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THE ALLOCHTHONOUS NATURE OF LOWER MISSISSIPPIAN WAULSORTIAN MOUNDS IN THE SACRAMENTO MOUNTAINS, NEW MEXICO

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Abstract—Waulsortian mounds comprise a distinctive assemblage of carbonate facies organized into a mounded geometry that is interpreted as forming as a result of in situ biohermal growth in a moderately deep water setting (>100 m). However, depositional features of well-exposed mounds in the Sacramento Mountains, New Mexico, indicate generation primarily by gravity-driven sedimentologic processes with biohermal growth either absent or playing a subsidiary role in mound development. The Sacramento mounds are interpreted here to have been generated by downslope movement and accumulation of allochthonous sediment resulting from a combination of gravity-driven sedimentary processes such as translation (glide and slump), creep, debris flow, grain flow, and turbidity current. Characteristics of the Sacramento mounds that are consistent with a gravity-driven allochthonous origin are: (1) dominance of debris flows and turbidites throughout mound core and flank facies, (2) abundant slump folds and clastic injection dikes within the mounds, (3) stratigraphic mix of non-compacted, early-cemented facies with severely overcompacted, late-cemented facies, (4) presence of extraclasts within debris flow units, and (5) the complete absence or localized distribution of framework or sediment-binding organisms within the mounds. Though the Sacramento mounds appear to have been generated primarily by allochthonous sediment accumulations, they also provided a substrate for local colonization by deep-water biotic communities of bryozoans, sponges, and microbes.

INTRODUCTION

The term "Waulsortian" was coined by Dupont (1863, 1865) to describe a geometrically distinctive assemblage of mounded carbonate facies exposed near the village of Waulsort, Belgium. Similar facies assemblages have since been recognized in western Europe, Canada, North Africa, and North America (Smith, 1982; Gutschick and Sandberg, 1983; Lane, 1984; Lees and Miller, 1985; Miller, 1986; Davies et al., 1989). The generalized Waulsortian mound facies assemblage consists of crudely bedded to massive, carbonate mud-rich, crinoidal-bryozoan-microbial "core" facies surrounded by bedded, crinoidal packstone to grainstone flanking facies that dip steeply (as much as 50°) away from the mound core (Wilson, 1975). The mound core and flanking facies are encased in rhythmically bedded, mud-rich, cherty limestones (Lees, 1982). The Waulsortian mound facies assemblage is apparently confined stratigraphically to the Lower Carboniferous (Tournaisian and Lower Visean; Lees et al., 1985).

Waulsortian mounds have been interpreted as deep water, biohermal buildups based on their mounded geometry, apparent core and flank facies relationship, and the deep water depositional setting (~100 m) of the encasing strata (Meyers, 1975; Wilson, 1975; Lees, 1982; Lees and Miller, 1985). Waulsortian mounds are unique in the geologic reef record in that they lack evidence of a frame-building or binding organism capable of generating a large biohermal buildup (James, 1984).

The Waulsortian mound facies of the Sacramento Mountains, New Mexico, are superbly exposed in three dimension, making these mounds the focus of Waulsortian mound research since they were first described and correlated to their European counterparts (Laudon and Bowsher, 1941; Bowsher, 1948; Pray, 1958). The purpose of this paper is to describe depositional features found in the Sacramento mounds that suggest they formed primarily as resedimented carbonate accumulations rather than in situ biohermal buildups.

WAULSORTIAN MOUNDS IN THE SACRAMENTO MOUNTAINS

Within the Sacramento Mountains a relatively thin succession (107 m) of Mississippian strata is preserved below the major erosional unconformity of the Mississippian–Pennsylvanian boundary. The Mississippian section is subdivided into three formations (Fig. 1): Caballero, Lake Valley, and Rancheria. The Lake Valley

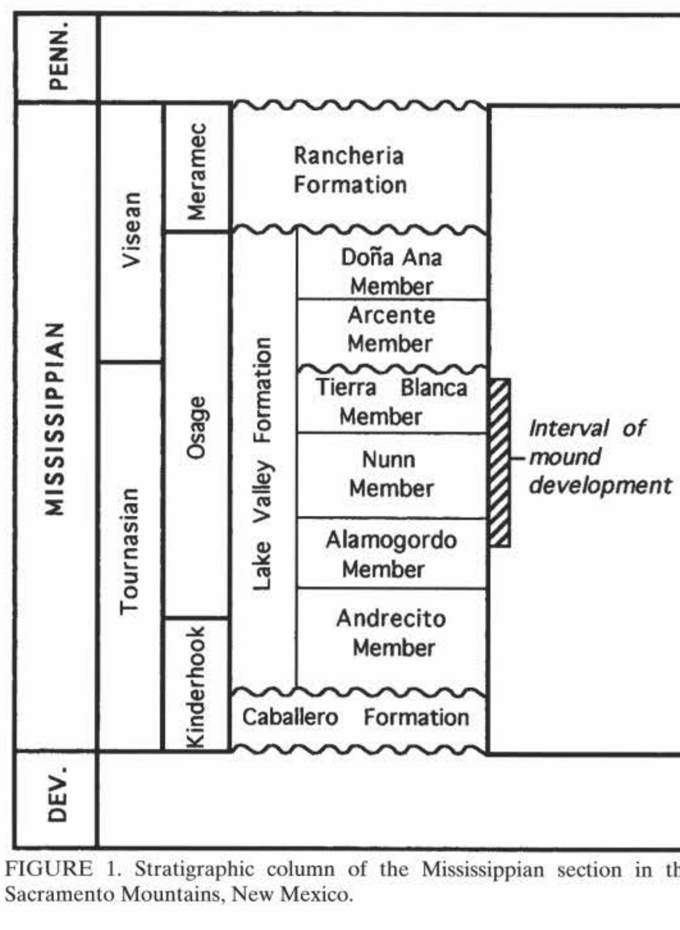


FIGURE 1. Stratigraphic column of the Mississippian section in the Sacramento Mountains, New Mexico.

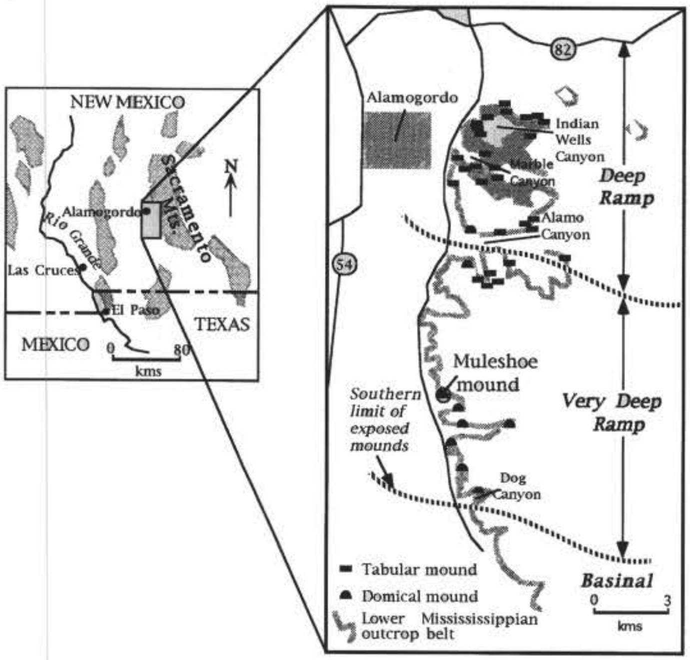


FIGURE 2. Map of study area showing the location of tabular and domical (Waulsortian) mounds and the position of the Tierra Blanca shelf margin in the Sacramento Mountains (modified from Ahr, 1989; position of Tierra Blanca shelf margin from Meyers, 1975).

Formation is further subdivided into six members: Andrecito, Alamogordo, Nunn, Tierra Blanca, Arcente, and Doña Ana. Waulsortian mounds have been recognized in the Alamogordo, Nunn, and Tierra Blanca members of the Lake Valley Formation (Lane and Ormiston, 1982).

The general paleogeographic setting of the Lake Valley Formation was a southward-deepening and southward-prograding carbonate ramp (Bachtel and Dorobek, 1995). The ramp geometry evolved into more of a platform geometry with a distinct break in slope during deposition of the Tierra Blanca Member (Meyers, 1975; Gutschick and Sandberg, 1983; Ahr, 1989). The mounds in the Sacramento Mountains occupy a north-south-trending outcrop belt that approximately parallels the Mississippian paleoslope (Fig. 2). Mound geometry changes from tabular to domical from north to south along the outcrop belt. The northern mounds generally have an elongate, low-relief, tabular form with as much as 30 m relief and are several 100 m lateral extent (Fig. 3A). These mounds commonly have channelized, scoured, or slump-scar bases and are composed dominantly of well-bedded to massive, crinoid-rich facies and carbonate megabreccia. Bedding commonly displays clinoform geometry, synsedimentary slump deformation, and intraformational truncation surfaces. Mounds in the south are much larger (100 m relief by 500 m diameter) and have a domical shape (Fig. 3B). Tabular mounds generally do not display the distinct core/flank facies relationship characteristic of Waulsortian mounds and for that reason only the southern domical mounds are considered when referring to Waulsortian mounds in the Sacramento Mountains.

The Waulsortian mounds in the Sacramento Mountains formed seaward of the Lake Valley shelf margin (Lane and Ormiston, 1982) in a lower slope/lower ramp setting. Mounds have not been recognized south of Dog Canyon (Fig. 2), where correlative strata thin and consist of sediment-starved basinal facies (Meyers et al., 1975; Ahr, 1989).

Allochthonous depositional features of the Sacramento mounds

The core and flanking facies of the Sacramento Mountains Waulsortian mounds contain an abundance of depositional features that are commonly present in association with allochthonous or resedimented material. These features are: (1) predominant mound composition of turbidite and debris-flow facies, (2) abundant slump folds and clastic injection dikes, (3) the apparent random stratigraphic mix of non-compacted, early-cemented facies with severely overcompacted, late-cemented facies, and (4) presence of extraclasts within debris flow units.

Both the core and flank faces of the mounds are primarily composed of resedimented deposits mostly of turbidite and debris-flow origin. The turbidite facies consist of thin-to-thick planar beds of abraded, crinoidal packstone to grainstone commonly displaying current lamination and normal size-grading (Fig. 4A). Turbidites are the most common facies within the mound flanks, where they are arranged in onlapping and downlapping stratal patterns. The turbidite strata display diagenetic fabrics indicative of severe overcompaction, such as highly stylotized grain boundaries suggesting a lack of early marine cementation and rapid burial (Fig. 4B). This is in contrast to other mound facies, which show little compactional effects such as debris-flow horizons.

Stacked debris-flow horizons (as much as 15 m thick) are common within mound cores and are intercalated with turbidite beds

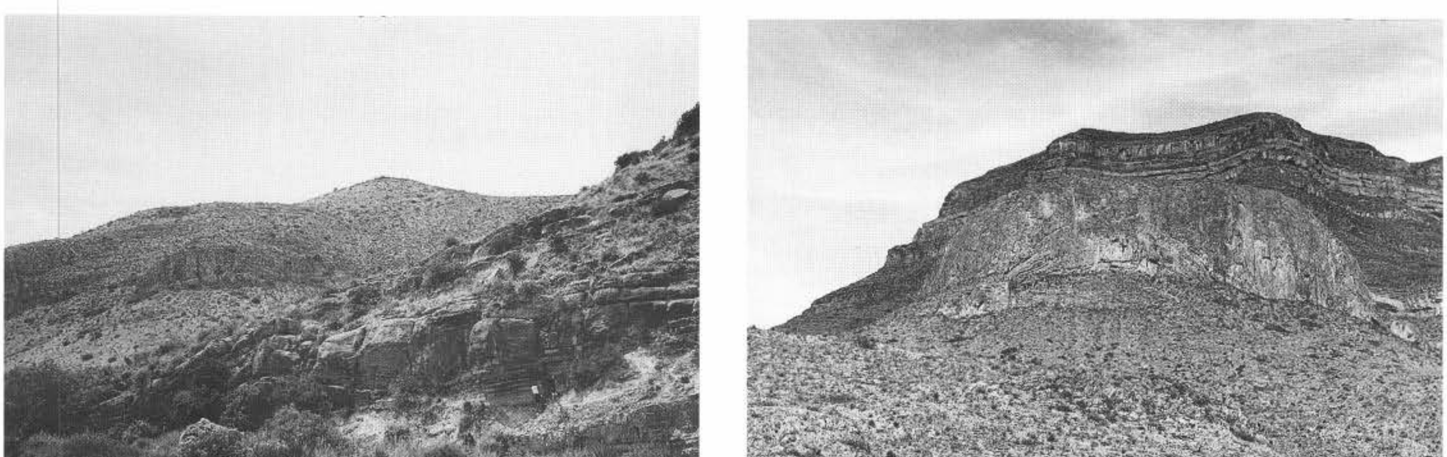


FIGURE 3. Mound Geometries. **A,** Outcrop photograph of a northern tabular mound within Marble Canyon, Sacramento Mountains. Refer to Figure 2 for location. **B,** Outcrop photograph of a southern domical mound. NW-SE-trending cliff face of Muleshoe mound, Sacramento Mountains. Refer to Figure 2 for location of Muleshoe mound.

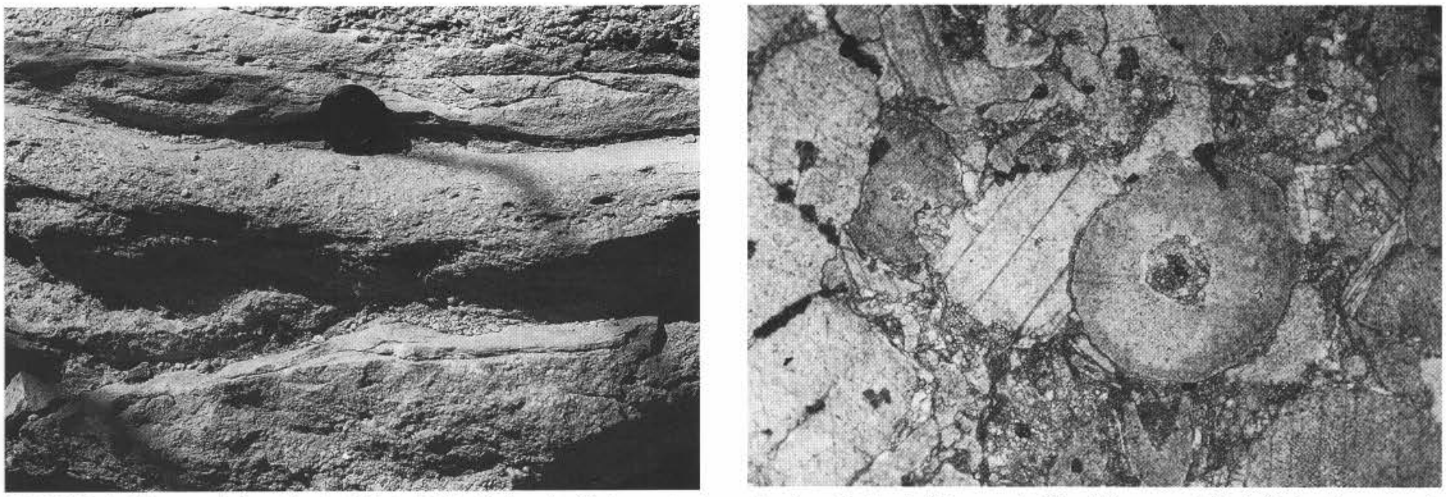


FIGURE 4. Characteristics of crinoidal turbidite facies. **A,** Outcrop photograph of graded beds (Bouma A–B) within mound flank facies. Lens cap is approximately 5 cm across. **B,** Thin section photomicrograph of highly stylotized and overcompacted crinoidal grainstone turbidite facies found on mound flanks.

within mound flanks (Lane and Ormiston, 1982). The debris flows are lens-shaped (Fig. 5A) and contain pebble- to boulder-size, bryozoan-crinoidal mudstone to packstone clasts encased in a mud- to grain-rich, crinoidal matrix (Fig. 5B). Locally the debris-flow units contain clasts of coarsely crystalline sucrosic dolomite. The beds from which the sucrosic dolomite clasts originated have not been identified within the study area. For this reason, these clasts have been termed "extraclasts" in this study.

Contorted and folded beds are present in thin- to thick-bedded, crinoidal packstone and grainstone facies, primarily at the base of debris-flow horizons within mound cores (Fig. 6A). However, in some cases the entire mound is apparently folded (Fig. 6B). Folded beds are bounded by completely undisturbed beds, are highly variable in fold geometry, display curvi-linear hingelines, and commonly contain clastic injection dikes.

Sediment injection dikes and injection fractures are concentrated along the base of mounded intervals (Pray, 1965; Lane and Ormiston, 1982). The injection dikes are steeply dipping to vertical (with horizontal epiphyses), planar to irregular margined, upward-tapering fractures (<1 m wide and as much 13 m in length) filled with laminated to homogenous, carbonate mud (Fig. 7). Laminations are parallel to fracture walls. The dikes extend upward into the mounds, where they cut both core and flanking strata. This cross-cutting relationship indicates that the fractures or injection dikes post-date the formation of the mound interval that they cut and that the mounds were at least semi-coherent when the fractures formed. Sedimentary injection dikes arise when the host strata are in a state of horizontal tension, and the underlying strata are unlithified with pore-water pressure temporarily in excess of lithostatic pressure, so that liquefaction can occur (Allen, 1982).

DISCUSSION

Each of the sedimentological features described in the previous section may be found locally in association with biohermal buildups (James, 1983, 1984). However, their dominance in the Sacramento system is unpredicted and difficult to explain in the context of a completely in situ biohermal origin for the mounds (Fig. 8A). For example, in both modern and ancient biohermal buildups resedimented material is the dominant component of flanking beds and is generally not present within mound cores. The flanking beds are generated by failure of the mound core facies forming resedimented flanking deposits that interfinger with the core (Longman, 1981). In contrast, the mud-rich "core" facies of the Sacramento mounds are primarily massive debris-flow horizons that are thickest near the "core" portion of the mounds. These debris flows contain extraclasts indicating sediment was not derived exclusively from a biogenic core. The debris flows thin outward from the core

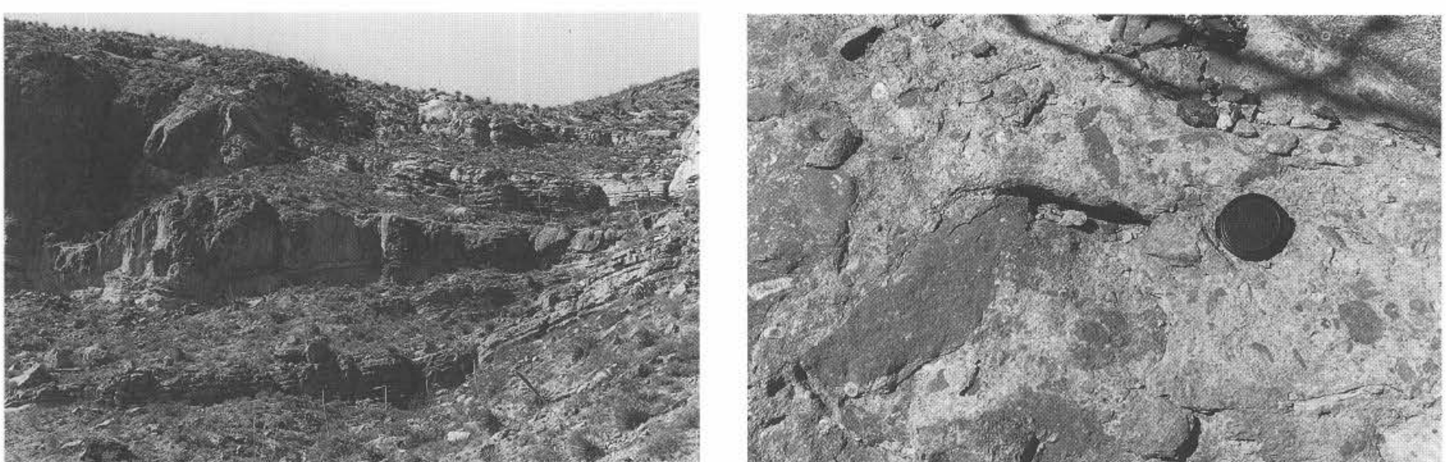
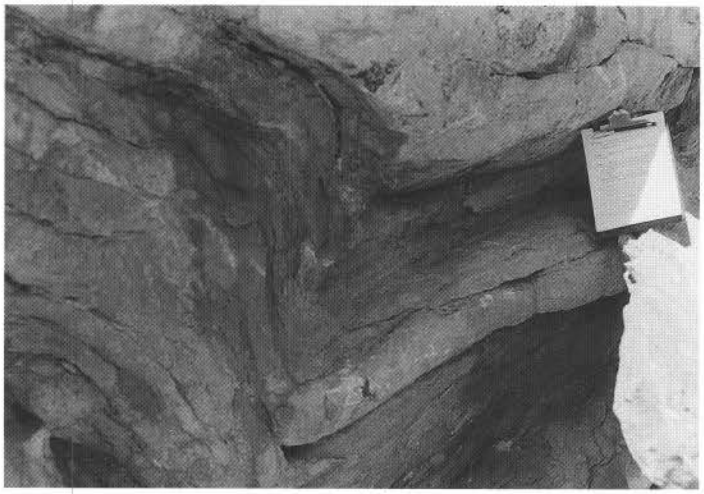


FIGURE 5. Characteristics of debris-flow units. **A,** Outcrop photograph of massive, lens-shaped debris flow intercalated with bedded crinoidal turbidites on the southeast flank of Muleshoe mound. **B,** Outcrop photograph of debris-flow fabric. Lens cap is approximately 5 cm across.



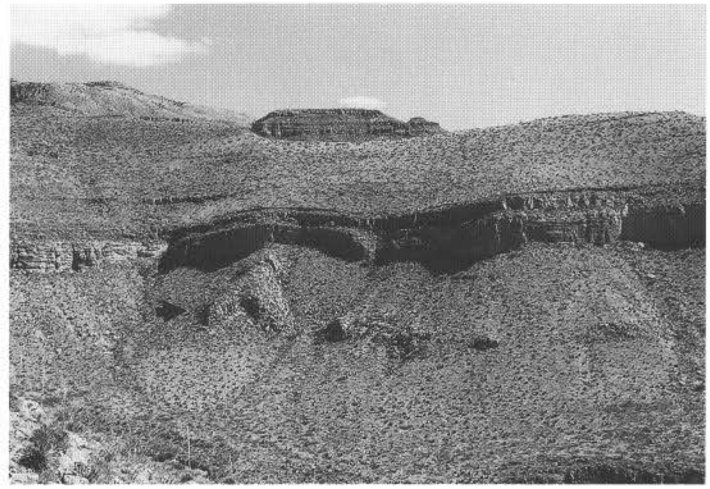


FIGURE 6. Characteristics of folded and contorted strata. **A,** Outcrop photograph of contorted crinoidal turbidite beds at the base of a mounded debris-flow interval within Muleshoe mound core facies. Clipboard is approximately 30 cm long. **B,** Thick-bedded crinoidal grainstone beds apparently folded into this striking upright geometry. Unnamed mound on the south side of Mule Canyon across from Muleshoe mound.

and become intercalated with thin-bedded, crinoidal turbidite horizons forming the grain-rich flanks. Burial and differential compaction between the relatively incompressible debris-flow horizons and the highly compacted crinoidal turbidites greatly enhanced the relief between the "core" and the "flanks."

Slump folding has been documented in fore-reef or flanking clinoforms of both modern and ancient biohermal buildups (Wilson, 1975; Enos and Moore, 1983) and is a plausible mechanism for formation of slump folds in the Sacramento mounds. Oversteepening, instability, and failure of the flank facies of the mounds may have caused the beds to detach from the biohermal topographic high. If this was the case, the vergence direction of slump fold axis should form a relatively concentric pattern around the domical mound and should have occurred periodically throughout the buildup of the mound. All vergence directions taken on folds in the Sacramento mounds indicate a southward to southwestward transport direction consistent with the regional paleoslope direction.

In the in situ bioherm model, formation of the injection dikes requires dilation fracturing in an early-cemented mound overlying uncemented, water-rich sediment (Pray, 1965). The steep sides and mass of the mound cause instability and extension resulting in fracturing, allowing the underlying, locally pressurized, water-rich, unlithified sediments to be injected into the fractures. The problem with this scenario is it requires one sedimentary facies to dehydrate and cement early, while the underlying facies (composed of very similar constituents) remains hydrated and uncemented. This type of behavior has not been documented in any other ancient or modern biohermal buildup.

FIGURE 7. Carbonate mud-filled clastic injection dike within a debris flow horizon. Lens cap is approximately 5 cm across.

Allochthonous sediment model

An alternative model to the in situ biohermal model is proposed here and is more consistent with the observations of depositional features within the Sacramento mounds. The allochthonous sediment model entails generation of the mounds by downslope movement and progressive accumulation of resedimented material (Fig. 8B). In this model, sediment generated in an upper ramp/upper slope environment was initially transported and deposited part way downslope by a combination of gravity-driven sedimentary processes such as debris flows, grain flows, and turbidity currents. The transported sediments were focused into preferred conduits along the slope resulting in relatively rapid, local accumulation rates and sediment buildup (generating the northern tabular mounds of the Sacramento Mountains). Rapid sediment accumulation rate, underconsolidation, and oversteepening may have lead to instability of the sediment and ultimately massive slope failure (Helwig, 1970; Allen, 1982). Large portions of the layered slope accumulations detached and moved further downslope as semi-coherent, creep horizons, glide blocks, slump masses, and debris flows. Frictional forces caused shear on the base of the slides and flows resulting in internal deformation (folds and contorted beds) and drag on the base and sides of the mass. Sedimentary loading by the rapidly deposited allochthonous material also generated fluid escape structures and contorted beds.

Downslope translation of the allochthonous material ceased when zones of decreased slope gradient were encountered, such as the toe-of-slope environment or previously deposited piles of allochthonous debris. These piles of debris formed obstacles that impeded the down-gradient flow of turbidity currents such that they were onlapped and downlapped by these facies forming a composite pile-up of debris or a "mound." The mounds may represent a single slope failure event or composite, progressive buildup from multiple episodes of slope failure and allochthonous sediment accumulation.

The allochthonous sediment mounds formed topographic highs on the sea floor that potentially served as an ideal substrate for local colonization by relatively deep-water biota such as sponges, bryozoans, and thrombolitic microbial buildups. Rare biotic

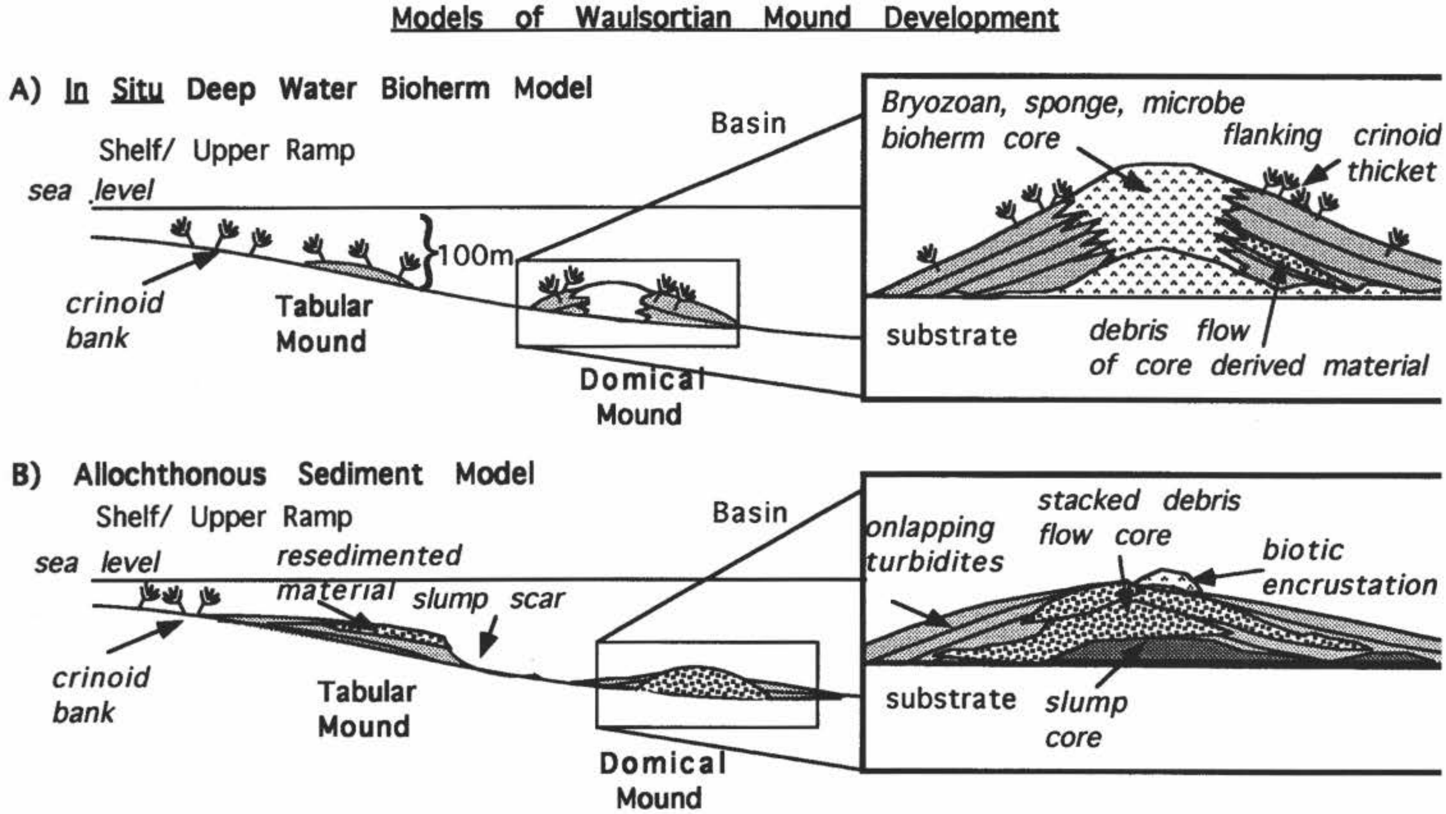


FIGURE 8. Schematic diagrams of alternative models for the generation of Waulsortian mounds. **A,** In situ bioherm growth model. Generalized from Lane et al. (1982). **B,** Allochthonous sediment model.

buildup facies have been documented in the Sacramento mounds (Ahr and Stanton, 1996; Jeffery and Stanton, 1996; Kirkby, 1994; Kirkby et al., 1997). However these buildups form a very small portion of the overall mound facies and have not been documented in association with all mound sites.

Sacramento mounds as allochthonous accumulations

The sedimentological features described are not only adequately explained by the allochthonous model, but are predicted to be present. For instance, the allochthonous model predicts that resedimented material should form the majority of depositional facies in conjunction with minor hemi-pelagic sedimentation.

In the allochthonous model, slump folding forms due to local deflection of shear stresses along the base of the slump block as it moves downslope. Slump folds would be expected to be concentrated along the base of mounded intervals and to display predominantly downslope or southward vergence directions, as is observed in the Sacramento mounds.

Clastic injection dikes are relatively common sedimentary structures associated with slumps, glide blocks, and debris flows in both modern and ancient settings (Allen, 1982). Semi-lithified to completely lithified, coherent slump masses and debris flows move down the slope loading the underlying unconsolidated sediment. As a result of bending and transport, the base of the slide may fracture, at which time the underlying overpressurized, water-rich sediments are injected into the overlying mass.

IMPLICATIONS OF THE ALTERNATIVE MODELS

Sedimentological features similar to those referred to here have been observed in other Waulsortian mounds worldwide suggesting the mounds may have formed by similar processes (Lees, 1964; King, 1986; Bridges and Chapman, 1988). Although the evidence to support the biohermal model for the formation of all Waulsortian mounds is seemingly very limited, the implications of this interpretation are profound. Waulsortian mounds currently interpreted as biohermal buildups are cited as unique examples of large, deep-water bioherms that filled the reefal niche following the Late Devonian mass extinction of the tabulate coral and stromatoporoid reefs (Heckel, 1974; Wilson, 1975).

If the Waulsortian mounds are allochthonous masses, then we are faced with a time span of approximately 40 Ma (Late Devonian to latest Mississippian) when there were no major organic framework builders. Interestingly, this same time span is unusual with respect to depositional setting. It is characterized by long-lived, extensive carbonate ramps dominated by crinoidal and oolitic grainstone facies (Ahr, 1989). In the absence of an organic buildup or a tectonic mechanism, development of a carbonate platform geometry with distinct shelf/slope break from a ramp may have been difficult to achieve. Also during this time interval, the depositional niche traditionally assumed by framework builders (equatorial, shallow-water area with moderate wave action) was filled by crinoid thickets and extensive ooid shoals.

Waulsortian mounds are a proven and recently rejuvenated hydrocarbon reservoir target in many basins throughout North America (Eby, 1995; Johnson, 1995). The two proposed models predict different depositional and diagenetic facies geometries and distributions, and would require different exploration and exploitation strategies.

CONCLUSIONS

A series of sedimentological features present in the Lower Mississippian Waulsortian mounds in the Sacramento Mountains suggest that the mounds formed primarily by gravity-driven slope processes, rather than in situ biohermal growth. An alternative model, referred to as the allochthonous sediment model, is proposed here that is more consistent with the depositional features observed. These features include: (1) dominance of transported sediment within the core and flank facies, (2) contorted beds and overturned folds within the mounds, (3) presence of clastic injection dikes into the base of some of the mounds, (4) presence of extraclasts in debris flow horizons, and (5) the rare distribution or complete absence of sediment-binding or framework organisms within the mounds.

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