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EUSTATIC AND TECTONIC CONTROLS ON CYCLIC SEDIMENT ACCUMULATION PATTERNS IN LOWER-MIDDLE PENNSYLVANIAN STRATA OF THE OROGRANDE BASIN, NEW MEXICO

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Abstract—The Lower-Middle Pennsylvanian Gobbler Formation and equivalent units of southern New Mexico is a 250–450-m-thick succession of shallow-marine sediments composed, in part, of 20–25 carbonate shoaling cycles. Cycle tops show evidence of subaerial exposure and meteoric diagenesis, including karstic solution pits, brecciation, cemented and oxidized crusts, and isotopic depletion of carbon in the rock matrix. Basinwide correlatability of cycles, exposure of cycle tops in both shelfal and basinal sequences, and average periodicities of 100,000–200,000 yrs implicate high-frequency, high-amplitude Carboniferous glacio-eustatic sea-level fluctuations as the primary control on cycle development. Cycle sets comprising five to seven cycles that alternate between shale- and carbonate-rich compositions record a ca. 1.0 Ma oscillation that represents a longer-period eustatic or tectonic cycle. These Lower-Middle Pennsylvanian strata were deposited during initial subsidence of the Orogrande Basin, a north-trending intracratonic trough formed during the Ouachita-Marathon orogeny. The broad western (Robledo) ramp was tectonically stable, while the narrow eastern (Sacramento) shelf exhibited considerable relief along a fault-bounded shelf margin and intrashelf graben. Structural features controlled sedimentation patterns on the eastern shelf, which is characterized by rapid lateral and vertical facies changes, variable cycle thicknesses, shelf-margin progradation, and development of phylloid-algal bioherms. Cycle thicknesses vary systematically across the basin from 6 m on the western ramp to 9 m on the eastern shelf, reflecting differential rates of subsidence.

INTRODUCTION

Lower and Middle Pennsylvanian strata in south-central New Mexico comprise a 250–450-m-thick, cyclic shallow-marine succession known as the Gobbler Formation in the Sacramento Mountains and the Lead Camp Limestone in the San Andres Mountains. These strata were deposited in the Orogrande Basin, an intracratonic trough formed through segmentation of the southwestern margin of the North American craton during the Permo-Carboniferous Ouachita-Marathon orogeny. The basin was bounded by a high-relief, faulted eastern shelf and a low-relief, flexural western ramp, and thus exhibited a fundamental tectonic asymmetry that is reflected in basin-scale differences in lithofacies, patterns of cyclicity and subsidence rates. The goals of this paper are (1) to develop a basinwide cyclostratigraphy, establishing detailed correlations within which to study depositional and tectonic events of the Orogrande Basin in Middle Pennsylvanian time; (2) to examine the sedimentology of the Gobbler Formation, and in particular, contrast sequences from opposite margins of the Orogrande Basin; and (3) to discuss the relative importance of eustatic versus tectonic controls on Gobbler Formation cyclicity.

Regional stratigraphy

In southern New Mexico, a moderately thick (≤2500 m) Permo-Pennsylvanian intracratonic-basin succession overlies a thin (0–800 m) lower-middle Paleozoic passive-margin succession along a major Mississippian-Pennsylvanian unconformity (Fig. 1). Within the study area, the Gobbler Formation (Sacramento Mountains), Lead Camp Limestone (San Andres Mountains) and equivalent strata in the Hueco Mountains are composed of 50–125 m of shallow-marine crossbedded sandstones, shales and limestones of Atokan age, overlain by 175–325 m of shallow-marine and basinal limestones and marls of late Atokan and Desmoinesian age. Marine sedimentation persisted in the Orogrande Basin through Late Pennsylvanian time, but basin subsidence was terminated by regional uplift in the early Wolfcampian, and Permian sedimentation was largely restricted-marine and continental in character. For a detailed summary of the Paleozoic stratigraphy of southern New Mexico, see Kottlowski et al. (1956), Pray (1961), and Kottlowski (1963).

Regional paleogeography

This study includes eight stratigraphic sections in the San Andres and Sacramento Mountains of south-central New Mexico and in the Hueco Mountains of west Texas (Fig. 2). The Gobbler Formation and correlative units were deposited within the Orogrande Basin, a 200-

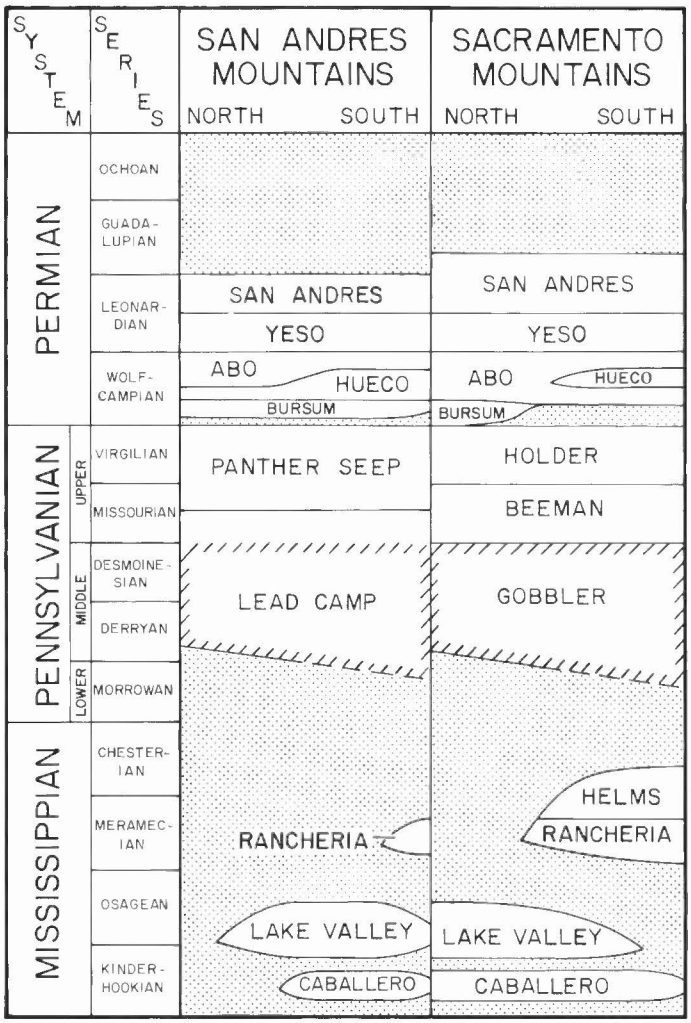


FIGURE 1. Permo-Carboniferous stratigraphy of the San Andres and Sacramento Mountains of southern New Mexico. Units included in this study are hachured. Data from Kottlowski et al. (1956), Pray (1961), Kottlowski (1963) and Bachman and Myers (1969).

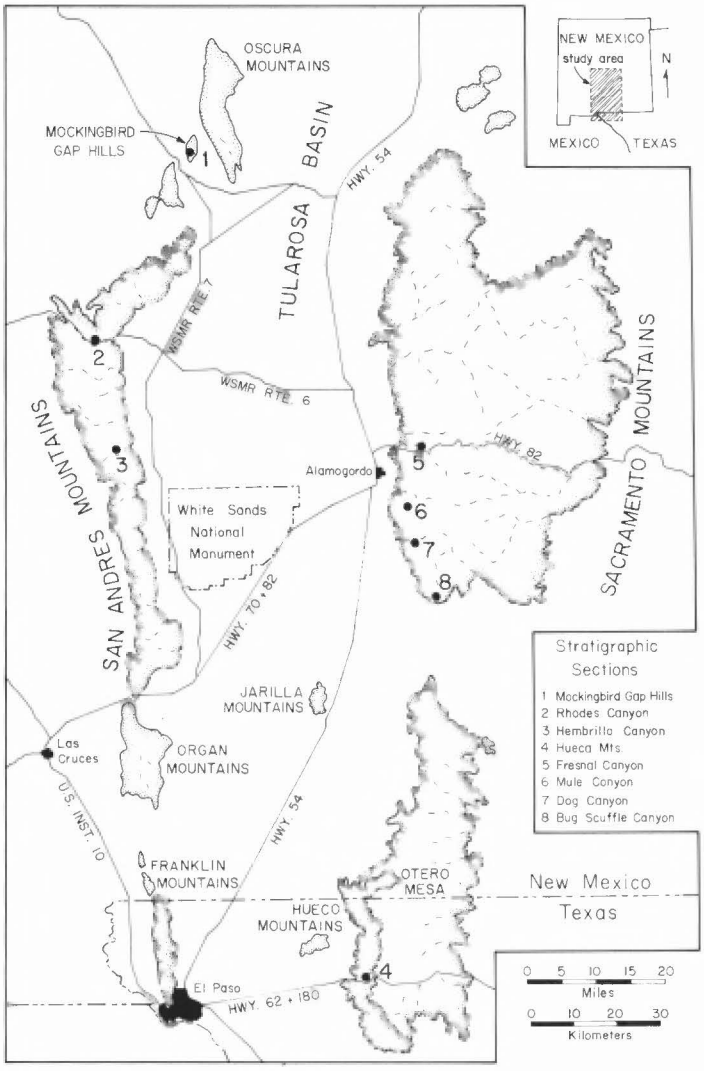


FIGURE 2. Location map for stratigraphic sections of the Gobbler Formation and equivalent units. New Mexico State Plane Coordinates: Mockingbird Gap Hills (37.16.5 N, 3.67.5 E), Rhodes Canyon (36.72.5 N, 3.46.0 E), Hembrillo Canyon (36.46.1 N, 3.48.2 E), Fresnal Canyon (36.45.6 N, 4.19.5 E), Mule Canyon (36.34.0 N, 4.14.3 E), Dog Canyon (36.25.0 N, 4.17.0 E), Bug Scuffle Canyon (36.10.7 N, 4.21.3 E); Hueco Mountains (31°51′ N, 106°02′ W). The Mockingbird Gap Hills, Rhodes Canyon, and Hembrillo Canyon sections are located on the White Sands Missile Range, and permission of the U.S. Army is required for access.

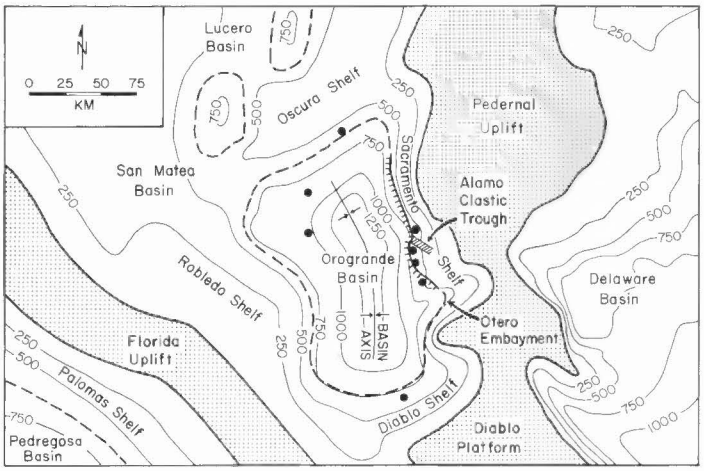


FIGURE 3. Outline map of the Orogrande Basin and vicinity. Pennsylvanian System isopachs are given in meters; areas of non-deposition are dotted. Study locales are shown as black dots. Data from Kottlowski (1963), Meyer (1966), and Wilson and Jordan (1988).

km-long intracratonic trough surrounded by highlands of the Pedernal uplift to the northeast, the Diablo platform to the southeast, and the Florida uplift to the southwest (Fig. 3; Kottlowski, 1963; Meyer, 1966). The basin was bounded on its western margin by the broad, low-relief Robledo ramp and on its eastern margin by the narrow, high-relief Sacramento shelf, which was divided into two tectonic blocks by the fault-bounded, intrashelf Alamo trough. The name Alamo trough is a new term introduced in this paper. The tectonic asymmetry of the basin is reflected in eastward displacement of its depositional axis (Fig. 3). The Orogrande Basin existed as a topographic feature from the Early Pennsylvanian through the Early Permian (end Wolfcampian).

Cyclostratigraphy and biostratigraphy

The Gobbler Formation and equivalent units are divisible into a 50–125-m-thick basal clastic unit overlain by a 175–325-m-thick carbonate unit (Figs. 4, 5). The latter comprises five cycle sets, each of which is 20–80 m in thickness and contains 4–7 shoaling-upward cycles (Fig. 6). Individual shoaling cycles are 3–20 m in thickness and grade upward from shaly and spiculitic deep-water marls to clean shallow-water limestones. Although the number and thickness of shoaling cycles in a given cycle set vary somewhat between study locales, cycle sets maintain a distinct identity across the basin, permitting correlation of sections on the western and eastern basin margins. Correlation of cycle sets is difficult only in the vicinity of the Alamo trough (e.g., Fresnal and Mule Canyon sections), which was tectonically active in Desmoinesian time and which locally altered shoaling patterns (Fig. 5).

Age assignments in Lower to Middle Pennsylvanian strata considered here are based largely on fusulinid biostratigraphy. In the San Andres Mountains, Kottlowski and others (1956) identified the Derryan (Atokan)-Desmoinesian contact based on first occurrence of *Fusulina* (now *Beedeina;* see Bachman and Myers, 1975) and the Desmoinesian-Missourian contact based on first occurrence of *Triticites* in their measured sections at Mockingbird Gap, Rhodes Canyon and Hembrillo Canyon. Although their Atokan-Desmoinesian contact appears to crosscut cycle boundaries (Fig. 4), it may be stratigraphically too high in the more basinal sections (e.g., Hembrillo Canyon), in which the paucity of *Beedeina* in shalier beds suggests facies control of fusulinid distribution.

In the Sacramento Mountains, age assignments for basal Gobbler Formation units are uncertain. Benne (1975) identified strata of Morrowan age in the southern part of the range based on conodonts and brachiopods, although Wilson (1989) observed Derryan (Atokan) fusulinids (e.g., *Profusulinella, Beedeina*) near the base of sections in both the northern and southern Sacramento Mountains. The Atokan-Desmoinesian contact falls within the first cycle set (Fig. 5) based on extrapolation of established contacts in the San Andres Mountains (Fig. 4). The contact between the lower and upper Desmoinesian Series is probably located within the third cycle set.

SEDIMENTOLOGY

Lithofacies

Shallow-marine units of the Gobbler Formation and equivalent units largely consist of fossil wackestones and packstones containing an open-marine biota, including echinoderms, bryozoans, brachiopods, phylloid algae, fusulinids, endothyrids, tubular foraminifera, rugose and tabulate corals, *Komia* (a small dendroid stromatoporoid), and *Chaetetes* (a sponge-like organism of uncertain affinity; Fig. 7A). Such muddy fossiliferous units are usually thick bedded and structureless owing to thorough bioturbation. Argillaceous mudstones and wackestones representing deeper-water conditions are dominant in basinal areas and as the basal units of shoaling-upward cycles (Fig. 7B). These units are dominated by an *in-situ* fauna composed of sponges and long-spined brachiopods. Widespread chertification probably reflects diagenetic re-

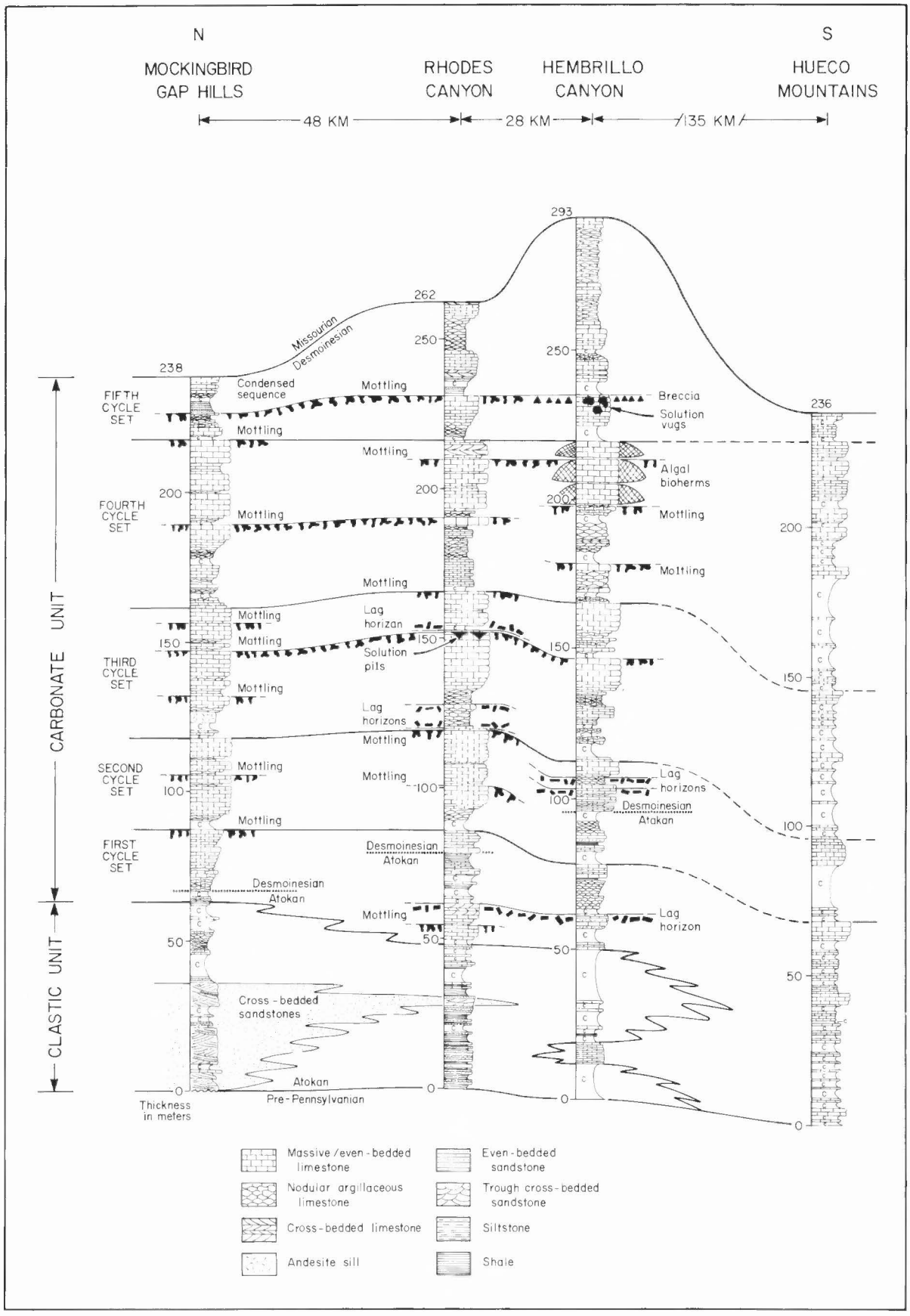


FIGURE 4. Stratigraphic cross section of the four study locales in the San Andres and Hueco Mountains. Correlations are based on two-level cycle hierarchy; position of Derryan (Atokan)-Desmoinesian and Desmoinesian-Missourian contacts are based on fusulinid biostratigraphy of Kottlowski et al. (1956). See Fig. 5 for cross-section location.

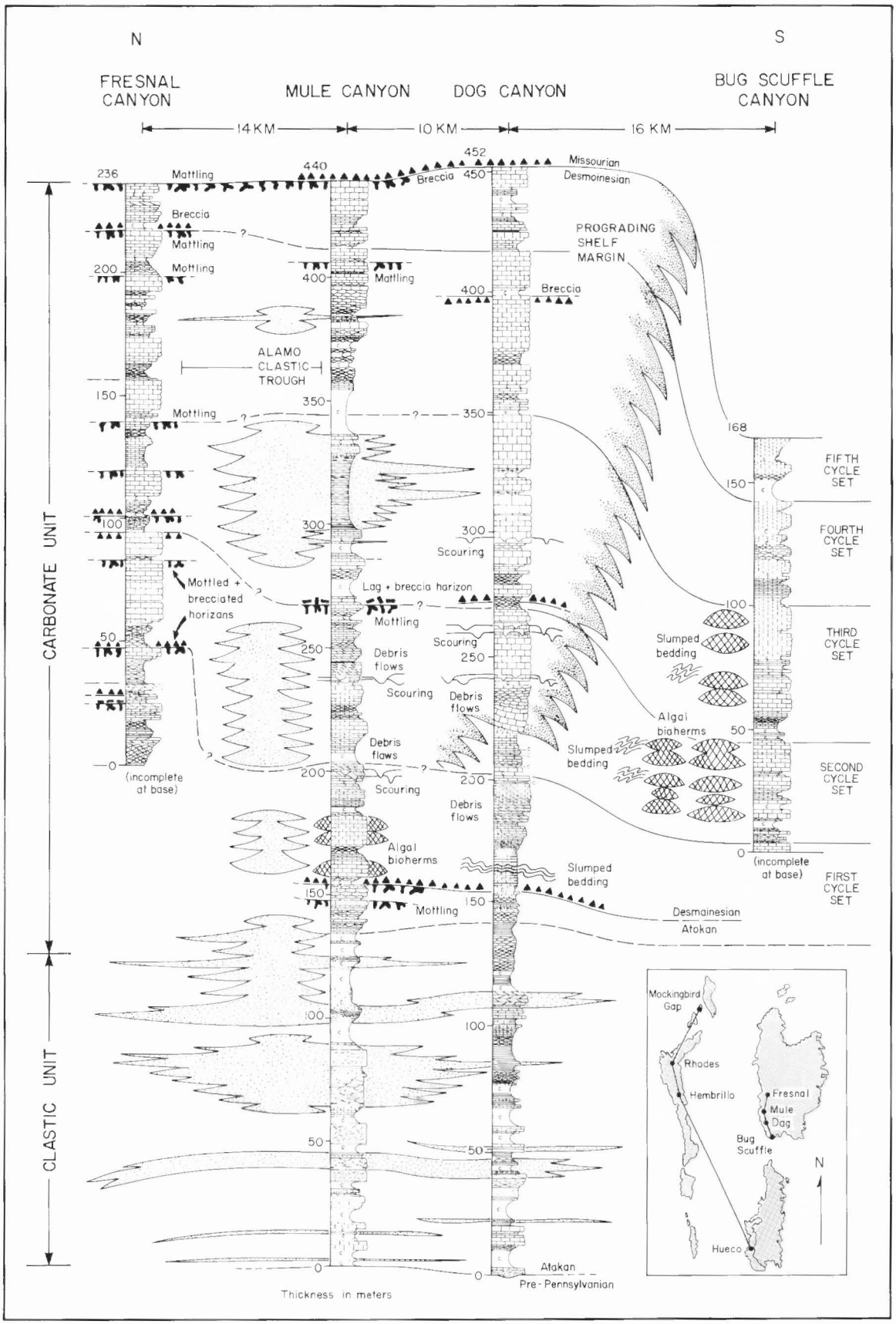


FIGURE 5. Stratigraphic cross section of the four study locales in the Sacramento Mountains. The lower part of the Gobbler Formation was not measured in the Fresnel and Bug Scuffle Canyon sections owing to incomplete exposure along fault escarpments. Correlations are based on two-level cycle hierarchy; approximate position of the Atokan-Desmoinesian contact within the first cycle set is extrapolated from the Mockingbird Gap Hills section (Fig. 4). Stratigraphic positions of Bug Scuffle bioherms (Algeo, 1989) and Alamo trough clastic units (Van Wagoner, 1977) are approximate.

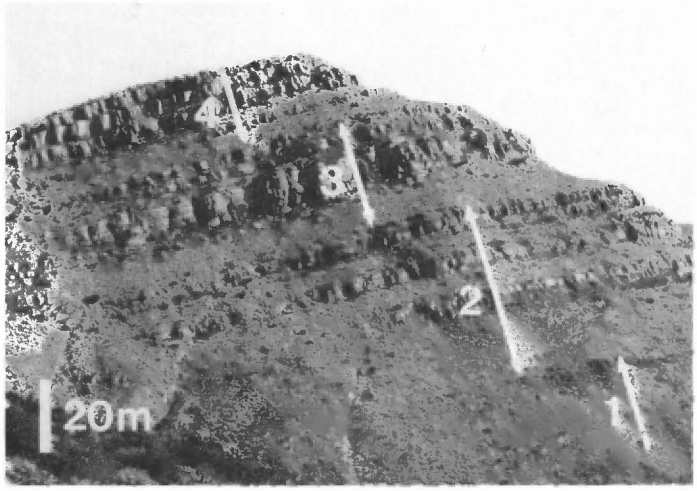


FIGURE 6. Two-level cycle hierarchy in the Mockingbird Gap Hills section. Cycle sets (numbered), each composed of 4–7 individual shoaling cycles, represent long-term (ca. 1.0 Ma) variation in the carbonate-to-shale accumulation ratio. Note decreasing shale content from base to top of each cycle set and overall upward decrease in shale content. Fifth cycle set not visible in photo. Outcrop scale for center of view.

mobilization of silica derived from abundant sponge spicules. Cross-bedded fossil grainstones exhibiting low-relief basal scouring are found in shallow-shelf areas at the top of shoaling-upward cycles (Fig. 7C).

Algal-plate wackestones and packstones occur widely as biostromal units and locally as low-relief (3–6 m) biohermal units within slope sequences. Bioherm growth was the result of *in-situ* baffling of sediment by dense thickets of benthic organisms. Core facies consist of massive units of unbroken phylloid algae (Fig. 7D), ramose bryozoa, and *Komia*, whereas flank facies are thin- to medium-bedded units of fossil wackestone and packstone containing abundant fragmented phylloid-algal debris.

Cyclicity and subaerial exposure

Shoaling-upward cycles are well developed at all study locales, range from 3 to 20 m in thickness, and comprise recessive marly bases grading upward to resistant limestone caps. Cycles are separated by sharp, disconformable surfaces exhibiting brecciation, karstic solution pits (Fig. 8A) and solution-enlarged joints (Fig. 8B), cemented or oxidized crusts (Figs. 8A, 8C), and/or diagenetically enhanced burrowed fabrics (Fig. 8D). These features are generally restricted to the uppermost few centimeters of each cycle and, collectively, demonstrate a recurrent genetic relationship between cycle tops and subaerial exposure.

Immediately overlying most exposure surfaces are centimeter-scale lag deposits of coarse-grained, echinoderm-rich fossil hash which contain an abundance of phosphatic grains, glauconite pellets and quartz sand typical of transgressive deposits on hiatial surfaces (Fig. 8C). Diagenetically enhanced burrowed fabrics, in which unsilicified burrows are encased in a silicified matrix, are the most ubiquitous cycle-top feature (Fig. 8D). Such fabrics are the product of early meteoric cementation of burrows, as a consequence of which later flux of silica-rich burial fluids downward from spiculitic basal sediments of the overlying cycle induced preferential silicification of the relatively more permeable interburrow matrix of the underlying cycle.

Carbon-isotopic evidence of meteoric diagenesis

Stable carbon isotopes demonstrate early meteoric diagenesis along cycle tops and provide additional evidence of subaerial exposure. About 400 carbon-isotopic analyses were run on matrix micrites, which were chosen for systematic analysis owing to the predominance of muddy lime facies in the Gobbler Formation and equivalents (see Given and Lohmann, 1986, for procedure). The Mockingbird Gap Hills section (see Bachman, 1968) was chosen for detailed analysis (n = 123) as its more landward location enhanced the probability of recording a meteoric-isotopic signature (Fig. 9). More limited isotopic analysis of other study locales showed carbon-isotopic patterns similar to that of the Mockingbird Gap Hills section (Algeo, 1989).

Most cycle tops exhibit ^{13}C depletion (Fig. 9), a characteristic feature of subaerially exposed carbonates on which soil horizons developed (Allan and Matthews, 1982; Lohmann, 1988). In such settings, isotopically light fluid carbon from soil-zone vegetation is released as CO_2 during organic decay, dissolves in downward percolating meteoric fluids, and becomes selectively incorporated in underlying limestones as meteoric cement. Although light carbon values occur predominantly at or just below the cycle tops, not all cycle-top samples yielded isotopically depleted carbon, owing to local variations in meteoric-fluid flux controlled by small-scale matrix heterogeneities (Fig. 9, inset).

In addition to cycle-top ^{13}C depletion, carbon isotopes exhibit progressively greater depletion toward the tops of cycle sets (Fig. 9). This suggests that shoaling cycles toward the tops of cycle sets were subjected to more prolonged subaerial exposure and, thus, that the elevation of sea-level lowstands varied cyclically through time. Petrographic evidence for subaerial exposure is generally strongest for those cycles exhibiting large isotopic depletions, and strongly altered cycle tops generally correlate well between sections. These observations suggest that variation in duration of subaerial exposure and degree of meteoric diagenesis existed from cycle to cycle.

SHELF-TO-BASIN SEDIMENTATION PATTERNS AND CONTROLS

Although correlation of cycle sets and, in some cases, individual shoaling-upward cycles is possible using a cycle hierarchy, considerable local variation exists in cycle composition and thickness. This variation reflects changes in depositional environments that are largely controlled by shelf-to-basin topography. Topographic relief on the eastern margin of the Orogrande Basin was developed along a fault-bounded shelf margin and intrashelf trough, whereas flexural subsidence of the western margin resulted in more uniform lithologies and greater lateral continuity of individual stratigraphic units.

Sacramento shelf structure

On the eastern margin of the Orogrande Basin, the Sacramento shelf was bounded by a north-south-trending fault and was divided into two independent tectonic blocks by the northwest-striking Alamo trough (Fig. 3). The shelf margin and intrashelf graben were probably bounded by high-angle faults having components of both normal and strike-slip motion, and fault movement appears to have occurred episodically during Desmoinesian time (Pray, 1961; Algeo, 1989). The Alamo trough, which was filled in part by terrigenous clastics derived from the Pedernal uplift, was markedly asymmetric and subsided more rapidly to the south as shown by sandstone isopach patterns, by rapid facies shifts from trough sandstones and deep-water limestones to shelf carbonates (Van Wagoner, 1977), and by frequent slumping and fining-upward grain flows along the southern margin (Fig. 5). Trough subsidence may have caused a mid-Desmoinesian deepening event recorded in the Fresnal and Mule Canyon sections, on the northern and southern margins of the trough, respectively, but not at the more distant Dog Canyon locale.

Shelf-to-basin sedimentation patterns

Eastern-shelf strata of the Fresnal, Mule and Dog Canyon sections are characterized by light-colored, massive wackestones and packstones and crossbedded grainstones, scoured contacts, laterally discontinuous units, irregular cycle thicknesses, and strongly developed exposure surfaces (Fig. 5). Rapid facies transitions occurred owing to changes in water depth and/or energy conditions in the shallow-marine environment. Resedimentation of shelf-margin material occurred through grain flows with channelized bases and through basinward-oriented debris flows, which developed by repeated slumping of the prograding Sacramento shelf margin along arcuate and sineform slump surfaces (Fig. 10A).

Slope strata, best exposed in the lower part of the carbonate unit at Dog Canyon, are characterized by thin-bedded calcitic turbidites inter-

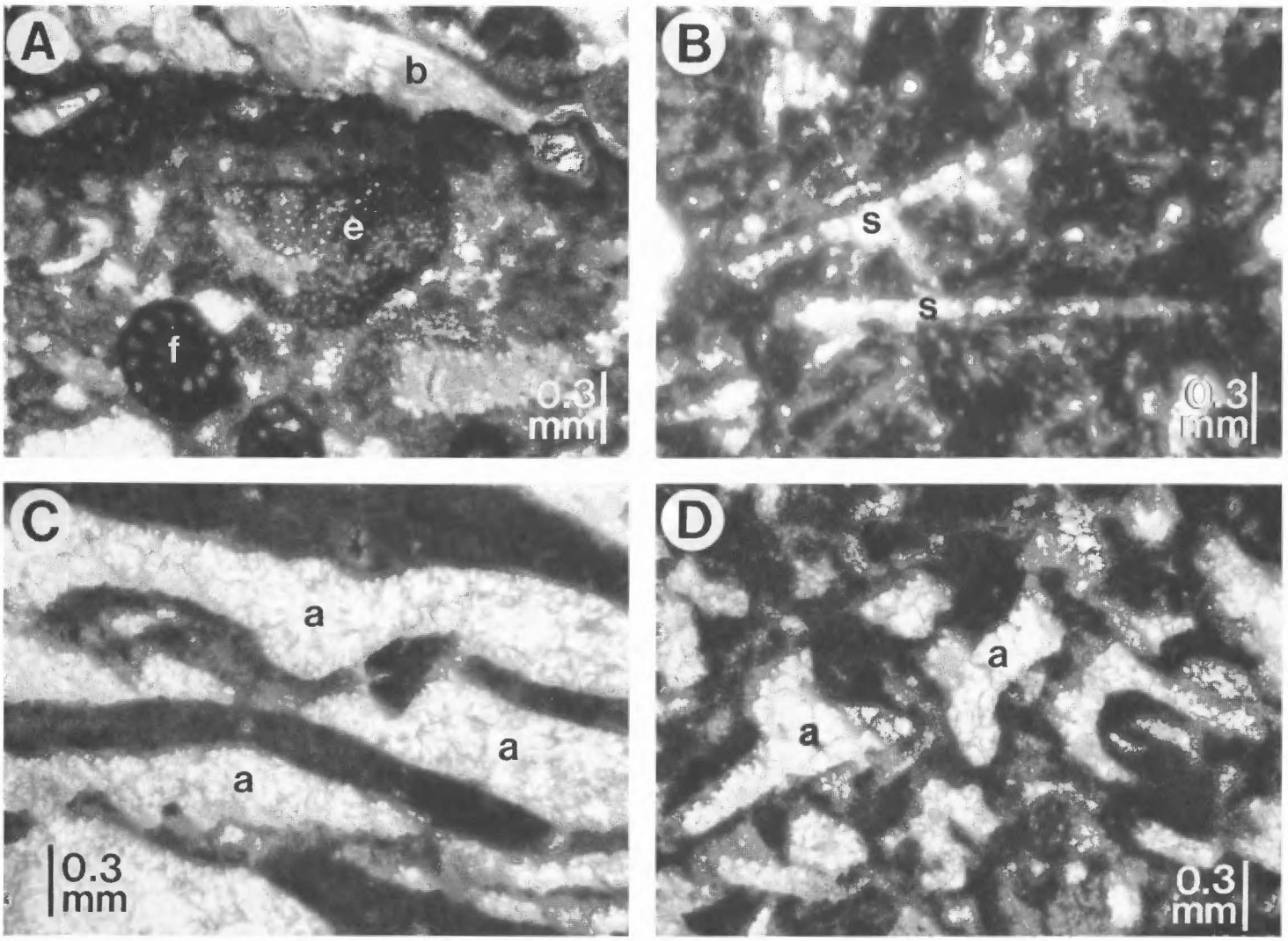


FIGURE 7. Microfacies of Lower-Middle Pennsylvanian strata, south-central New Mexico. A, Open-marine wackestone/packstone, shelf facies. B, Argillaceous spiculitic wackestone, shelf cycle-base and basinal facies. C, Whole algal plate wackestone/packstone, mound core facies. D, Fragmental algal plate wackestone/packstone, mound flank facies. a = phylloid alga (cement-filled mold); b = brachiopod; e = echinoderm; f = fusulinid; s = sponge spicule.

bedded with basinal shales, synsedimentary slumping (Fig. 10B), and phylloid-algal bioherms (Fig. 5). Such features are common downslope from carbonate shelf margins and suggest water depths from 100 to 600 m (Wilson, 1969). An exceptionally large algal bioherm between Ed and Bug Scuffle Canyons is 25 m wide, several hundred meters long and exhibits multiple growth stages (Fig. 10C). Core facies in this mound are massive beds of unbroken phylloid algae, bryozoa, and *Komia*. Proximal mound flanks are thick-bedded, steeply dipping (to 35°) units of fragmented phylloid-algal debris, which thin and flatten distally. Slump folds (Fig. 10D) and calcite-filled fractures formed through gliding along decollement surfaces parallel to bedding on steeply dipping mound flanks.

Basinal strata at Bug Scuffle Canyon are characterized by dark-colored, thin-bedded, cherty mudstones and wackestones, laterally continuous units, relatively uniform cycle thicknesses, and weakly developed cycle tops exhibiting limited evidence of subaerial exposure (Fig. 5). The prevalence of chert nodules and beds is probably due to abundant sponge growth in deeper water. Strata on the western ramp are characterized by open-marine carbonates exhibiting even bedding, regular cyclicity, and an absence of structures related to shallow-water sediment transport (Fig. 4). Lateral facies changes occur gradually over 75 km along strike, indicating only a slight increase in water depths at Hembrillo Canyon relative to the Mockingbird Gap Hills.

Progradation of Sacramento shelf margin

The Sacramento shelf margin actively prograded basinward during Desmoinesian time, passing southwestward through Dog and Ed Canyons but stopping short of Bug Scuffle Canyon (Fig. 11). Shelf-margin progradation is marked by superposition of shelf facies on slope and basinal facies along a scoured surface associated with basinward-oriented debris flows (Fig. 10A). The rate of shelf-margin progradation can be estimated based on the difference in stratigraphic elevation of the shelf-to-basin transition at Dog and Ed Canyons. The contact is 30 ± 5 m higher stratigraphically at the latter locale, which, at an average basinal sedimentation rate of 39 ± 6 m/Ma (see below), is equivalent to a time interval of 0.75 ± 0.25 Ma. Because the shelf margin did not prograde directly between these locales, the distance between them (9.5 km) must be reduced by the cosine of the angle (ca. 65°) between the sections and the direction of shelf progradation. Thus, the shelf margin prograded about 4.0 km in an interval of 0.75 ± 0.25 Ma, yielding an estimated progradation rate of 5.3 ± 2.0 km/Ma.

Basin subsidence and cycle thickness

Shoaling-upward cycles in the Gobbler and correlative formations show systematic variation in non-decompacted thicknesses across the basin, reflecting differential rates of sediment accumulation and basin

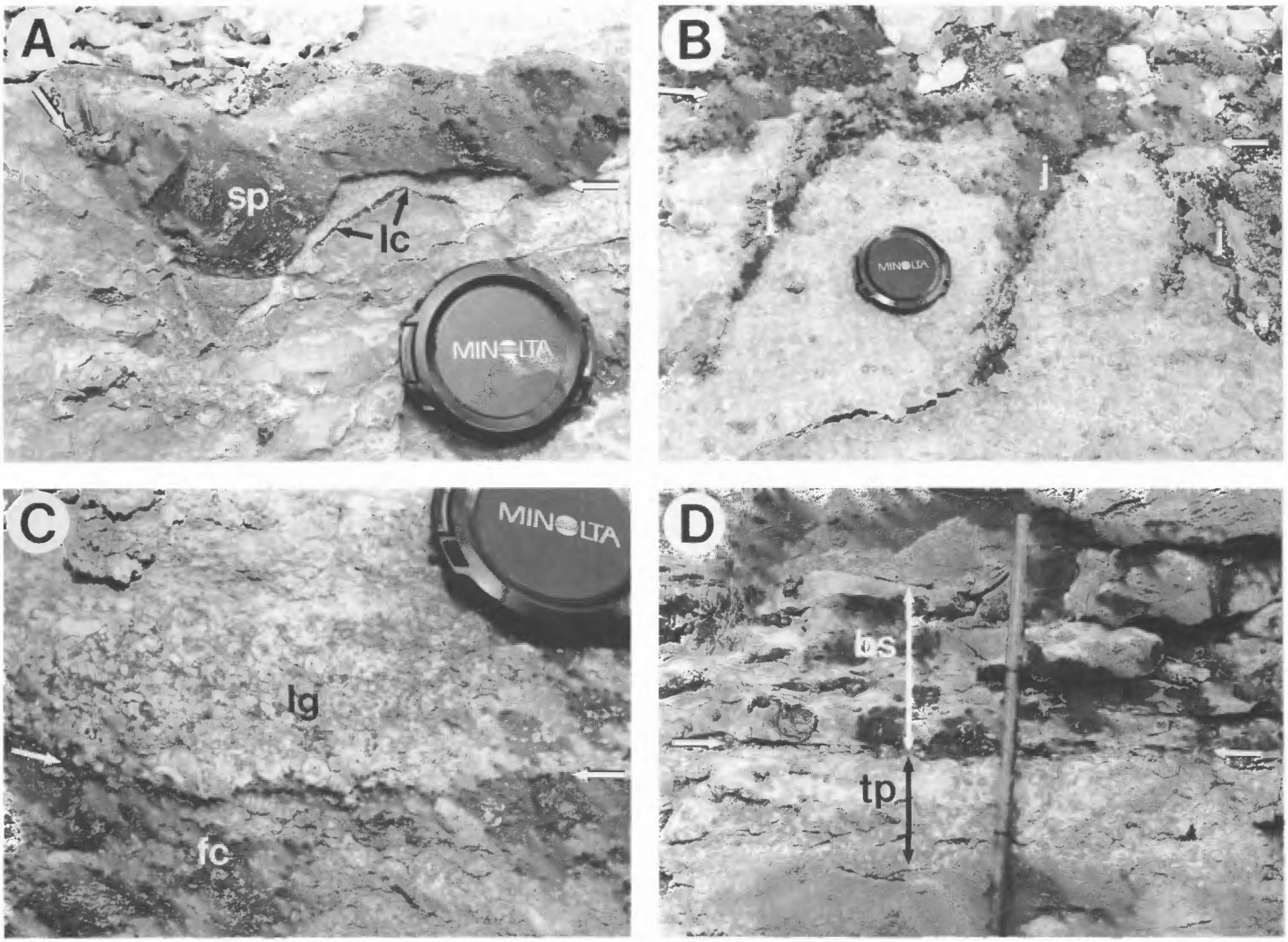


FIGURE 8. Cycle-top structures. A, Karstic solution pit lined by cemented laminar crust and infilled by chertified fossil lag. B, Solution-enlarged joints, accentuated by later chertification. C, Coarse-grained echinoderm-rich fossil lag overlying oxidized ferruginous crust at top of cycle. D, Diagenetic enhancement of burrowing at top of underlying cycle due to downward flux of silica from cherty basal unit of overlying cycle. bs = cycle-base unit; fc = ferruginous crust; j = joint; lc = laminar crust; lg = lag; sp = solution pit; tp = cycle-top unit. Arrows indicate position of cycle tops. Lens cap is 5 cm in diameter; rod in D is marked in 1 ft increments.

subsidence (Fig. 12). On the western ramp, shoaling cycles exhibit a strong mode at 6 m and limited thickness variation, suggesting relatively uniform subsidence rates and absence of tectonic instability. On the eastern shelf, shoaling cycles exhibit a mode at 9 m and much greater thickness variation, reflecting greater variation in basin subsidence and, probably, tectonism. Basinal cycles have a modal thickness of 4.5 m, indicating lower sedimentation rates and/or greater relative compaction of basinal strata. On average, cycle thicknesses suggest that the eastern shelf subsided at about 1.5 times the rate of the western ramp (9 m vs. 6 m; Fig. 12).

Sedimentation rates and cycle periods

Modal cycle thicknesses of the Gobbler Formation, in conjunction with the total thickness and duration of the Desmoinesian Series, allow calculation of long-term accumulation rates and cycle periods (Table 1). Within the study area, the Desmoinesian Series averages 167.5 ± 7.5 m in thickness on the western ramp and 275 ± 25 m on the eastern shelf. Current best estimates of the duration of the Desmoinesian Epoch are 4.0 Ma (Klein, 1990) to 4.5 Ma (Harland et al., 1989). This yields long-term accumulation rates of 39 ± 4 m/Ma on the western ramp and 65 ± 10 m/Ma on the eastern shelf. Although the Desmoinesian Series is incompletely exposed in basinal areas, cycle-set thicknesses suggest that basinal accumulation occurred at about 60% of the rate of shelf accumulation, yielding an estimated long-term accumulation rate of 39 ± 6 m/Ma for basinal strata. A modal cycle thickness of 6 ± 0.75 m and a long-term accumulation rate of 39 ± 4 m/Ma for the western ramp yield a modal cycle periodicity of $150{,}000 \pm 35{,}000$ yrs, while corresponding estimates of 9 ± 0.75 m and 65 ± 10 m/Ma for the eastern shelf yield a modal periodicity of $140{,}000 \pm 35{,}000$ yrs.

CONTROLS ON CYCLICITY

Several observations are relevant in identifying the dominant controls on cyclicity in Lower-Middle Pennsylvanian strata of south-central New Mexico. Cycle sets, and in some cases individual shoaling-upward cycles, are correlatable across the basin over distances of tens of kilometers, requiring a mechanism of at least basinwide operation. Subaerial exposure of cycle tops in both shelfal and basinal sequences demonstrates relatively large-amplitude (probably a few tens of meters or more) changes in relative sea level. Average cycle periods of 140,000 to 150,000 yrs indicate high-frequency changes in relative sea level. The only known mechanism to produce such large-amplitude, high-frequency changes of relative sea level over significant lateral distances

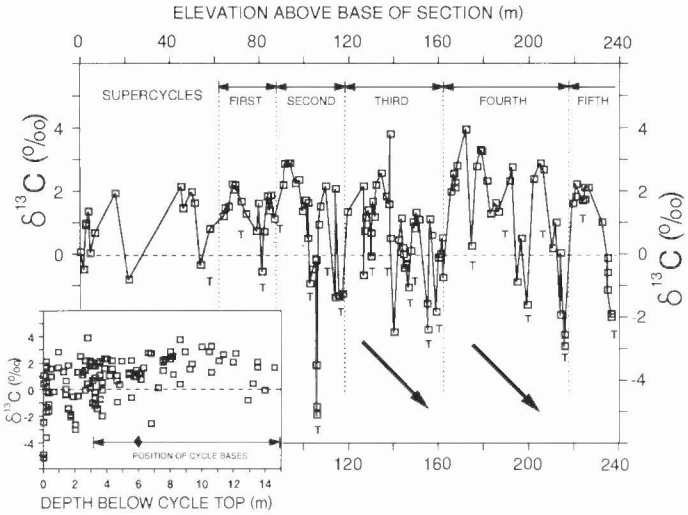


FIGURE 9. Carbon-isotope stratigraphy of matrix micrites in the Mockingbird Gap Hills section. Note that most cycle tops (T) exhibit negative $\delta^{13}C$ excursions and that some cycle sets (especially the third and fourth) show greater cycle-top excursions toward the top of the cycle set (arrows). Cumulative plot of $\delta^{13}C$ versus depth below individual cycle tops (inset) demonstrates that ^{13}C depletion occurs mainly at or just below cycle tops and that relatively heavy $\delta^{13}C$ values characterize cycle bases (at depths of 3–15 m), a pattern typical of all study locales.

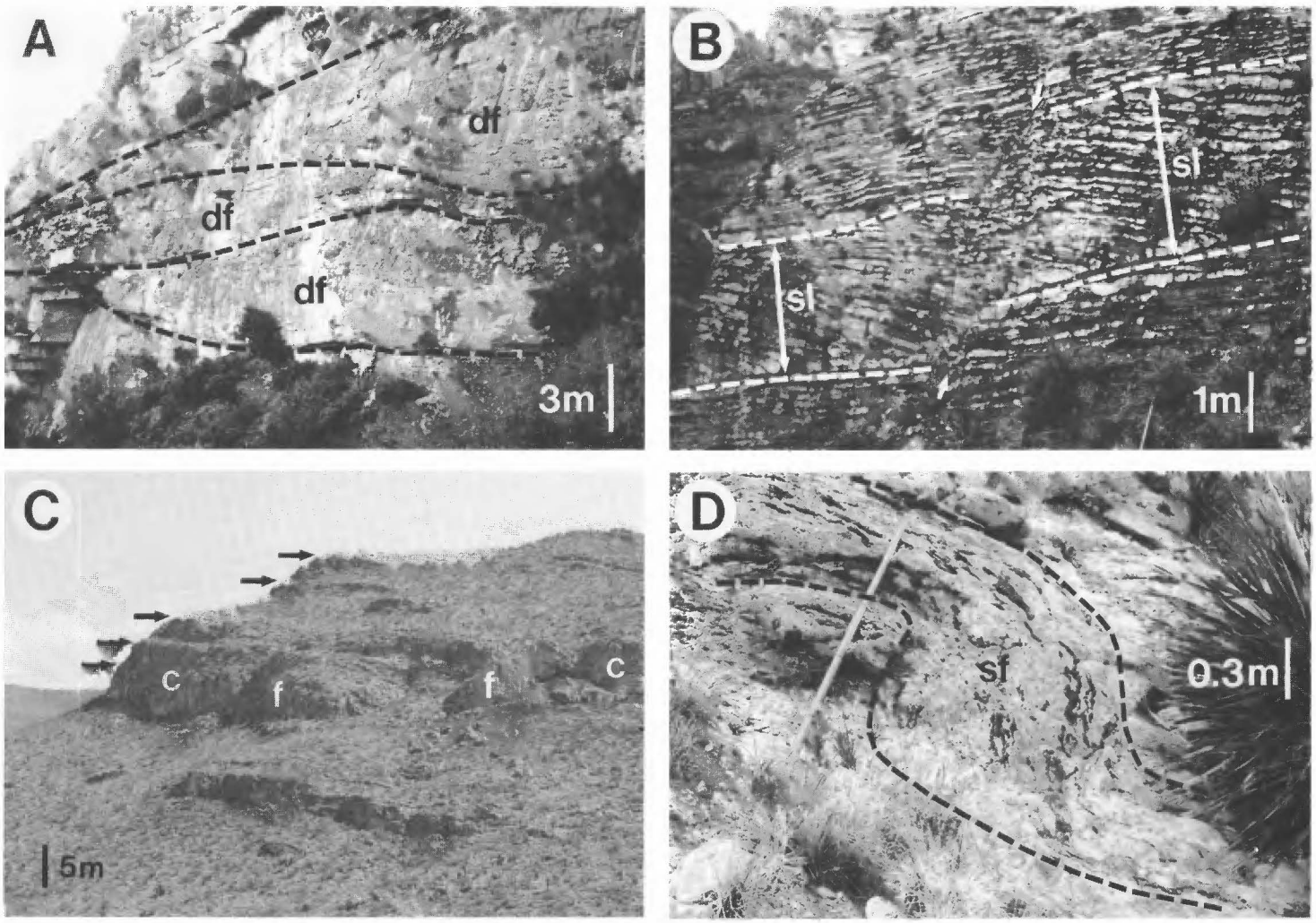


FIGURE 10. Sedimentary structures of slope environments. A, Debris flows associated with basinward progradation of Sacramento shelf margin (Dog Canyon). Note multiple arcuate and sineform slump surfaces (dashed). Vegetated hillslope below debris flow units conceals thin-bedded slope deposits similar to B. B, Cohesive synsedimentary slide in thin-bedded top-of-slope calcitic turbidites (upper and lower contacts dashed; Dog Canyon). Note flat-lying beds above and below slide. Apparent offset in middle of photo (arrows) is due to a shift in perspective. C, Phylloid algal mound north of Bug Scuffle Canyon in southern Sacramento Mountains. Note multiple growth stages (arrows). D, Soft-sediment slump fold in biohermal flank beds (dashed), accentuated by thinned and contorted chert nodules. c = mound core; df = debris flow; f = mound flank; sf = slump fold; sl = slide. Outcrop scales for center of view.

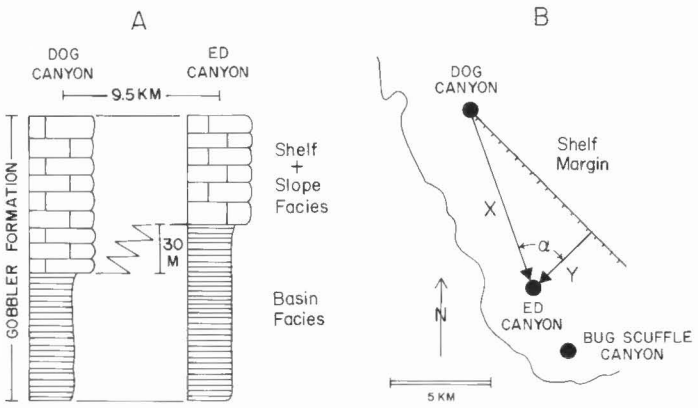


FIGURE 11. Rate of Sacramento shelf-margin progradation. A, Stratigraphic elevation of toe of basinward-prograding shelf margin is 30 ± 5 m higher at Ed Canyon than at Dog Canyon, 9.5 km to the northwest. B, Shelf margin prograded along line Y, perpendicular to shelf margin, rather than along line X, the direct line between study locales, so that the distance between sections (9.5 km) must be reduced by cos(65°) to arrive at progradation distance (4.0 km).

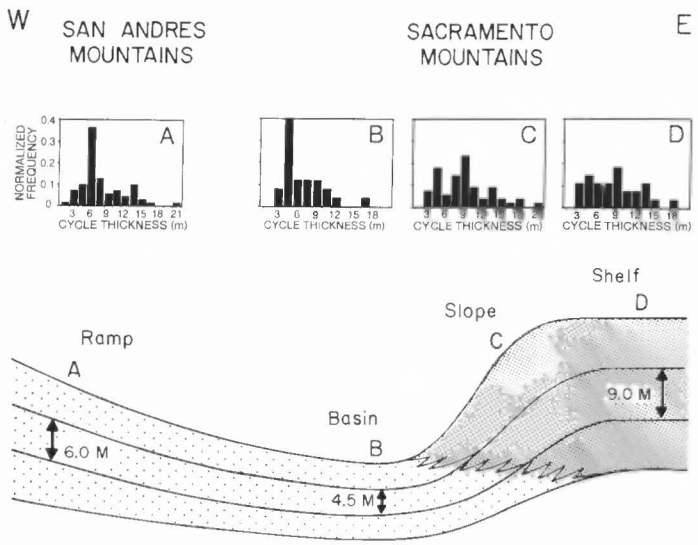


FIGURE 12. Regional variation in non-decompacted cycle thicknesses. Cycles on the western ramp have a modal thickness of 6 m, thinning to 4.5 m eastward toward the basin center. Cycles on the eastern shelf exhibit more variable but generally greater thicknesses (9 m mode). Major intrasectional changes in lithology and cycle thickness occur where the shelf margin prograded basinward over basin and slope deposits (as at Dog Canyon). Location of sections in relation to shelf margin: A = Mockingbird Gap Hills and Hueco Mountains, Rhodes and Hembrillo Canyons, B = Bug Scuffle Canyon, C = Dog Canyon, D = Mule and Fresnal Canyons.

is glacio-eustasy, which is a likely mechanism in view of the well-documented Permo-Carboniferous Gondwanan Ice Age (Veevers and Powell, 1987). Although calculated periods of 140,000–150,000 yrs do not exactly match a known orbital period, they fall squarely within the Milankovitch band and suggest possible modulation of cyclicity in the Pennsylvanian strata considered here by the Earth's short- (ca. 100,000 yr) or long-period (ca. 400,000 yr) eccentricity cycles (Heckel, 1986). Lack of correspondence between cycle and orbital periods may be due to the non-linear response of ice-sheet volume and eustasy to the Earth's orbital cycles or, alternatively, to uncertainties in the duration of the Desmoinesian Epoch.

Although shoaling-upward cycles in the Gobbler and correlative formations are primarily eustatic in origin, tectonic controls influenced the facies composition and thickness of cycles at individual locales. This is most evident on the eastern basin margin, where facies character changes abruptly from shelf to trough or basinal locales. Some units, e.g., calcitic turbidites, grain flows and debris flows associated with shelf and trough margins, reflect processes of sediment redistribution and are probably autocyclic in origin.

TABLE 1. Cycle periods in the Lead Camp (San Andres Mountains) and Gobbler (Sacramento Mountains) Formations.

	San Andres Mountains	Sacramento Mountains
Modal Cycle Thickness (m)	6±0.75	9±0.75
Desmoinesian Series Thickness (m)	167.5±7.5	275±25
Average Sediment Accumulation Rate (m/Ma)	39±4	65±10
Average Cycle Period (1000 yrs)	150±35	140±35

Note: Desmoinesian Series duration = 4.0–4.5 Ma based on Harland et al., 1989; Klein, 1990.

Cycle sets reported here record long-term (ca. 1.0 Ma) variation in the ratio of carbonate-to-shale accumulation, although the source of such variation is unknown. Eustatic control, for example, may have occurred through cyclic variation in the elevation of successive sea-level highstands, altering rates of carbonate production. Alternatively, tectonic control may have occurred through episodic basin subsidence or highland uplift, inducing pulses of fine-grained clastic influx which limited or diluted carbonate production. Two observations favor a eustatic origin: (1) greater cycle-top ^{13}C depletion toward the tops of cycle sets suggests cyclic variation in the elevation of sea-level lowstands, and (2) existence of similar cycle hierarchies in other Carboniferous sections (e.g., Ramsbottom, 1979) requires a globally operative mechanism such as eustasy.

CONCLUSIONS

1. Lower-Middle Pennsylvanian strata in south-central New Mexico (Gobbler Formation and equivalent units) comprise a 250–450-m-thick succession of shallow-marine clastics and limestones exhibiting shoaling-upward cyclicity.

2. Shoaling cycles are 3 to 20 m in thickness, grade upward from shaly and spiculitic deep-water marls to clean shallow-water limestones, and show evidence of subaerial exposure at cycle tops.

3. Negative $\delta^{13}C$ excursions at or just below cycle tops document early meteoric diagenesis and suggest development of soil horizons on subaerially exposed cycle tops.

4. Both shelf and basinal locales show petrographic and isotopic evidence of subaerial exposure, although such exposure appears to have been more limited in intensity and, possibly, duration in basinal settings.

5. Groups of 4–7 shoaling cycles comprise cycle sets 20 to 80 m thick, reflecting long-term (ca. 1.0 Ma) variation in the carbonate-to-shale accumulation ratio.

6. Cycles and cycle sets provide a two-level hierarchy permitting basinwide correlation of cyclostratigraphic units.

7. The western basin margin was a tectonically stable ramp (Robledo ramp) characterized by cycles of regular thickness and uniform facies composition.

8. The eastern basin margin was a narrow, high-relief shelf (Sacramento shelf) characterized by rapid lateral and vertical facies changes, lateral discontinuity of units, and irregular cycle thicknesses.

9. The Sacramento shelf was transected by the tectonically active Alamo trough, through which clastics derived from highlands to the east were channeled basinward.

10. The Sacramento shelf margin prograded basinward at a rate of 5.3 ± 2.0 km/Ma during the Desmoinesian Epoch.

11. Systematic variation in modal cycle thicknesses across the basin (9 m on the eastern shelf vs. 6 m on the western ramp) reflect differential rates of sediment accumulation and subsidence on the eastern and western basin margins.

12. In conjunction with modal cycle thicknesses, long-term accumulation rates of 39 ± 4 m/Ma for the western ramp and 65 ± 10 m/Ma for the eastern shelf yield estimated cycle periods of $150{,}000 \pm 35{,}000$ yrs and $140{,}000 \pm 35{,}000$ yrs, respectively.

13. Evidence of large-amplitude, high-frequency changes of relative sea level operating over significant lateral distances supports a glacio-eustatic mechanism associated with the Permo-Carboniferous Gondwanan Ice Age for genesis of Gobbler Formation shoaling cycles.

14. A eustatic origin for cycle sets is suggested by increasing ^{13}C depletion toward cycle-set tops and by existence of similar cycle hierarchies in other Carboniferous sections.

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