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Deep-Water Density Current Deposits of Delaware Mountain Group (Permian), Delaware Basin, Texas and New Mexico[1]

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ABSTRACT

The Guadalupian Delaware Mountain Group is a 1,000-1,600-m (3,281-5,250-ft) thick section of siltstone and sandstone deposited in a deep-water density-stratified basin surrounded by carbonate banks or reefs and broad shallow evaporite-clastic shelves. The most prevalent style of basinal deposition was suspension settling of silt. Laminated siltstone beds are laterally extensive and cover basin-floor topographic irregularities and flat-floored channels as much as 30 m (99 ft) deep and 1 km or more wide. Channels can be observed in outcrop at the basin margin and can be inferred from closely spaced wells in the basin. The channels are straight to slightly sinuous, trend at high angles to the basin margin, and extend at least 70 km (43 mi) into the basin. Sandstone beds, confined to channels, form numerous stratigraphic traps. Hydrocarbon sealing beds are provided by laminated organic siltstone, which laterally can form the erosional margin where channels are cut into siltstone beds. Thick beds of very fine-grained sandstones fill the channels. These sandstones contain abundant large and small-scale traction-current–produced stratification. These sandy channel deposits generally lack texturally graded sedimentation units and show no regular vertical sequence of stratification types or bed thickness.

Outcrop and subsurface evidence indicates Delaware Mountain Group sediments were deposited by saline density currents. Dense saline water originated on evaporitic shelves and spilled across the carbonate rim, down steep marginal slopes, and into the basin. Basinal waters were density stratified. Denser flows moved along the basin floor cutting channels or depositing sand in existing channels; less-dense flows moved along density interfaces in the water column and carried silt-size material far into the basin where it settled to the floor as thin alternating layers of detrital silt and organic debris. Little proximal to distal change occurred in the size or nature of the channels. Exploration predictions based on submarine fan models formed by turbidity currents would anticipate very different proximal-distal changes in sandstone geometry and facies.

INTRODUCTION

During the middle Permian (Guadalupian) the Delaware basin was a nearly circular basin approximately 160 km (100 mi) in diameter. The deeper water central basin was rimmed by banks and reefs adjacent to broad shallow-water shelves, lagoons, sabkhas, and alluvial plains. Approximately 1,000-1,600 m (3,281-5,250 ft) of terrigenous silt and sand of the Delaware Mountain Group (Guadalupian) (Figure 1) was deposited in the central basin, where water depths are estimated to have been 300-600 m (984-1,969 ft) (King, 1948; Newell et al, 1953; Meissner, 1972; Harms, 1974; Crawford, 1979).

Previous sedimentological studies of the three Delaware Mountain Group formations (Brushy Canyon, Cherry Canyon, and Bell Canyon) (Harms, 1968, 1974; Jacka et al, 1968; Payne, 1976; Williamson, 1978, 1979; Berg, 1979; Bozanich, 1979) have generated much controversy regarding depositional processes. This paper summarizes primarily outcrop and subsurface data from the Brushy Canyon and Bell Canyon Formations (Harms, 1968, 1974; Williamson, 1977, 1978, 1979), and draws on other recent studies of the Delaware Mountain Group and time-equivalent shelf facies to interpret their depositional processes.

We conclude that the basinal sediments of these formations were deposited by saline density currents (Figure 2). Dense shelf water spilled through channels in surrounding carbonate banks, flowed down marginal slopes, and along the basin floor. The denser flows cut channels or deposited sandstone beds confined to channels. At other times, less-dense shelf water spread over more-dense stagnant basin water, as density interflows and rained suspended silt over the basin floor. As a result, the rocks show a distribution of facies, geometry of sandstone units, and vertical arrangement of textures and structures different from rocks common to turbidity currents and submarine fans dominated by episodic sediment-gravity flows. Sandstone mostly is confined to nonbranching linear channels, which form numerous stratigraphic traps. The geometry and trend of channel fills are directly related to the depositional mechanism. One must understand the origin of the channels and the channel fill to better define exploration objectives and aid in develop-

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and siltstone. Erosional channels filled with lime mudstone in a style similar to Delaware Mountain Group channel fills suggest that density current processes were important in the Leonardian as well as in the Guadalupian (Harms and Pray, 1974). The Ochoan Series overlying the Delaware Mountain Group reaches a maximum thickness of about 550 m (1,804 ft) and consists mainly of evaporites with increasing amounts of red siltstone in the younger rocks. Evidence indicates that the varved evaporite units of the Castile Formation were abruptly deposited in fairly deep unagitated water in a restricted basin (Anderson et al, 1972; Dean and Anderson, 1982).

Shelf-To-Basin Sediment Supply

One of the most perplexing problems of Delaware basin stratigraphy is the relationship of shelf to basin terrigenous sediments. The thin widespread siltstone and sandstone units of the Artesia Group are believed to represent sediment supply routes for the petrographically similar siltstones and sandstones of the Delaware Mountain Group (Hull, 1957). These shelf units extend nearly to the shelf-margin crest, but few indications exist of how terrigenous sediment was transported through the carbonate shelf margin and down the slope. The origin of the shelf clastics and their relations to basinal sedimentation have generated a great deal of discussion regarding the influence of tectonics and sea level changes on sedimentation. One hypothesis states that the alternations of carbonate and terrigenous rocks on the shelf represent great fluctuations in sea level (10s to 100s of meters). According to this scenario, terrigenous sediments were spread across the shelf and into the basin during lowstands of sea level (Jacka et al, 1968; Meissner, 1969, 1972; Silver and Todd, 1969; Dunham, 1972). More recently, Pray (1977) proposed that the lack of emergence indicators in the Capitan (J. A. Babcock, 1977; Yurewicz, 1977) and the evidence for subaqueous deposition of shelf clastics and evaporites (Sarg, 1977) suggest that small sea level fluctuations (less than 0.5 m or 1.6 ft) satisfactorily explain sedimentation in the Guadalupian. Pray proposed that terrigenous clastics may have been supplied to the basin during maximum sea level by subaqueous currents originating from the spilling of saline lagoon waters.

We believe sufficient evidence exists to demonstrate contemporaneous carbonate and clastic deposition in a subaqueous environment at the outer shelf (Neese and Schwartz, 1977; Wheeler, 1977; Hurley, 1978; Crawford, 1981; McDermott and Scott, 1981). Great variations in sea level (10s to 100s of meters) are unnecessary to explain the observed sedimentation patterns. The mechanism for silt and sand transport and the conduit types that delivered sediment to the basin remain poorly explained, although recent studies have begun to resolve these problems (Crawford, 1981; McDermott and Scott, 1981).

At least three occurrences of terrigenous-filled slope-feeder systems have been recognized in outcrops of the Delaware Mountain Group: (1) a 100-m (328-ft) deep, 175 to 700-m (574 to 2,297-ft) wide channel filled with siltstone, sandstone, and conglomerate that probably is correlative with the Brushy Canyon Formation (Harms, 1974), (2) a "sheet" of Shattuck sandstone (a thin member of the Queen Formation), traceable across the shelf edge and 20-30 m (66-98 ft) down the foreslope separating the Capitan Limestone from the Goat Seep Dolomite (Crawford, 1981), and (3) basinward-trending channels (generally 35-m (115-ft) deep, 400-m (1,312-ft) wide) in the Cherry Canyon Formation sandstone tongue. These channels are transitional with shelf-edge facies of the Grayburg Formation and are filled with sandstone and allochthonous carbonate (McDermott and Scott, 1981).

Two of these occurrences are channel fills and are probably representative of the conduit types that delivered basin sediment. The sandstone sheet described by Crawford (1981) is interpreted to have been deposited where sand and silt spilled over a large area of the shelf margin. Stratigraphic relations at the basinward edge of the Shattuck spillover indicate that the shelf sandstones represent a relatively long time period, enough for at least 50 m (164 ft) of Goat Seep carbonate to prograde beyond the first sandstone that spilled over the shelf edge (Crawford, 1981). The distribution of sandstone in the subsurface (Williamson, 1978; Bozanich, 1979) suggests that both types of sediment delivery were important along various parts of the basin margin at different times.

LITHOLOGY OF DELAWARE MOUNTAIN GROUP

General

Siltstone and sandstone are the major lithologies of the Delaware Mountain Group. Limestone, dolomite, and conglomerate are estimated to comprise less than 5% of the total volume of Delaware Mountain Group rock in the basin, although these rock types are more common along the basin margins. Practically no clay shale occurs in the Delaware Mountain Group and siltstones and sandstones contain no significant detrital clay-size minerals. Dark fine-grained rocks resembling clay shale are actually fine-grained siltstone with abundant clay-size organic matter. In the Cherry Canyon and Bell Canyon Formations, most of the sandstone in outcrop and in the subsurface is very fine grained. Sandstones in outcrops of the Brushy Canyon Formation generally are fine-grained or very fine-grained, with granules or pebbles of older carbonate rock. The mineralogy, stratification types, fossils, and sedimentary structures in the Delaware Mountain Group formations generally are very similar.

Siltstone

Siltstone is the most common rock type in the Delaware Mountain Group. Siltstone comprises approximately 60-70% (estimate from measured sections) of the upper Bell Canyon Formation in the Delaware Mountains and the Brushy Canyon Formation along the western face of the Guadalupe Mountains (Figure 3). A comparable percentage of siltstone is estimated for the upper Bell Canyon Formation in the subsurface of the northern part of the basin. A higher proportion of sandstone and carbonate rocks is present within about a 20-km (13-mi) belt rimming the basin's edge. Bozanich (1979) noted that siltstone accounts for only about 25% of the section in the Cherry Canyon Formation within a 35-km (22-mi) band adjacent to the eastern shelf margin.

The dominant sedimentary structure in outcrops and cores of siltstone is even parallel light and dark laminae ranging from 0.2 to 2 mm (0.01 to 0.08 in.) thick (Figures 4A-C, 5A). Light-gray laminae are coarser grained and contain little organic matter, whereas darker laminae contain abundant organic matter and are composed of slightly finer silt grains. Individual laminae are graded in terms of organic material, with organic content increasing upward. No discernible textural grading of the quartz and feldspar fraction occurs within siltstone laminae or beds. The median diameter of the siltstone ranges from 10 μm to 60 μm. Laminated siltstone commonly contains 5-30% very fine grained sand having a maximum size of 0.1 mm (0.04 in.).

Most siltstone laminae are nearly horizontal and parallel with boundaries of interbedded sandstones. However, in some outcrops and cores, siltstone beds and laminae are locally inclined at angles to the overall bedding (Figures 4D, 6B). Siltstone laminae and beds drape underlying erosional surfaces, marking channel margins. Siltstone beds also cover ripple marks, convex-upward tops of sandstones, and small scours. In all examples, siltstone laminae and beds maintain a nearly constant thickness laterally and mimic the configuration of underlying surfaces. Relations of these siltstones are best observed on outcrops along the western face of the Guadalupe Mountains. The massive, nearly vertical exposures of this area show that siltstone beds drape the erosional outlines of channels and can be traced across channels into interchannel areas with no appreciable change in thickness (Figure 6B). Similar types of mantling relations can be observed on a smaller scale in outcrops in the Delaware Mountains. Laminated siltstone is interpreted from subsurface data to drape large channels and extend into interchannel areas (Williamson, 1978; Berg, 1979) where it can be traced for several kilometers by log correlations.

Features of the laminated siltstone indicate that sediment was deposited from suspension, largely unaffected by bottom currents. Evidence supporting this kind of origin include (1) siltstone drapes underlying surfaces as a uniformly thick blanket, (2) 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 enriched in marine palynomorphs, suggestive of very slow deposition rates, and (4) individual graded silt-organic laminae in siltstone.

The siltstone is subarkosic (15-25% feldspar), and similar in composition to the interbedded sandstone. Clay minerals, micas, and microcrystalline carbonate are minor components of most siltstone except for a few dark, clayey, or calcareous siltstones with abundant organic matter. Siltstone is cemented by sparry calcite with lesser amounts of authigenic clay, quartz, and feldspar. Porosity ranges from less than 5% for the finer grained varieties to 22% for some weakly cemented sandy coarse siltstones. Acid-insoluble organic matter from siltstone samples is mostly amorphous and unstructured kerogen. 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.

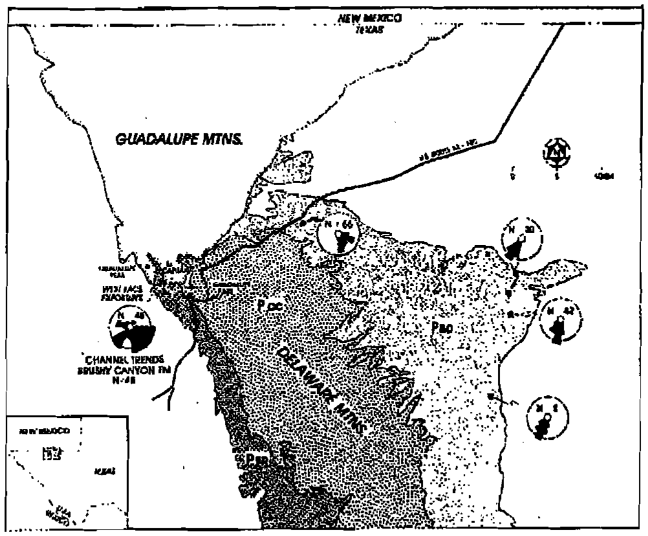

Figure 3—Simplified geologic map of Guadalupe and Delaware Mountains. Outcrop of Delaware Mountain Group is stippled. (PBR = Brushy Canyon, PCC = Cherry Canyon, PBC = Bell Canyon.) Paleocurrent measurements of ripple marks in Bell Canyon Formation in Delaware Mountains and channel trends in Brushy Canyon Formation along west face of Guadalupe Mountains are shown.

Source rock analyses of nine representative siltstone core samples from the upper part of the Bell Canyon Formation in the El Mar and Grice fields show large amounts of unstructured type II kerogen (terminology of Tissot and Welte, 1978). Total organic carbon (TOC) by weight ranges from 0.44 to 5.64% with a mean of 2.58%. Extractable organic matter ranges from 180 ppm (bioturbated, sandy coarse-grained siltstones) to 2,847 ppm (laminated fine-grained siltstone; Figure 5B) with a mean value of 1,513 ppm. The total C^{15+} hydrocarbon fraction ranges from 99 to 1,550 ppm (mean = 789 ppm). The Delaware Mountain Group siltstones seem to be good source rocks and are the most likely source for oils in the interbedded sandstones.

Even parallel laminae are by far the most prevalent structure in siltstones, although bioturbated (Figures 5C, D) siltstones are present at many levels. The degree of bioturbation ranges from slightly disrupted zones less than 1.0 cm (0.39 in.) thick to moderately churned zones several meters thick. Nearly all disruption of laminae is caused by crawling or browsing traces parallel with bedding (*Helminthoida* of the *Nereites* ichnofacies). Rare backfilled vertical burrows identified as *Zoophycus* have been reported from cores of the Cherry Canyon Formation (Bozanich, 1979). Rare occurrences of impressions

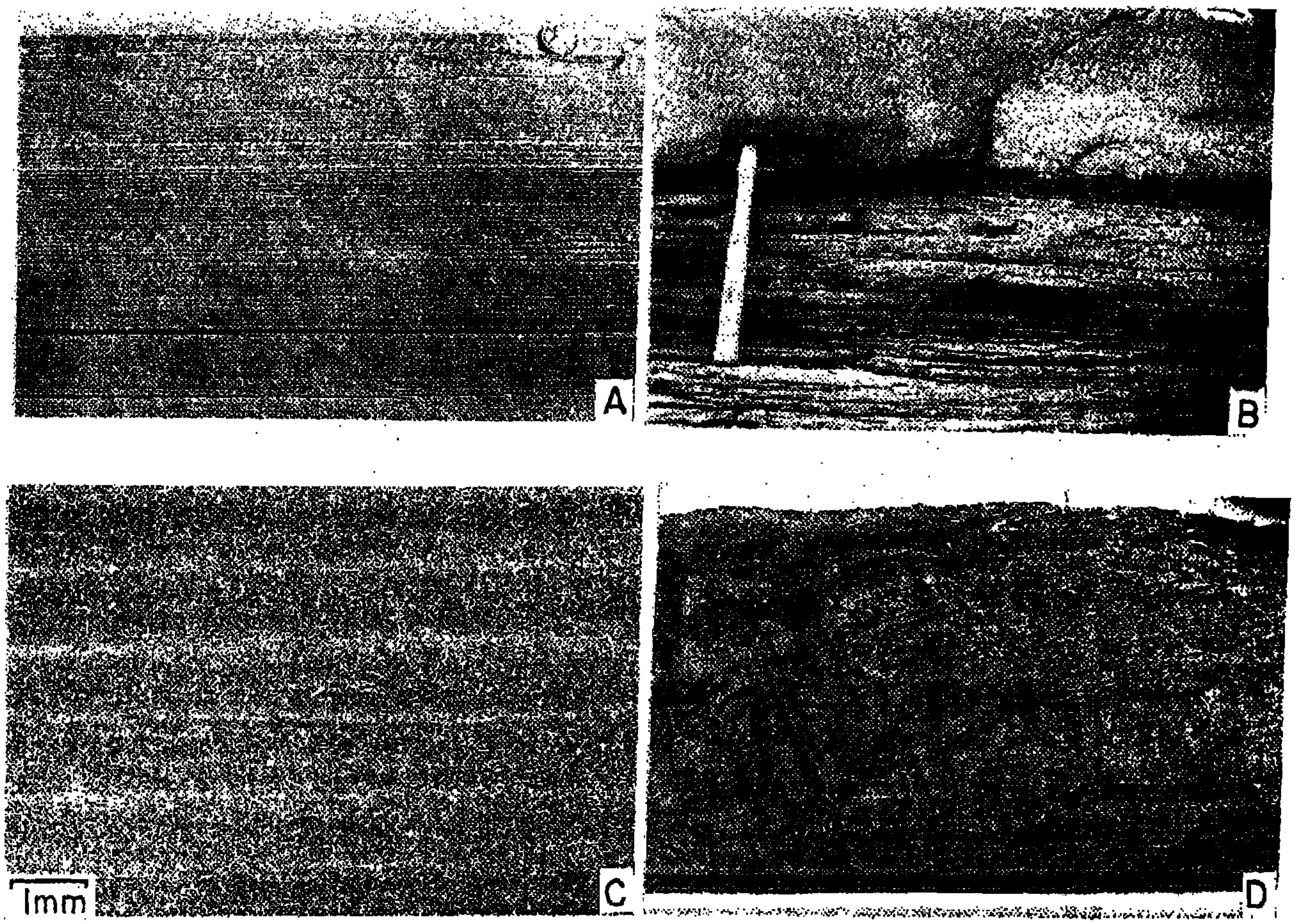

Figure 4—Laminated siltstones: (A) close-up of outcrop of laminated siltstone, Bell Canyon Formation, penny for scale; (B) sandstone-siltstone contact, Bell Canyon Formation; (C) negative print of thin section of laminated siltstone; organic-rich laminae (light colored) separate sandy, coarse silt laminae, Bell Canyon Formation; (D) siltstone-filled channel, Cherry Canyon Formation at Guadalupe Pass. Laminated siltstone is inclined as much as 25° and drapes the erosional margin of the channel.

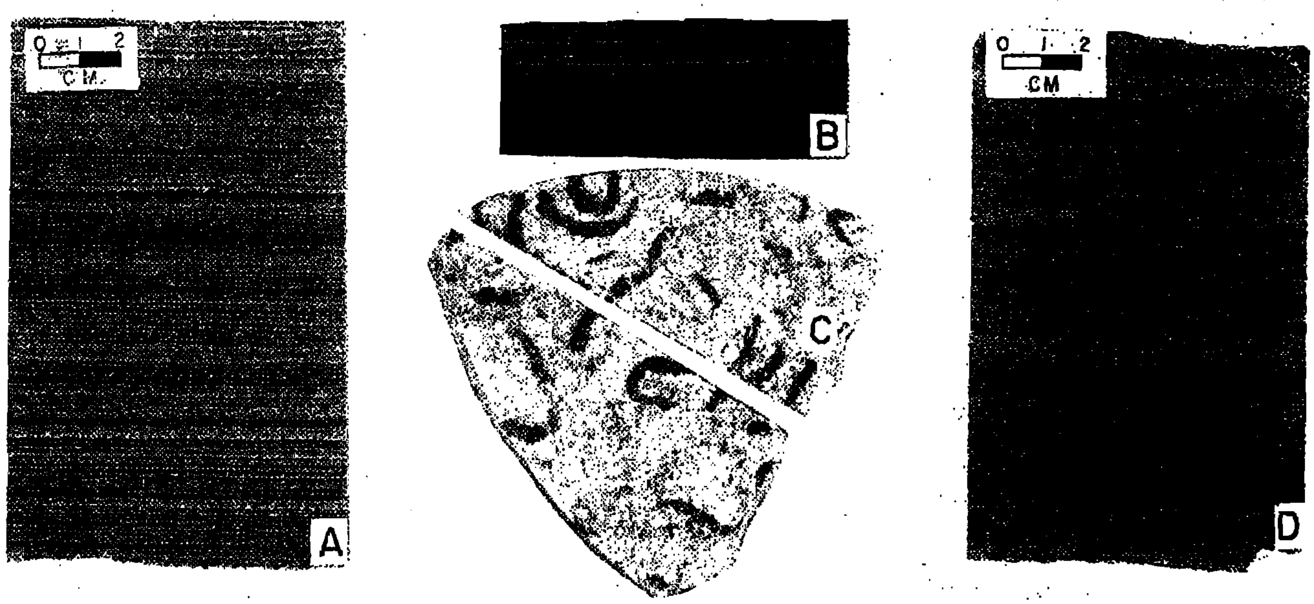

Figure 5—Cores of siltstone, Bell Canyon Formation. (A) Core slab of laminated siltstone typical of subsurface. Note similarity to outcrop (Figure 4A). (B) Organic-rich clayey siltstone. TOC typically is 3.5-5.0% in this lithology. (C) Carbonized crawling or browsing traces (*Helminthoida*) along siltstone bedding plane. (D) Bioturbated siltstone with slightly disrupted texture caused by bedding plane traces similar to Figure 5C.

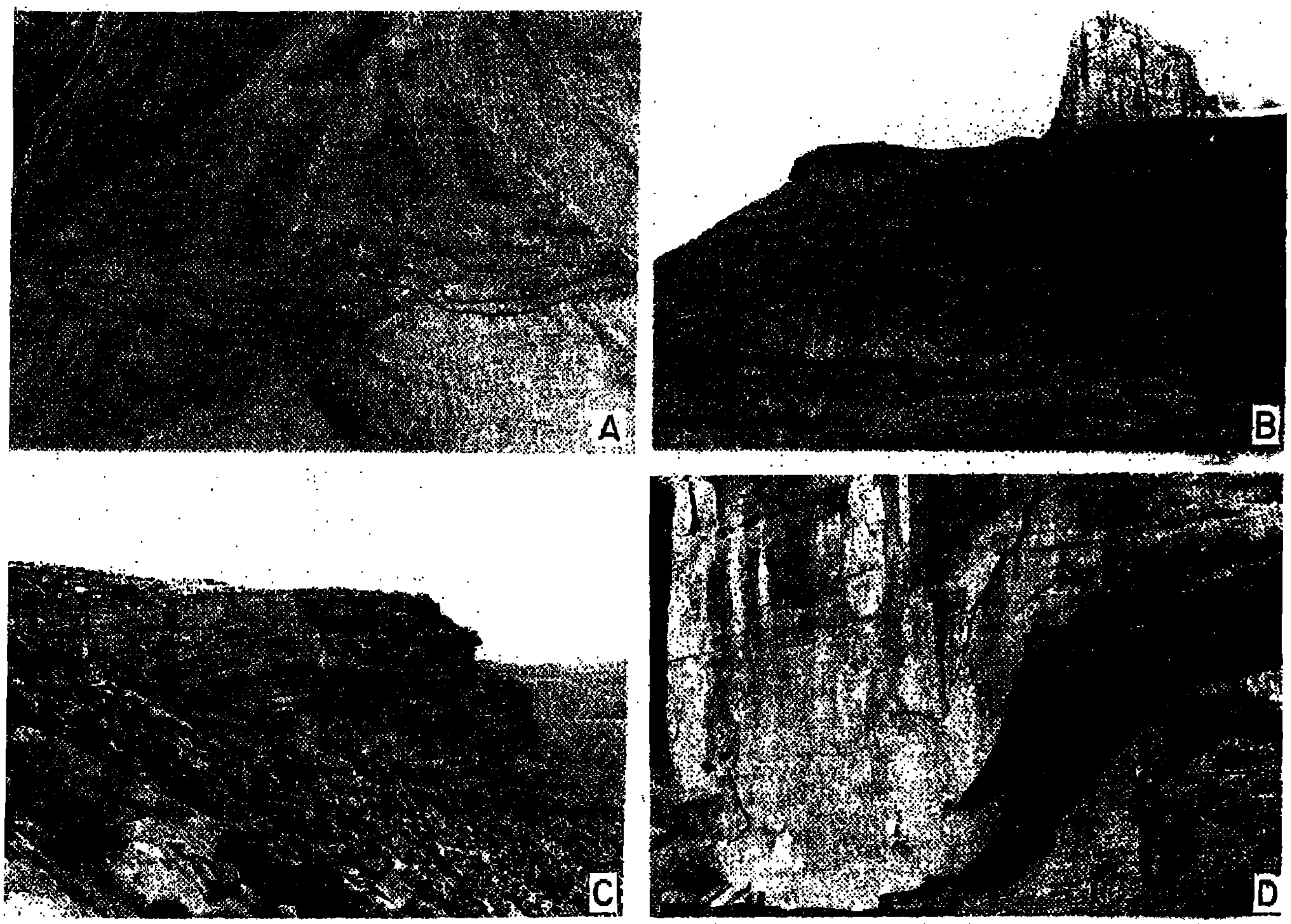

Figure 6—Channels in the Brushy Canyon Formation, Guadalupe Mountains. (A) Oblique aerial view of western face of Guadalupe Mountains showing positions of prominent erosion surfaces. (B) Covering beds of dark-gray siltstone diverge about abutting beds of sandstone. Siltstone beds drape and are parallel with channel erosional surfaces. (C) Flat-topped beds of sandstone abut steep channel wall. (D) Local scour within channel-fill complex.

of plants or soft-bodied organisms, including an excellently preserved worm impression (Williamson, 1978), have been found on outcrop. Bioturbated siltstone most commonly occurs immediately above and below sandstone-filled channels and in association with thin rippled zones in laminated siltstone. These associations suggest temporary aeration of bottom waters may have resulted from the rapid influx of more oxygen-rich surface water by currents transporting sand and silt.

Ripples are a common sedimentary structure in siltstone, but constitute only a few percent of the siltstone beds examined in cores and on outcrops. Most ripples occur within layers only one ripple-set thick and parallel with underlying laminations. Ripples are asymmetric, have rounded profiles, an average spacing of 8-10 cm (3.15-3.94 in.), heights less than 1 cm (0.39 in.), and long straight to slightly sinuous crests. Transport directions measured in outcrops are basinward at high angles to the adjacent shelf margin. The rippled zones are composed of well-sorted quartz silt that resembles the coarser fraction of underlying laminated units. These relations suggest that ripples formed by reworking and winnowing of unconsolidated laminated silt by basinward-flowing currents.

Sandstone

The distribution of sandstone in the Delaware Mountain Group is controlled by the positions of erosional channels. Sandstone-filled channels are well defined on outcrops (Figure 6), and can be mapped from subsurface data. Sandstone percentage depends upon the number and size of channels in any particular location rather than the proximity to the basin margin.

Most sandstones are texturally submature, moderately to well-sorted subarkoses. Cherry Canyon and Bell Canyon sandstones are silty and very fine grained. Maximum quartz or feldspar grain size generally is 0.25 mm (0.01 in.); mean grain size for 53 outcrop and core samples of Bell Canyon sandstones averages 0.09 mm (0.004 in.). Sorting (sigma 1) averages 0.58 phi. Most Bell Canyon sandstones contain 20-50% coarse silt grains. Approximately 40% of the Bell Canyon samples have a weak second mode of anomalously well-rounded medium-size sand grains that compose less than 2% of the sand fraction. These grains are probably reworked eolian or beach sand grains, which have been transported into the basin by bottom currents. Sand grains in the Delaware Mountain Group typically are subangular to subrounded.

Sandstones in the Cherry Canyon and Bell Canyon Formations generally contain 20-50% medium and coarse silt grains. Outcrops of Brushy Canyon sandstones tend to be slightly coarser grained with mean diameters in the very fine to fine sand-size range. Sandstones in the few cores available for the Brushy Canyon are very fine-grained and similar in texture to the Bell Canyon and Cherry Canyon sandstones.

The composition of framework grains for the Delaware Mountain Group sandstones varies little with stratigraphic or geographic position (Hull, 1957; Harms, 1974; Payne, 1976; Williamson, 1978; Berg, 1979; Watson, 1979). Quartz comprises 65-80% of the framework fraction, feldspar 10-25%, and sedimentary and the low-rank metamorphic rock fragments 5-15%. Carbonate rock clasts as large as pebbles or cobbles occur near the basin edge and angular siltstone rip-up clasts are common. Fusulinids and lesser amounts of other transported fossil fragments occur in all formations, but are most abundant in outcrops near the shelf margin.

Delaware Mountain sandstones generally are weakly cemented by calcite or dolomite and small amounts of quartz and authigenic clay. Porosity values are 15-25% in outcrops and in the subsurface. Less porous more tightly calcite-cemented sandstones are in beds with abundant transported skeletal grains and carbonate rock clasts. Horizontal permeability values range from less than 0.1 to 200 md. The amount of authigenic pore-lining chlorite and mixed-layer chlorite/smectite (corrensite) control permeability in Bell Canyon sandstones with porosity greater than 20% (Williamson, 1978). Small amounts of kaolinite and anhydrite cement have also been reported from Delaware Mountain Group reservoirs (Berg, 1979; Jacka, 1979). Petrographic and geochemical data indicate authigenic chlorite and small amounts of quartz and feldspar overgrowths formed during shallow burial (less than 1,000 m or 3,281 ft). Most calcite and dolomite cement precipitated later, and may have formed near present burial depths after the Tertiary tectonic tilting of the basin (Williamson, 1978).

Conglomerate and Limestone

Conglomerate and limestone beds compose a small fraction (less than 5%) of the Delaware Mountain Group, but form prominent outcrops along the southeastern and western faces of the Guadalupe Mountains. Spectacular carbonate megabreccias composed of large boulders (up to 4 m or 13 ft in diameter) of shelf-margin limestone mixed with basinal siltstone and sandstone, and interbedded with carbonate turbidites, form prominent marker beds in the Bell Canyon and Cherry Canyon Formations. The megabreccias occur within about 16 km (10 mi) of the shelf edge and were deposited by debris flows or other types of high-density gravity flows associated with steep basin slopes (Newell et al, 1953; Rigby, 1958; Crawford, 1981).

Massive conglomerate beds from 1-10 m (3.3-33 ft) thick occupy erosional depressions within the lower part of the Brushy Canyon Formation exposed on the western face of the Guadalupe Mountains. Clasts of carbonate rocks derived from the adjacent Permian shelf are up to 30 m (98 ft) in maximum dimension and interbedded with siltstone and sandstone. The conglomerates are poorly sorted, lack internal stratification, terminate laterally by onlapping against sloping boundaries, and may contain large boulders extending above the upper bed's surface. The conglomerates may have been emplaced by debris flows, but they lack basally aligned fabrics and steep marginal slopes. No single transport mechanism adequately explains the observed features. Similar types of conglomerates are not seen in other Delaware Mountain Group outcrops or in the subsurface.

Limestone beds, which thicken updip and are transitional with the Capitan and Goat Seep formations, have been used to stratigraphically subdivide the Bell Canyon and Cherry Canyon Formations into several members. The limestones grade basinward into dark calcareous siltstones and provide good correlation tools in the subsurface. Koss (1977) traced one of these limestone units in outcrop (Pinery Limestone Member of the Bell Canyon Formation) 23 km (14.3 mi) basinward. The sequence thins from 33 m (108 ft) at the basin margin to 6 m (20 ft) at the most basinward outcrop. The limestone beds commonly are texturally normally graded, have erosional bases, and have other structures indicative of turbidity current deposition. Calcareous beds present in cores taken farther basinward generally are organic-rich laminated silty dolomicrite or dolomitic siltstone. Resedimented skeletal debris rarely occurs in the central part of the basin.

CHANNELS AND SANDSTONE GEOMETRY

Sandstone-filled channels in the Delaware Mountain Group are well exposed in outcrop and form important subsurface hydrocarbon reservoirs. Prominent erosion surfaces with as much as 30 m (98 ft) of relief and 1 km (0.62 mi) or more in width occur in the Brushy Canyon and Cherry Canyon Formations along the western face of the Guadalupe Mountains (Figure 6). Smaller channels and partly exposed large channels can be identified throughout the Delaware Mountain Group in the more subdued topography of the Delaware Mountains to the east and southeast of the Guadalupe Mountains. The large channels formed by these prominent erosion surfaces have flat floors and steep walls, which commonly dip 10°-30°. Sandstone beds are restricted to channel floors and abut the steep channel walls, whereas siltstone beds extend across channel floors, slopes, and interchannel areas without appreciable changes in thickness. Not all channels are filled with sandstone. Most are filled in a complex unordered way with siltstone and sandstone. The channels in the Guadalupe Mountains trend southeastward, nearly perpendicular to the shelf margin (Figure 3). Directional features within the channel-filling sandstone also show basinward transport.

Sandstone- and siltstone-filled channels comparable in scale to those described from outcrops are present in the subsurface. The major sandstone-filled channels form stratigraphic traps where they are incised into less perme-

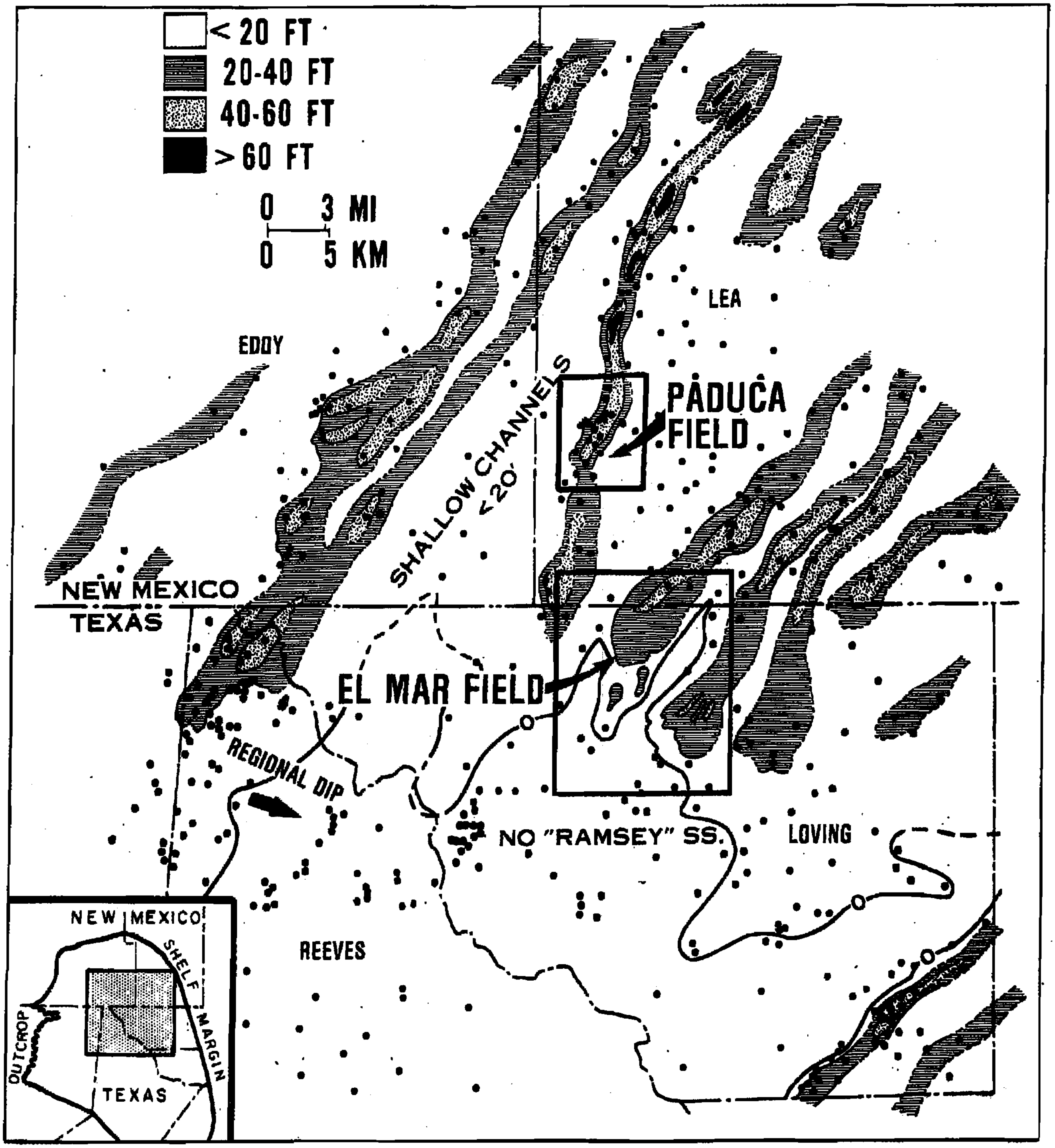

Figure 7—Regional sandstone isolith map of the Ramsey sandstone, upper Bell Canyon Formation. This map is a simplified interpretive version, which emphasizes the maximum northeast-southwest continuity of major channels. Approximately 700 gamma ray-sonic logs and conventional cores from 45 wells provide control.

able laminated siltstone. More than 150 fields have produced 138.8 million barrels of oil from the Delaware Mountain Group (Weinmeister, 1978). Most of the production is from the upper part of the Bell Canyon Formation, the most densely drilled interval in the Delaware Mountain Group. The geometry and style of channel fills on a regional and local scale are best illustrated by the Ramsey sandstone, the informally named uppermost thick sandstone of the Bell Canyon Formation (see Grauten, 1965, for a review of Bell Canyon subsurface stratigraphy). The Ramsey sandstone is the main producing unit in most fields and has the greatest amount of subsurface control.

A regional isolith map of the Ramsey sandstone(Figure 7) shows a prominent S15°W trend of thick sandstones (6-24 m or 20-79 ft) separated by a basinward-thinning "sheet" of interbedded thin sandstone and siltstone. The areas of thickest sandstone mark the axes of

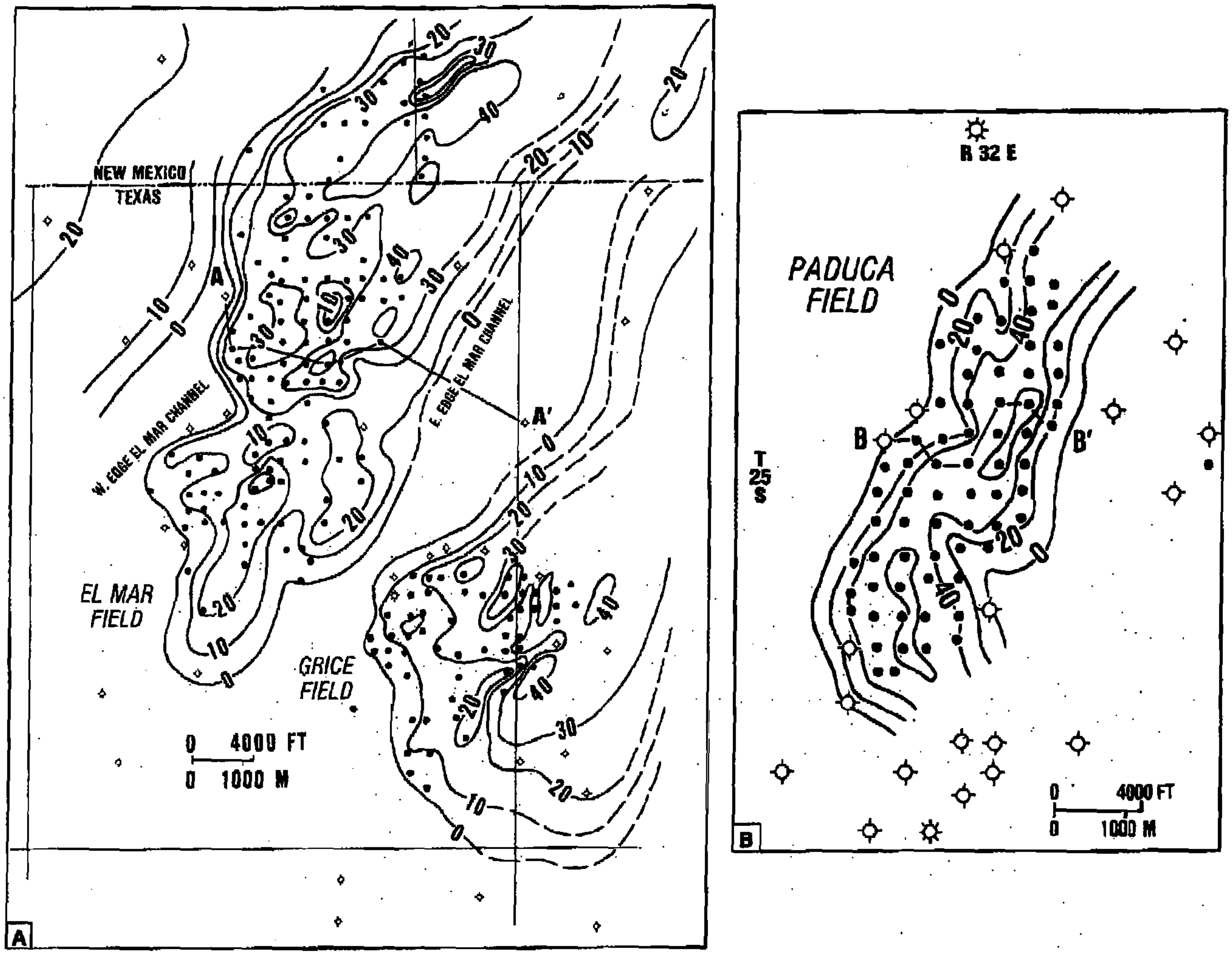

Figure 8—Sandstone isolith maps of Ramsey sandstone, upper Bell Canyon Formation (see Figure 7 for locations); contour values are in feet: (A) El Mar and Grice fields, Loving County, Texas and Lea County, New Mexico; (B) Paduca field, Lea County, New Mexico (Paduca field map modified from Weinmeister, 1978).

deep broad erosional channels filled in a complex way by sandstone and siltstone. The dimensions and geometry of the channel fills are comparable to the large channel fills exposed on outcrops of the Delaware Mountain Group. The deep channels extend far into the basin (at least 70 km or 43 mi from the shelf margin) and are the major stratigraphic controls of oil accumulations in the northern Delaware basin. Oil fields are aligned along these sandstone-filled channels. The accumulations are trapped where channel-fill sandstones abut the updip (to the northwest) erosional margins of the channels. Lateral and top seals for the traps are the relatively impermeable laminated siltstone.

The thin sandstones (less than 6 m or 20 ft) that separate major channels are interpreted to be similar to overlapping sand-filled shallow channels mapped in outcrops of the upper Bell Canyon Formation (Williamson, 1978). Core and log control in these areas is not sufficient to unequivocally demonstrate channeling, but analogy with Bell Canyon outcrops and the discontinuous occurrence of sandstone in the subsurface suggest the presence of thin channel fills interbedded with suspension-deposited blankets of siltstone.

Cores and mechanical logs from several Delaware Mountain Group fields provide the best evidence for the occurrence of major erosional channels (Weinmeister, 1978; Williamson, 1978; Berg, 1979; Jacka, 1979). Channel margins are defined by the zero sandstone isolith where closely spaced well control is available. Channels range from 1.5 km to more than 6.0 km (0.9 to 3.7 mi) in width and generally are 10 to 25 m (33-82 ft) in depth. Depth estimates usually are minimum estimates because of shallow incomplete well penetrations. The channels tend to become shallower and broader basinward. Sandstone isolith maps and cross sections from Paduca field (35 km or 21.7 mi downchannel from the shelf margin) and El Mar field (50 km or 31 mi downchannel from the shelf margin) are given to illustrate the nature of channels and internal complexities of the channel fills (Figures 8, 9).

Cross sections through the subsurface channels are very similar to the channels exposed along the western face of the Guadalupe Mountains. Laminated siltstone covers the erosional margins of the channels and can be correlated into interchannel areas. Like many of the channels in outcrop, the flows that eroded the channels

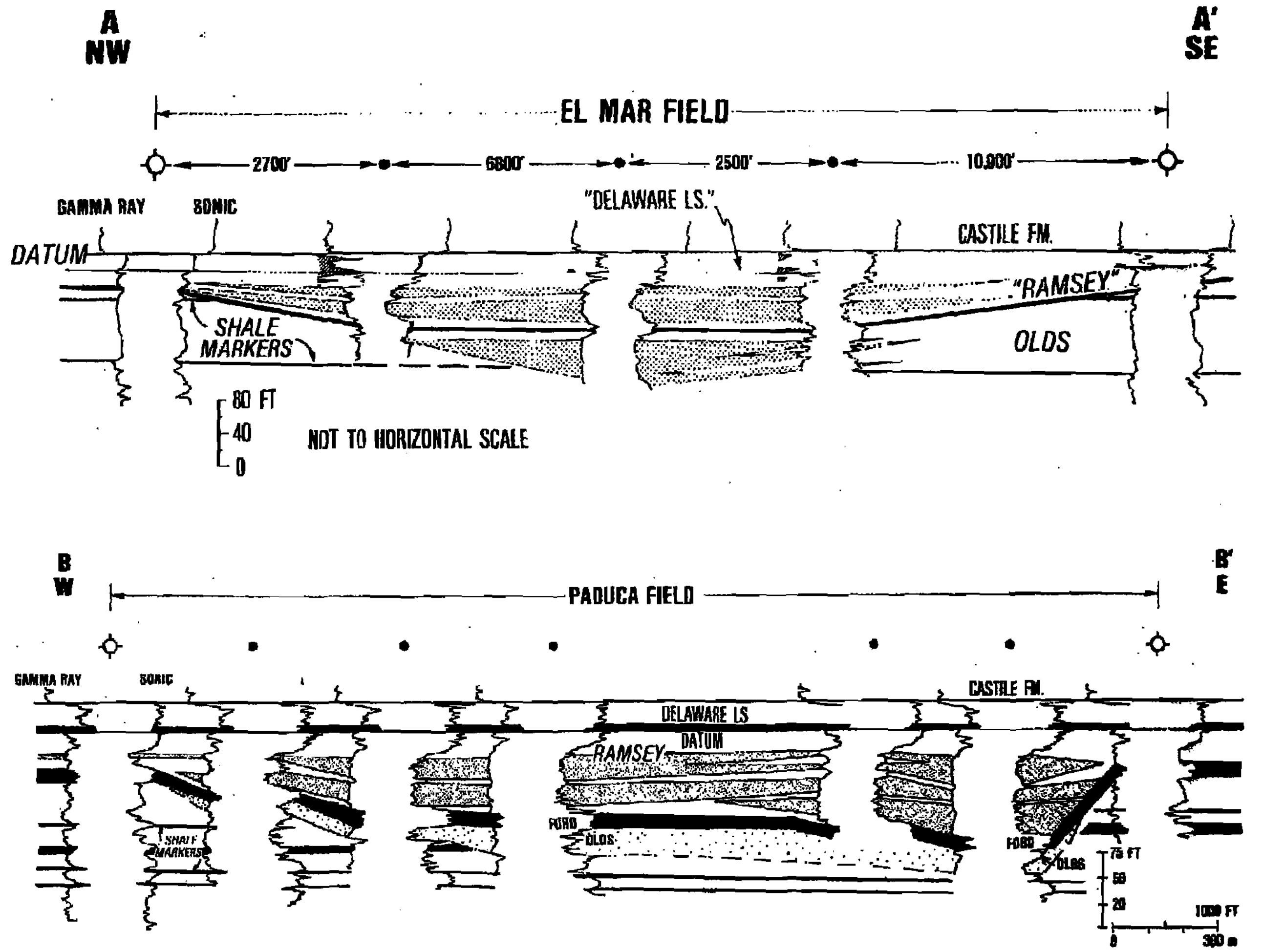

Figure 9—Stratigraphic cross sections showing large erosional channels, upper Bell Canyon Formation (see Figure 8 for location of sections): (A) El Mar field, Texas; (B) Paduca field, New Mexico. Section BB' modified from Berg (1979).

did not necessarily fill the channel. Impermeable siltstones draping channel margins may provide lateral barriers to oil migration, be updip seals, or vertically segment reservoirs.

The distribution of sandstone and orientation of channels in subsurface indicate that the major source of sediment input was from the northern and eastern shelves in the late Guadalupian (upper Bell Canyon). Older sandstones in the Bell Canyon Formation ("Olds," "Hays") appear to extend slightly farther basinward than the Ramsey sandstone. Often, these sandstones occupy the same erosional channel. These relations suggest that erosional channels are backfilled by progressive upchannel migration of sand deposition. Changes in relative sea level or shifting of depositional loci on the shelf could have caused retreat of the sediment source and led to backfilling of channels.

Channel trends and the sedimentation style are not well known for the older part of the Delaware Mountain Group. Well density in the older formations (Cherry Canyon and Brushy Canyon) rarely is sufficient to define channel trends. At least five small fields produce from the lower Bell Canyon and Cherry Canyon Formations in the northern part of the basin (Cromwell, 1979). One of these fields, the Indian Draw field, produces from a north-south trending channel approximately 1.5 km (0.9 mi) wide. Productive Cherry Canyon sandstones in the Rhoda Walker field along the eastern shelf margin also show indications of overlapping sandstone-filled channels oriented nearly perpendicular to the shelf margin (Bozanich, 1979).

SEDIMENTARY STRUCTURES AND STRATIFICATION IN SANDSTONE

Sedimentary structures and stratification within the Delaware Mountain Group sandstone beds provide useful records of processes and the relative frequencies of processes in the basin. Horizontal lamination (Figures 10A, B) and cross-stratification (Figures 10C, D, 11-13) are common on outcrops and in cores of Delaware Mountain Group sandstones. In the Bell Canyon and Cherry Canyon Formations, the very fine grain size of the sand, lack of clay-size material, and relatively good sorting make stratification difficult to see. The coarser grain size and greater range of grain sizes in sandstone outcrops of the Brushy Canyon make stratification more

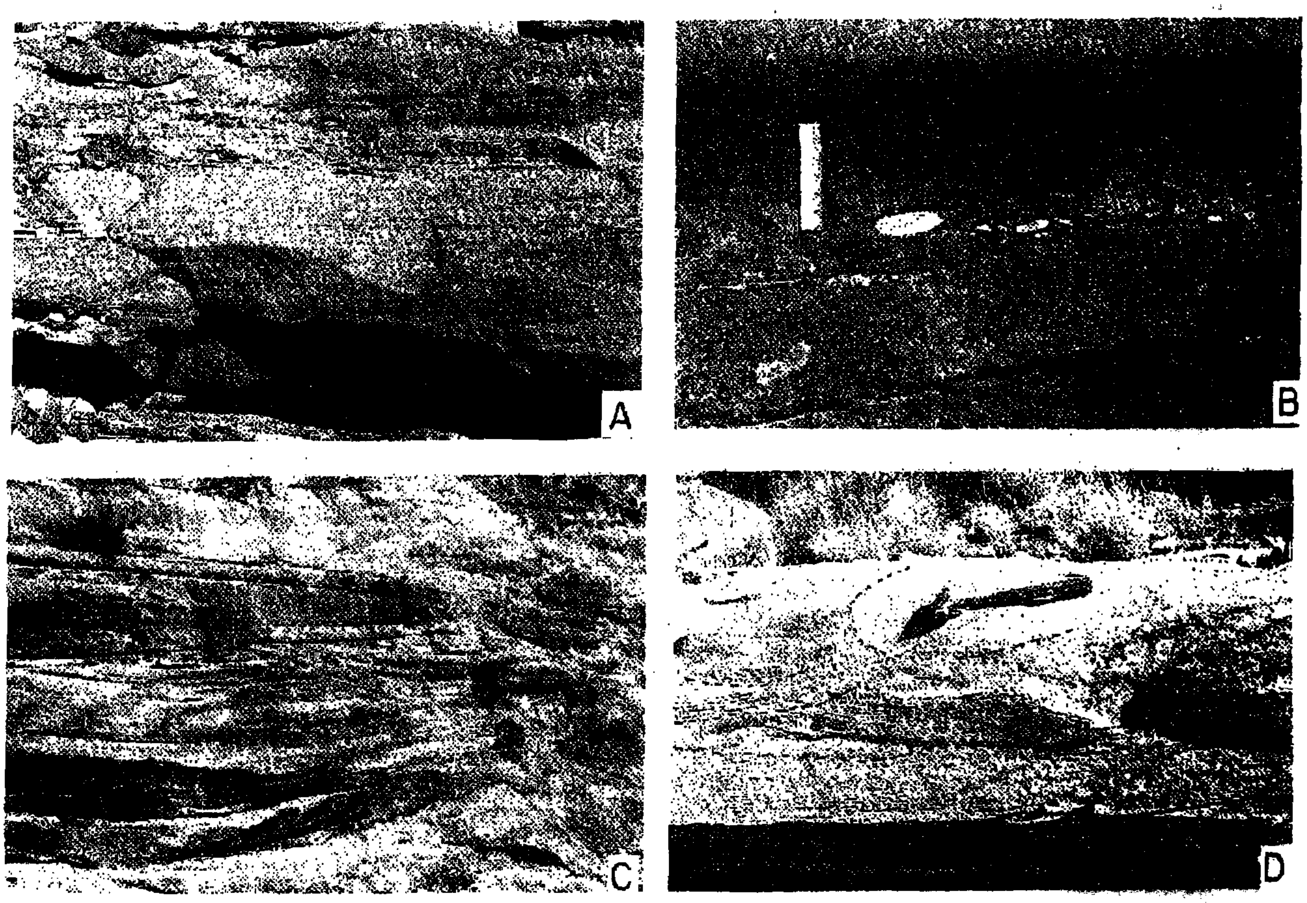

Figure 10—Horizontal lamination of trough cross-stratification in Delaware Mountain Group sandstones: (A) horizontal lamination in very fine-grained Bell Canyon sandstone (scale 20 cm); (B) horizontally stratified fine-grained sandstone with scattered carbonate pebbles and cobbles aligned in bedding, Brushy Canyon Formation (scale 15 cm); (C) broad, shallow-trough cross-strata viewed in upcurrent direction, Brushy Canyon Formation; (D) trough cross-stratification with set boundaries dashed, very fine-grained sandstone, Bell Canyon Formation.

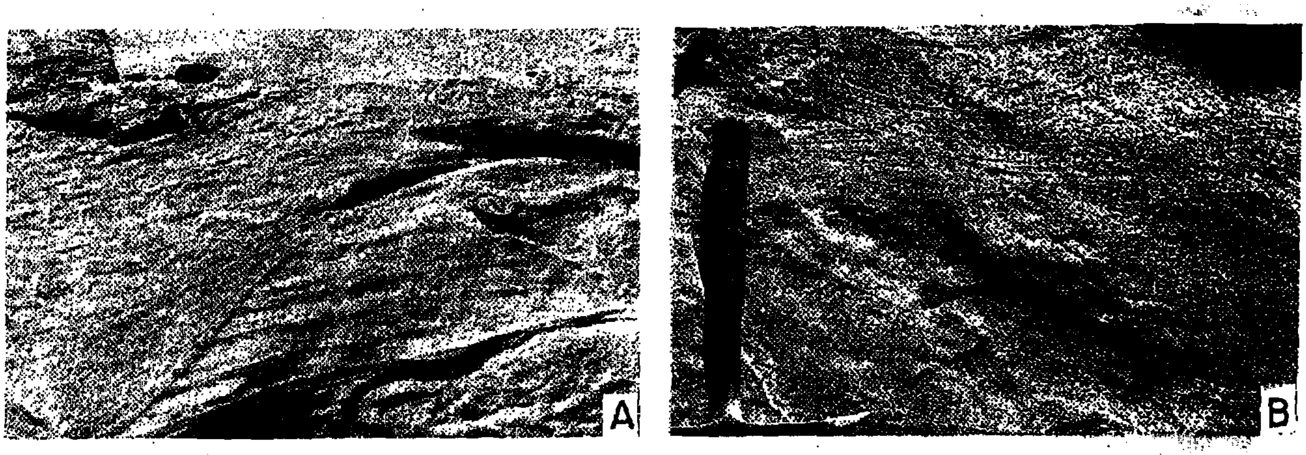

Figure 11—Trough-filled scours and trough cross-stratification: (A) steep-sided trough-filled scour in very fine-grained sandstone, Bell Canyon Formation; view is nearly perpendicular to master bedding. Note steeply dipping onlapping laminae filling scour and nearly horizontal laminae truncated by scour. (B) Close-up of trough cross-lamination showing multiple scours and trough infilling, very fine-grained sandstone, Bell Canyon Formation; view perpendicular to bedding.

clearly visible. In the Brushy Canyon Formation, crude horizontal lamination is the most common structure in sandstone beds (Figure 10B). Trough-shaped cross-stratification is common, but not nearly as abundant as horizontal lamination. Asymmetric ripples and small-scale cross-stratification are less abundant, but do occur in some sandstone beds. These structures suggest that powerful currents forming flat beds were most common,

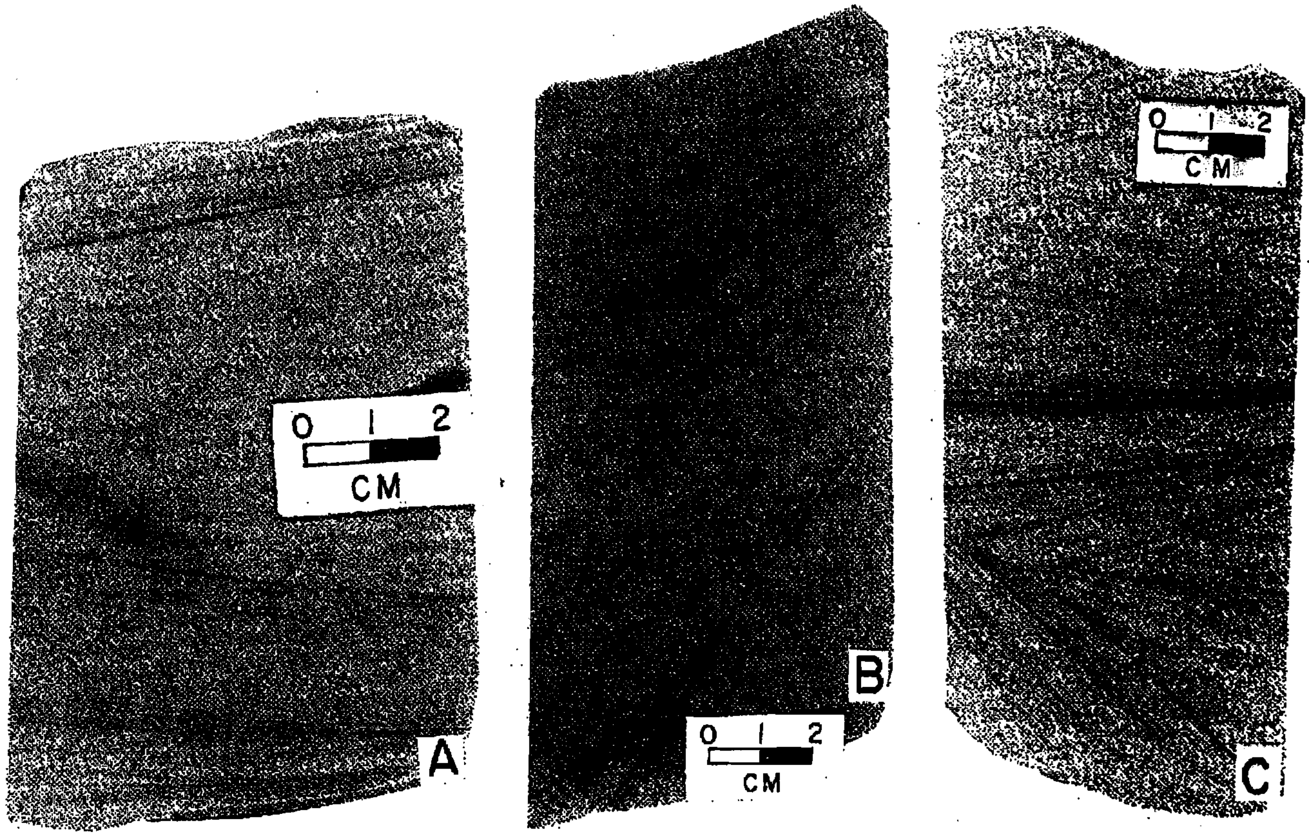

Figure 12—Core slabs of stratified very fine-grained sandstone, upper Bell Canyon Formation. Cores are from several different Bell Canyon reservoirs. Cross-stratification with anomalously steep dips and laminae onlapping set boundaries are similar to trough-filled scours observed on outcrop (Figure 11). Much of the structureless sandstone observed in Delaware Mountain Group sandstone cores shows faint cross-lamination or horizontal lamination similar to that seen in these core slabs.

but flow at lower relative velocities also occurred and produced bed configurations suggesting less energetic transport.

The relative proportions of stratification types in the Bell Canyon and Cherry Canyon Formations are more difficult to assess because of the large percentage of megascopically structureless sections. Approximately 40% of Bell Canyon sandstone beds observed in outcrop (131 beds measured) are megascopically structureless and 70% of upper Bell Canyon sandstone beds observed in cores (163 beds measured) are megascopically structureless. Most of the sandstone is not truly structureless, but is cross-stratified or horizontally laminated. Scattered patches of faint cross-stratification and horizontal lamination are common in otherwise "structureless" sandstone outcrops and cores. X-radiographs of 45 structureless core slabs from 25 wells revealed faint lamination in nearly 70% of the samples. Nearly equal amounts of cross-stratification and horizontal lamination were noted. Therefore, only a few of the massive sandstones are truly structureless. These sandstones may have been deposited by rapid fallout of sand and silt from suspension without time for development of any internal organization within the beds, or any original lamination was destroyed by liquefaction or dewatering during porosity adjustments soon after deposition.

Cross-stratification in Delaware sandstones includes "normal" trough-shaped open-form sets from a few centimeters to 1 m (3.3 ft) thick (Figures 10C, D). These trough sets are common in Brushy Canyon, but are less abundant in the finer grained Cherry Canyon and Bell Canyon Formations. Cross-stratification in these units more commonly takes the form of poorly organized asymmetric trough-filled scours and large-scale ripple-drift cross-lamination (megaripple-drift) (Figures 11-13A-C). These stratification types are largely confined to silty, very fine-grained sandstones. The steep-sided U-shaped (transverse to flow) scours are filled by curving trough laminae that lap onto the sides of the scour surface. Laminae commonly have less steep dips in the upper part of the fill. Bedding plane exposures of the scours show elliptically shaped depressions less than 1 m (3.3 ft) in maximum dimension that have been asymmetrically filled by laminae dipping toward the center of the scour. Orientations of the long dimensions of scours generally are similar to paleocurrent measurements of ripples, but the scour orientation contains a great deal more variation.

The puzzling feature of these scours is their steep sides (some nearly vertical) and the steep dips of sandstone laminae (up to 75°) that fill the scours. Soft-sediment deformation or differential compaction are not preva-

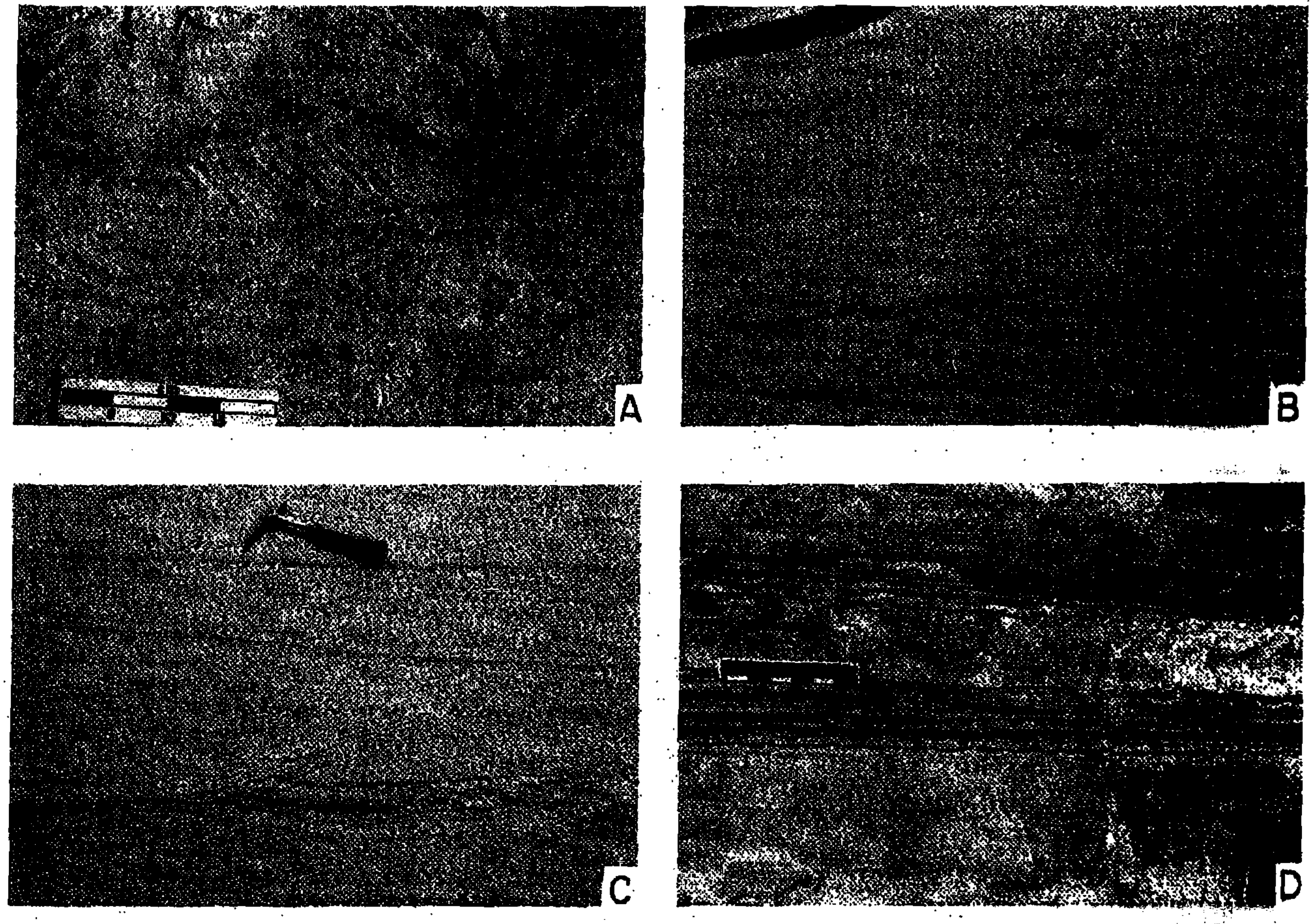

Figure 13—(A) Megaripple-drift cross-lamination (modified Type A) in very fine-grained sandstone, Bell Canyon Formation; flow from left to right. Bedforms were periodically draped by laminae of sand deposited by rapid fallout from suspension. (B) Megaripple-drift cross-lamination in very fine-grained sandstone (transitional between sinusoidal and Type B). View is slightly oblique to bedding plane. Dark horizontal lines are iron stains related to modern ground water. Paleoflow from left to right. (C) Close-up of Figure 13C. Note the preservation of stoss and lee sides and the slight downcurrent migration of megaripple crests. (D) Beds of rippled very fine-grained sandstone alternating with beds of horizontally stratified sandstone, Brushy Canyon Formation.

lent. Erosional bases of scours truncate underlying undeformed horizontal lamination and cross-stratification. Similar types of scours occur less commonly in Brushy Canyon sandstones. Cores from the Bell Canyon and Cherry Canyon Formations show steep-sided trough-shaped scours and an unusual form of cross-stratification with converging inclined lamination that onlaps scour surfaces (Figure 12). These features are interpreted to be trough-filled scours similar to those observed in outcrop.

The trough-filled scours are the most common type of cross-stratification in thick Bell Canyon and Cherry Canyon sandstones. The excavation and initial filling of the scours must have been nearly instantaneous to preserve such steep slopes. Sand and silt laminae were "plastered" against the scour surface as discrete laminae from a highly turbulent flow. In some scours, trough sets assume a more regular open form and lower dips, suggesting that downchannel migration of dune bedforms caused the final filling of the scour holes. More commonly, scours resemble potholes that were eroded and simultaneously filled by steeply dipping sand and silt laminae. These structures suggest that bed configurations developed when transported sediment concentrations were much higher than those leading to the trough cross-strata that appear to be more typical of fluvial processes.

In several exposures, the trough-filled scours were filled with inclined lamination and then overridden by megaripple-drift cross-lamination. The megaripple-drift lamination is a larger scale version of Type-B ripple-drift stratification (Jopling and Walker, 1968). Type-B ripple drift has continuous laminae across the ripple form and an asymmetrical ripple profile with a slight downcurrent migration of the ripple throughout the set. Megaripple-drift cross-lamination in Delaware Mountain Group sandstones (Figures 13B, C) generally has crest spacings of 0.8-1.2 m (2.6-3.9 ft) and shows steeply asymmetric crests. These crests appear to be nonlinear, although their plan views are not well exposed. Megaripple-drift occurs overlying steepsided trough-filled scours and in individual sandstone beds up to 2.5 m (8.2 ft) thick with no discernible breaks in sedimentation. Less commonly, a modified type of megaripple-drift cross-stratification similar to Type-A ripple drift (Jopling and Walker, 1968) also is present in Delaware Mountain Group sandstone

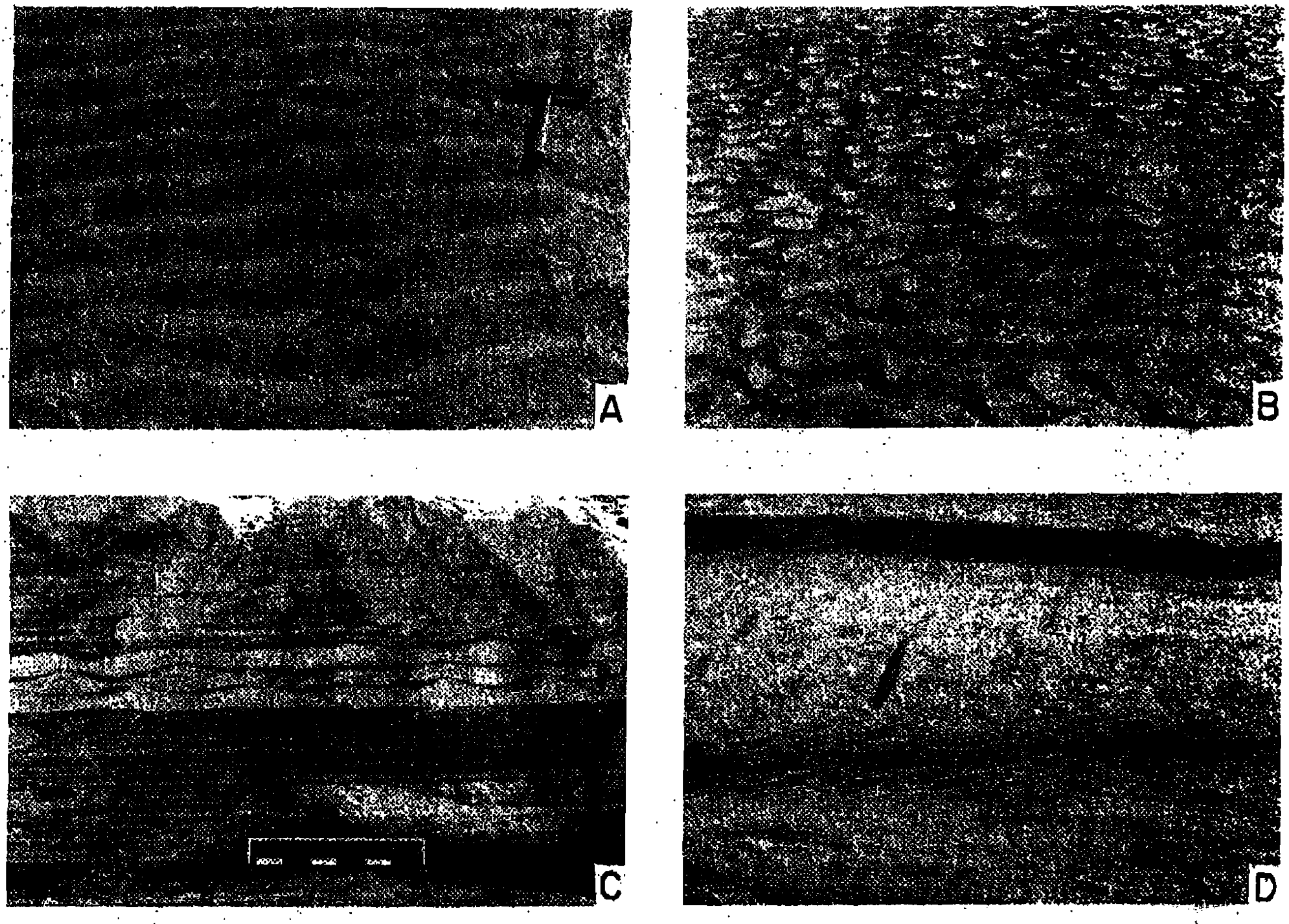

Figure 14—Ripples and ripple-stratification: (A) linear asymmetric current ripples at top of very fine-grained sandstone bed, Bell Canyon Formation; (B) cuspate ripples in very fine-grained sandstone, Bell Canyon Formation; (C) rounded asymmetric ripples of coarse silt with intervening lenses of dark siltstone, transport from right to left, Brushy Canyon Formation; (D) ripple-drift cross-lamination in very fine-grained sandstone, Bell Canyon Formation. Long-crested form of ripples shown on bedding plane parallel with 14 cm pencil.

(Figure 13A). Type A preserves only the leeward sides of ripples. Delaware Mountain Group Type A differs in that ripple forms are larger (30-40 cm or 11.8-15.7 in. ripple length, 8-12 cm or 3.1-4.7 in. height) and sets of cross-laminae are commonly separated by less inclined laminae. Episodes of megaripple migration were separated by rapid fallout of sand and silt from suspension resulting in draped lamination that preserved underlying bedforms (e.g., Gustavson et al, 1975, p. 266).

The occurrence of megaripple-drift cross-stratification indicates exceptionally high rates of sediment supply and aggradation, yet adequate time for development of megaripple bedforms. The association of megaripple-drift stratification and trough-filled scours suggests deposition from highly turbulent flows where rapid fallout of sand and silt from suspension accompanied tractive bedload deposition. The high concentration of suspended sand and silt in the flow could have increased the viscosity of the flow enough to produce the somewhat unusual types of cross-stratification present. Large-scale bedforms in silty very fine-grained sand are rare in most deposits. The bedform sequence normally expected for this size sediment is ripples to flat bed with increased flow velocity (Harms et al, 1975; Middleton and Southard, 1978). Southard and Grazer (1982) have recently experimentally produced "anomalously large ripples" in silt by increasing the effective viscosity of the flow. High-viscosity density underflows might explain the megaripple-drift cross-lamination common in silty very fine-grained sandstones of the Delaware Mountain Group. The increased viscosity might be attributed to the abundant silt and very fine sand in suspension, the interpreted high salinity of the flows, or both.

Ripples, small-scale cross-stratification, and ripple-drift cross-lamination (Type A) are also common in Delaware Mountain sandstones (Figures 13D; 14; 15D, E). Most ripples are long-crested, asymmetric current ripples (Figure 14A) or strongly curved lunate or linguoid forms (Figure 14B). The ripples are 10-20 cm (3.9-7.9 in.) apart, 1-3 cm (0.4-1.2 in.) high, and indicate unimodal transport downchannel at high angles to the basin margin. The ripples resemble current ripples formed in very fine or fine sand by unidirectional flow, except that the profiles at the crest lines are rounded rather than angular. These forms suggest that the ripples developed under current-dominated processes, but the flow also contained an

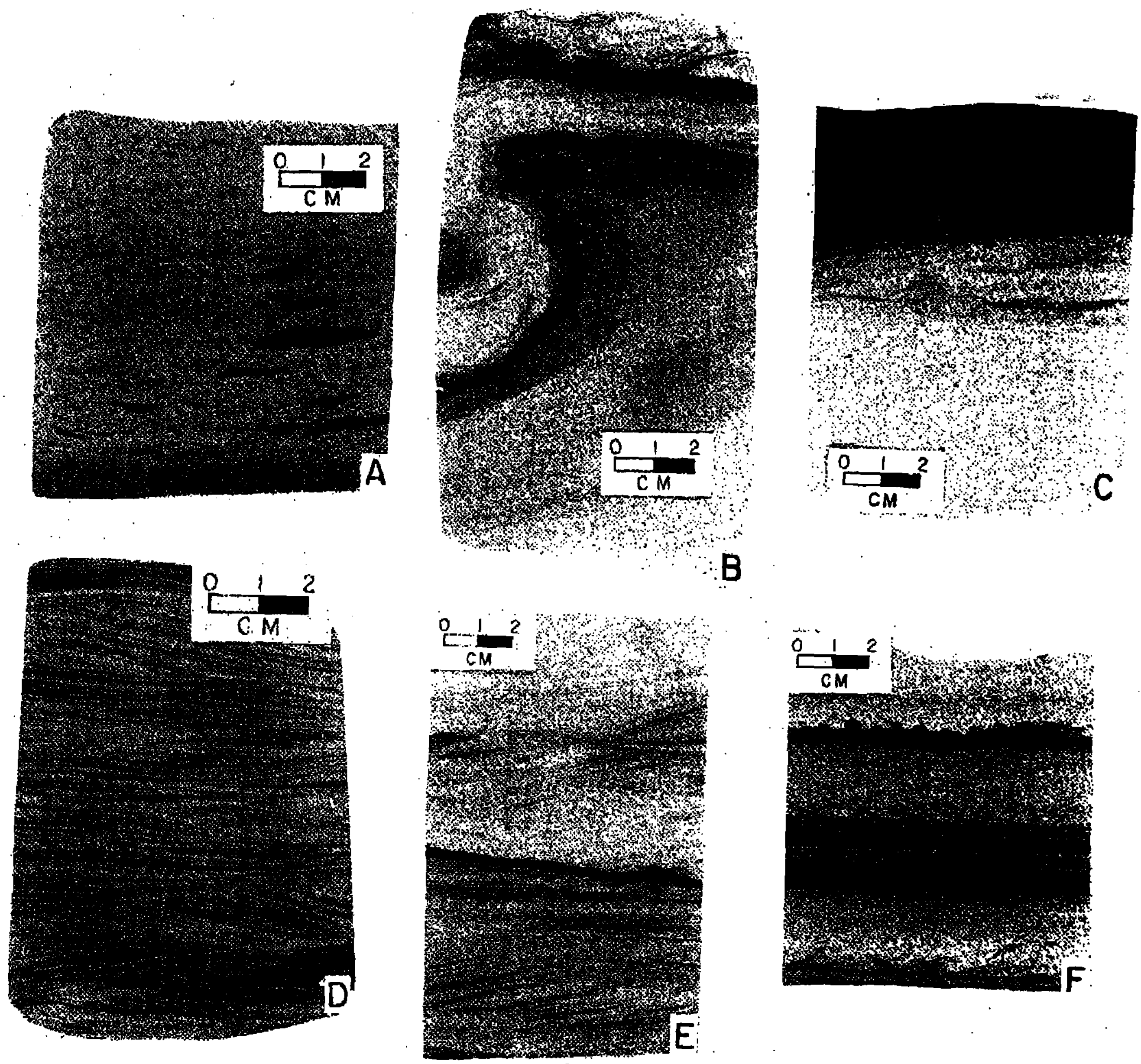

Figure 15—Core slabs of Bell Canyon sandstones. (A) Very fine-grained sandstone with gravel-size siltstone rip-up clasts; (B) sandstone beds separated by laminated siltstones with flame structures; soft-sediment deformation is evident and siltstone rip-up clasts are concentrated at the top of the lowermost sandstone bed; (C) sharp upper contact of sandstone bed with siltstone, with siltstone rip-up clasts concentrated at top of sandstone; (D) ripple-drift cross-laminated siltstone; (E) ripple-drift cross-laminated silty, very fine-grained sandstone with thin dark siltstone drape separating sedimentation units; (F) thinly interbedded siltstone and sandstone with flame structures.

oscillatory component (Harms, 1969). Many of the thin single-ripple-thick zones at the tops of thick-bedded sandstones probably were formed by reworking of sands by weak bottom currents.

Prelithification deformation structures are relatively rare in sandstone beds. The most dramatic examples of deformation occur where conglomerate rests on sandstone in some Brushy Canyon outcrops. Dikes and sills formed by sand injection were observed in a few areas, but little evidence exists for liquefaction in most Delaware Mountain outcrops and cores. Load features and flame structures commonly occur at the bases of thin-bedded sandstones interbedded with siltstones (Figure 15B, F). Sole marks and structures formed by organisms are rare in sandstones. Cylindrical burrows of unknown affinity ranging from 2-5 mm (0.08-0.2 in.) in diameter occur in a few sandstone beds, and s-shaped depressions 10-15 cm (4-6 in.) long on bedding planes were noted. Most sandstones in the study area show no evidence of bioturbation.

The stratification types described above do not occur in well-ordered or cyclic sequences. Many beds show only cross-lamination, horizontal lamination, or massive apparently structureless sandstone (Figure 16). Sedimen-

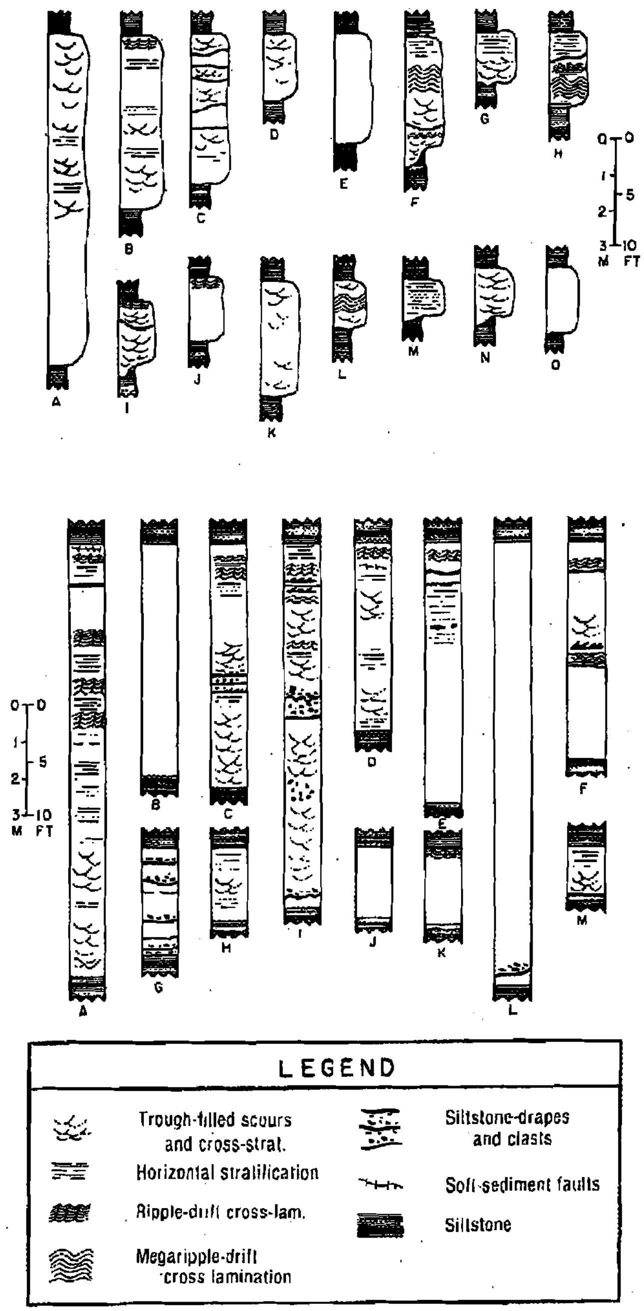

Figure 16—Representative vertical sections of sandstone beds on outcrops (top) and cores (bottom) of the upper Bell Canyon Formation. All are silty, very fine-grained sandstones from channel fills with little vertical variation in grain size. Letters refer to locations given in Williamson (1970).

tation units interpreted to represent one flow event generally are difficult to delineate in sandstone beds. Where sedimentation units can be distinguished by intercalated siltstone drapes, erosive contacts, or basal zones of rip-up clasts, the units range from 0.3 m (1 ft) to several meters thick. In sedimentation units with several types of stratification, and in sandstone beds composed of many sedimentation units, stratification types do not occur in any regular vertical arrangement other than a tendency for ripples to be present near the tops of thick sandstone beds.

Sandstone bed contacts are sharp, either planar or erosional and irregular (Figures 6D; 15B, C); texturally graded beds are rare. Modal analyses of quartz and feldspar maximum grain diameters (100-150 grains per thin section measured in 1/4 phi intervals) of samples taken from the base, middle, and top of 11 sedimentation units show no significant differences in mean grain size or sorting. Grain size ranges from 0.025 to 0.2 mm (0.001 to 0.007 in.). A few sandstones have a minor second mode of medium sand (less than 2%). The medium sand-size grains are not preferentially concentrated near the bases of sedimentation units or at the bases of sandstone beds. Some sedimentation units have a pebble zone of siltstone rip-up clasts concentrated at their bases (Figure 15A); however, no regular upward decrease occurs in the size of the clasts or proportion of matrix, nor are the clasts always concentrated exclusively at the bases of units (Figure 15B, C). Clasts commonly are aligned along horizontal planes throughout the entire thickness of sandstone, and their relative positions are not adequately explained by size and density segregation occurring during deposition from a turbulent suspension.

The assemblage of stratification types and structures is similar for most of the Delaware Mountain Group sandstones. The same stratification types observed on outcrops are present in the subsurface with approximately the same relative frequency of occurrence. Unordered vertical sequences of stratification within thick sedimentation units record irregular fluctuations of flow velocity. Changes from upper to lower and lower to upper flow regimes were common as evidenced by uninterrupted alternations between cross-lamination (trough, trough-filled scours, megaripple-drift, ripples) and horizontal lamination. Most of the sandstones are characterized by structures produced by traction transport and stratification indicative of grain-by-grain bedload deposition from turbulent flows. Cross-stratified beds up to several meters thick attest to the importance of traction transport and flows of long duration.

SUMMARY

The Guadalupian Delaware Mountain Group is a basinal deposit of siltstone and sandstone with unusual characteristics. The unit is 1,000-1,600 m (3,280-5,249 ft) thick and fills a circular basin 160 km (99 mi) in diameter surrounded by carbonate banks or reefs. Basin-margin relations observed on outcrop and in subsurface correlations indicate water depths of several hundred meters within the basin at the time of deposition.

The prevalent style of deposition is laminated siltstone beds, which are laterally extensive and cover basin-floor topographic irregularities and flat-floored channels as much as 30 m (98 ft) deep and 1 km or more wide. The channels commonly are filled with sandstone beds confined to the channel and with mantling siltstone beds, which extend into interchannel areas. These features can be observed in outcrops at the basin margin and inferred from closely spaced wells for oil fields within the basin. The channels trend into the basin at its margins, but extend northeast-southwest far across the basin center for an interval at the very top of the group (Ramsey sandstone), which is best known in the subsurface.

We believe the Delaware Mountain Group sediments are best interpreted as deposits of saline-density currents. The dense water that propelled these currents was spawned in the broad shallow evaporitic shelves adjacent to the carbonate rim that encircled the basin. The saline currents probably flowed mainly through narrow channels cutting across this carbonate rim, carrying terrigenous sediments from land sources into the basin. Basinal waters were density stratified. Denser flows moved along the basin floor cutting channels or depositing sand in existing channels; less-dense flows moved intrastratally and carried silt-size material far into the basin, where it settled to the floor as thin alternating layers of detrital silt and organic debris.

The channels are very long, straight to slightly sinuous, and relatively steep walled. Potential reservoir sandstone beds are confined to channels and terminate abruptly at channel margins. Hydrocarbon sealing beds are provided by laminated organic siltstone, or the lateral seal of potential traps can be formed by the erosional margin where the channel is incised into siltstone beds. Little proximal to distal change occurs in the size or nature of these density-current channels. Exploration predictions based on well-known models of fans formed by turbidity currents would anticipate very different proximal-distal changes in channel style, size, and extent.

From a detailed sedimentologic point of view, the deposits of these saline-density currents form interesting and poorly understood bed configurations and stratification types. The flows were powerful and easily eroded or transported sediment. Much of the sediment was silt or very fine-grained sand with little clay-size detritus, and flows were probably nonturbid but more dense and viscous than fresh surface water. Because of these conditions, we have as yet very little experimental data to guide interpretations of sedimentary structures. Many of the tractional deposits also show clear evidence of rapid local deposition. Disequilibrium transport has been little studied, especially where bedforms are large. Sedimentary structures observed in the Delaware Mountain Group should provide a useful stimulus to the design and scope of future experimental studies aimed at understanding the response of finer sediment in flows of denser and more viscous liquids.

Similar density-current deposits have not as yet been recognized in other basin or geologic systems. However, they may be anticipated wherever a deep basin is surrounded by broad confined evaporitic shelves or lagoons. In such geographic situations, the Delaware basin example may provide a useful model for interpreting stratigraphic relations or for hydrocarbon exploration.

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