Sedimentology of Guadalupian deep-water clastic facies, Delaware Basin, New Mexico and Texas

Charles R. Williamson

1980, pp. 195-204. https://doi.org/10.56577/FFC-31.195

in:

Trans Pecos Region (West Texas), Dickerson, P. W.; Hoffer, J. M.; Callender, J. F.; [eds.], New Mexico Geological Society 31st Annual Fall Field Conference Guidebook, 308 p. https://doi.org/10.56577/FFC-31

This page is intentionally left blank to maintain order of facing pages.

SEDIMENTOLOGY OF GUADALUPIAN DEEP-WATER CLASTIC FACIES, DELAWARE BASIN, NEW MEXICO AND WEST TEXAS

CHARLES R. WILLIAMSON
Union Science & Technology Division
Union Oil Company of California
Brea, California 92621

INTRODUCTION

The Delaware Mountain Group is a 1000- to 1600-m thick section of siltstone and sandstone that was deposited in the deep-water Permian Basin. Sandstones of the Delaware Mountain Group are the principle reservoirs in more than 100 oil and gas fields, and fine-grained, highly organic siltstones interbedded with the sandstones are considered to be source rock facies for oil in Delaware Basin reservoirs (Collins, 1975). Excellent outcrops along the western edge of the basin and abundant subsurface data provide an opportunity to study the facies distribution, sandstone geometry and reservoir properties of deep-water clastic sediments in a structurally undeformed setting. This paper summarizes outcrop and subsurface studies of the Bell Canyon Formation, the uppermost member of the Delaware Mountain Group. A more complete discussion of the results presented here can be found in Williamson (1978, 1979). Many of the same observations and interpretations are equally applicable to other members of the Delaware Mountain Group (Harms, 1974; Payne, 1976; Bozanich, 1979).

The deep-water depositional setting of the Delaware Mountain Group is well established by stratigraphic relations with time-equivalent shelf and shelf-margin rocks and has led many workers to suggest that sediments of the Delaware Mountain Group were deposited by turbidity currents (Newell and others, 1953; Hull, 1957; Silver and Todd, 1969; Meissner, 1972; Berg, 1979). A submarine fan depositional model for the Delaware Mountain Group proposed by Jacka and others (1968) commonly is cited as an example of deep-sea sedimentation in an intracratonic basin. However, results of this study indicate that most sand in the Bell Canyon Formation was deposited in nonbranching, nearly parallel submarine channels oriented at high angles to the shelf margin with no discernible fan morphology. The channels were cut by bottom-hugging, clay-free density currents and filled by sand and silt in a complex, unordered manner, similar to that described by Harms (1968, 1974) from his study of outcrops of the slightly older Brushy Canyon Formation. Laminated, highly organic siltstone was deposited as a suspension blanket and occurs in channels and interchannel areas. The sandstone-filled channels are up to 8 km wide, 35 m deep and extend more than 70 km basinward. The channels set up numerous stratigraphic traps against regional monoclinal dip as a result of the pinchout of channel sandstone into less permeable interchannel siltstone.

PALEOGEOGRAPHIC SETTING

Major tectonic elements of the Permian Basin were developed in Pennsylvanian or Early Permian time (Oriel and others, 1967). Through much of the Permian, a deep-water basin was separated from the shelf areas by carbonate reefs or banks developed along the shelf margin, and the Delaware Basin was connected to more open oceanic areas through channels at the southern end of the basin.

The Guadalupe Mountains, uplifted by Tertiary faulting, expose outcrops of the Guadalupe Series making it possible to trace shelf-edge and slope carbonate rocks into the basin. The present relief between shelf rocks deposited near sea level and time-equivalent rocks near the base of the slope can be used to estimate Permian water depth in the basin. Estimates for the Bell Canyon Formation range from about 100 m (King, 1934) to 730 m (Adams, 1936). uncertainties exist depending upon where the measurements are made, allowance for differential compaction, and the amount of regional tectonic tilting inferred. Most workers agree that maximum depths near the end of Bell Canyon deposition exceeded 300 m, and probably were closer to 500 m (Meissner, 1972).

STRATIGRAPHY

Stratigraphic correlations among rocks of the shelf, shelf-margin and basin have long been a source of controversy for the Delaware Basin. Figure 1 was compiled from several sources and represents the most widely used stratigraphic terminology for the Delaware Basin. *Shelf* refers to a complex of shallow-water peritidal, lagoonal and emergent flat environments where water depths probably never exceeded several meters.

The Bell Canyon Formation is the youngest formation of the Delaware Mountain Group. Maximum thickness of the Delaware Mountain Group is greater than 1600 m near the center of the Delaware Basin (Oriel and others, 1967). The lithology of this thick basinal section is mostly siltstone and fine-grained sandstone with a few thin limestone beds. Conglomerate and coarser grained sandstone are present only in the Brushy Canyon Formation (Harms, 1974). Megabreccias composed of silty sandstone and allochthonous carbonate blocks occur in the Bell Canyon Formation, but are restricted to within several kilometers of the basin margin.

The Leonard Series underlying the Delaware Mountain Group consists of basinal siltstone, chert and dark limestone. The Ochoa Series overlying the Delaware Mountain Group reaches a maximum thickness of about 550 m and consists principally of evaporates with increasing amounts of red siltstone in the younger rocks. Shelf-margin rocks equivalent in age to the Delaware Mountain Group are dominantly limestone and dolomite (Capitan and Goat Seep Formations). The Lamar Limestone, the uppermost member of the Bell Canyon Formation, can be traced in outcrop to the base of the Guadalupe Mountains where it grades into the lower slope carbonate rocks of the Capitan Formation (Tyrell, 1962, 1969; Babcock, 1977). Basinward, the Lamar becomes a dark calcareous siltstone which is referred to in the subsurface as the "Delaware Lime."

Shelf rocks that are time-equivalent to the Delaware Mountain Group are described by Meissner (1972) and Smith (1974). In simplified terms, the shelf section consists of alternating thick carbonate units and relatively thin siltstone and sandstone units which grade toward the shelf into redbeds and evaporites.

One of the most perplexing problems of Delaware Basin stratigraphy is the general lack of terrigenous material in shelf-margin rocks. Thin widespread siltstone and sandstone units within the

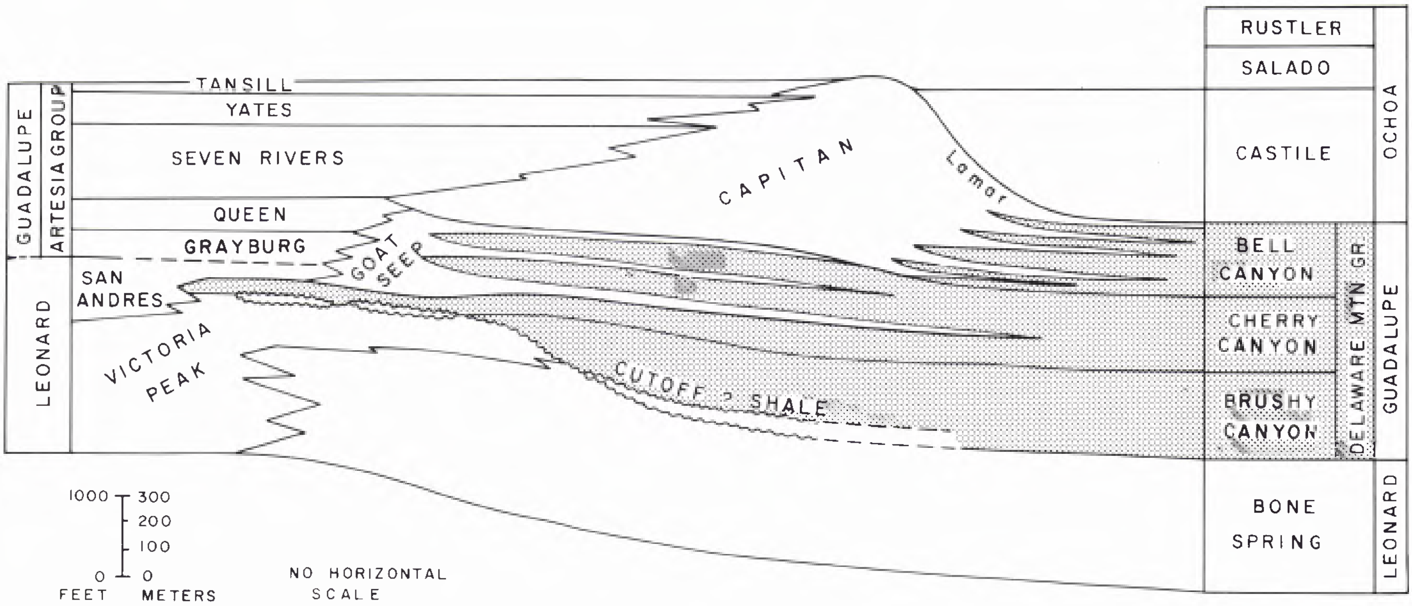

Figure 1. Permian stratigraphic relations, Delaware Basin. Adapted from King, 1948; Newell and others, 1953; Silver and Todd, 1969.

Artesia Group are believed to represent sediment supply routes for the petrographically similar siltstones and sandstones of the Delaware Mountain Group. These shelf terrigenous units extend nearly to the shelf-margin crest (Neese and Schwartz, 1977), but there is little direct evidence of how terrigenous sediment was transported through the carbonate shelf-margin and into the basin.

LITHOLOGY OF THE DELAWARE MOUNTAIN GROUP

Two main rock types are present in the Delaware Mountain Group: coarse siltstone (fig. 2) and very fine-grained sandstone (fig. 3). Despite the small difference and gradation in mean grain size between these two rocks, distinction generally is easy because of contrasts in sedimentary structures, stratification, organic content and weathering. Siltstone and sandstone are estimated to account for greater than 95 percent of the total rock volume of the Bell Canyon Formation. It is important to note that there is practically no clay shale in the Delaware Mountain Group. The lack of clays greatly affects mechanisms of sediment dispersal and the diagenetic history of these rocks.

Siltstone

Siltstone is the most abundant rock type in the Delaware Mountain Group. Approximately 60 to 70 percent of the upper Bell Canyon Formation is siltstone as estimated from measured sections and subsurface mapping. Three major variations in siltstone are recognized: 1) evenly laminated, sandy coarse siltstone (fig. 2A); 2) bioturbated, sandy coarse siltstone (fig. 2B); and 3) highly organic, clayey medium to coarse siltstone. All types are gradational with one another.

The siltstone is subarkosic and commonly contains 5 to 30 percent very fine sand-sized grains. Clay minerals, micas and microcrystalline carbonate are minor components of most siltstone except for a few clayey or calcareous siltstones with abundant

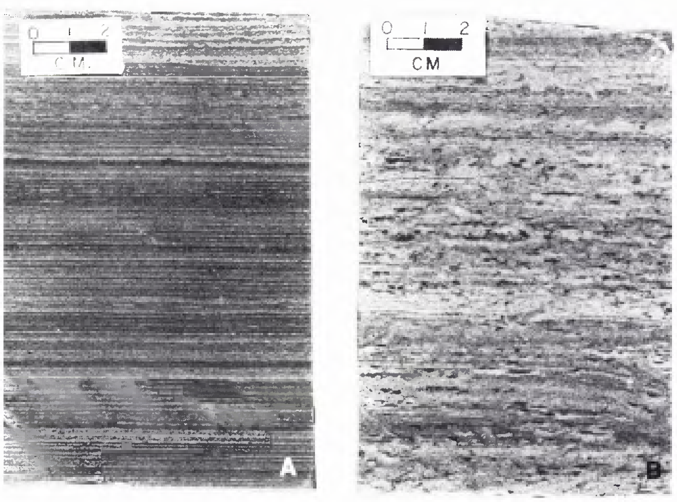

Figure 2. Core slabs of Bell Canyon Formation; A.—Laminated siltstone, B.—Lightly bioturbated siltstone.

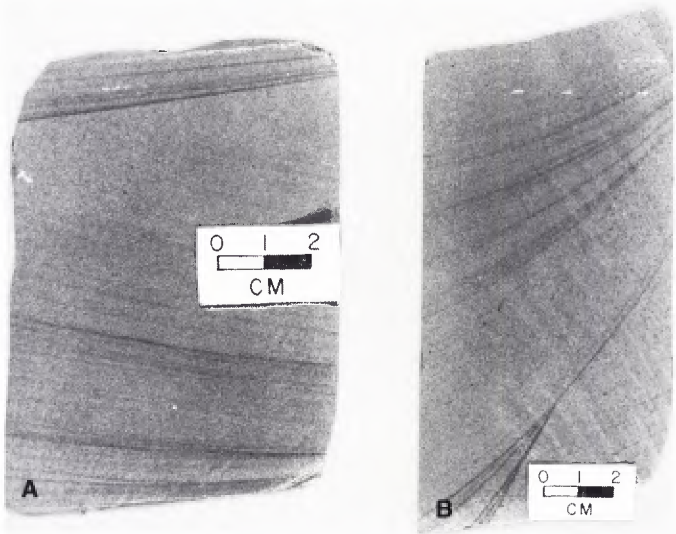

Figure 3. Core slabs of Bell Canyon Formation sandstone showing trough cross-stratification.

organic matter. Porosity ranges from less than 5 percent for the finer grained varieties to 22 percent for some weakly cemented, sandy coarse siltstones. Acid-insoluble organic matter from siltstone samples is mostly amorphous and unstructured. Residues contain abundant marine palynomorphs and pyrite with very little land-derived plant cuticle or woody fragments. Only the more buoyant types of land-derived palynomorphs such as bladdered conifer pollen are present.

The dominant structure of most siltstone is even parallel lamination. Well developed, parallel laminae in siltstone generally range from 0.2 to 2 mm in thickness and are the result of variations in texture and organic content. Light gray laminae are coarser and contain little organic matter whereas darker laminae contain far more and are composed of slightly finer silt grains. Individual laminae are graded, with increasing organic content upward. There is no discernible textural grading of the quartz and feldspar fraction within siltstone laminae or beds.

Most siltstone laminae are nearly horizontal and are parallel with interbedded sandstone. However, in some outcrops and cores, beds and laminae of siltstone are inclined at angles to the overall bedding. Laminae and beds of siltstone drape underlying erosional surfaces marking the margins of channels and also mantle ripple marks, convex-upward tops of sandstones, and small scours. In all examples, siltstone laminae and beds maintain a nearly constant lateral thickness and mimic the configuration of underlying surfaces. In outcrop, mantling siltstone beds can be traced across channels and into interchannel areas with no appreciable change in thickness. The draping and mantling relations of siltstones over surfaces on which they rest was noted by Harms (1974) in outcrops of the Brushy Canyon Formation. Siltstone in the Bell Canyon Formation shows similar mantling relations in outcrop and can be inferred from subsurface data to drape large channels and extend into interchannel areas where it can be traced for several kilometers by log correlations.

Features of the siltstone indicate that sediment was deposited from suspension, largely unaffected by bottom currents. Evidence supporting settling from suspension is: 1) siltstone draping on underlying surfaces as a blanket of uniform thickness; 2) the regularity of delicate laminae, lateral continuity of siltstone units, and the general lack of evidence for bottom current activity; 3) abundance of laminated organic material rich in marine palynomorphs suggestive of very slow rates of deposition; and 4) individual graded silt-organic laminae in siltstone.

Sandstone

Sandstone in the Bell Canyon Formation is texturally submature, moderately to moderately well sorted, silty very fine-grained subarkose. Most samples contain 20 to 50 percent coarse silt grains. There is little variation in grain size or sorting, either laterally or vertically within the basin. The only grains coarser than medium sand are rare fossil fragments and angular siltstone clasts of intraformational origin. Sandstone is mineralogically similar to siltstone except that it generally contains less mica, clay and organic material than siltstone. Most sandstone is weakly cemented by calcite and small amounts of quartz and authigenic clay. Porosity values commonly are 20 to 25 percent and horizontal permeability values range from less than 0.1 md to 200 md.

Many outcrops and cores of sandstone show few visible sedimentary structures. The fine grain size of the sand, lack of clay-sized material and good sorting make recognition of stratification difficult. Most of the sandstone is not truly structureless, but is cross-stratified or horizontally laminated. Scattered occurrences of faint, trough cross-stratification and horizontal lamination are common in otherwise "structureless" sandstone cores and outcrops, and X-radiography of 45 randomly chosen structureless slabs from 25 wells revealed faint horizontal or cross-stratification on 70 percent of the samples. Some sandstones probably do lack stratification, but these are less common.

CHANNELS AND SANDSTONE GEOMETRY

Outcrop and subsurface studies show that the configuration of submarine channels is the primary control of sandstone geometry in the Bell Canyon Formation. Most sandstone beds are confined to channels whereas siltstone beds extend across channels and into interchannel areas. Two main types of sandstone-filled channels are present: 1) broad (1-3 km), shallow (less than 5 m), subparallel, overlapping channels and 2) deep (20 m to greater than 35 m), flat-floored, elongate channels with maximum channel depths from 2 km to greater than 8 km at the basinward ends.

The shallow channels are exposed in outcrop and can be inferred from subsurface data. Sandstone geometry is a thin, sheetlike discontinuous sandstone body that is a complex of many different amalgamated sandstone beds and thin siltstone beds which separate the sandstones. Sandstones appear to be laterally continuous along many kilometers of outcrop in Culberson County (figs. 4 and 5), other than for local erosional relief along the bases of beds. The channel relations can be seen only in well exposed, continuous outcrops. More proximal channels are exposed in Delaware Mountain Group outcrops along U.S. Route 180 (Jacka and others, 1968) and the west face of the Guadalupe Mountains (fig. 6) as described by Harms (1974). The apparent lack of channels in many Bell Canyon outcrops located farther basinward is the result of the limited size of the exposures relative to channel dimensions, low angles of truncation at margins of channels and complex amalgamation of sandstones which obscures outlines of individual channels. The presence of thin, sheetlike sandstone-filled channels similar to those observed in outcrop can be inferred from the regional sandstone isolith map prepared from subsurface data (fig. 7). The basinward-thinning sheet of sandstone (less than 20 ft or 6 m) which separates thicker northeast-southwest trends (fig. 7) probably is analogous to the overlapping, shallow channels observed in outcrop (fig. 5).

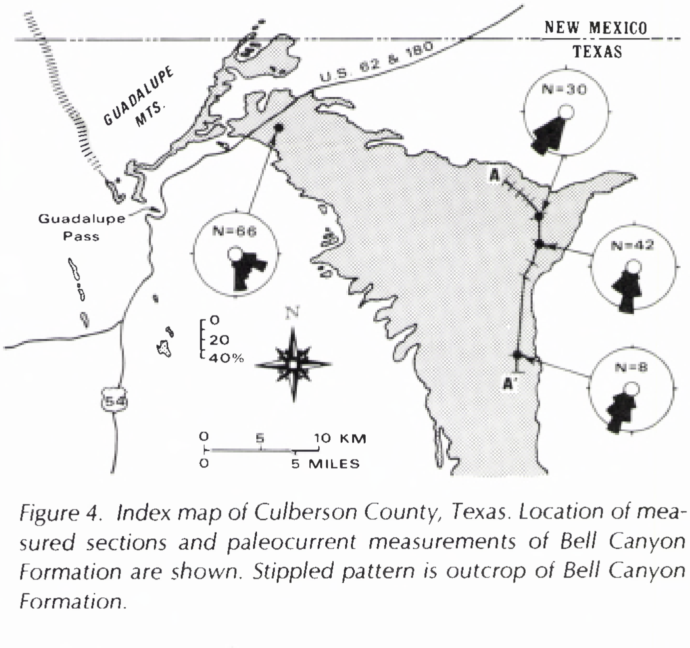

Figure 4. Index map of Culberson County, Texas. Location of measured sections and paleocurrent measurements of Bell Canyon Formation are shown. Stippled pattern is outcrop of Bell Canyon Formation.

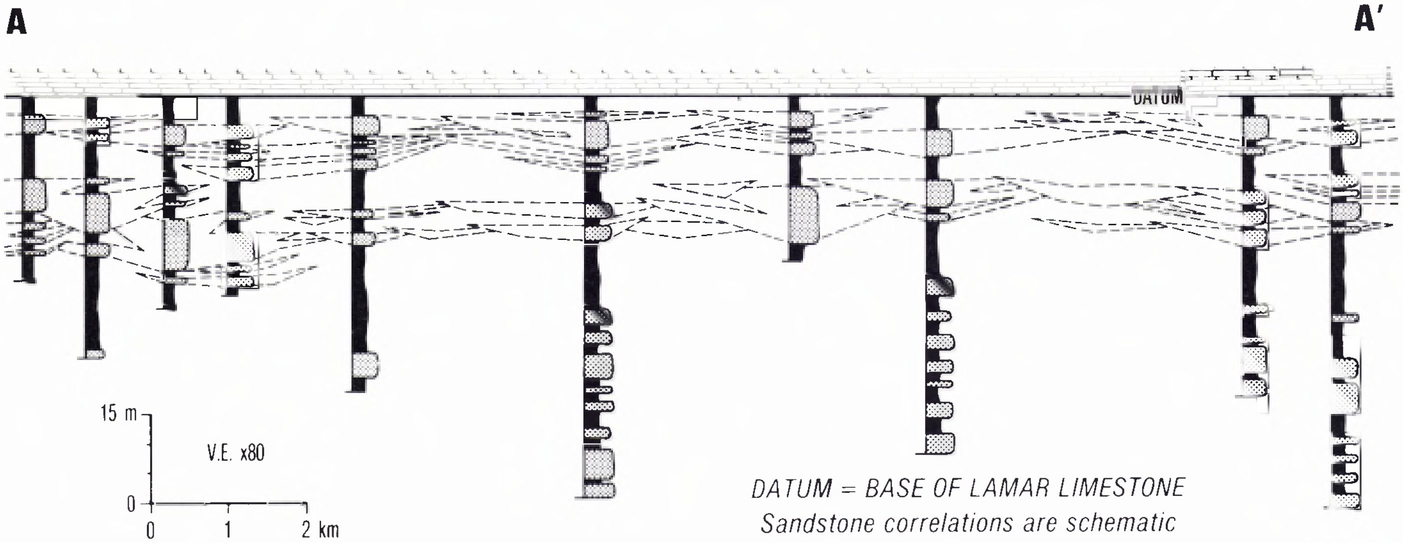

Figure 5. Stratigraphic cross-section for upper part of Bell Canyon Formation, Culberson County, Texas. See Figure 4 for location.

The northeast-southwest trend of thick sandstones (greater than 20 ft or 6 m) shown on the regional "Ramsey" isolith map (fig. 7) marks the axes of deep, broad erosional submarine channels that have been filled by porous, massive sandstone and lesser amounts of siltstone. The major input of sand was clearly from the northern shelf. This map represents a simplified, more interpretive version of an original map (Williamson, 1979) which was based on 700 gamma-ray/sonic logs and 45 conventional cores. The deep channels extend far into the basin (at least 70 km from the shelf edge) and are the major stratigraphic controls of oil accumulations in the northern Delaware Basin. Oil fields are aligned along these sandstone-filled channels.

Detailed studies of cores and mechanical logs from several Delaware Mountain Group fields confirm the presence of sandstone-filled channels (Payne, 1976; Weinmeister, 1978; Williamson, 1978; Berg, 1979; Cromwell, 1979). The channel dimensions are best defined by the zero sandstone isolith where closely spaced well control is available. A sandstone isolith map and cross-section from the El Mar Field are shown (figs. 8 and 9) to illustrate the geometry of the channel fills. The El Mar and Grice fields are stratigraphic traps producing from the upper Bell Canyon Formation (mostly "Ramsey") at the basinward termination of the sand-fill channels.

SEDIMENTARY STRUCTURES AND STRATIFICATION

A large variety of sedimentary structures and stratification types occurs in Bell Canyon sandstone and siltsone. The same stratification types observed in outcrops are present in subsurface cores with approximately the same relative frequency of occurrence. The dominant stratification types in Bell Canyon sandstone are trough cross-stratification (fig. 3), asymmetric trough-filled scours, and horizontal lamination with lesser amounts of ripple- and megaripple-drift cross-lamination. Most "massive bedding" is found to be cross-stratified or horizontally laminated when x-radiographed.

The assemblages of stratification types and structures generally are similar for most Bell Canyon sandstones with the exception of a few sandstones that fill steeply incised channels near the shelf margin. A few of these sandstones show a different suite of structures related to episodic types of high-density sediment gravity flows generated on the steep shelf margin. Most sandstones of the Bell Canyon Formation, however, are characterized by tractively produced structures and stratification indicative of grain-by-grain deposition. Only a few of the massive beds probably are truly homogeneous and were rapidly deposited without time for development of any internal arrangement within the beds.

VERTICAL TRENDS IN TEXTURES AND STRATIFICATION

In the Bell Canyon Formation, structures and textural trends of sandstones show little regular vertical order (fig. 10). Sedimentation units generally are difficult to delineate in thick-bedded sandstone outcrops and cores. Where sedimentation units can be distinguished by intercalated siltstone drapes, erosive contacts, or basal zones of rip-up clasts, the units commonly range from 0.3 to several meters in thickness. More than 22 m of sandstone with no observable siltstone partings or obvious erosional surfaces within the sandstone are logged in one well near a channel axis. Presumably this does not represent one flow event but illustrates the difficulty of distinguishing individual sedimentation units in many of the thick sandstone beds.

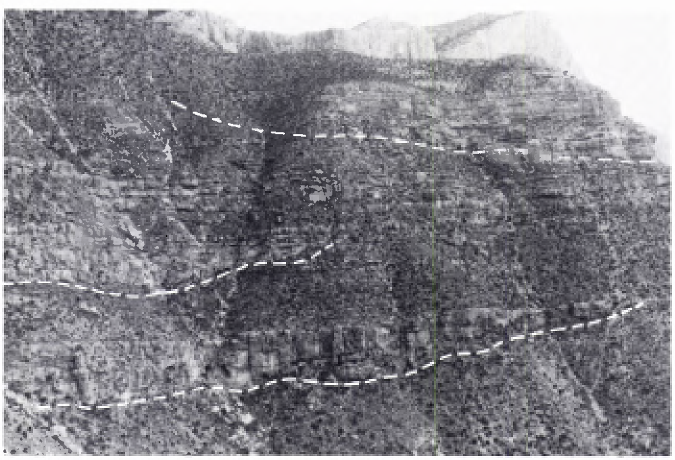

Figure 6. Channels in Cherry Canyon Formation, Shirttail Canyon, west face of the Guadalupe Mountains. Major erosional surfaces are dashed. Photo courtesy of Al Crawford.

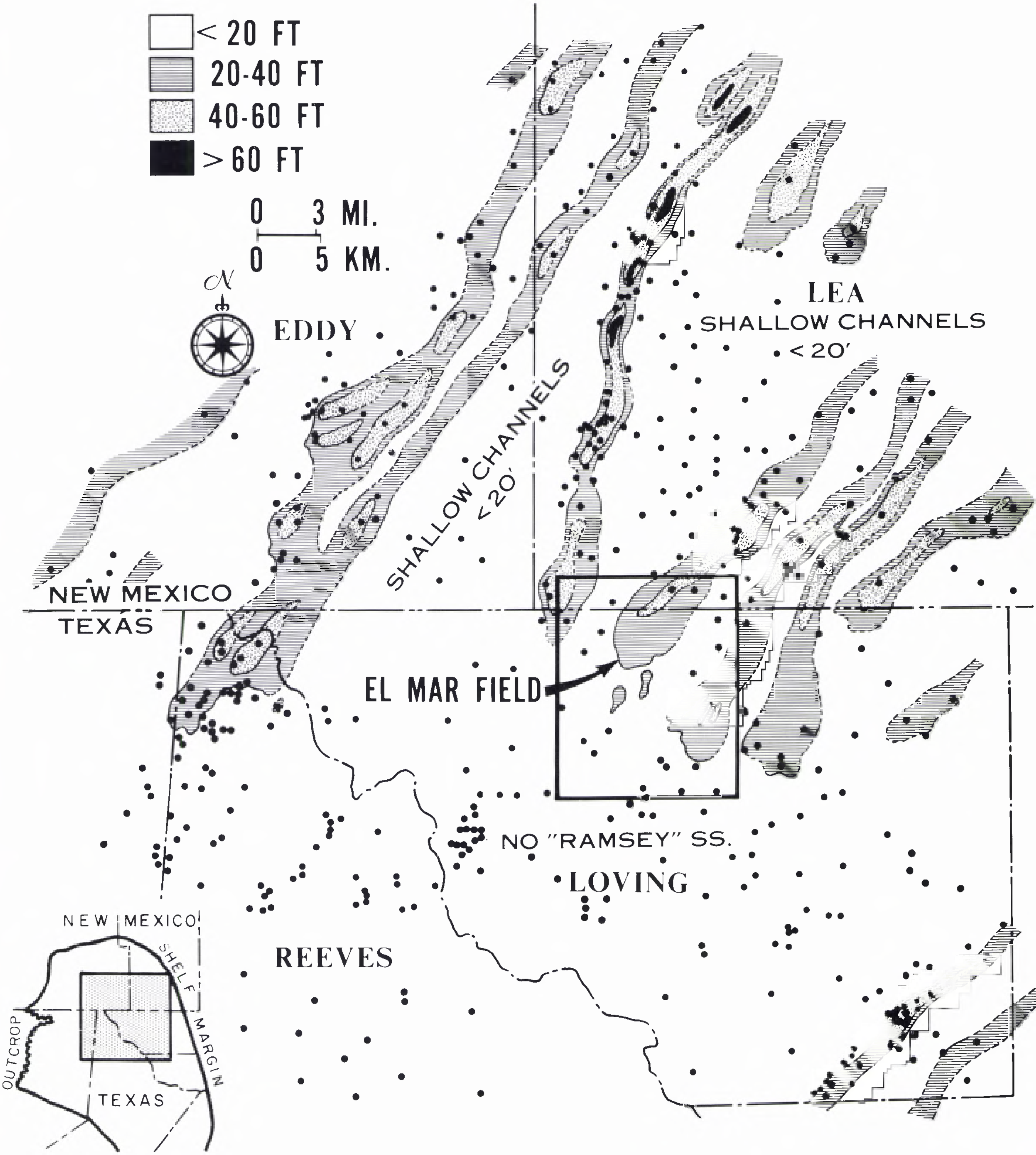

Figure 7. Regional sandstone isolith map of the "Ramsey" interval, Bell Canyon Formation. Map emphasizes interpretation of maximum northeast-southwest continuity of major channels. Approximately 700 well logs and 45 conventional cores provide control.

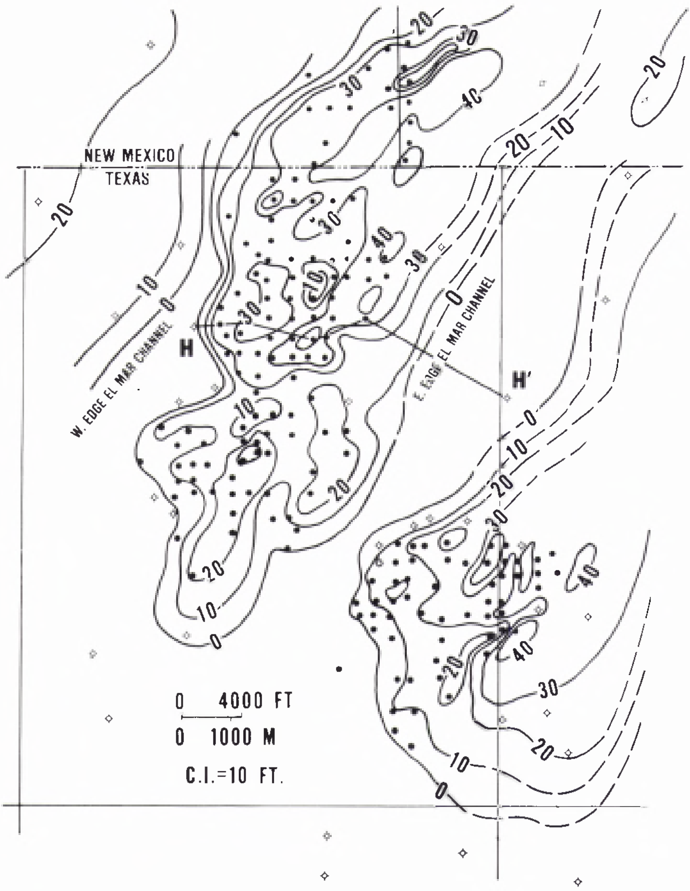

Figure 8. Sandstone isolith map of the "Ramsey" interval, El Mar and Grice Fields, Loving County, Texas, and Lea County, New Mexico. See Figure 7 for location.

Texturally graded beds are present but are rare in Delaware Mountain Group sandstone; most are thin beds (less than 0.5 m) in the upper parts of channel-fill sequences. Sedimentation units commonly have a pebble zone of siltstone rip-up clasts concentrated at their bases; however, there is no regular upward decrease in the size of the clasts or proportion of matrix, nor are the clasts always concentrated exclusively at the bases of sedimentation units. Clasts commonly are aligned along horizontal planes throughout the entire thickness of sandstone, and their occurrence is not adequately explained by size and density segregation during deposition from a turbulent suspension.

The vertical arrangement of stratification types does not indicate deposition by currents with steadily waning velocities. Changes from upper to lower and lower to upper flow regimes were common as evidenced by uninterrupted alternations between cross-lamination and megaripple-drift cross-lamination, and horizontal lamination. Irregular fluctuations in velocity and flow strength are recorded by unordered vertical sequences of stratification within sedimentation units. Dispersed gravel-sized siltstone clasts aligned along stratification planes and cross-stratified and rippled beds several meters thick attest to frequent fluctuations in flow strength and current competency.

DISCUSSION OF DEPOSITIONAL PROCESSES

Many processes have been invoked to explain the transport of sand and silt into the Delaware Basin: turbidity currents (Newell and others, 1953; Hull, 1957; Jacka and others, 1968; Silver and Todd, 1969; Meissner, 1972; Payne, 1973; Berg, 1979), wind (Adams, 1936; Hull, 1957), debris flows and submarine slides (Newell and others, 1953; Rigby, 1958), suction currents (Jacka and others, 1968), undertow (King, 1948) and cold or saline density currents (Harms, 1968, 1974; Jacka and others, 1968; Motts, 1972, Payne, 1973). It has been generally recognized that the Delaware Mountain Group does not display the same assemblage of sedi-

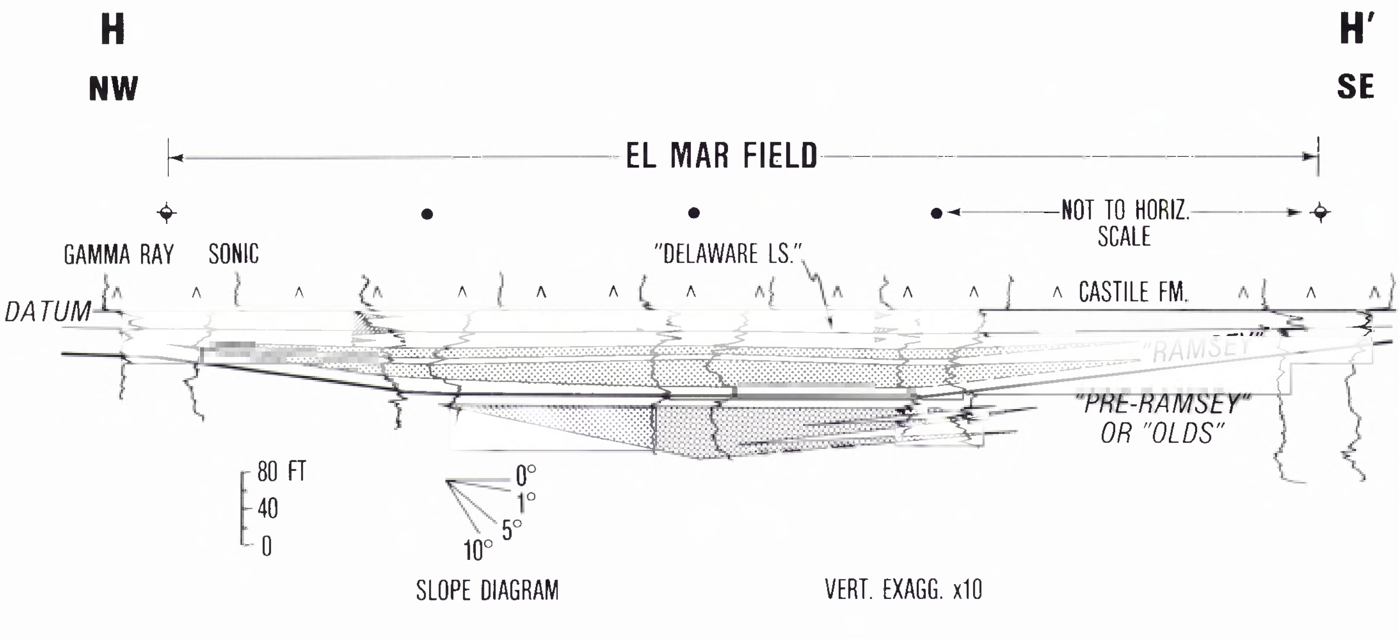

Figure 9. Well log cross-section, El Mar Field, Loving County, Texas. Stippled pattern indicates sandstone. Line of section shown in Figure 8.

mentary structures and facies commonly present in deep-water submarine fans. Harms' (1968, 1974) study of the Brushy Canyon Formation led him to propose that silt and sand was transported mainly by nonturbid cold or saline density currents which flowed basinward from shelf areas, eroded submarine channels and deposited silt and sand in the basin. This type of mechanism best explains the features observed in the Bell Canyon Formation (fig. 11). Density currents flowed into a density-stratified basin and transported silt and sand as density interflows which sheared off and moved along density stratification planes (to deposit silt from suspension) or underflowed as bottom-hugging currents (to cause channel erosion and sand deposition) depending upon the density contrast between the flow and basin waters. Channels were cut by density underflows and subsequently filled in a complex unordered way by silt deposited from suspension and sand carried along the floors of the channels.

The even parallel lamination in Delaware Mountain Group siltstone was caused by episodic peaks in the delivery of coarse-grained sediment to the basin which probably was related to a greater incidence of storm activity during certain seasons. The highly organic, finer grained layers represent normal background slow rates of suspension sedimentation in an oxygen-starved, restricted basin. The coarser layers were deposited by suspension fallout from weak horizontal currents (less than 10 cm/sec) that flowed at intermediate levels in the water column along density stratification planes.

Interpreted flow characteristics of currents transporting sand into the Delaware Basin differ from those attributed to turbidity currents or other types of sediment-gravity flows. Sand deposited by turbidity currents generally shows a more regular vertical sequence of structures and textures indicative of deposition from high-velocity episodic currents with an abrupt onset, and gradually decelerating flow. Sedimentation units commonly are texturally graded and seldom have such abundant large-scale cross-stratification. Structures and features of Bell Canyon sandstones suggest deposition from lower velocity, more long-lived types of flows with frequent irregular fluctuations in velocity. Vertical trends of textures and structures in sedimentation units and sandstone beds record frequent variations in flow regime with no apparent breaks in sedimentation. Sedimentation units rarely are texturally graded nor do they fine upward into overlying siltstone. Sedimentation units are thick and there are few proximal to distal changes in the basin.

The lack of prominent proximal to distal facies changes and changes in bed thickness in sandstone suggests that currents flowed more continuously and were able to minimize facies differences along channels, as in many fluvial systems. Sediment was moved largely as bedload, and there was adequate time for large bedforms to develop. The prevalence of traction-produced stratification indicates that much of the sediment was transported by bedload rolling, sliding and saltation. Some discrete, thin-bedded sedimentation units show textural grading and a more regular vertical sequence of small-scale structures suggestive of deposition from steadily waning flow. These turbidites are at the tops of channel fills and in interchannel areas and represent only a few percent of observed sandstones.

No modern analogue is known for the type of basinward-flowing density currents proposed here. In some glacial lakes, deposition from nearly continuous cold-water density underflows with irregular variations in flow velocity, produces thick sequences of tractively stratified silt and sand (Jopling and Walker, 1968; Stanley, 1974). These processes and deposits are similar in many respects but on a much smaller scale than what I envision for the Delaware Mountain Group. Rapid rates of aggradation are recorded in the glaciolacustrine deposits by a variety of climbing ripples. There is no regular vertical order to stratification. Graded beds are rare. Flows generally are less than 100 cm/sec, and sand and silt are carried largely as bedload. Flow units are thick and many fluctuations

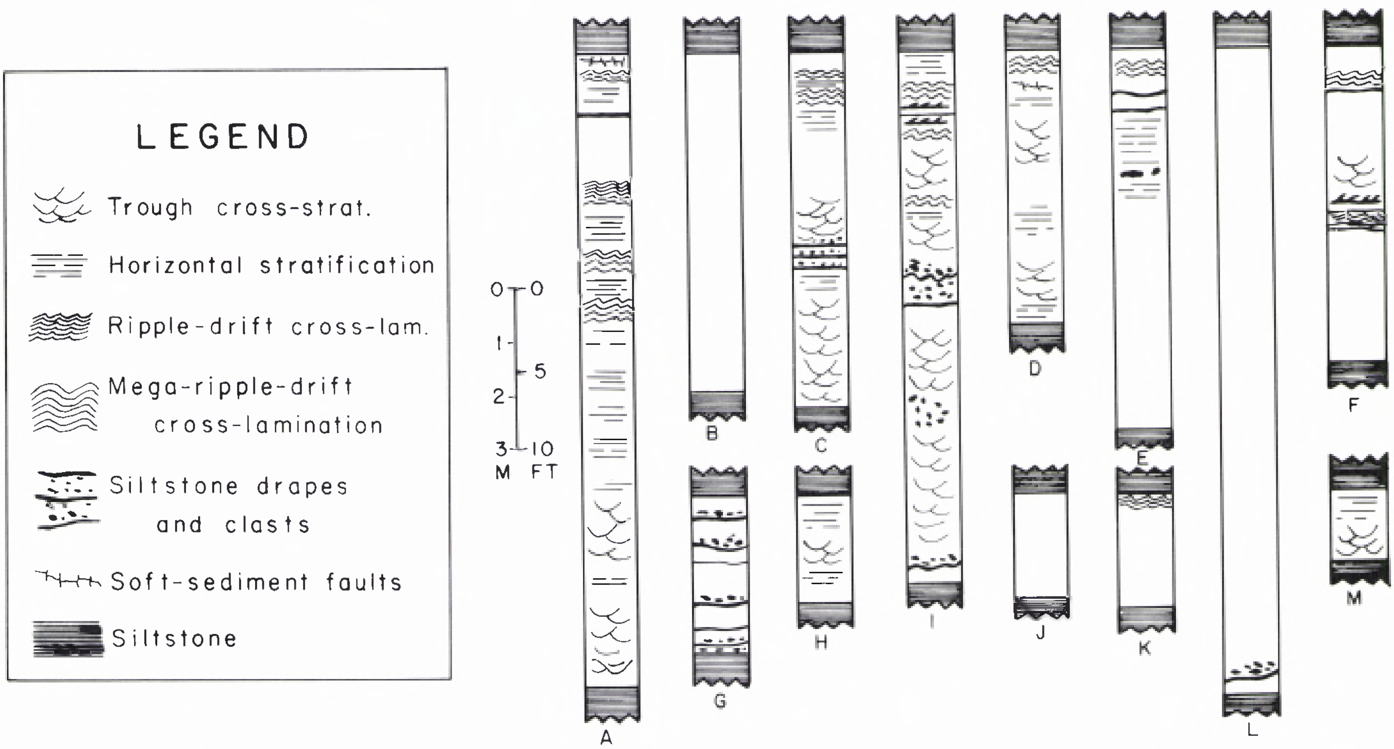

Figure 10. Representative vertical sections of sedimentary structures in Bell Canyon sandstones from conventional cores.

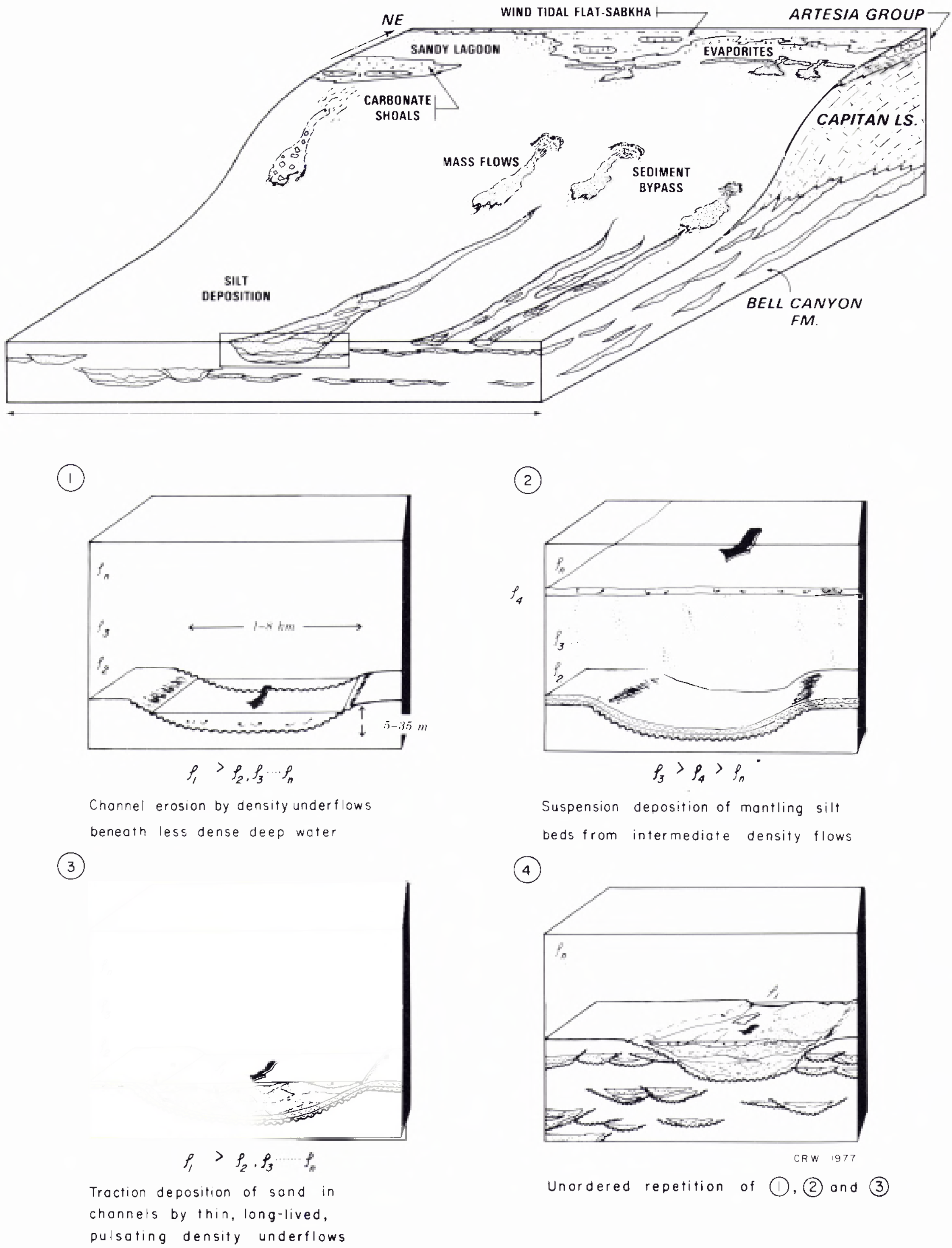

Figure 11. Depositional model for Bell Canyon Formation and inferred sequence of events leading to channel filling. Modified from Harms (1974).

in flow strength are recorded within the units. Periods of interflow across thermal stratification planes by intermediate density flows have also been observed in glacial lakes (Gustavson, 1975) and result in draped lamination and blanket suspension deposits of sand, silt and mud.

Density flows that deposited Delaware Mountain Group sediments probably were caused by increases in salinity as a result of evaporation. Density interflows and underflows could have been generated during ebb flow from saline lagoons following the passage of storms. The density and velocity of storm-generated flows would determine the level at which flow would leave the bottom and move horizontally across basin density stratification planes as interflows. Interflow of sediment-laden water along density stratification planes has been well documented in modern lakes and oceans (Drake and others, 1973; McCave, 1972; Gustavson, 1975); however, I am unaware of any examples of recent storm-generated saline density currents transporting sand-sized sediment into a euxinic basin. The ability of hurricanes and tropical storms to transport sand and silt seaward from lagoons has been documented by Hayes (1967) and Kumar and Sanders (1976), but I do not know of any modern facies tract comparable to the Guadalupian of the Delaware Basin where saline lagoons were perched near a steep shelf margin bordering a euxinic, deep-water basin.

ACKNOWLEDGMENTS

This study is part of a Ph.D. dissertation done at the University of Texas at Austin under the supervision of Dr. Earle F. McBride. John C. Harms, Alan J. Scott and Robert L. Folk read earlier versions of the manuscript. The research was partly supported by the Texas Petroleum Research Committee, Geological Society of America and Sigma Xi. Exxon Company, U.S.A. and Amoco Production Company provided base maps and access to cores.

REFERENCES

Adams, J. E., 1936, Oil pool of open reservoir type: American Association of Petroleum Geologists Bulletin, v. 20, p. 780-796.

Babcock, L. C., 1977, Life in the Delaware Basin: The paleoecology of the Lamar Limestone: Society of Economic Paleontologists and Mineralogists (Permian Basin Section), Publication 77-16, Field Conference Guidebook, p. 357-389.

Berg, R. R., 1979, Reservoir sandstones of the Delaware Mountain Group, southeast New Mexico: Society of Economic Paleontologists and Mineralogists (Permian Basin Section), Publication 79-18, Symposium and Field Conference Guidebook, p. 75-95.

Bozanich, R. G., 1979, The Bell Canyon and Cherry Canyon Formations, eastern Delaware Basin, Texas: Lithology, environments and mechanisms of deposition: Society of Economic Paleontologists and Mineralogists (Permian Basin Section), Publication 79-18, Symposium and Field Conference Guidebook, p. 121-141.

Collins, A. G., 1975, Geochemistry of oilfield waters: Amsterdam, Elsevier, 496 p.

Cromwell, D. W., 1979, Indian Draw Delaware field: A model for deeper Delaware Sand exploration: Society of Economic Paleontologists and Mineralogists (Permian Basin Section), Publication 79-18, Symposium and Field Conference Guidebook, p. 142-152.

Drake, D. W., Kolpack, R. L., and Fischer, P. J., 1972, Sediment transport on the Santa Barbara-Oxnard Shelf, Santa Barbara Channel, California, *in* Swift, J. P., and others (*eds.*), Shelf sediment transport: Process and pattern: Stroudsburg, Pa., Dowden, Hutchinson and Ross, p. 307-331.

Gustavson, T. C., 1975, Sedimentation and physical limnology in proglacial Malaspina Lake, southeastern Alaska: Society of Economic Paleontologists and Mineralogists, Special Publication 23, p. 249-263.

Harms, J. C., 1968, Permian deep-water sedimentation by nonturbid currents, Guadalupe Mountains, Texas: Geological Society of America, Abstracts for 1968, Special Paper 1221, p. 127.

———, 1974, Brushy Canyon Formation, Texas: A deep-water density current deposit: Geological Society of America Bulletin, v. 85, p. 1763-1784.

Hayes, M. O., 1967, Hurricanes as geological agents: Case studies of Hurricanes Carla, 1961, and Cindy, 1973: Texas Bureau of Economic Geology, Report of Investigations 61, 54 p.

Hull, J. P. D., Jr., 1957, Petrogenesis of Permian Delaware Mountain sandstone, Texas and New Mexico: American Association of Petroleum Geologists Bulletin, v. 41, p. 278-307.

Jacka, A. D., Beck, R. H., St. Germain, L. C., and Harrison, S. C., 1968, Permian deep-sea fans of the Delaware Mountain Group (Guadalupian), Delaware Basin: Society of Economic Paleontologists and Mineralogists (Permian Basin Section), Publication 68-11, Field Conference Guidebook, p. 49-90.

Jopling, A. V., and Walker, R. G., 1968, Morphology and origin of ripple-drift cross-lamination with examples from the Pleistocene of Massachusetts: Journal of Sedimentary Petrology, v. 38, p. 971-984.

King, P. B., 1934, Permian stratigraphy of Trans-Pecos Texas: Geological Society of America Bulletin, v. 45, p. 697-798.

———, 1942, Permian of West Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 26, p. 535-763.

———, 1948, Geology of the southern Guadalupe Mountains, Texas: U.S. Geological Survey Professional Paper 215, 183 p.

Kumar, N., and Sanders, J. E., 1976, Characteristics of shoreface storm deposits: modern and ancient examples: Journal of Sedimentary Petrology, v. 46, p. 145-162.

McCave, I. N., 1972, Transport and escape of fine-grained sediment from shelf areas, *in* Swift, J. P. and others (*eds.*), Shelf sediment transport: Processes and pattern: Stroudberg, Pa., Dowden, Hutchinson and Ross, p. 225-248.

Meissner, F. F., 1972, Cyclic sedimentation in Middle Permian strata of the Permian Basin: West Texas Gelogical Society Pub. 72-60, Cyclical sedimentation in the Permian Basin (2nd ed.), p. 203-232.

Motts, W. S., 1972, Geology and paleoenvironments of the northern segment, Capitan shelf, New Mexico and West Texas: Geological Society of America Bulletin, v. 83, p. 701-722.

Neese, D. A., and Schwartz, A. H., 1977, Facies mosaic of the upper Yates and lower Tansill Formations, Walnut and Rattlesnake Canyons, Guadalupe Mountains, New Mexico: Society of Economic Paleontologists and Mineralogists (Permian Basin Section), Publication 77-16, Field Conference Guidebook, p. 437-450.

Newell, D. A., Rigby, J. K., Fischer, A. G., Whiteman, A. J., Hickox, J. E., and Bradley, J. S., 1953, The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico: San Francisco, Freeman and Co., 236 p.

Oriel, S. S., Myers, D. A., and Crosby, E. J., 1967, West Texas Permian Basin region, *in* Paleotectonic investigations of the Permian System in the United States: U.S. Geological Survey Professional Paper 515-C, p. C17-C60.

Payne, M. W., 1973, Basinal sandstone facies of the Delaware Mountain Group, West Texas and southeast New Mexico (Ph.D. dissertation): Texas A&M University, College Station, 150 p.

———, 1976, Basinal sandstone facies, Delaware Basin, West Texas and southeast New Mexico: American Association of Petroleum Geologists Bulletin, v. 60, p. 517-527.

Rigby, J. K., 1958, Mass movements in Permian rocks of Trans-Pecos Texas: Journal of Sedimentary Petrology, v. 28, p. 298-315.

Silver, B. A., and Todd, R. G., 1969, Permian cyclic strata, northern Midland and Delaware Basins, West Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 53, p. 2223-2251.

Smith, D. B., 1974, Sedimentation of upper Artesia (Guadalupian) cyclic deposits of northern Guadalupe Mountains, New Mexico: American Association of Petroleum Geologists Bulletin, v. 58, p. 1699-1730.

Stanley, K. O., 1974, Morphology and hydraulic significance of climbing ripples with superimposed microripple-drift cross-lamination in lower Quaternary lake silts, Nebraska: Journal of Sedimentary Petrology, v. 44, p. 472-483.

Tyrrell, W. W., Jr., 1962, Petrology and stratigraphy of near-reef Tansill–Lamar strata, Guadalupe Mountains, Texas and New Mexico: Hobbs, Roswell and West Texas Geological Societies Guidebook, Publication No. 62-48, p. 59-75.

———, 1969, Criteria useful in interpreting environments of unlike but time-equivalent carbonate units (Tansill–Capitan–Lamar), Capitan reef complex, West Texas and New Mexico: Society of Economic Paleontologists and Mineralogists, Special Publication 14, p. 80-97.

Weinmeister, M. P., 1978, Origin of upper Bell Canyon reservoir sandstones (Guadalupian), El Mar and Paduca fields, southeast New Mexico and West Texas (M.S. thesis): Texas A&M University, College Station, 96 p.

Williamson, C. R., 1978, Depositional processes, diagenesis and reservoir properties of Permian deep-sea sandstones, Bell Canyon Formation, Texas–New Mexico (Ph.D. dissertation): University of Texas, Austin, 261 p.

———, 1979, Deep-sea sedimentation and stratigraphic traps, Bell Canyon Formation (Permian), Delaware Basin: Society of Economic Paleontologists and Mineralogists (Permian Basin Section), Symposium and Field Conference Guidebook, Publication 79-18, p. 39-74.

Sand dropseed plant and spikelet, *Sporobolus cryptandrus*.