New Mexico and serve as an important locality for interpreting Pennsylvanian strata in that region.

INTRODUCTION

Sedimentary facies recording repeated shallowing and deepening in nearshore and coastal- plain environments are a common stratigraphic motif. Facies alternations record fluctuations in the position of a shoreline in response to variations in eustatic sea level, tectonic uplift and subsidence, sediment delivery or in situ production, or some combination of all of these variables. Because the sedimentary facies marking these changes tend to be repeated vertically in the same order, they are commonly referred to as cycles. Where cycle thicknesses can be inferred to represent relatively short periods of time (10s to 100s of thousands of years), interpretations for cycle origin typically de-emphasize tectonic driving forces, which tend to be unidirectional over such time spans. Instead, explanations focus on eustatic (typically glacioeustatic) mechanisms or those related to temporal (allogenic) or spatial (autogenic) variations in sediment supply to a shoreline where accommodation space is being generated at more or less uniform rates.

Late Paleozoic strata around the world are notable for remarkable facies cyclicity, most generally ascribed to glacioeustasy in response to glaciation of Gondwana. Some cyclic sections are almost entirely carbonate and bear resemblance to carbonate-platform cycles recognized widely in the geologic column (James, 1984). Others, especially near foreland basins related to the consolidation of Pangea, are notable for alternations of marine limestone and shale with nonmarine sandstone, shale and, in some instances, coal. These mixed carbonate-clastic cycles include the well-known Pennsylvanian cyclothems of the midcontinent region of North America (Wanless and Sheppard, 1936; Heckel, 1984) and the upper Mississippian Yoredale cycles of Great Britain (Leeder and Strudwick, 1987).

Pennsylvanian strata in New Mexico are, likewise, remarkably cyclical. Most past studies have focused on the carbonate-platform cycles in the southern part of the state (e.g., Wilson, 1967; Algeo et al., 1991; Soreghan, 1994). Grossly similar, limestone-dominated cycles are also known in the northern part of New Mexico (Wiberg and Smith, 1993) but alternations of limestone and clastic facies, derived from Ancestral Rocky Mountain uplifts, are also widespread, albeit less well studied.

OBJECTIVES

This paper describes a well-exposed Pennsylvanian section of alternating limestone and clastic facies east of Albuquerque, New Mexico. Although arguably reflecting cyclic fluctuations in sea level, the facies alternations are remarkably complex and do not repeat in the same fashion through a single section. In a strict sense, therefore, these facies successions are not cyclic, because they are not repetitive. The qualified use of "cycle" is retained, however, for describing strata that represent gross alternations of marine and nonmarine facies, even though no preferential facies-stacking pattern is present.

The objectives of this paper are principally descriptive and illustrative. High-quality outcrops are restricted to roadcuts and, even there, are incomplete because of numerous faults. Nonetheless, the Tejano Canyon section is likely the best exposed example of limestone-clastic "cycles" in northern New Mexico and serves as a valuable site to contemplate the origins of facies alternations and for interpreting more characteristically poorly exposed outcrops or subsurface sections elsewhere in the region.

STRATIGRAPHY AND GEOLOGIC SETTING

Middle and Upper Pennsylvanian (Atokan-Virgilian) strata form the crest and most of the eastern dip-slope of the Sandia Mountains, directly east of Albuquerque, New Mexico (Fig. 1). These rocks generally rest directly on Proterozoic plutonic and metamorphic rocks, although Mississippian strata are locally present (Kelley and Northrop, 1975). The Atokan to lowermost Desmoinesian Sandia Formation is approximately 55 m thick and consists of sandstone and shale intimately interbedded with subordinate limestone. The overlying Madera Formation (Desmoinesian-Virgilian) consists of a lower, cliff-forming interval (~140 m thick) composed predominantly of limestone and an upper interval (~260 m thick) of interbedded sandstone, limestone, and shale (Kelley and Northrop, 1975). Early workers (Read et al., 1940) referred to these intervals as the gray limestone member and arkosic limestone member, respectively. In the Manzano and Manzanita Mountains to the south (Fig. 1), Myers (1973) redefined a Madera Group composed of the Los Moyos Limestone and Wild Cow Formation in place of the members of Read et al. (1940). Although not formally extended to the Sandia Mountains, Myers' (1973) stratigraphic nomenclature could be equally well applied there. The lower, gray limestone member of the Madera Formation is best exposed in the Sandia Mountains and forms the crest of the range. Both the Sandia Formation and the arkosic limestone member of the Madera Formation are slope formers, with local protruding ledges of limestone or well-

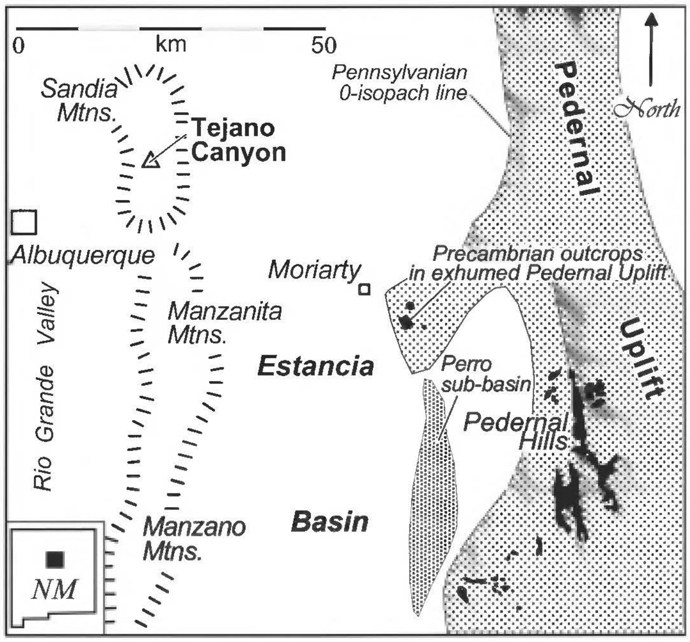

FIGURE 1. Map of a part of north-central New Mexico showing location of present-day features and Pennsylvanian tectonic elements. Extent of Pedernal uplift and Perro sub-basin based on data in Broadhead (1997).

cemented sandstone.

Pennsylvanian strata in the Sandia-Manzano Mountains region were deposited on a west-sloping ramp within an epicontinental sea of complex bathymmetry that was broken by deeper basins and high-standing uplifts of the ancestral Rocky Mountains. Clastic sediment in the Sandia Mountains was apparently derived from the Pedernal Uplift, 60 km to the east (Fig. 1). The uplift and ramp were locally separated by the deep Perro sub-basin of the Estancia Basin (containing >1500 m of Pennsylvanian rocks; Broadhead, 1997), which was often overfilled to permit clastic sediment delivery westward onto the ramp, especially during periods of low sea level.

Wiberg (1993) and Wiberg and Smith (1993) described the cyclic facies character of the gray limestone member of the Madera Formation augmented by correlation of five well-exposed sections in the northern half of the Sandia Mountains. Well-defined asymmetric cycles, 2–12 m thick, of upward-shallowing shale and limestone are capped by subaerial exposure surfaces or terrigenous-clastic facies of either nonmarine or shallow-marine origin. Using lithostratigraphic correlation to a biostratigraphically well-known section in the Manzanita Mountains (Myers, 1988), Wiberg and Smith (1993) demonstrate that 15 cycles in the lower Madera Formation correlate to the same number of cycles, with a similar stacking pattern of thickness and interpreted relative paleobathymmetry, in the midcontinent and elsewhere. Inter-regional correlation implies a dominant eustatic control on cycle development, despite proximity to upland source areas for clastic sediment and a complex tectonic setting.

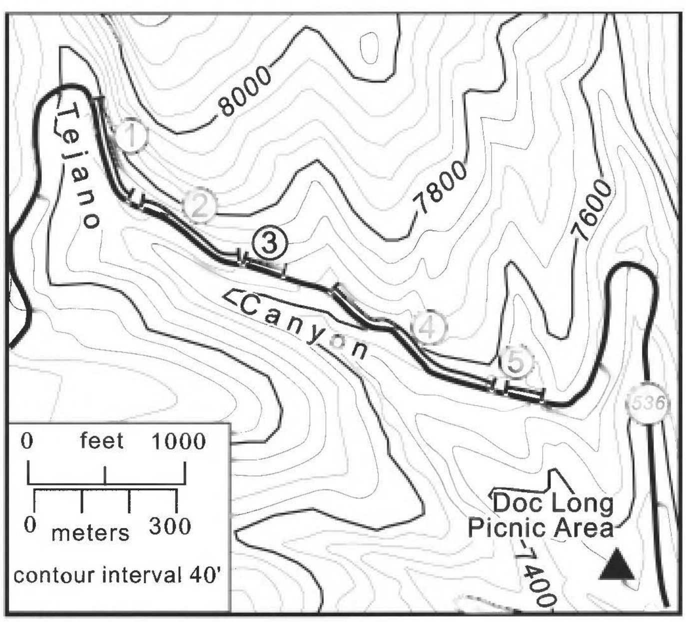

FIGURE 2. Topographic map of Tejano Canyon showing location of the five roadcut sections along state highway 536.

STUDY SITE

Tejano Canyon is a prominent drainage on the eastern dip slope of the Sandia Mountains, and road cuts there along state highway 536 provide exposure of about 300 m of east-dipping Pennsylvanian section (Fig. 2). The ~1-km-long stretch of roadcuts trends nearly parallel to structural dip. The approximately 300 m of strata are nearly 100% exposed except for local colluvial cover. The section is, however, incomplete and discontinuous because of fault interruptions. Correlations of strata across these faults are not possible, suggesting that the faults produce apparent omission of section along the line of exposure provided by the roadcuts. Broad correlations suggest that the Tejano Canyon roadcut section includes 37 m of the Sandia Formation, 38 m of the gray limestone member of the Madera Formation, and 225 m of upper arkosic limestone member. The section is described in 5 segments separated by faults or covered intervals (Figs. 3–7). The Tejano Canyon section, therefore, is not a complete stratigraphic section through Pennsylvanian strata nor can most of it be correlated in detail to other localities. These deficiencies, however, do not limit the ability to use the excellent roadcut outcrops, unmatched to in exposed stratigraphic thickness anywhere else in northern New Mexico, to evaluate the nature of limestone-clastic cycles.

METHODOLOGY

Standard stratigraphic section measurement and petrographic methods were employed in this study. All sections (Figs. 3–7) were initially measured using a tape and with a descriptive graphic log drawn at a scale of 1:100. Selected intervals were redescribed with a graphic log drawn at a scale of 1:40 including most of section 2 (Fig. 4) and about half of section 4 (Fig. 6). Greater attention was given to intervals containing intimately interbedded limestone and clastic facies rather than those dominated by limestone. Limestones were classified according to the scheme of Dunham (1962). Twenty-seven thin sections of sandstones and 38 of limestones were examined. Nine grainstone and three sandstone thin sections were stained with Alizarin Red S and KFeCN to facilitate identification of ferroan calcite, which stains blue-purple in this mixture.

FACIES AND DEPOSITIONAL ENVIRONMENTS

Facies, defined on the basis of field descriptions after the sections were completed, are summarized in Table 1. Facies identifiers are assigned for convenience in identifying the facies in Figures 3–7. Depositional interpretations for each facies are provided in Table 1 and in Figures 3–7 and require little further discussion.

Clastic facies are assigned to either marine or nonmarine environments primarily on the presence of fossils. Shale and siltstone facies ($s) containing only macerated plant matter and no obvious marine invertebrates may represent nearshore lagoons or estuaries of intermediate environmental classification. Most sandstones with marine fossils (Sfx, Sfl) represent deposition at sites of energetic waves or currents on the shoreface, in tidal channels or, where gradational with underlying nonmarine sandstones (Sx), in estuaries. The importance of waves is illustrated not only by the rarity of tidal indicators but by the well developed ravinement surfaces (syn. transgressive surfaces of erosion; labeled on Figs. 3–7). Thin, typically graded, sandstone beds and lenses within limestones suggest offshore transport by storm waves and

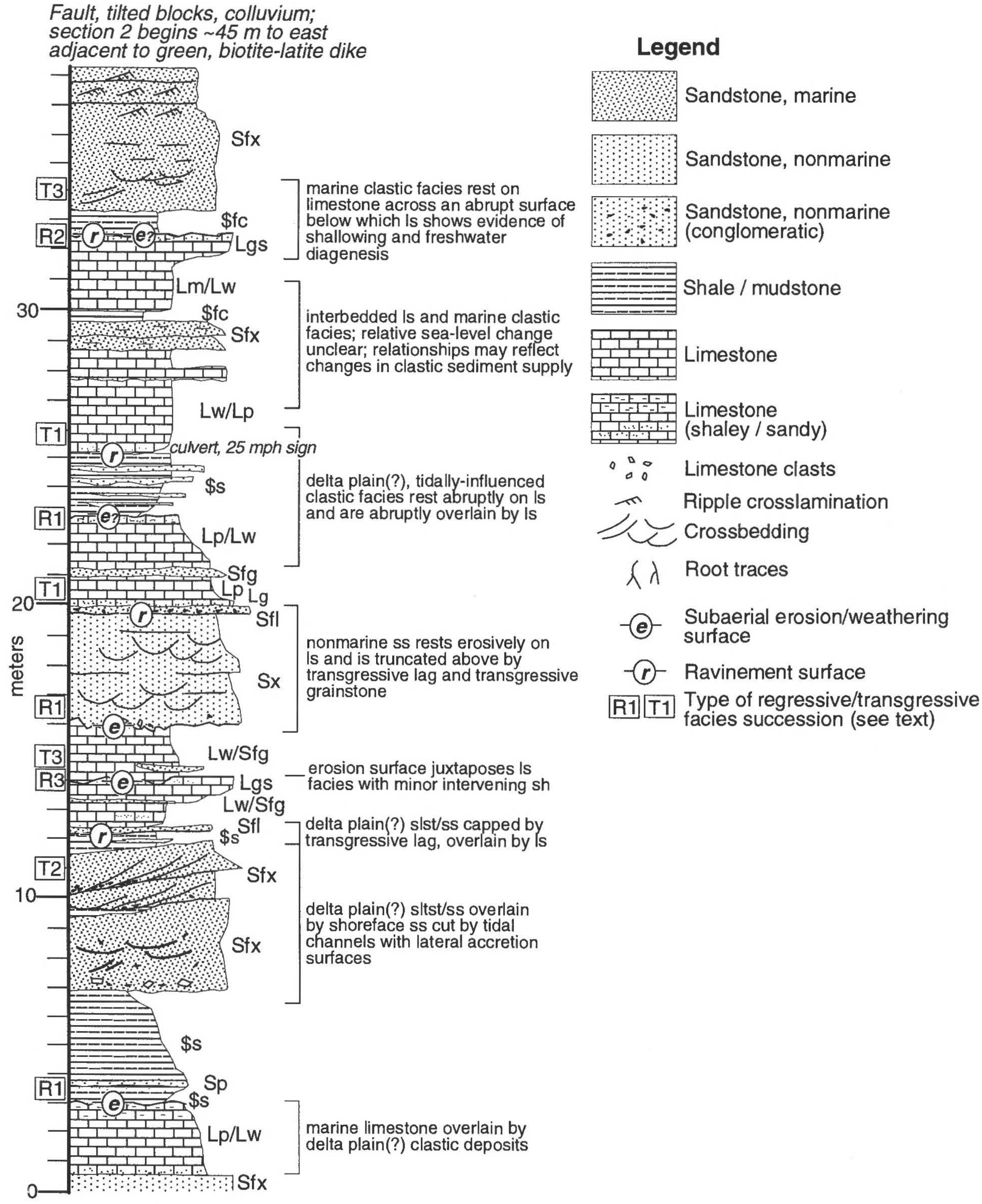

FIGURE 3. Section 1, in the Sandia Formation. See Table 1 for facies definitions and text for discussion of the nature and origin of different types of regressive and transgressive transitions.

currents (Sfg). Nonmarine sandstones, typically as amalgamated channels (Sx), represent fluvial processes, probably on a coastal delta plain, given association with finer facies containing arguable evidence of tidal influence ($s). Braided stream deposition is suggested by high width:depth ratios of channels (>15:1), lack of lateral-accretion surfaces, dominance of plane lamination and scour-fill stratification and paucity of floodplain deposits.

Depositional environments for limestones are interpreted on the basis of hydraulics implied by the proportion of lime mud (micrite) that is present. Grainstones (Lg, Lgs) represent limey facies deposited above wave base, principally along shorefaces starved of clastic sediment or, less commonly, formed offshore shoals. Progressively muddier facies (Lp, Lw, Lm) represent less energetic environments with lime mudstone (Lm) also recording environments of likely lower productivity of invertebrate macrofauna. Common upward progression from mudstone, through packstone and wackestone to grainstone, suggests progressive shallowing on a gently sloping ramp (cf. Heckel, 1994; Wiberg and Smith, 1993). No obvious intertidal carbonate facies, such as those containing tidal laminites, fenestral porosity, or primary dolomite, were identified.

DIAGENESIS

Though detailed investigation of diagenetic features or patterns was not undertaken, some observations from petrographic study are noteworthy for interpreting the section. Longman (1980) demonstrated the utility of petrographic features to interpret diagenetic histories of lime-

TABLE 1. Summary of Facies in Pennsylvanian Strata in Tejano Canyon, Sandia Mountains, New Mexico.

Facies-Identified	Facies Description	Field characteristics	Fossils	Petrographic characteristics	Depositional interpretation
Sfx	Sandstone; fossiliferous; cross-bedded, plane bedded, massive	Med. to crs. sand; trough, planar, or low-angle cross-bedding, less commonly massive or plane laminated; tan or gray; fossiliferous	Common brachiopods, crinoids, bivalves, bryozoans; less comm on rugose coral, fusulinids,ostracodes	Arkosic to quartz-rich; fossil content as high as 30%; highly compacted (sutured grain boundaries, deformed mica, pressure-solution penetration of quartz grains into fossils); 10–30% calcite	Mostly shoreface deposits; one locality includes lateral-accretion surfaces suggesting deposition in tidal channels Where found gradationally overlying facies Sx and below ravinement surface may represent delta-front or estuarine deposits.
Sfg	Sandstone; fossiliferous; graded bedding	Fine to med. sand; typically massive but normally graded; thin (1–10 cm) with sharp, locally erosive, base and abrupt top; tan or gray; enclosed in limestone or calcareous shale	Variable; where present, disarticulated brachiopods and crinoids are most common	Arkosic to quartz rich; slight to extensive calcite cementation/replacement	Storm beds deposited near or below storm wave base
Sfl	Sandstone; fossiliferous, lag deposit	Poorly sorted med. to crs. sand, with granules; 1–20 cm thick; tan or gray; black phosphatic peloids; generally sharp base and top; tabular and continuous; found at facies transitions between shale or sandstone lacking marine fossils and very fossiliferous calcareous shale or limestone	Brachiopods, crinoids, bivalves, gastropods, fusulinids, ostracodes, and rare fish skeletal fragments	Quartz-rich, highly compacted with minor ferroan calcite cement and local hydroxyapatite cement (or pseudomatrix?) and as much as 40% calcite replacement of framework grains. Some specimens contain marked concentrations of heavy minerals (zircon, magnetite)	Transgressive lags and condensed sections deposited on ravinement surfaces
Sx	Sandstone; non- to very sparsely fossiliferous; cross-bedded or massive	Poorly sorted, med. to crs. sand, commonly with pebbles to 3 cm; tan; trough crossbedded, low-angle crossbedded, or, less commonly, massive; scour surfaces and erosional bases, local shale partings	Rare carbonized plant fragments and woody impressions; very rare, highly abraded brachiopod shells and crinoid ossicles	Arkosic, generally highly compacted with illite, chlorite and minor calcite cement; pebbles are most commonly bull quartz and megacrystic microcline, also numerous limestone clasts	Nonmarine sandstone deposited in fluvial channels, possibly delta distributaries. Presence of intrabasinal clasts suggests that channels rest erosively on marine facies updip
Sp	Sandstone, non- or very sparsely fossiliferous; plane laminated	Fine-grained micaceous sandstone; horizontal laminations with rare burrows; most commonly tan to green brown but red in some cases	Rare, carbonized plant fragments	Arkosic to quartz rich; generally highly compacted with illite, chlorite and minor calcite cement	Nonmarine sandstone deposited on floodplains or in interdistributary lagoons during floods
$fc	Shale, sparsely fossiliferous; calcareous	Fissile shale, black or dark gray; clay rich, calcareous; typically a sharp base and gradational top to facies Lm	Brachiopods, articulated crinoid ossicles (in some cases approaching 1 cm in dia.); bryozoans	(Not examined petrographically)	Offshore-ramp deposits below wave base in areas of limited carbonate production because of water depth or terrigenous clastic sediment input
$s	Shale, silty and sandy with rare, or no, marine fossils	Fissile shale, gray to black, with flaser to lenticular bedded tan siltstone and fine sandstone, rare bipolar ripple cross laminations; carbonaceous, coaly; ferruginous staining, locally pyritic	Rare, highly macerated plant fragments and small ostracodes	Silty fine sandstones are quartzose, highly compacted with illitic and chloritic cement and as much as 15% calcite replacement of framework grains	Interdistributary lagoons or bays with salinity conditions inappropriate for diverse marine taxa; tidal influence
Mm	Mudstone, massive	Massive, commonly blocky-jointed mudstone; calcareous root traces and burrows; drab green or red	Plant fragments	(Not examined petrographically)	Paleosols developed on floodplains or exposure surfaces

TABLE 1. (cont.)

Facies-Identified	Facies Description	Field characteristics	Fossils	Petrographic characteristics	Depositional interpretation
Sfx	Sandstone; fossiliferous; cross-bedded, plane bedded, massive	Med. to crs. sand; trough, planar, or low-angle cross-bedding, less commonly massive or plane laminated; tan or gray; fossiliferous	Common brachiopods, crinoids, bivalves, bryozoans; less comm on rugose coral, fusulinids,ostracodes	Arkosic to quartz-rich; fossil content as high as 30%; highly compacted (sutured grain boundaries, deformed mica, pressure-solution penetration of quartz grains into fossils); 10–30% calcite	Mostly shoreface deposits; one locality includes lateral-accretion surfaces suggesting deposition in tidal channels Where found gradationally overlying facies Sx and below ravinement surface may represent delta-front or estuarine deposits.
Lgs	Limestone, grainstone, sparry; massive	Highly fossiliferous spar-rich grainstone; oolitic coatings on fossils; usually in thick massive beds; uncommon exhibiting planar, trough or low-angle crossbeds	Brachiopods, crinoids, bivalves and gastropods (commonly only as casts), bryozoans, fusulinids, trilobites, ostracodes; generally disarticulated and broken except for some brachiopods, ostracodes and gastropods	Little or no compaction, 5–10% terrigenous-clastic grains. Fossils and peloids surrounded by thin isopachous, commonly oolitic, rims of marine calcite cement; remaining pore space filled with coarse-grained, nonferroan sparry calcite of presumed meteoric-phreatic origin. Rare micritic meniscus and pedant cement of meteoric-vadose origin. Some beds capped by 2–10 mm laminar crusts of micritic calcite, ferruginous material and chert of pedogenic origin	Shallow-water skeletal shoreface deposits deposited above fairweather wave base. Cementation by dominantly fresh water prior to compaction and evidence for subaerial exposure in some beds suggests deposition during regression and diagenesis during exposure.
Lg	Limestone, grainstone (generally lacking obvious sparry cement)	Highly fossiliferous, thin (typically <20 cm), fissile to crenulated limestone	Brachiopods, crinoids, fusulinids, ostracodes, strongly crushed molds of molluscs, rare fish-bone or scale fragments	Highly compacted, stylolitic grainstone composed of fossils, peloids, rare grapestone, squashed phosphatic grains, and <15% terrigeneous clastic grains. Minor to extensive rims of microcrystalline marine calcite cement. In rare cases where porosity was not completely occluded by compaction, late-stage ferroan calcite spar cement is present.	Shallow-water, wave agitated limestone deposited nearshore or, less commonly, as offshore shoals. Cementation mostly by marine cement followed by compaction before subsequent exposure to meteoric water
Lp	Limestone, packstone; massive with lenses or layers of grainstone	Sparsely to highly fossiliferous; massive or thick bedded with irregular layers of grainstone and sandstone Sfg); may contain prominent (burrow mottling	Brachiopods, crinoids, bryozoans, rugose corals, rare fusulinids and trilobite fragments	Most fossils oriented parallel to bedding; shells are bored but generally lack oolitic rims; micritic matrix locally recrystallized to microspar; some beds contain peloids and streaks of organic matter or, rarely, phosphatic grains; grainstone layers compacted and stylolitic with little or no cement	Deposition on shallow ramp below fairweather wave base; grainstone and sandstone layers likely record storms including offshore transport of shoreline clastics
Lw	Limestone, wackestone, massive	Sparsely fossiliferous, massive wackestone to packstone; may be burrow mottled	Brachiopods, crinoids, bryozoans, ostracodes, gastropods, sponge spicules, phylloid algae	Fossils randomly oriented or oriented parallel to bedding; shells are bored but generally lack oolitic rims; micritic matrix locally recrystallized to microspar where overlain by nonmarine clastics	Deposition on shallow ramp below storm wave base or in protected nearshore lagoon (less likely with presence of diverse marine fauna)
Lm	Limestone, lime mudstone (micrite)	Gray to black limestone with rare fossils and peloids; rare chert nodules; pronounced diagenetic bedding (cf. Bathurst, 1987)	Rare; partially articulated crinoids, sponge spicules, brachiopods, ostracodes	Micritic texture with local neomorphic microspar; stylolitic zones with concentrations of organic matter, peloids	Deposition on outer ramp at depths beyond those optimal for most taxa

stones. Heckel (1983) applied these arguments to interpreting the relative roles of marine and meteoric waters in the diagenesis of limestones in midcontinent cyclothems. Although not supported by rigorous geochemical analyses, the same approach was taken in this study and provided consistent interpretations. The key features of the Longman (1980) and Heckel (1983) petrographic scheme are outlined in Table 2. Sparry calcite is characteristic of both meteoric-phreatic and deep-burial cements. The two may be distinguished with some confidence, however, by noting the relationship between timing of cementation and compaction and also the iron content of the cement (Table 2). Marine-phreatic cements, in contrast, are commonly cloudy, bladed or micritic isopachous rims on allochems. Although meteoric-vadose calcite can

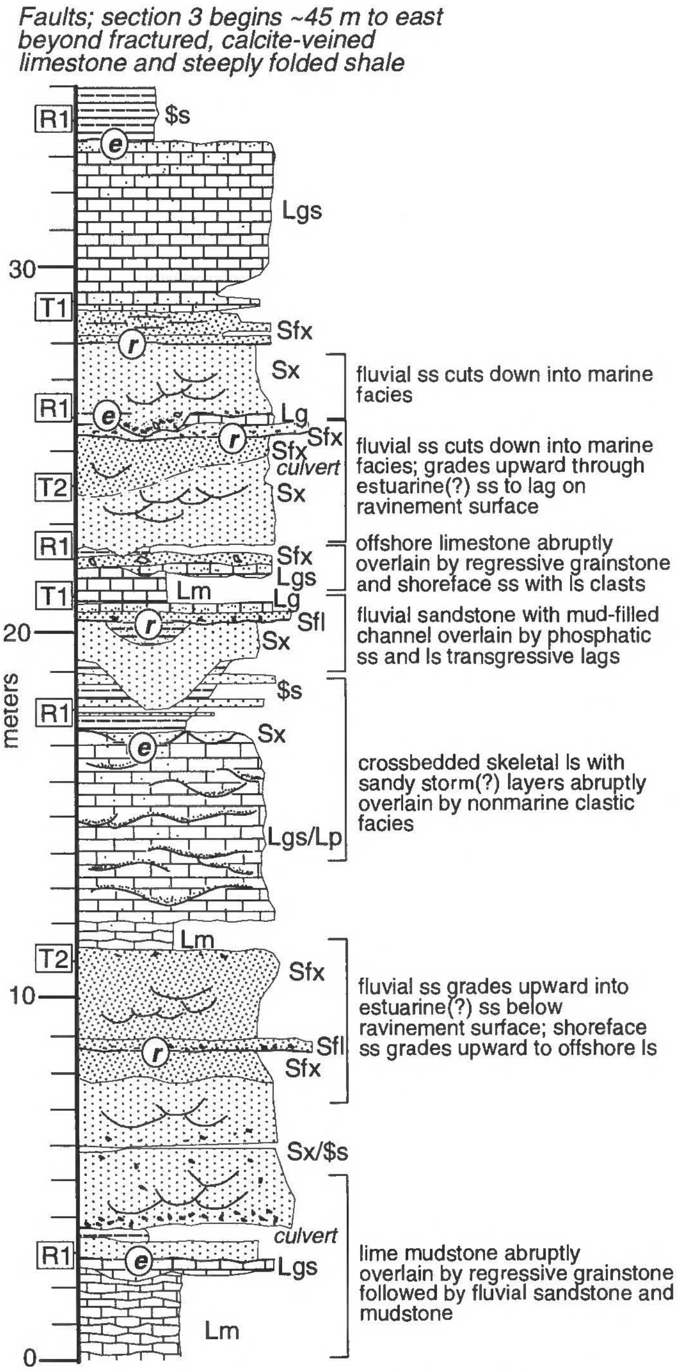

FIGURE 4. Section 2, in the gray limestone member of the Madera Formation. Symbols as in Figure 3.

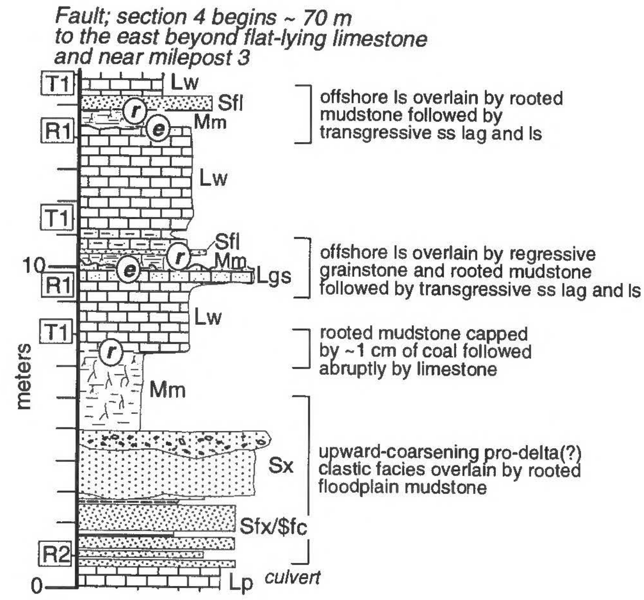

FIGURE 5. Section 3, in the arkosic limestone member of the Madera Formation. Symbols as in Figure 3.

be similarly fine grained, this cement is typically distributed as meniscus films and in pendant forms that distinguish it from early marine cement.

The approach of Heckel (1983) is especially enlightening for petrographic study of grainstones, which may be deposited in shallow water during either rise or fall of eustatic sea level. In both cases, Madera Formation grainstones typically consist of abraded allochems rimmed with early marine cement. Those at the top of upward-shallowing successions are notably sparry in outcrop (Lgs) and are observed in thin section to be composed of >30% coarse clear spar that fills all pore spaces between the widely spaced allochems suggesting final cementation, prior to compaction, by influx of fresh water (Fig. 8a). Transgressive grainstones at the base of such successions are, in contrast, highly compacted (Lg), giving a crenulated or fissile appearance that is petrographically seen to result from extensive pressure solution. Allochems feature rims of early marine cement but with little or no additional pore-filling cement (Fig. 8b); where present, such cement is a post-compaction, usually ferroan, calcite spar consistent with precipitation from late-stage cementation by deep-burial fluids.

Sandstone cementation varies according to depositional environment. Petrographically examined sandstones have a highly compacted fabric demonstrated by (1) pressure-solution contacts between quartz grains and between quartz grains and carbonate allochems, (2) fractured feldspars, and (3) mica grains that are strongly deformed at contacts with adjacent grains. Nonmarine sandstones commonly contain illite and chlorite, rare quartz or feldspar overgrowths, and typically less than 10% calcite as replacement of feldspar. Marine sandstones share the

Table 2. Summary of calcite cement types and environments represented in Pennsylvanian limestones, Tejano Canyon, Sandia Mountains, New Mexico (after Longman, 1981 and Heckel, 1983)

Hydrological environment	Cement composition	Cement texture
Marine-phreatic ("early marine")	High-Mg calcite (micritic or radial bladed), nonferroan	isopachous, preceding compaction
Meteoric-phreatic	Low-Mg calcite (spar), nonferroan	isopachous and/or porefilling coarse, clear spar
Meteoric-vadose	Low-Mg calcite (micritic or microcrystalline), nonferroan or ferroan	meniscus, pendant; may form laminar crusts; linings around irregularly shaped root pores.
Deep-burial connate	Low-Mg calcite (spar), ferroan	isopachous and/or porefilling coarse, clear or cloudy spar, post-dating development of compactional fabric.

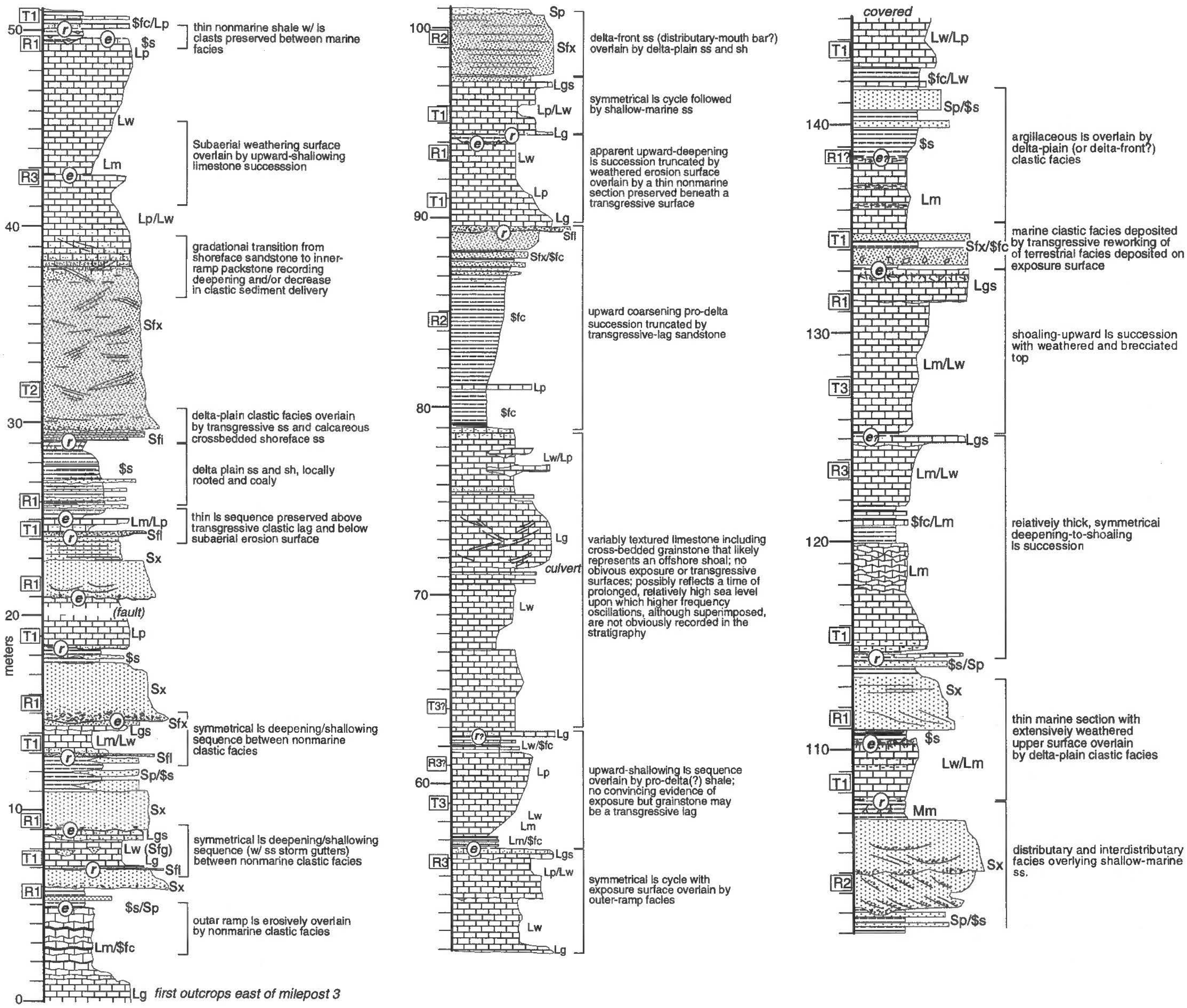

FIGURE 6. Section 4, in the arkosic limestone member of the Madera Formation. Symbols as in Figure 3.

compacted fabric but generally lack significant clay and contain 10-30% calcite spar that is clearly replacive and postdates compaction. In two stained thin sections, this spar is ferroan calcite. The source of calcite in the marine sandstone is likely internal to the sandstone beds, because (1) if the source was external it would likely have caused similar large-scale replacement in adjacent nonmarine sandstones and (2) there is no known viable transport mechanism for introducing significant amounts of dissolved calcium carbonate into a sandstone (Walderhaug and Bjørkum, 1998). The same marine sandstones contain 10–30% carbonate fossils. It is likely that the calcite in these sandstones is derived from dissolution of fossils during compaction, inferring that some of these "sandstones" originally contained as much as 50% carbonate fossils and were on the cusp of being called calcareous sandstones or arenaceous limestones.

TYPES AND ORIGINS OF CYCLES

The Pennsylvanian strata at Tejano Canyon consist of a highly varied and intimately interbedded assemblage of lithofacies that do not follow one another in a repetitive fashion (Figs. 3–7). Nonetheless, it is possible to identify transitions between nonmarine and marine facies, ravinement surfaces, and subaerial erosion/weathering surfaces that record the shifting shorelines that are ubiquitous in upper Paleozoic strata worldwide. Although lithofacies cyclicity, in the strict sense, is not present, transgressive-regressive cycles can be recognized (e.g., Fig. 9) and their origins, in turn, addressed. Twenty-nine such transgressive-regressive cycles are interpreted. Some transgressive-regressive cycles are only about 1 m thick (e.g., at 21 m in section 2, Fig. 4). In other cases, fluvial sandstone rests on erosional surfaces that all but remove intervening marine facies (e.g., 25 m in section 2, Fig. 4). Thin regressive grainstones and even thinner (10–30 cm) transgressive-lag facies are important to interpreting cycle origins (Fig. 10). These thin intervals, essential to interpreting the stratigraphy, are rarely exposed in natural outcrops on the Sandia Mountains dipslope.

Type 1 regression: nonmarine clastic facies resting on subtidal limestone

Most (64%) upward transitions from marine to nonmarine strata place nonmarine rocks, most commonly sandstone, erosively upon limestone.

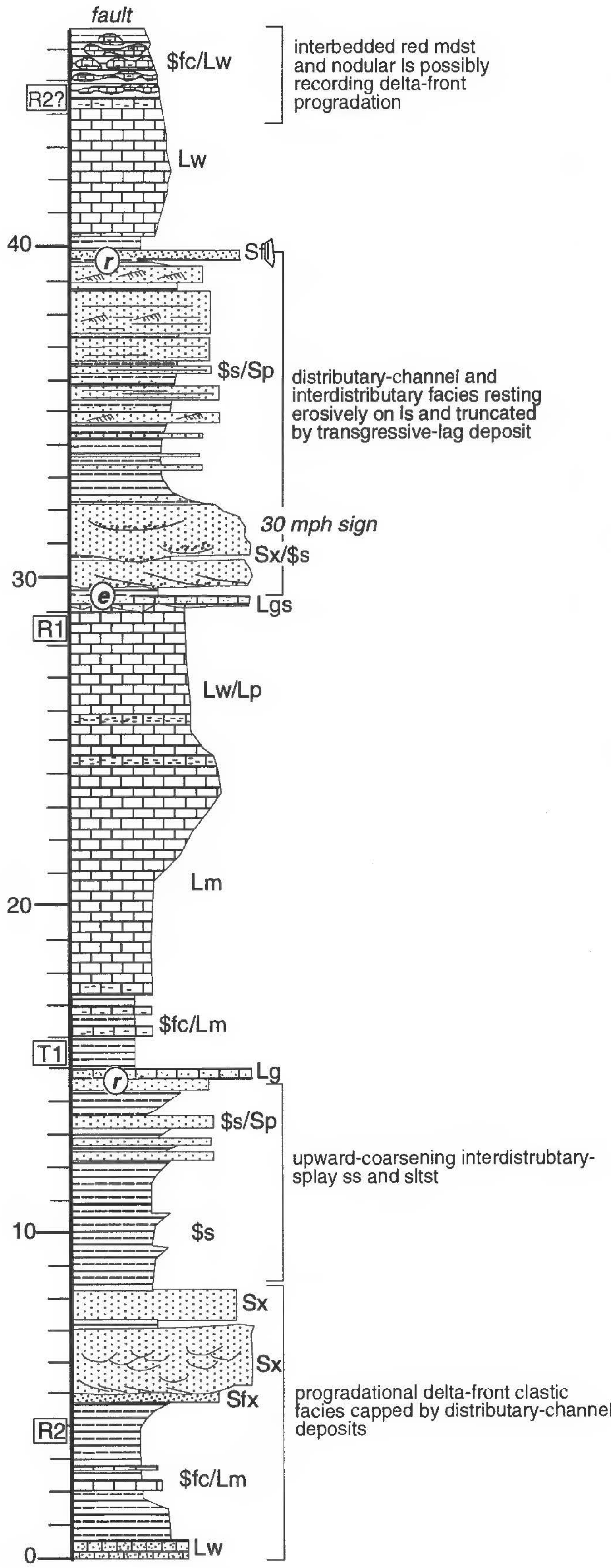

FIGURE 7. Section 5, in the arkosic limestone member of the Madera Formation. Symbols as in Figure 3.

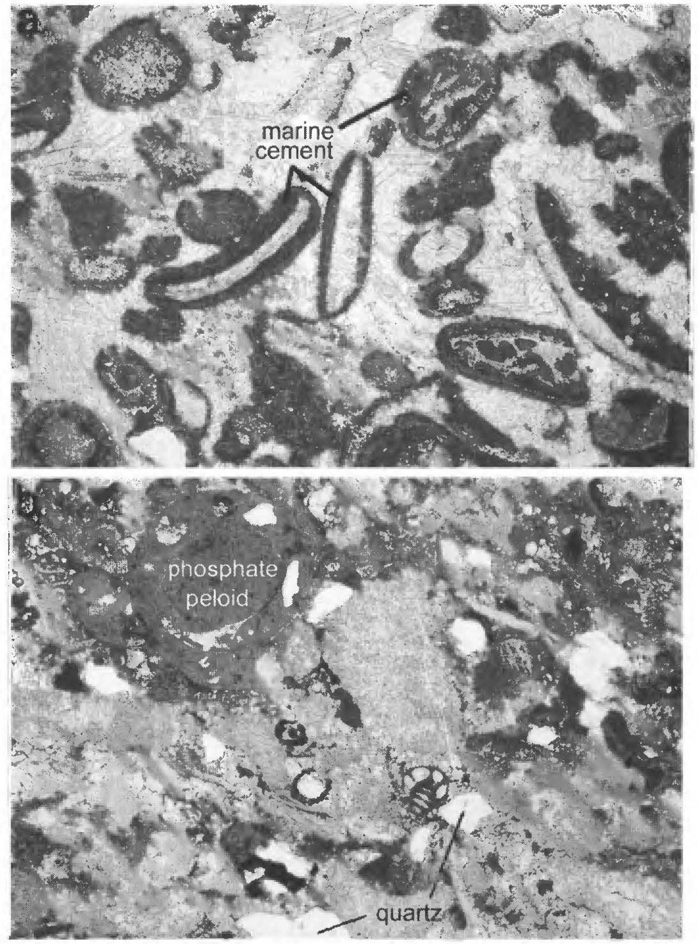

FIGURE 8. Photomicrographs (each 3.5 mm across) of contrasting compaction and cementation in grainstones. **a,** A regressive grainstone (collected at 14.2 m in section 4, Fig. 6) showing widely spaced (noncompacted) fossil fragments rimmed with oolitic and abraded, micritic marine-calcite cement and dominant, pore-filling sparry calcite of interpreted meteoric-phreatic origin. **b,** Transgressive grainstone (collected at 20.8 m in section 4, Fig. 6) showing highly compacted fabric of fossil fragments (mostly from echinoderms), detrital quartz grains and phosphatic peloids.

In about half of these situations, limestone below the erosional surface typically coarsens upward, usually very abruptly, from wackestone to grainstone or packstone within less than 1 m of the contact, consistent with shoaling conditions, but intertidal facies are notably absent. The remainder of the transitions place nonmarine facies abruptly on offshore limestone; shallower-water grainstones may have been present but eroded away. The uppermost regressive grainstone, where present, exhibits extensive evidence of meteoric diagenesis in the form of phreatic sparry cement and, in some cases, vadose cement and root traces.

Some variations are appropriately grouped with this type of facies transition. In one case (32 m in section 1, Fig. 3) marine clastic rocks rest on an upward-shallowing limestone succession that exhibits evidence of early freshwater diagenesis. This suggests exposure and then subsequent removal during transgression of whatever nonmarine deposits, if any, may have been deposited on top of the limestone. In other cases (e.g., 22 m in section 2, Fig. 4) a thin (<0.50 m) interval of marine sandstone is found on top of the regressive grainstone and below the nonmarine clastic facies. Marine sandstone, in this and similar stratigraphic positions elsewhere in the section, contains abundant limestone clasts suggesting up-dip exposure and erosion of marine facies.

Type 1 regressions are most consistent with a drop in relative sea level (Fig. 11). Although thin intertidal limestones may have been erod-

FIGURE 9. Outcrop expression of transgressive-regressive cycles between 16 and 29 m in section 4 (Fig. 6). Nonmarine clastic facies ($s, Sx) are sandwiched between marine limestone in the lower part of the view; sandstone (Sfl) and grainstone (Lg) transgressive lags are present at the top of the clastic interval. The middle limestone is capped by a regressive grainstone (Lgs) and erosively overlain by a distributary-channel sandstone (Sx), which grades upward, along a channel-form transition, into estuarine(?) sandstone (Sfx). Limestone deposited on top of this sandstone (24.5 m, Fig. 6) was largely eroded away prior to deposition of the uppermost nonmarine sandstone (Sx).

ed away, their absence in all cases suggests that carbonate deposition did not fill all available accommodation space. Likewise, the near absence of marine clastic facies, and their thinness when present, argue against a marine to nonmarine transition by simple progradation of a clastic shoreline and, instead, forced regression (Posamentier et al., 1992) by sea level fall.

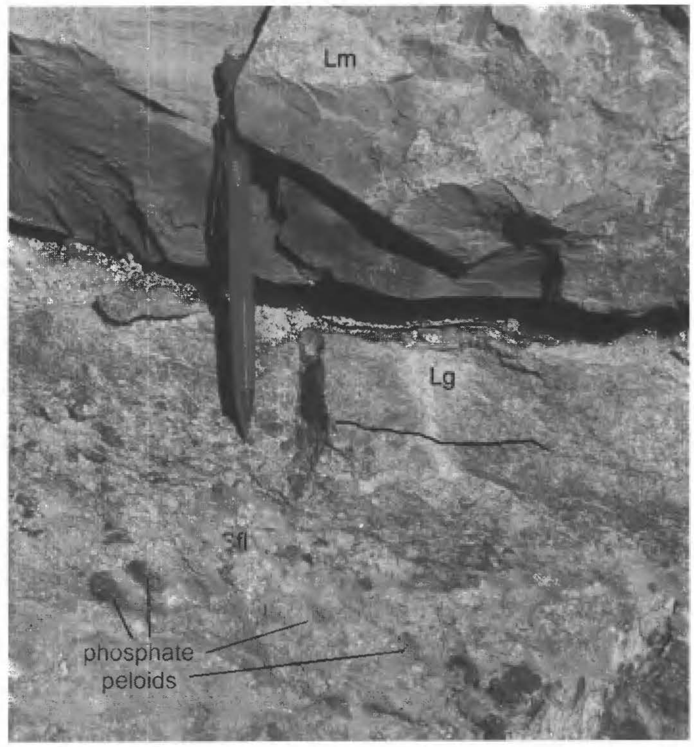

FIGURE 10. Close view of transgressive surface in a type 1 transgressive interval at 20.5 m in section 4 (Fig. 6). The transgressive-sandstone lag with prominent phosphatic nodules (Sfl, seen here in bedding plane view) overlies a ravinement surface that truncates diverse delta-plain facies (Fig. 6). The overlying, thin transgressive limestone, illustrated in Figure 8b, is highly compacted and also contains phosphate. The overlying micritic limestone (Lm) records relatively deep outer-ramp facies deposited during transgression or at high stand.

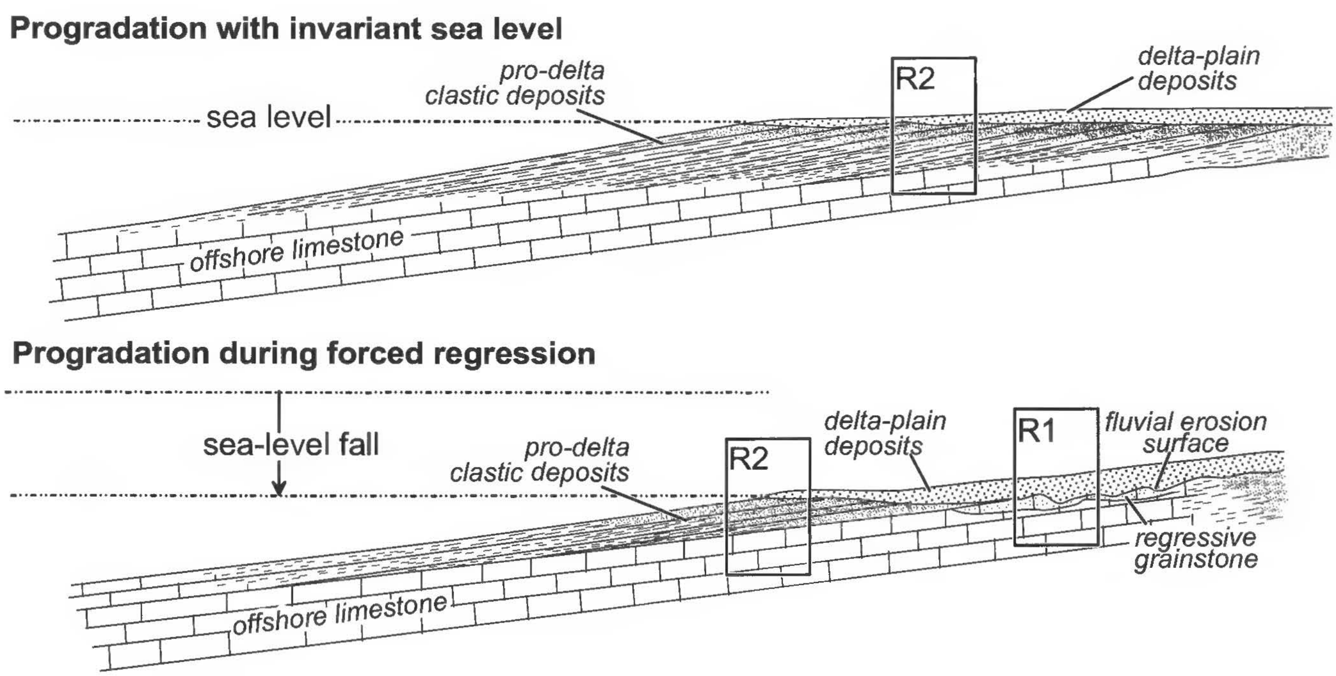

FIGURE 11. Schematic illustrations of limestone-clastic transitions during regression with or without sea-level change and sites of type 1 (R1) and type 2 (R2) regressive facies successions. Gradation of limestone to upward-coarsening marine clastic facies (R2) suggests shoreline progradation, which may or may not accompany sea level fall. Juxtaposition of subtidal limestone and fluvial sandstone (R1) does require sea-level fall, which may also account for the common presence of an erosional regressive grainstone in such successions. This type of regressive facies succession is most common (64%) at Tejano Canyon. R2 facies successions produced by forced regressions will be relatively thin, compared to those produced by high-stand progradation, and will occupy positions generally farther seaward of the average coastline position. Thus, R2 successions at Tejano Canyon, which are 4–10 m thick and found in a limestone-dominated, and hence generally deeper water, part of the section are likely also produced by sea-level fall.

Type 2 regression: upward coarsening clastic sequence above limestone

Limestone can be succeeded by upward coarsening shale and sandstone, with sparse marine fossils, that could represent progradation of a delta front (e.g., 79–89 m in section 4). The progradation of a clastic delta front may have been induced by sea-level fall but autogenic abandonment of a distributary and avulsion to a new position on a delta plain can cause abrupt progradation of clastic sediment into a nearshore environment that previously featured clear-water carbonate productivity (Fig. 12; cf., Ferm, 1970). Thinner successions (1–5 m in section 3, 0–5 m in section 5) may also record a prograding delta. The paucity of offshore shale and thinness of the clastic interval suggest, however, introduction of clastic sediment into a site of diminished accommodation space during relative sea-level fall. Type 2 regressions are recorded primarily in the limestone-dominated, and likely overall deeper water, part of the section, where preservation of progradational clastic facies during sea-level fall would be more likely (Fig. 11).

Type 3 regression: subaerial exposure surface within subtidal limestones

Most regressions recorded at Tejano Canyon feature placement of clastic facies above limestone, but some intervals (e.g., 40–65 m of section 4, Fig. 6) feature stacked successions of upward-shallowing, subtidal limestone. In most cases, cycles are capped by grainstone (± minor clastic rocks) resting with a distinct erosional contact on an underlying wackestone. This regressive grainstone exhibits evidence of meteoric diagenesis in the form of phreatic sparry cement and, in some cases, vadose cement, root traces, and laminar calcite and silica crusts of likely pedogenic origin.

These subaerially exposed subtidal limestones, comparable to those well known from the literature of carbonate cycles (James, 1984), are interpreted to result from a drop in relative sea level. The absence of intertidal facies, but evidence of freshwater diagenesis and exposure, indicate that carbonate-sediment production did not fill all available accommodation space. Erosion of intertidal facies is unlikely both because pedogenic crusts are preserved in some cases and because one would not expect erosion to have completely removed those facies in every cycle.

Type 1 transgression: abrupt transition from nonmarine clastic facies to marine limestone

Most nonmarine clastic facies are abruptly terminated by a ravinement surface and succeeded by marine limestone. A thin transgressive

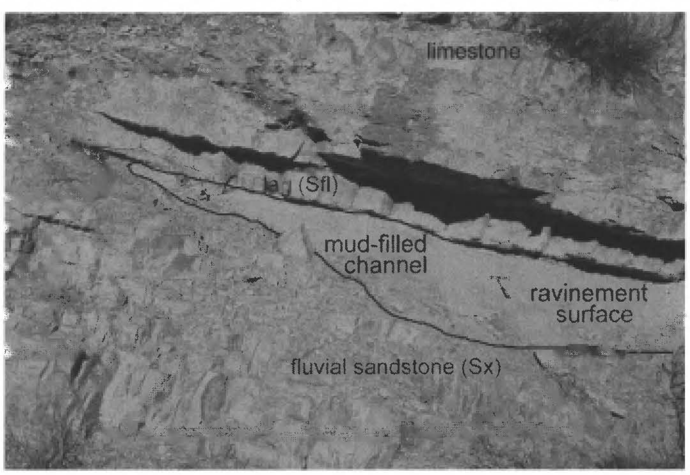

FIGURE 12. View of mud-filled channel within a fluvial-clastic interval (Sx) at 20.5 m in section 4 (Fig. 6). The muddy deposit underlies the ravinement surface, overlain by a transgressive-lag (Sfl) and marine limestone. Deposition of the muddy channel fill may record stagnation of flow as base level rose during sea-level rise.

sandstone (Sfl) is commonly present but otherwise there are no marine clastic facies. The transgressive lag commonly consists of a pebbly sandstone (Sfl) and overlying grainstone (Lg), with a combined thickness generally less than 20 cm (Fig. 10). Both facies commonly contain phosphatic peloids (Figs. 8b, 10) and concentrations of heavy minerals. Transgressive grainstone is typically overlain by lime mudstone (Lm) or wackestone (Lw) forming the base of another upward-shallowing succession. The maximum flooding surface can be equated with a position within or at the top of the transgressive grainstone. The thinness of transgressive deposits is typical of wave-dominated coastlines where shoreface erosion, rather than deposition, dominates during transgression.

A particularly notable transgressive interval of this type is located at 20 m in section 2 (Figs. 4, 12). A paired transgressive sandstone and grainstone lag deposit truncates fluvial channels, one of which is filled with green mudstone, rather than sand. This relationship is consistent with muddy backfilling and abandonment of a channel as base level rose during transgression.

Type 1 transgressions record shoreline retreat by wave erosion. An abrupt rise in sea level is not required for such a transition. A shift in a clastic-sediment point source (e.g., delta-lobe switch) or decrease in volume of clastic sediment caused by changing runoff or sediment-load conditions can lead to transgression on a wave-dominated coastline as long as accommodation space is being generated by subsidence, sediment compaction, or eustatic rise in sea level, which may also have been persistent throughout part or all of the period of prior progradation.

Type 2 transgression: gradation from nonmarine to marine sandstone

Some transgressions at Tejano Canyon are marked by relatively thick successions of marine clastic facies resting on nonmarine facies or, rarely, subaerial erosion/weathering surfaces. The upward transition from clastic facies to limestone clearly does not represent the onset of transgression, although it would be reasonable, in most circumstances, to place the maximum flooding surface at this transition.

The best examples of this type of transition are in section 2 (at about 8 and 24 m; Fig. 4) where nonmarine sandstone (Sx) grades abruptly upward into marine sandstone of similar texture (Sfx). The transition appears to, at least partly, follow the base of a channel-form scour surface comparable to those within the nonmarine sandstone (Fig. 9). The calcareous, fossiliferous sandstone either contains, or is truncated by a transgressive lag (Sfl) and is overlain by limestone or additional marine sandstone.

These transgressive intervals are consistent with deposition during marine flooding of distributary channels to form estuaries. Transgressive lags and ravinement surfaces are present within the marine sandstone indicating that marine conditions were established prior to shoreface retreat over the location of the section, implying backflooding of channels. As with type 1 transgressions, such a succession of facies does not require relative sea-level rise coincident with the onset of transgression. The differences between the two types do suggest, however, a more persistent filling of available accommodation space by clastic sediment during type 2 transgressions.

Type 3 transgression: limestone or marine shale deposited on exposed limestone

Within the limestone-dominated part of the section containing type 3 regressive successions, transgressive intervals likewise lack significant clastic sediment. Subaerial exposure surfaces developed on subtidal limestone are overlain abruptly by offshore lime mudstone, wackestone, or calcareous shale marking renewed marine flooding. Thin transgressive limestone lag deposits are sometimes present. Transgressive transitions of this type, although not common at Tejano Canyon, require relative sea-level rise (eustatic rise, increased subsidence, or both) because there had not been any prior sediment delivery, or in-situ sediment production, whose rate could be decreased to account for shoreline retrogradation.

Alluvial sedimentation during regression or transgression?

Nonmarine sandstone most commonly rests in direct and erosive contact on subtidal limestone (type 1 regressive successions), suggesting erosion during base-level fall; aggradation, however, may not have occurred until the onset of the next transgression. Type 2 transgressive successions imply transition from nonmarine to marine sedimentation during transgression, which may have been initiated prior to deposition of some or all of the nonmarine facies. Relative sea-level rise also causes base-level rise and provides a mechanism for aggradation of fluvial channels near sea level. As sea level continues to rise, the relative rates of sea-level rise and influx of detrital sediment will determine the shoreline dynamics. In the case of type 1 transgressive successions, fluvial aggradation may have been driven, or enhanced, by base-level rise accompanying a relative sea-level change but sediment supply was unable to keep up with that rise. In one case, an abandoned, mud-filled channel is preserved beneath the ravinement surface (Fig. 12). Type 2 transgressions could, then, be interpreted as conditions where sand influx continued during sea-level rise, partially filling estuaries, but was unsuccessful at maintaining or prograding the shoreline position. In fact, evidence of extensive clastic shoreline aggradation/progradation during sea-level rise or highstand is lacking at Tejano Canyon and may only be recorded by the few type 2 regressive intervals.

CONCLUSIONS

The Pennsylvanian section exposed in Tejano Canyon records diverse shallow-marine and coastal/delta-plain environments, locally featuring either carbonate or clastic sedimentation, responding to changing sea levels. Except where complicated by offshore-shoal or storm facies, most limestone-dominated intervals consist of cyclic repetitions of facies forming either symmetrical or asymmetrical transgressive-regressive successions.

The lack of true overall facies cyclicity in the section is driven primarily by the processes related to deposition of the clastic facies. Upward-shallowing limestone successions are not generally stacked on top of one another, but are separated by clastic deposits whose internal facies succession is not simply repeated from one transgressive-regressive cycle to the next. The variable depths of erosion at the base of nonmarine intervals and the amount of the underlying limestone succession that has been removed introduce further complexity. The cause of strictly "noncyclic" facies successions, depends, therefore, on the locations of principal river systems, the stability of their deltas, the volume and caliber of sediment supplied by them and the extent of channel incision and planation during sea-level lowstands. These parameters determine depth of incision and extent of clastic sediment delivery at a site as sea-level fall drives progradation, and how the clastic coastal plain/delta plain, if established, will respond during subsequent transgression.

Given that transgressive-regressive cycle variation is largely driven by the nature of the clastic-sediment influx and erosion at the base of fluvial and distributary channels, considerable lateral variation in cycle expression should be expected. Wiberg and Smith (1993) demonstrated this for the lower part of the Desmoinesian section in the Sandia Mountains. Strata in section 2 at Tejano Canyon (Fig. 4) are correlative to sections lacking nonmarine clastic facies elsewhere in the Sandia Mountains. Only sections located immediately down depositional dip to the west of Tejano Canyon contain any sandstone at all, and these are thin marine lags and sand sheets. These sandstones are interpreted to represent transgressive reworking of fluvial-channel sand preserved beneath transgressive deposits at Tejano Canyon (Wiberg and Smith, 1993).

The apparent complexity of the Tejano Canyon "cycles" is reduced if emphasis is placed on identifying the stratigraphic signatures of regression and transgression rather than focusing on repetitive facies patterns, which are virtually nonexistent. Although some gross aspects of the stratigraphy aid in identifying transgressive and regressive intervals (e.g., upward coarsening/shoaling limestone facies, alternations of marine and nonmarine sandstones) relatively small features are critical to proper identification of cycle boundaries and interpretations of their origins. Ravinement surfaces and associated thin lag deposits are generally not exposed on adjacent hillslopes, nor are weathered limestone horizons or cycles <3-m thick, although these features play an important role in interpreting the roadcut sections.

A strong case can be made that the cyclicity in the Tejano Canyon section is driven by relative sea-level fluctuations, rather than by autogenic processes. Most transgressive facies successions are, objectively and cautiously, ambiguous with regard to driving mechanism. The overwhelming majority of regressional transitions, however, exhibit compelling evidence for subaerial exposure of subtidal limestone facies that require relative sea-level fall (Fig. 11, bottom). The question, then, is whether eustasy or tectonics drove these fluctuations in accommodation. In the absence of a known tectonic mechanism to produce alternating subsidence and uplift at the temporal scale suggested by Madera Formation cycles (100s of ky; Wiberg and Smith, 1993) and with contemporaneous glaciation in Gondwana widely accepted, a eustatic origin is more strongly suggested.

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