GUADALUPIAN DEPOSITIONAL CYCLES OF THE DELAWARE BASIN AND NORTHWEST SHELF*

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ABSTRACT

Ancient deep-sea fans, consisting of channel, levee, overbank, and fringe deposits are recorded in Brushy Canyon, Cherry Canyon, and Bell Canyon Formations (Guadalupian) of the Delaware Basin. Sediment economics and depositional processes that characterized the Delaware Basin were very similar to those operating in modern continental borderland basins off southern California.

Margins of the Delaware Basin were incised by numerous submarine canyons whose associated deep-sea fans coalesced around the basin margin to form a compound submarine apron or bajada.

Proximal fan deposits consist predominantly of deeply incised channels which are filled with thin, laminated and small current-rippled flow units and thick avalanche and mudflow deposits. Intermediate fan deposits consist of channel-levee-overbank deposits. Intermediate fan channels contain thick, clean, well-sorted, current-ripple crossbedded sandstones deposited as major flow units (3-10 feet thick). Distal fan deposits also consist of aggradational channel-levee-overbank deposits, but the distal channels contain thinner flow units. Overbank deposits consist of laminated and small current-rippled siltstones. A peripheral aureole of finely laminated silty shale, deposited by dilute suspensoid clouds which traveled beyond the limits of the channels, formed a fringe around the fans.

Strong circumstantial evidence indicates that throughout most of Guadalupian time the geologic history and sediment economics of the Delaware Basin and Northwest Shelf may be related within the context of glacially controlled eustatic sea level changes.

During times of low standing sea level large volumes of clastic sediment were prograded across constricted shelf lagoons, swept into heads of submarine canyons by longshore and tidal currents, and introduced into the Delaware Basin via the channel-levee-overbank system. Carbonate production and reef growth ceased on the outer platform. Subaerially exposed, permeable backreef carbonates became converted to vadose caliche pisolites as sea level fell. Introduction of progressively large volumes of clastic sediment into the Delaware Basin during lagoonal constriction is recorded by basinward expansion and progradation of fan over fringe deposits and erosion in submarine canyon and proximal fan.

As sea level rose during deglaciation, shelf lagoons expanded and the volume of clastic sediment reaching the outer platform progressively diminished; carbonate production and reef growth resumed. Distribution of progressively smaller volumes of clastic sediment to the basin caused fans to "shrink" or recede toward canyon mouths. Fringe deposits were laid down over the shrinking fans as the locus of sediment accretion migrated toward the canyon mouth and finally, up the canyon. Smaller carbonate fans then prograded relatively short distances basinward.

AUTHORS' NOTE

Since this paper was published in 1968, some interpretations are now considered to be obsolete and new evidence has emerged to strengthen interpretation of Guadalupian cycles in terms of the glacial-eustatic hypothesis. New evidence concerning deposition of shelf sandstone also is presented.

Additional evidence supports the glacial-eustatic hypothesis as an explanation for the cyclic sedimentation in the Delaware Basin and Northwestern Shelf. Jacka and Franco (1974, p. 82) have presented evidence which documents a minimum 120 foot drop in sea level in outer shelf exposures of the Yates Formation in Walnut Canyon, Carlsbad Caverns National Park. A collapsed cave system contains large tumbled blocks which are intermeshed with clastic and carbonate internal sediment. A subterranean stream deposit of current-rippled sand occurs on the floor of the paleo-cave. Large solution channels, formed by enlargement of joints, later were filled upward from the base by horizontally layered Permian sand. What can be seen of the collapsed cave system encompasses a vertical stratigraphic interval of 120 feet, all of which represents a paleo-vadose environment. This records a major eustatic drop of sea level wherein the entire shelf was exposed and sea level retreated down the foreslope. Throughout the Guadalupe Mountains the major drop of sea level is recorded in the upper Yates by development of solution-enlarged joints which interconnected the approximately 120-foot stratigraphic interval. The solution channels became filled with dripstone cements and clastic internal sediment which is layered horizontally and commonly contains current ripples. A collapsed cave system in the upper Yates also has been observed in the subsurface of a cored interval

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(see Jacka and Franco, 1974, p. 82) on the Central Basin Platform.

Numerous disconformities occur throughout the Yates and Tansill Formations and most of them probably record smaller scale eustatic cycles than the major one in the upper Yates. Throughout the Capitan Reef complex dissolution of aragonitic shelled molluscs records repeated episodes of subaerial exposure of the reef complex followed by submergence and resumption of reef growth.

Our original interpretation that the pisolite deposits on the shelf areas represent ancient calcrete or petrocalcic horizons is unacceptable to the senior author who now considers them to be subaqueously deposited accretionary grains. Jacka is in essential agreement with Kendall (1969) and Esteban (1976).

As noted by Esteban (1976) laminae in most Permian pisoliths are sharply defined and highly concentric (see Plate 18A and 18B). Laminae in calcrete concretions (pisoliths) are less well-defined, discontinuous and crudely concentric (Plate 19B). Subsequent to deposition of Permian pisoliths in subtidal to supratidal environments, many intervals were subjected to subaerial exposure and vadose diagenetic features were superimposed upon the original grainstones. Vadose phenomena include perched lenses of internal sediment (Plate 18C and 19C) and pendants, which represent gravitational geopetal cements, consisting of convex downward arched micritic laminae. Layers of internal sediment and pendants (Figure 19B) also are abundantly found in calcretes. Permian pisoliths exhibit many grains which were broken on the sea floor and broken fragments served as nuclei for precipitation of subsequent accretionary laminae.

Pedogenic calcretes represent subsurface soil horizons which are indurated heavily by precipitation of calcium carbonate which has been translocated downward (illuviated) from surficial horizons. The calcium carbonate has been illuviated in ionic form by penetration of wetted fronts and precipitated by evaporation. In mature pedogenic calcrete concretionary structures (pisoliths) are formed in place by alteration of preexisting textures. As noted by Esteban (1976), the Permian pisoliths represent grainstones and do not record alteration of original fabrics.

Most sand probably was transported to submarine canyons by eolian action. Deposition of very well sorted, very fine grained sand and silt on the shelf by wind action would explain the well sorted character of the Delaware Mountain Group sandstones in the Delaware Basin. In other words, a pre-sorted supply of sand was transported from shelf to basin.

Jacka and Franco (1974) have shown that Middle Permian Artesia Group sands, in the subsurface of the Northwest Shelf, predominantly consist of eolian sands deposited on deflation flats. A great many of these sands are red to red-brown in color in the subsurface. The coloration reflects the presence of illuviation cutans, known as ferriargillans, as grain coatings, and the sands represent entisols. Adhesion ripples are represented abundantly in these sands in cores. A great many sand grains in the deep sea fans of the Delaware Basin contain remnant ferriargillans which were degraded during transport from shelf to basin. Degraded ferriargillans commonly are engulfed by quartz overgrowths and appear as "dust rings."

ADDITIONAL REFERENCES

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SEDIMENT ECONOMICS OF THE DELAWARE BASIN

In Permian time the Delaware Basin was a yoked deep-sea basin surrounded by the Diablo and Central Basin Platforms, the Southern Shelf, and the broad Northwest Shelf (Figure 1). Throughout much of the Permian, carbonate banks and reefs existed on the outer portions of shelves and platforms, and the Delaware Basin margin consisted of steeply dipping forereef talus beds which descended to water depths of up to 1800 feet (Figure 3).

Margins of the Delaware Basin were incised by numerous submarine canyons which extended well back into the shelves and platforms. Off submarine canyon mouths deep-sea fans coalesced to form a compound submarine apron or bajada which tapered basinward. Sediment was introduced peripherally into the Delaware Basin via canyons.

The Cherry Canyon and Bell Canyon Formations of the Delaware Basin display rhythmic alternations of thick clastic and thin carbonate intervals (Figure 2). The shelf interval equivalent to the Cherry Canyon and Bell Canyon Formations exhibits alternations of thick carbonate and thick clastic

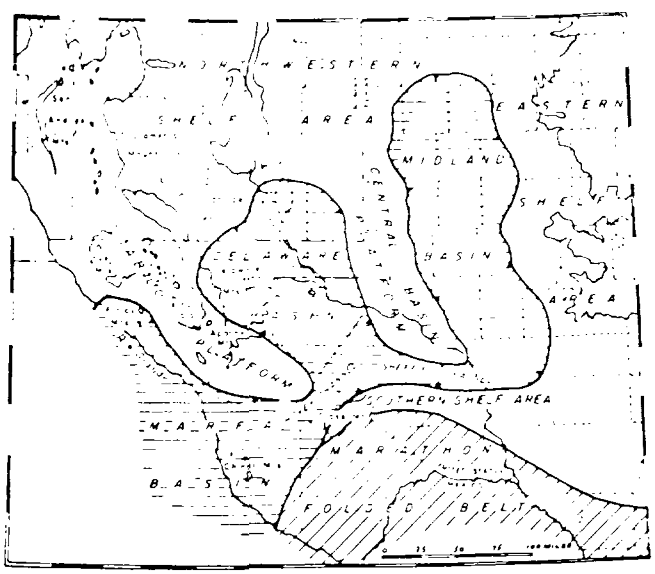

FIGURE 1. Index map relating Guadalupe Mountains and Delaware Basin to other structural features of Permian age in west Texas and New Mexico (after King, 1934, Bull. Geol. Soc. America, v. 45, p. 704).

intervals.

Much evidence indicates that sediment economics of the Delaware Basin and adjacent shelf and platform areas are related to glacial-eustatic sea level changes. During low stands of sea level (glacial intervals) large volumes of clastic sediment were prograded across constricted shelf lagoons and platforms, swept into submarine canyon heads by longshore and tidal currents, and introduced into the Delaware Basin via the channel-levee-overbank system. Carbonate production and reef growth diminished on the outer platform. Introduction of progressively larger volumes of clastic sediment into the Delaware Basin during lagoonal constriction is recorded by basinward expansion and progradation of fan over fringe deposits and erosion in submarine canyon and on proximal fan (Figure 5).

As sea level rose (during deglaciation), shelf lagoons expanded and the volume of clastic sediment reached the outer shelf progressively diminished; carbonate production and reef growth increased (Figure 4). Distribution of progressively smaller volumes of clastic sediment to the basin caused fans to "shrink" or slowly recede toward canyon mouths. Fringe deposits were laid down over shrinking fans as the locus of sediment accretion migrated toward the canyon mouth and finally, up the canyon. Smaller carbonate fans then prograded relatively short distances into the "starved basin." Submarine canyons and channels which had been deeply incised into the proximal fan during the progradational phase subsequently became "filled" with predominantly fine-grained, laminated, thinly bedded distal types of deposits during the recessional or "shrinking fan" phase.

In the manner outlined above, thick clastic progradational-recessional fan-fringe sequences and thin carbonate fan deposits came to be rhythmically intercalated in the Delaware Basin (Figures 6 and 7, Plates 16 and 17).

ENVIRONMENTAL FRAMEWORK OF PERMIAN DEEP-SEA DEPOSITS

Ancient Submarine Canyons of the Delaware Basin-Northwest Shelf Area

Last Chance Canyon-Sitting Bull Canyon Area

The Cherry Canyon tongue, subjacent lower San Andres, and superjacent upper San Andres (Figure 2), exposed in Last Chance Canyon, New Mexico, accumulated in an ancient

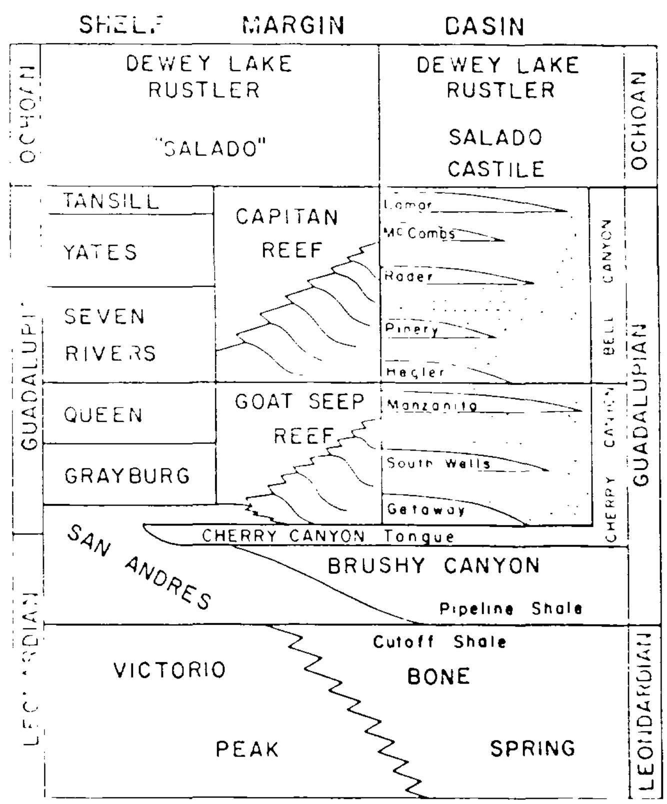

FIGURE 2. Correlation chart, Guadalupe Mountains and Delaware Basin.

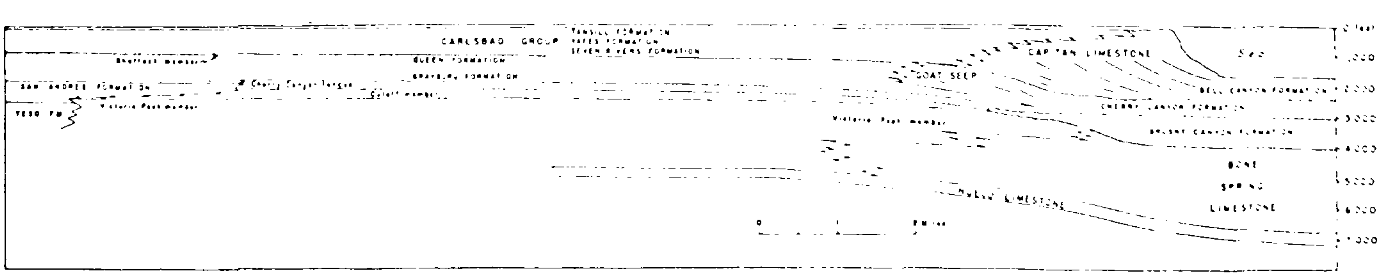

FIGURE 3. Northwest-southeast cross-section through Guadalupe Mountain - Delaware Bain area showing inferred stratigraphic relationships at end of Guadalupian interval (adapted from Boyd, 1958).

submarine canyon which extended back into the Northwest Shelf approximately 11 miles behind the contemporary basin margin (Figure 7, Location 1). The Cherry Canyon tongue, lower San Andres, and upper San Andres consist of fairly broad, deep channel fills, and mass flows oriented east-southeast, perpendicular to the margin of the Delaware Basin. Axial inclinations of channel floors range from as much as 10° in the Cherry Canyon tongue to 2° in the upper San Andres. Boyd (1958) has referred to the 5°-10° inclinations of Cherry Canyon deposits, seen in axial erosional sections, as giant foresets (Plate 1). Cherry Canyon tongue and upper San Andres deposits shingle downcanyon toward the Delaware Basin (Plate 1). Sediment consists of siltstone, very fine-grained sandstone, calcarenite, and conglomeratic lime mudstones or intraclastic biomicrudite. Abundant paleo-current indicators are oriented east-southeast toward the Delaware Basin. The Cherry Canyon fauna principally represents a thanatocoenosis, consisting of shallow marine invertebrates, such as fusulines, corals, bryozoans, brachiopods, pelecypods, gastropods, trilobites, crinoid columnals, and echinoid fragments, which were transported to the deep canyon axis. Shells are predominantly concentrated at bases of channels and scour and fill structures. Most shells are unbroken and in an excellent state of preservation. Thick intervals within the Cherry Canyon tongue have been completely homogenized by burrowing organisms (Plate 2).

Mudflow deposits consist of large clasts of limestone, siltstone, and fossil debris incorporated within a matrix of microgranular lime mud (Plate 2). The mudflows commonly display hummocky, irregular upper surfaces, are lens-shaped (biconvex or plano-convex) in transverse sections, and are confined by channels (Plate 1).

Mass flow deposits in the Cherry Canyon tongue probably reflect accumulation on steep slopes and subsequent development of slides, avalanches, and mudflows triggered by overloading, seismic shock, storm wave pressures, etc. Undercutting of canyon walls, followed by collapse and avalanching, probably played an important role. Thus, a canyon may have been widened throughout its existence.

Width of the ancient Last Chance-Sitting Bull submarine canyon is difficult to determine. The northwestern and southwestern margins of the Cherry Canyon tongue can be seen in Last Chance Canyon. The northeastern limit of the Cherry Canyon tongue cannot be delineated in the outcrop because the lower San Andres, Cherry Canyon tongue, upper San Andres, and Grayburg Formations dip eastward beneath the surface along the Huapache monocline near the mouth of Last Chance Canyon. The Cherry Canyon tongue was confined to the canyon axis, because submarine canyon deposits of the lower and upper San Andres extend northwest and southwest of the Cherry Canyon tongue pinchout. The ancient submarine canyon was wider than the two mile exposure width of the Cherry Canyon tongue, but neither the southwest nor northeast boundaries have been established.

In Last Chance Canyon maximal water depths of 400-500 feet probably existed in early Cherry Canyon time.

By Grayburg time sediment accretion had converted this former segment of the submarine canyon into a shallow tidal inlet. The Grayburg Formation, overlying the upper San Andres, consists of intertidal, algal flat, and supratidal deposits. The basal Grayburg sandstones contain many opposed SE-NW current ripples which record ebb and flood tidal currents (Plate 2).

Lithologic changes in the section exposed in Last Chance Canyon (Locality 1, Figure 7) reflect the relationship of the head of the ancient submarine canyon to the mainlai shoreline (Locality 1, Figure 7). When the shelf lagoon w expanded, clastic sediment was accumulating far to tl northwest of the basin margin. Indigenous production carbonate sediment characterized the outer shelf lagoon, a carbonate was the main sediment supplied to the canyon durii upper and lower San Andres times. Constriction of the sh lagoon brought stream mouths closer to the outer shel resulting in an influx of clastics which stifled carbona production. The submarine canyon intercepted large volum of clastic sediment during such intervals as recorded by t Cherry Canyon tongue and lower Grayburg. Width of the sh lagoon thus determined whether carbonate or clastic sedime was delivered to the submarine canyons.

West Dog Canyon - Shumard Canyon-Bone Canyon Area

A submarine canyon, exposed in the West Dog Canyo Cutoff Ridge area (Figure 7, Location 3), trends NW-SE a obliquely intersects the southwest margin of the Guadalu Mountains in the Shumard Canyon-Bone Canyon area (Figu 7, Locations 4 and 5).

In West Dog Canyon the Cherry Canyon tongue displa "giant foresets" inclined toward the southeast, like the otl Cherry Canyon tongue in Last Chance Canyon, and consi of deep water deposits. Above the Cherry Canyon tongue t upper San Andres, Grayburg, and Queen Formations a wedge-shaped and thicken toward the southeast down the a of the ancient submarine canyon. The Queen Formati thickens toward the southeast in West Dog Canyon from feet to approximately 400 feet.

In West Dog Canyon (as in Last Chance Canyon) deep-wa deposits of the Cherry Canyon tongue and upper San Andr are succeeded by shallow tidal inlet deposits of the Graybu and Queen in which giant current ripple cross-bedded un record both flood and ebb directions. As shelfward segments the canyon became filled, the position of the head migrat toward the shelf margin.

Eastward from Shattuck Valley (Figure 7, Location adjacent to the previously described submarine canyon, t Grayburg and Queen Formations consist of a sheet-like sh facies, each approximately 300 feet thick. The shelf faci consists of environmental bands deposited parallel to t Northwest Shelf margin.

Previously enigmatic relationships in Bone Canyon (Figu 7, Location 5), Shumard Canyon (Figure 7, Location 4), a the region to the northwest are readily explained by t submarine canyon relationships. Giant blocks of limeston present in the Bone Spring Formation in Bone Canyon, we interpreted by Newell, et al. (1953) as patch reefs. Pray a Stehli (1962) have shown that these represent allochthono blocks of carbonate debris transported from adjacent shall water environments by submarine slides. Geopetal fabrics a contorted beds beneath the blocks indicate an allochthono origin. These huge allochthonous blocks of Pray and Stel tumbled down into the canyon axis as undercutting a collapse of adjacent canyon walls widened the canyon. Bo Canyon and Shumard Canyon expose southwest-northea trending canyon fill deposits of the Victorio Peak, Bo Spring, Cutoff, and Brushy Canyon Formations and t Cherry Canyon tongue. All of these formations consist large channel cut-and-fill structures just as in Last Chan Canyon (Plate 3). The Victorio Peak has not been examined detail yet, but the Bone Spring, Cutoff, Brushy Canyon (Pla

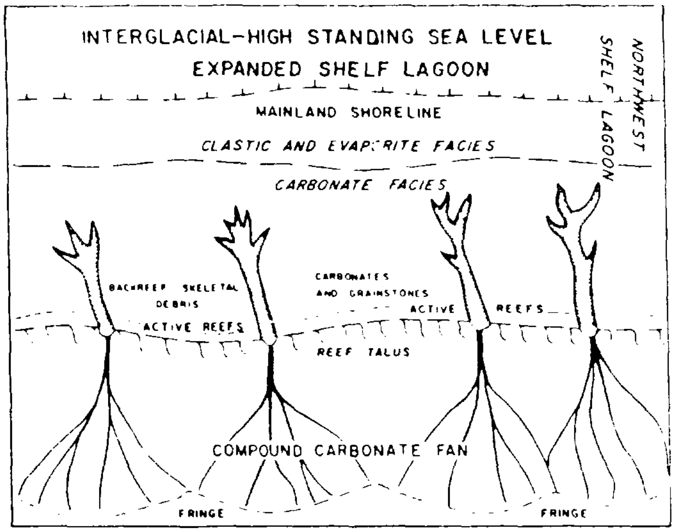

FIGURE 4.

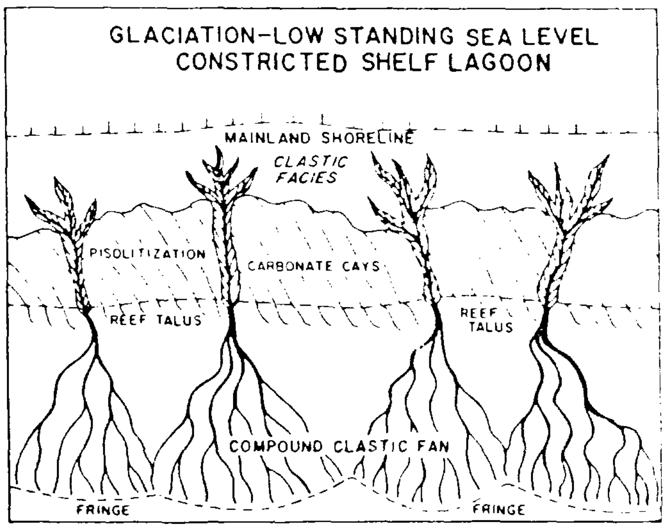

FIGURE 5.

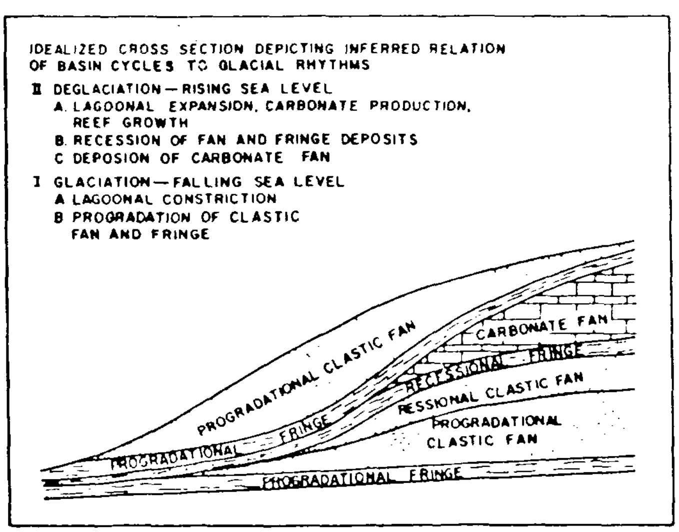

FIGURE 6.

4), and Cherry Canyon tongue represent deep-water deposits.

The post-Cutoff erosional unconformity and the overlap relationships of the Brushy Canyon and Cherry Canyon clastics in Bone Canyon and Shumard Canyon represent submarine erosion and widening of the canyon followed by deposition of Brushy Canyon and Cherry Canyon clastics in the canyon axis. Recognition of the reason for the submarine erosional surface removes the necessity of finding an equivalent unconformity in the shelf formations.

The possibility exists that many of the large present canyons along the Guadalupe Mountain front may represent sites of ancient canyons. Much detailed field work would be required to evaluate this possibility.

Ancient submarine canyon deposits of the Delaware Basin and Northwest Shelf are remarkably similar to recent deposits described by Shepard and Dill (1966).

Deep-Sea Fan Deposits of the Delaware Basin

Deep-sea fans of the Delaware Mountain Group, like their modern analogues, consist of channel, levee, and overbank deposits. Proximal, intermediate, and distal components of fans may be distinguished (Figure 8). A sheet-like peripheral aureole of fringe deposits accumulated beyond the distal fan. As previously indicated, the fringe consists of silt and shale deposited by low velocity, dilute suspensoid clouds which traveled out beyond the channels.

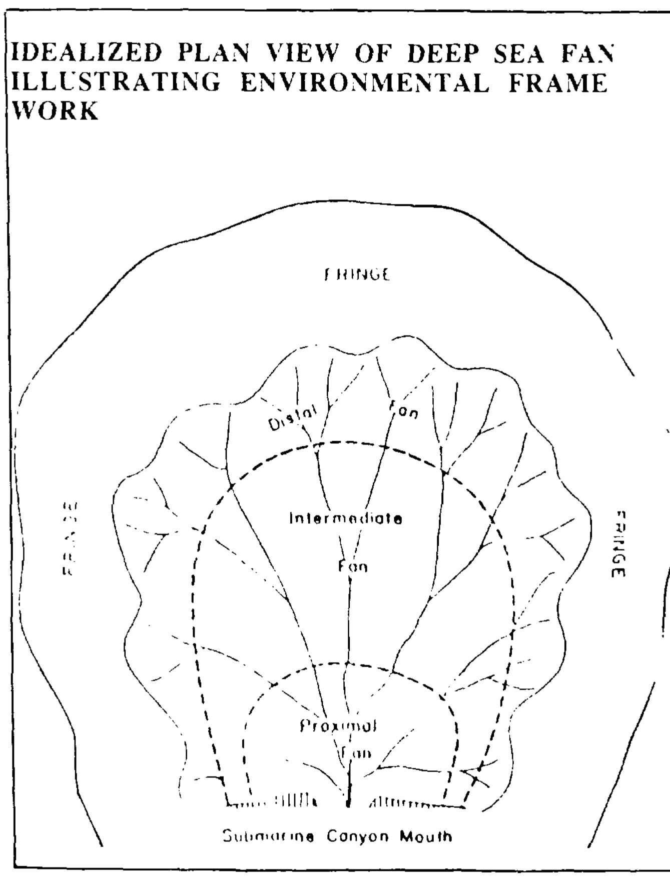

FIGURE 8.

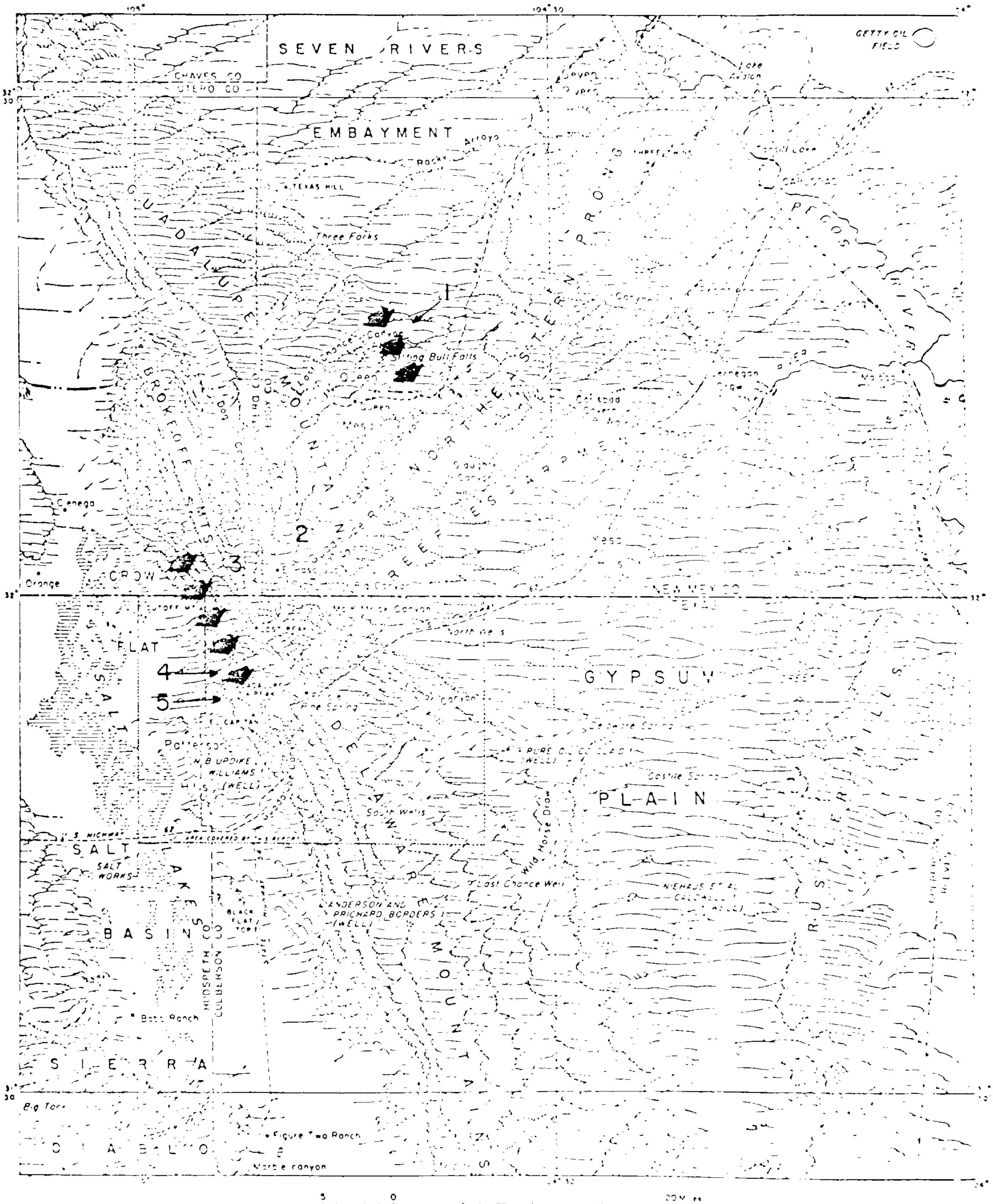

FIGURE 7. Physiographic map of Guadalupe Mountains and northwestern Delaware Basin. Compiled from various sources, including maps by U. S. Geological Survey and U. S. Forest Service. Arrows indicate approximate positions of ancient submarine canyon exposures. Locality (1) = Last Chance Sitting Bull Submarine Canyon; (2) = Shattuck Valley; (3) = West Dog Canyon; (4) = Shumard Canyon; (5) = Bone Canyon.

Proximal Fan Deposits

Proximal fan deposits (Figure 8, Plate 5) are characterized by deeply incised channels (up to over 50 feet) "filled" predominantly with distal fan and fringe deposits which consist of minor flow units (Figure 15). Hummocky upper-surfaced mass flows (avalanches, mudflows, and slides), like those found in submarine canyon "fill" deposits, are confined to the incised channels (Plate 5); however, they are thinner and occur with lower frequency than in submarine canyons. Skeletal material of transported shallow-water invertebrates is of slightly smaller size and somewhat less abundant than in submarine canyon deposits but more abundant than in intermediate fan deposits. The only time much sediment accumulated on the proximal fan is during initial phases of basinward progradation and during the "shrinking fan" or recessional phase so that only "distal" types of deposits and mass flows are recorded. Excellent exposures of the Cherry Canyon proximal fan are exhibited in road cuts of Guadalupe Pass (Plate 5).

Deeply incised proximal fan channels are analogous to fan valleys of modern deep-sea fans.

Intermediate Fan Deposits

Intermediate fan deposits consist of sharply defined channel and overbank deposits (Figure 8, Plate 7). Channels are wider and less deeply incised than those of the proximal fan. Intermediate fan channel deposits are characterized by truncated major flow units up to 10 feet thick (Figure 14, Plate 8) and transported shallow-water invertebrate skeletal material is concentrated at bases of channels and individual flow units along with lithic clasts (Figure 14). Channel complexes in the upper Cherry Canyon and Bell Canyon Formations may range up to 440 yards in width.

Overbank deposits are characterized by distinct varve-like laminae of sand, silt, and shale, and small climbing ripple or ripple drift cross-lamination (Plate 9). Small cut-and-fill structures and micro-flame structures are commonly present. Unless viewed within the context of stratigraphic relationships, it would be impossible to distinguish overbank from fringe deposits, because both reflect the same depositional mechanisms. Overbank deposits flank channels, while fringe deposits represent sheet-like or blanket accumulations. Intermediate fan deposits fit into vertical sequences which constitute progradational and recessional phases of activity (Figures 6 and 17; Plates 16 and 17).

In Guadalupe Pass road cuts, Cherry Canyon proximal fan deposits overlie intermediate fan deposits of the Brushy Canyon Formation.

Distal Fan Deposits

Channels of the distal fan are thinner and less deeply incised than intermediate fan channels, and are "filled" with minor flow units (Plate 7). Little or no skeletal material is found in the channels.

Fringe Deposits

Fringe deposits are characterized by distinctly laminated, small current ripple crossbedded units. Laminated units consist of organic-rich varve-like laminae consisting of silt and shale. These probably represent traction-plus-fallout structures, for the most part. Small climbing ripples, micro-flame structures, and small cut-and-fill structures preclude a dominantly suspension settling origin for these deposits. As previously indicated, it is not possible to distinguish fringe from overbank deposits unless closely viewed within the context of stratigraphic relationships. Both overbank and fringe deposits contain a pelagic/planktonic faunal assemblage of fish remains and ammonoid cephalopods.

RECENT CONTINENTAL BORDERLAND BASINS OFF SOUTHERN CALIFORNIA

Off southern California and Baja California a series of basins and ridges of complex structural origin exists between the continent and Pacific Ocean. Although most of the ridges are submerged, some of them penetrate the surface and form islands, such as Santa Catalina and San Clemente. This complex of basins and troughs which occurs instead of a continental terrace or island arc is called a continental borderland.

The mainland shelf of the innermost borderland basins is incised by numerous submarine canyons, many of which are presently active. Nearly all the sediment which has accumulated in the basins consists of deep-sea fans associated with submarine canyons incised into the narrow shelves off southern California and Baja California.

Santa Monica and San Pedro Basins (Gorsline and Emery, 1959)

Santa Monica and San Pedro basins, two of the northernmost inner basins of the continental borderland (Figure 9), have been intensively investigated by Gorsline and Emery (1959). Maximal water depth in the basins is approximately 3000 feet. Numerous submarine canyons are incised along the narrow shelf off the California coast. A compound deep-sea fan or bajada lies at the base of the slope opposite closely spaced submarine canyon mouths. Four of the canyons, Hueneme, Mugu, Dume, and Redondo, head within 1000 feet of shore and intercept large volumes of sand and mud which are funneled into the basin. Longshore currents transport large volumes of well-sorted sand to the canyon heads. As much as 400,000 cubic meters of sand is trapped annually behind individual groins. At the base of the slope initial inclination of the fans is 2° and the gradient tapers basinward to 0.2°. A deep-sea channel, flanked by natural levees, initiates at the mouth of each submarine canyon. The channels pursue relatively straight courses across the fans. Deep-sea channels contain fine-to very fine-grained, well-sorted sands, and skeletal material of shallow-water invertebrates transported from the adjacent shelf. Channel widths range up to greater than 300 yards.

The subsea fans initiate in water depths of approximately 1800 feet in the Santa Monica and San Pedro basins.

Northern San Diego Trough (Hand and Emery, 1964)

Newport, Oceanside and Carlsbad canyons enter the northern San Diego Trough (Figure 10). Of these only Newport Canyon is presently active. Deep-sea fans, consisting of channel, levee, and overbank deposits, lie off each canyon mouth. The channels are relatively straight and diverge like distributaries of a subaerial delta. The fact that channel floors are commonly built above the adjacent basin plain indicates that crevassing must commonly occur as it does in subaerial deltas. Channels contain very well-sorted, very fine to fine-

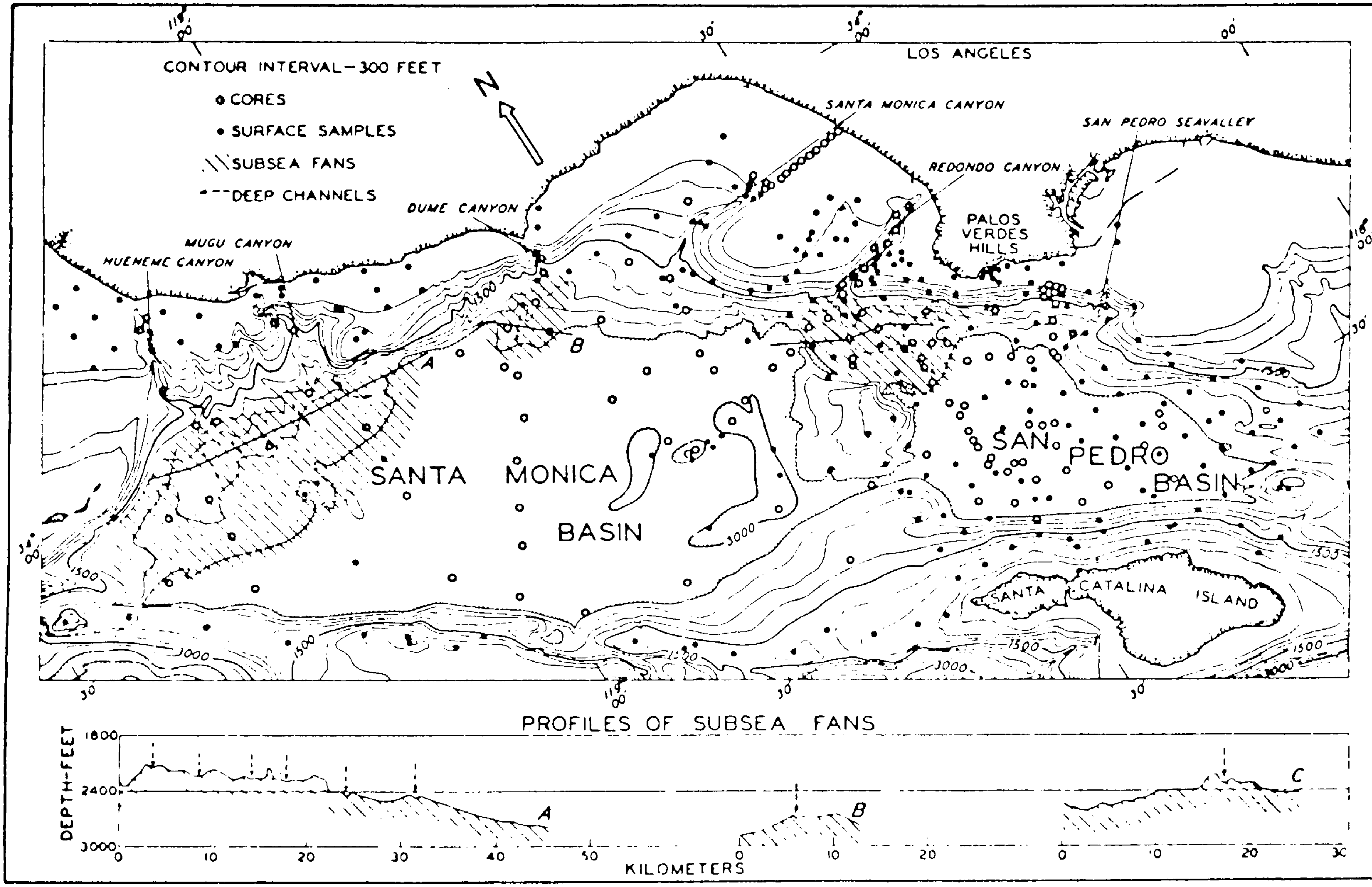

FIGURE 9. Santa Monica and San Pedro Basins (after Gorsline and Emery, Bull. Geol. Soc. America, 1959, v. 70, p. 280).

grained sands and abundant skeletal material of shallow-water invertebrates transported from the shelf. Graded bedding, small current ripples, and parallel plane laminae are sedimentary structures commonly found in channels.

Subsea overbank deposits consist predominantly of silt and lutum deposited in a manner similar to that of subaerial flood-plain deposits.

DIRECTIONAL FEATURES AND CURRENT FLOW PATTERNS

Jacka has collected 1585 directional measurements from the Bell Canyon Formation (Figure 13), St. Germain (1966) has obtained 1198 from the Brushy Canyon (Figure 11), and Beck (1967) has 616 measurements from the Cherry Canyon Formation (Figure 12).

In many exposures it is possible to determine orientation of channel axes. Long axes of nearly all channels in the area studied are oriented NW-SE, perpendicular to the NE-SW trending margin of the Northwest Shelf. Channel deposits appear lenticular in transverse views, pod-shaped in oblique cuts, and tabular in longitudinal sections.

Directional information was obtained from exposures which permitted the orientation of various sedimentary structures to be determined. The direction data were obtained mainly from large and small current ripple deposits. In many exposures the axes of these structures could be measured directly (Plates 9 and 10). In other exposures the axial orientations had to be inferred from various oblique views.

Besides large and small current ripples, directional data were collected from pullover structures (Plate 13), imbricated cobbles (Plate 12), scour and fill structures, and aligned fusuline shells (Plate 13). Directions obtained from these structures fall within the same range as those obtained from ripple deposits.

In several thick channel bodies directional measurements were obtained from several successive flow units. The flow units were traced laterally and a number of measurements were

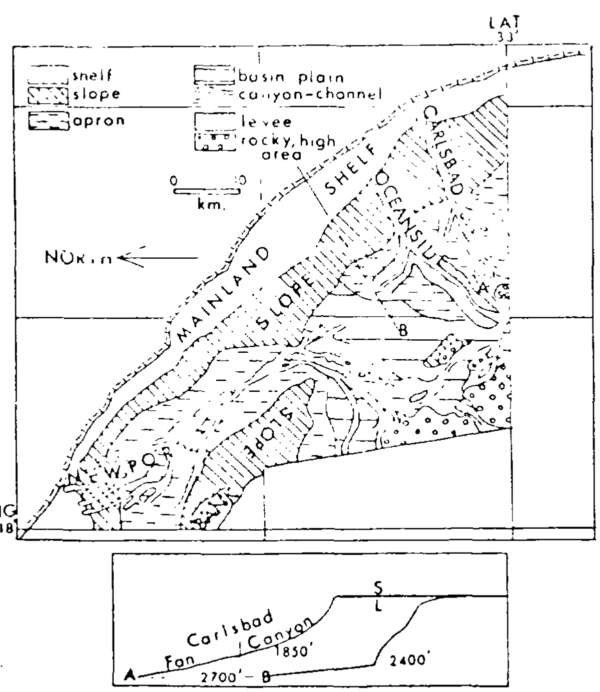

FIGURE 10. Submarine canyons and deep-sea fans of northern San Diego Trough (adapted from Hand and Emery, Jour. Geology, 1964, v. 72, p. 529).

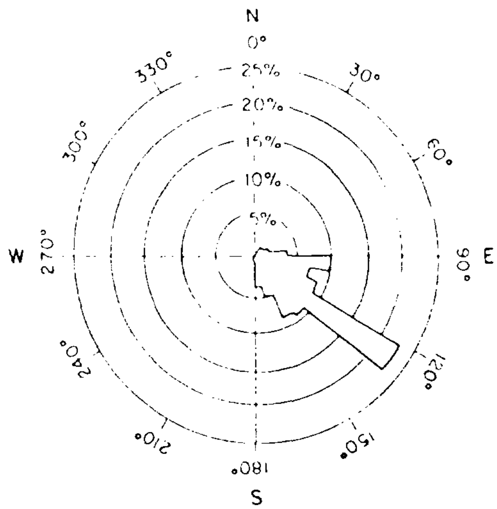

FIGURE 11. Rose diagram based on 1198 measurements by St. Germain (1966). The percentage of directional measurements falling within each class interval is proportional to the length of the line.

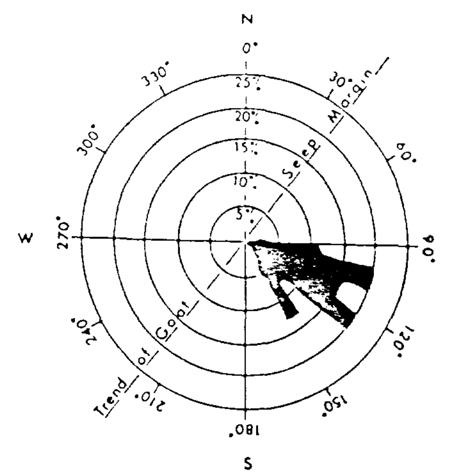

FIGURE 12. Rose diagram based on 616 measurements by Beck (1967).

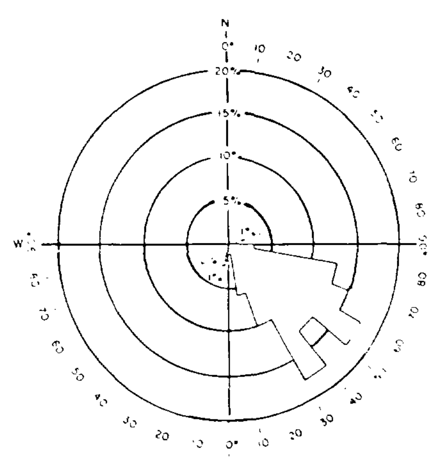

FIGURE 13. Based on 1595 measurements by Jacka.

recorded from each flow unit. Thus, both vertical and lateral variation in current flow direction could be evaluated. Lateral variation in flow direction within individual flow units is negligible. Variation among successive minor flow units may exceed 60°. Overbank deposits show more vertical variation than channel deposits.

The amazingly uniform paleocurrent patterns recorded in the Brushy Canyon, Cherry Canyon and Bell Canyon Formations (Figures 11, 12 and 13) constitute strong evidence that these units were deposited in relatively straight, anastomosing deep-sea channels. By their very nature fluvial, transitional, and shallow marine deposits exhibit much greater variation in current flow patterns.

Many investigators have suggested that flame structures (load waves and pockets) may be used as current flow indicators. In Delaware Mountain Group exposures "tongues" of flame structures most commonly point toward channel axes, perpendicular to the true current flow direction.

SEQUENCES THAT CHARACTERIZE DELAWARE MOUNTAIN EXPOSURES

Well-developed sequences of sedimentary structures are exhibited by Delaware Mountain deposits. These sequences are designated as flow units. A flow unit records accumulation of an individual bottom flow deposit.

For convenience Delaware Mountain flow units are classified into two categories based in large part on thickness: (1) major flow units, which range in thickness from three to possibly ten feet, and (2) minor flow units, which range in thickness from less than one foot to three feet. Major flow units were deposited in deep-sea channels and could also be designated as axial flow units. Minor flow units characterize overbank deposits that flank channels and fringe deposits out beyond the channels, but may also be found in channels.

Major or Axial Flow Units

Major or axial flow units are apparently all confined to deep-sea channels in the Delaware Mountain Group (Figure 14, Plate 8). The following sequence of sedimentary structures may be found in a major flow unit from the bottom (a) to the top (e).

(a) *Massive interval.* A basal scour is commonly lined with chips and pebbles, or blocks of silty or shaly material eroded from subjacent deposits. Detrital fossil material of shallow-water invertebrates may also be concentrated in the basal zone. Graded bedding would probably be present in this zone if enough grain size variation existed in the coarse fraction. The absence of grading probably indicates that the supply of coarse constituents consisted predominantly of well-sorted sand and silt. The writers share Sanders' (1965) opinion that such structureless coarse-grained layers may reflect deposition by some type of mass flow, such as inertia flow (flowing grain layer, avalanching flow, or impact flow).

(b) *Interval of large current ripple cross-bedding.* This interval commonly exhibits a conformable succession of large cuspate or barchanoid ripple cross-bedded sets. The thickness of each set probably records the approximate ripple height. The cross-bedded units diminish upward in thickness from two feet to six inches. Uniform current flow directions in each interval are recorded by the axial orientation of the structures. This interval commonly constitutes the greatest thickness of a major flow unit. Large ripple drift or climbing ripples are most commonly found.

(c) *Lower interval of plane parallel lamination.* The plane parallel laminae may reflect deposition during a plane bed or smooth phase of tractional transport. That this could represent the upper flow regime seems questionable, because it is preceded by the large ripple or dune phase which is in the lower flow regime. This interval is not invariably present and large ripple laminae may grade upward into small ripple laminae.

Recent flume experiments by Kuenen (1966) indicate that individual laminae of laminated sequences consist of thin contrasting patches, each of which contains particles of similar composition, weight, density, and shape. The laminae accumulate from a moving, saltating, carpet-like traction flow by a "kind-seeks-kind" mechanism. For each lamina or patch, moving particles in the carpet join similar stationary ones on the bottom while repelling or bypassing dissimilar ones.

(d) *Interval of small current ripple cross-bedding.* This zone consists of a conformable succession of small current ripple cross-bedded sets which range in thickness from four inches to one-forth inch. Convolute laminae were produced by the syndepositional hydroplastic deformation of small current ripples. Current flow directions obtained from both intervals of current ripple lamination are identical. Small ripple drift of climbing ripples predominate.

(e) *Upper interval of parallel lamination.* A distinct to indistinct parallel lamination characterizes this interval. The laminae very likely represent traction-plus-fallout structures (Sanders, 1965).

(f) *Pelitic interval.* The uppermost interval of an idealized complete major flow unit consists of a thin shaly layer in which no internal features are found. The pelitic interval is commonly poorly developed or absent in Delaware Mountain flow units. This results from a lack of or small supply of clay-sized material in the flow, or from truncation by the following flow. In part a pelitic interval may consist of pelagic material that accumulated over a long period of time.

The genetic sequence of structures in a major flow unit records progressive diminution in velocity and density of a deposition current.

In deep-sea channels most of the deposits represent truncated major flow units, consisting of massive, laminated and large ripple crossbedded units.

Deposition of flow units up to ten feet thick is more easily digested if accumulation is restricted to relatively narrow channels.

Minor Flow Units

All the sequences described by Bouma (1962) represent minor flow units in the Delaware Mountain Group (Figure 15, Plates 7 and 8). Minor flow units range in thickness from less than one foot to three feet. Sequences designated by Bouma as truncated types may or may not exclusively reflect truncation of other types. In fact, in many instances the truncated sequences of Bouma seem to represent accretionary sequences in the Delaware Mountain Group.

In the Delaware Mountain Group minor flow units characterize overbank deposits, flanking the channels, and as fringe deposits beyond the channels. Minor flow units also characterize distal channel deposits (Figures 8 and 17).

Volume of sediment introduced from submarine canyons probably controlled flow velocity and thickness of flow unit deposition. Thus, infrequent introduction of a smaller volume would account for sporadic intercalation of minor flow units in intermediate channel deposits with major flow units.

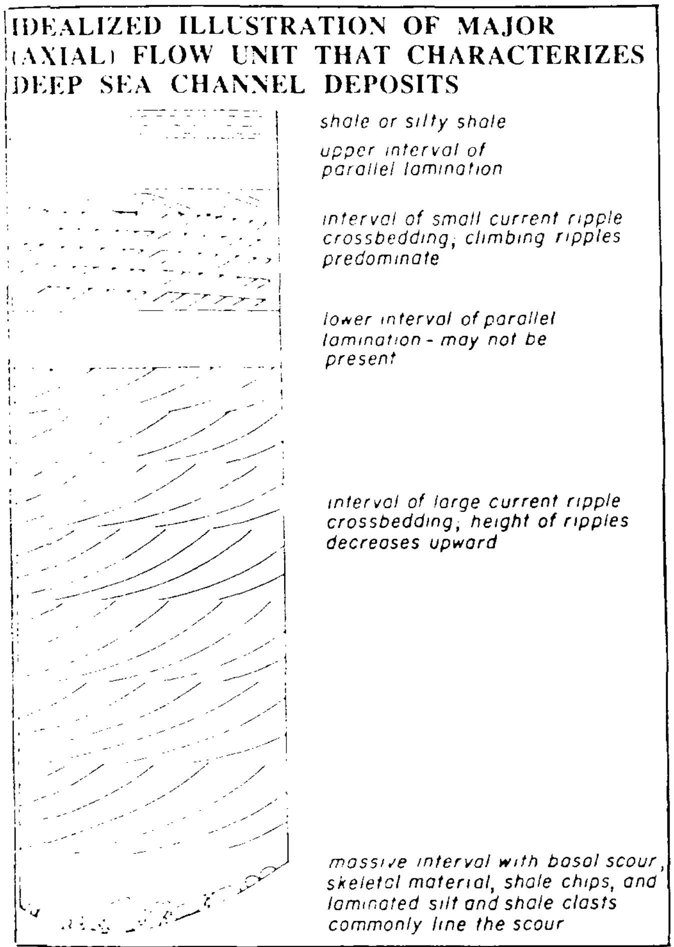

FIGURE 14. Major flow units characterize intermediate fan channel deposits in the Delaware Mountain Group. Major flow units range in thickness from 3–10 feet and most commonly have been partially truncated.

Other Sedimentary Structures Found In Delaware Mountain Group Exposures

Graded Bedding: Ambiguity exists concerning application of the term graded bedding. The following two types of graded bedding can be isolated:

1. Classical graded bedding consists of large clasts, plus sand, plus matrix at the base grading upward to matrix only at the top of a unit. Lower portions of such graded beds display poor sorting in each horizontal interval.
2. Little or no "matrix" but upward decrease in grain size and good sorting in each horizontal interval. This is also referred to as massive bedding and the origin has been previously discussed.

The non-matrix type of graded bedding characterizes massive-laminated-rippled clastic flow units of the Delaware Mountain Group.

The matrix type of graded bedding clearly represents deposition by highly viscous carbonate mud flows and not "turbidity currents." Pebble- to cobble-sized clasts and coarse invertebrate skeletal material such as large mollusk shells were transported up to 25 miles into the basin by these highly viscous mud flows (Plate 11). Coarse skeletal material and allochthonous clasts were seldom transported more than 10 miles basinward by clastic flows.

Sole Marks: Sole marks or hieroglyphs are features found on undersides (soles) of beds. The following varieties of sole marks are found in Delaware Mountain deposits: groove casts, flute casts, load pockets and waves (flame structures), slide marks (Plate 14), and organic hieroglyphs (Plate 15).

Convolute Lamination: Convolute lamination records syndepositional hydroplastic deformation of current ripples concurrent with ripple migration and sediment fallout (Sanders, 1965) (Plate 12).

Lithic Clasts: Clasts are fragments or pieces which were scoured or ripped from previously deposited cohesive or partially indurated older sediments and redeposited in younger beds (Plates 11 and 12). Clasts consist of silty shale, siltstone and carbonate, and range in size from small chips to boulders over 20 feet in diameter in proximal fan exposures of an avalanche deposit in the Rader Member of the Bell Canyon Formation exposed along Highway 62 (Plate 5).

Aligned Skeletal Debris: Elongated invertebrates, such as fusulines and certain bryozoans, commonly display downcurrent alignment of the Delaware Mountain Group (Plate 13). Downcurrent alignment of skeletal debris predominates in plane-parallel laminated intervals, but skeletal components concentrated in small current ripple troughs are oriented perpendicular to current flow direction.

Post-Depositional Soft-Sediment Deformation: Plastic deformation in the form of rolled, twisted, folded and overthrust beds is common in carbonate fan deposits of the Cherry Canyon and Bell Canyon Formations (Plate 15). Carbonate muds show a greater tendency for plastic deformation than clastic muds, possibly because of greater cohesion. Pull-over (Plate 13) structures result when a current rips up and overturns a cohesive layer in the downcurrent

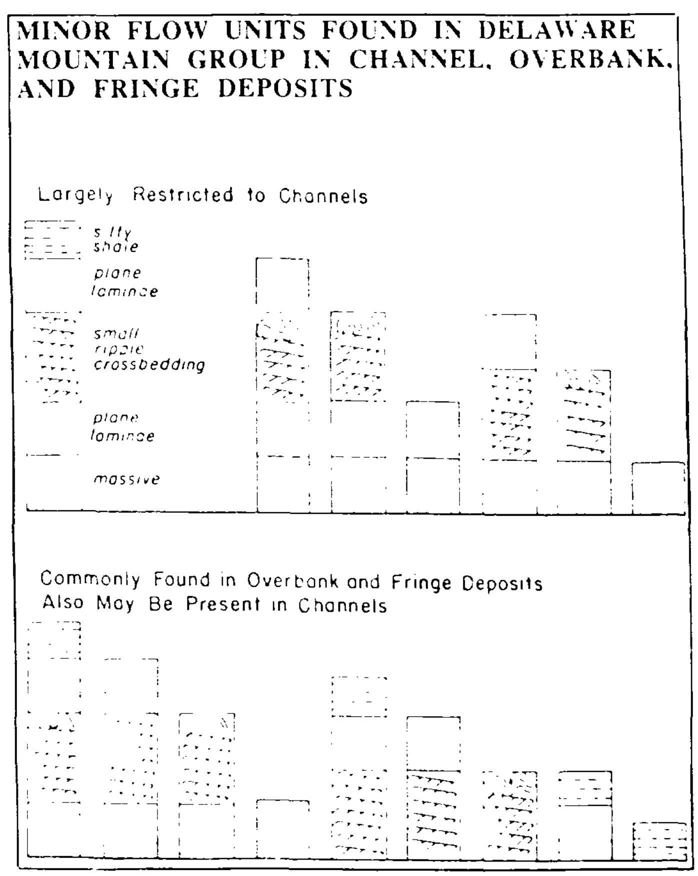

FIGURE 15. All of the Bouma sequences shown in Figure 16 represent minor flow units.

direction. Sand dikes (Plate 13) represent quicksand intrusions into an overlying interval of siltstone or silty shale.

INFERENCES REGARDING DEPOSITIONAL DYNAMICS OF DELAWARE MOUNTAIN GROUP

The Delaware Mountain Group consists almost exclusively of channel, overbank, and fringe (see Figure 8) deposits which record deposition by various types of bottom flows, such as inertia flows or flowing-grain layers (Sanders, 1965), viscous mudflows, submarine avalanches, and turbulent suspensions from which tractional, traction-plus-fallout, and suspension settling structures were deposited. Deposition in the upper flow regime is possibly reflected by coarse plane-parallel laminae which may record plane-bed or smooth-phase transport. Deposition in the lower flow regime is recorded by large current ripples, small current ripples, and plane-parallel laminae consisting of sand, silt, and shale laminae.

Numerous examples of mudflow deposits grading upward into laminated and rippled units (Plate 8) tend to support Sanders' (1965) postulation that a mass flow (viscous mudflow or inertia flow) may "shear out" from under a turbulent suspension. The turbulent suspension may subsequently overtake and continue beyond the mass flow, so that in places its deposits overlie those of the mass flow. It is possible that the laminated-current rippled intervals into which the mudflows grade was churned from beneath the viscous flow and thrown into turbulent suspension above the mudflow. Many exposures clearly reveal that highly viscous carbonate mudflows plowed and churned through underlying deposits (Plate 11). Cobbles transported in basal portions of mudflows commonly foundered down into subjacent sands.

Large current ripple cross-bedded units, such as those found in the Delaware Mountain Group, have not been reported from other so-called turbidite deposits. This either means that greater flow velocities are recorded in Delaware Mountain channel deposits or that distal deposits have been investigated in most so-called turbidite sequences. The giant ripples record flow velocities of three to five knots (Dill, 1967, oral communication).

The well-sorted, clean nature of the sand and silt supports the postulation that well-sorted sediment was delivered to submarine canyon heads by longshore and tidal currents. In their textural characteristics Delaware Mountain deposits closely resemble those of modern deep basins off southern California.

Although the processes and products of submarine avalanches and mudflows are rather easily visualized, it is exceedingly difficult to explain exactly by what mechanisms major and minor flow units were laid down in deep-sea channels and overbank deposits. The writers wish to submit two postulations:

1. "Suction currents" initiated by large-scale avalanching in submarine canyons, related to under-cutting and collapse of canyon walls, moved down-canyon as swift turbulent underflows eroding and picking up sediment during initial phases and depositing the sediment down-fan. High velocity air "suction currents" are commonly produced by large subaerial avalanches. A large submarine avalanche deposit within the Rader Member of the Bell Canyon Formation is well exposed along Highway 62 (Plate 5). Contained within a sand matrix are two kinds of carbonate boulders: (1) dark conglomeratic lime-mudstone which was soft and putty-like at the time of its implacement, and (2) crushed reef rock which was lithified prior to its transportation. Mixing of lithified reef rock with semi-consolidated material from well down in the canyon axis suggests that the avalanche was initiated by undercutting and collapse of the entire canyon wall.

2. High density, high velocity salinity currents swept down canyon axes with great velocity and turbulence, picking up and eroding sediment along its path. Such currents could have been generated by storm tides piling up water in the highly saline shelf lagoon; the return flow would have entered canyon heads and moved with high velocity. Hurricane tides pile up water in lagoons behind barrier islands of the Texas coast. The return flow is a very swift surface flow because it is less dense, which cuts channels through the barriers. If the lagoonal waters were more highly saline than sea water the return flow would be an underflow.

In neither of the above postulated mechanisms would the sediments be moving the water. The flow of water would originate by a separate mechanism and would acquire sediment in the manner of a subaerial river. Longshore and tidal currents were probably the main agents for delivering large sediment volumes to the submarine canyons.

ORIGIN AND SIGNIFICANCE OF PISOLITES IN THE BACKREEF DEPOSITS

Thomas (1965, 1965a, and 1968) and Dunham (1965) have independently established that Permian pisolites of the Guadalupe Mountains are ancient vadose caliche deposits. Permian pisolites exhibit the same suite of field relationships, textures, and structures found in recent and Pleistocene caliche (Plate 19) and in laterites and bauxites. Although the concentric internal structure of pisolites superficially resembles that of oolites and oncolites (algal "biscuits"), they possess many attributes which are uniquely produced by vadose (zone of aeration) processes (Plates 18 and 19). Vadose pisolites commonly fall within the same size range as oolites.

Vadose caliche pisolites display the following relationships and characteristics:

1. Teepee structures, bearing a close resemblance to modern caliche "anticlines" (Price, 1923; Blank and Tynes, 1965), are abundantly present in pisolite intervals (Plate 19).

2. Ancient joints have been filled from above with sand and carbonate sediment.

3. Former solution passages became lined or coated with dark laminar films of microgranular calcite or dolomite (Plates 18 and 19) deposited by evaporation of water films. Filling of solution channels consists of multiple intercalations of dark microgranular laminar films, coarse drusy calcite, internal sediment, and fibrous calcite or dolomite (Plate 19). Drusy and fibrous calcite were precipitated slowly in water-filled passages and may reflect temporary rises of water table.

4. Pisolites show partial to complete loss of original depositional textures and structures (Plates 18 and 19).

5. Large and small concretionary composite forms are abundant in pisolite deposits (Plate 18 and 19). Several generations of solution-truncation, each followed by deposition of evaporite films, are commonly recorded in one composite pisolite (Plate 18).

6. Laminae from adjacent pisolites commonly grow together into a void (Plate 18).

7. Associated with pisolites are crumbly fractures produced by vadose leaching, partial collapse, and incipient transportation by vadose water.

Pisolites have been found in Grayburg-Queen-Seven Rivers outer shelf carbonates up to 12 miles behind the Goat Seep and Capitan reefs. This indicates considerable constriction of the shelf lagoon and exposure of broad bands of reef and backreef carbonates during low stands of sea level (see Figure 18).

Pisolites clearly record multiple alternations of solution and redeposition of carbonate in the vadose zone. This may reflect changes in climate from one of continuous aridity to one of seasonal rainfall. Seemingly a rainy season would be required to produce the observed solution effects. Deposition of microgranular vadose films would reflect a return to aridity. Precipitation of coarsely crystalline drusy calcite and fibrous carbonate probably records slow precipitation in water-filled voids during times when the water table rose.

The thickest pisolite intervals with the largest pisolites are restricted to former skeletal carbonates, calcarenites, and oolites located immediately behind the reefs. Dense accumulations of carbonate associated with pisolitization obliterated nearly all permeability. Pisolite intervals thin toward the lagoon and contain smaller pisolites than those of the immediate backreef area. This relationship probably reflects thinning of the vadose zone on lagoonward sides of carbonate islands. Where the vadose zone was thickest, vadose processes operated for longer time intervals, producing larger pisolites, better developed solution passages, teepee structures, etc.

CHARACTERISTICS OF DEPOSITIONAL ENVIRONMENTS REPRESENTED IN EXPOSURES OF OUTER SHELF SEDIMENTS OF THE NORTHWEST SHELF

Goat Seep and Capitan Reef Tracts

The Goat Seep and Capitan reefs consist of sponge-bryozoan-algal frameworks and "rubble ramparts" consisting of brachiopods, corals, mollusks, fusulines and other skeletal material. The reef tracts were broken by large submarine canyons and smaller tidal passes. Oolites and calcarenites accumulated in tidal passes and channels.

Backreef Skeletal Calcarenite Apron

Sediments of the immediate backreef zone consist of skeletal material and carbonate sand deposited by storm washover and tidal currents. Tidal passes and surge channels extended into the backreef area and contain oolite and calcarenite.

Supratidal Deposits

Carbonate and clastic supratidal deposits consist of dessicated algal mats (stromatolites), some of which formed flat pebble conglomerates, and carbonate mud or siltstone containing molds of crystals, blades, rosettes, and nodules of anhydrite pseudomorphous after gypsum (Plate 22).

Intertidal Deposits

Clastic and carbonate intertidal deposits exhibit a variety of well-developed sedimentary structures. Tidal flats were dissected by tidal channels which display parallel laminae, small and large current ripples recording both flood and ebb directions, and sharp- to round-crested wave ripples. Tidal channels contain sand, calcarenite or oolites. Interchannel flats are distinctly laminated and contain flat- and round-crested wave ripples, ladder ripples, small current ripples, and burrowed and churned intervals.

Nearshore Clastics

Nearshore clastics consist of clean, well-sorted sands and silts. Shoreline-strike sand bodies parallel the NE-SW trending margin of the Northwest Shelf and display the following upward sequence of sedimentary structure: (a) wave-rippled, burrowed and churned very fine sand, (b) small and large current ripples oriented parallel to the shoreline, and (c) laminated beach and washover fan deposits (Plate 20).

Approximately 80% of the current ripples reflect longshore current flow toward the northeast and 20% to the southwest. Shoreline-strike sand bodies were deposited during low-intermediate stands of sea level when the reef tract and backreef areas were exposed as carbonate islands. Islands would have imposed a barrier to winds blowing from the south or southeast. Hence, the longshore current data seemingly record prevailing winds blowing from west-northwest or west-southwest.

Subtidal Clastics and Carbonates

Subtidal deposits consist of gray silts or carbonate pellet muds which may be intensively burrowed.

SEDIMENT ECONOMICS OF THE NORTHWEST SHELF

Sediments which accumulated on outer segments of the Northwest Shelf are exposed in the Guadalupe Mountains. Facies relationships are based exclusively on outcrop studies.

Lagoonward from the shelf margin, carbonate facies deposited during high stands of sea level (interglacials) were: (1) active reefs, (2) backreef skeletal carbonates, oolites, and calcarenites, and (3) lagoonal lime muds (Figure 16a).

The following facies, lagoonward from the shelf margin, were deposited during a period of lagoonal constriction: (1) subaerially exposed reef and backreef carbonates, (2) supratidal carbonates and anhydrites, (3) carbonate algal flats, (4) carbonate intertidal deposits, and (5) lagoonal carbonate muds (Figure 16b).

As a lagoon progressively constricted, clastic sediment was prograded across it to the outer shelf where carbonate production was stifled. The following facies characterized a highly constricted lagoon: (1) a broad belt of carbonate islands, (2) supratidal anhydritic sands and silts, (3) clastic algal flats, (4) clastic intertidal deposits, (5) shoreline-strike sands, and (6) lagoonal sandy silts (Figure 16c).

During lagoonal expansion, following a low stand of sea level, the following facies were represented in a lagoon of intermediate width-landward from the shelf margin: (1) carbonate islands, (2) supratidal carbonates or clastics and anhydrites, (3) carbonate or clastic algal flats, (4) intertidal clastics or carbonates, (5) clean shoreline-strike sands reworked from low-stand deposits, and (6) lagoonal silts and silty shales.

POSSIBLE EXPLANATIONS FOR GUADALUPIAN DEPOSITIONAL CYCLES OF DELAWARE BASIN AND NORTHWEST SHELF

Glacial-Eustatic Hypothesis

Progradational-recessional fan-fringe cycles in the Delaware Basin and depositional rhythms recording expansion and constriction of shelf lagoons on the Northwest Shelf reflect glacially-controlled eustatic sea level changes. Continuous subsidence of the platform is assumed.

Glacial Interval–Low Standing Sea Level. A constricted shelf lagoon would encompass latter phases of falling sea level and initial phases of rising sea level.

1. As sea level progressively dropped during a glacial

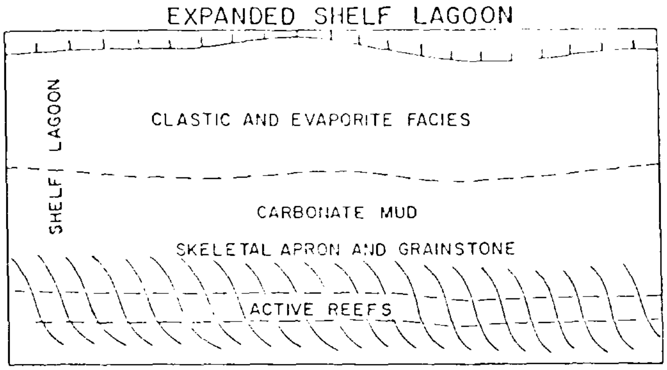

FIGURE 16a.

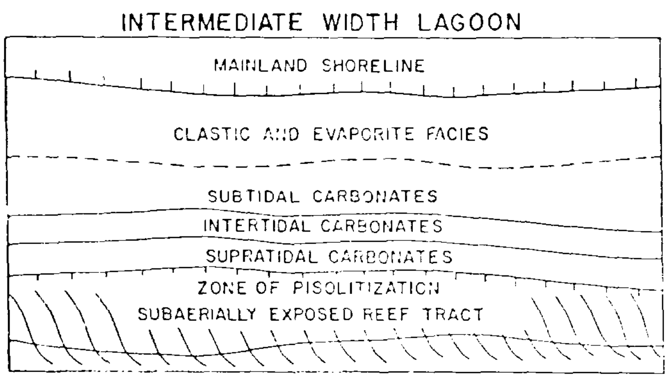

FIGURE 16b.

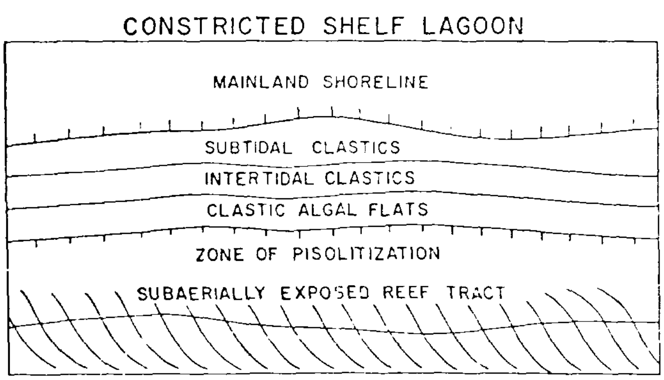

FIGURE 16c.

interval, emergence of reef and backreef belts created supratidal, algal flat, and intertidal environmental bands on lagoonward sides of islands. Lowering of sea level caused environmental bands on each side of the lagoon to converge as the lagoon constricted (Figure 16c). Lagoonal constriction enabled clastic sediment to reach the outer shelf. Longshore currents, tidal currents and littoral drift swept large volumes of sand and silt into heads of submarine canyons that joined large tidal passes through the reefs. The upward sequence of lagoonal, intertidal, algal flat, and supratidal flat deposits records lagoonward migration of environmental belts as sea level fell.

2. Indigenous carbonate production and talus accretion on the outer platform displayed minimal rates. Reef growth may have continued on the upper talus slope during low stands.

3. In the Delaware Basin the upward sequence of fringe, distal fan, and intermediate fan deposits (Plates 16 and 17) records basinward progradation of deep-sea fans as progressively larger volumes of clastic sediment were introduced via the canyon-channel-overbank system. The locus of sediment accretion shifted progressively basinward from the submarine canyon and proximal fan. Erosion and deep incision of submarine canyon "fill" and proximal fan deposits accompanied maximal fan developments (Figure 5).

4. During glacial intervals the climate changed from continual aridity to wet season-dry season and subaerially exposed backreef skeletal carbonates and calcarenites became converted to vadose caliche pisolites. Alternating intervals or heavy infiltration (monsoon season) are required to produce the solution passageways and solution-truncation effects. Dry intervals or seasons are required to produce deposition of calcite films by evaporation.

Interglacial–High Standing Sea Level. An expanded lagoonal belt would exist during latter phases of rising sea level and initial phases of falling sea level.

1. The progressive rise in sea level which accompanied deglaciation caused divergence of environmental belts on each side of the shelf lagoon and a consequent diminution of clastic sediment supply to the outer shelf. On the outer shelf the upward succession of supratidal, algal flat, intertidal, and backreef skeletal-calcarenite apron deposits records progressive expansion of the shelf lagoon. During stands of sea level outer shelf intertidal, algal flat, and supratidal environments ceased to exist (Figure 16a).

2. Indigenous carbonate production on the platform, reef growth, and talus accretion occurred at maximal rates.

3. During deglaciation, progressively smaller volumes of clastic sediment were introduced into the Delaware Basin. This is reflected in the upward sequence of recessional phase distal fan, fringe, and carbonate fan deposits (Figure 17; Plates 16 and 17). The locus of greatest sediment accretion shifted progressively toward the basin margin and up the submarine canyon during the recessional "shrinking fan" phase. Thus, the channels which had been incised into proximal fan and canyon "fill" deposits became filled with distal fan, fringe, mass flow, and carbonate fan deposits.

4. Deposition of evaporites may reflect a change in climate to extreme aridity during interglacials.

DISCUSSION

Detailed reconstructions of Pleistocene history indicate that the association of *glacial intervals-low standing sea level-more humid climate* and *interglacial-high standing sea level-more arid climate* are correct.

Sediment economics and depositional dynamics recorded by depositional cycles in the Cherry Canyon and Bell Canyon Formations of the Delaware Basin and in the Grayburg, Queen,

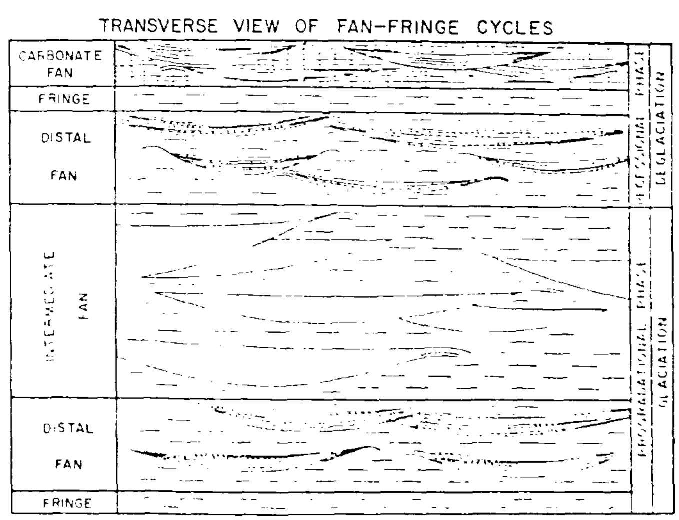

FIGURE 17.

Seven Rivers, Yates, and Tansill Formations (Figure 2) of the Northwest Shelf can be precisely explained by the glacial-eustatic hypothesis. Glacial processes are rhythmic and reverse themselves within short time intervals.

It is a well-established fact that multiple glaciations occurred in the Late Paleozoic (Late Pennsylvanian-Permian). Glacial effects are recorded in Africa, India, Australia and South America.

Whether or not, or the extent to which, continents and ocean basins have undergone relative changes in position has not been precisely determined. It is, therefore, presently impossible to determine relative proximity of the Permian Basin area to continental glaciers in the Permian Period.

The environmental framework and lithologies indicate that the Permian Basin region was part of a subtropical high pressure belt in Permian and much of Pennsylvanian time. In the Pennsylvanian record, a sharp boundary separates the coal basins of central Texas from evaporite-red bed deposits to the west. Coal basins of the mid-continent and Appalachian region probably reflect hot-humid climates of a tropical low pressure belt (equatorial zone). The boundary (latitude) separating coal basins of the mid-continent from desert deposits to the west runs approximately north-south with respect to present coordinates. This would tend to indicate that either a major shift in the earth's axis of rotation or a change in distribution of continents has occurred.

Pleistocene subtropical high pressure belts responded sensitively to Pleistocene glacial rhythms even in areas up to 2000 miles from the glaciers. Pluvial intervals, marked by increased rainfall, reflect glacial episodes. During interglacials the climate returned to its former aridity.

CONCLUSIONS

1. The following depositional environments can be distinguished in Delaware Mountain Group exposures: (1) submarine canyon "fill," (2) proximal fan, (3) intermediate fan, (4) distal fan, and (5) fringe (Figure 8). These deposits are very similar to those reported from modern continental borderland basins off southern California (Figures 9 and 10). Deep-sea fans, each located off the mouth of a submarine canyon, coalesced to form a compound submarine bajada in the Delaware Basin.

2. Sediment economics and depositional dynamics of Delaware Basin and Northwest Shelf can be precisely related within the context of a glacial-eustatic hypothesis. Numerous cycles of expansion and constriction of shelf lagoons controlled sediment economics of both basin and shelf.

3. It is postulated that currents which deposited clastic fan-flow units may have been generated by (a) high velocity, turbulent "suction currents" or undertows associated with large-scale submarine avalanching caused by undercutting and collapse of canyon walls, and (b) saline density currents of high velocity and turbulence which swept down canyons in response to return flow of water piled up in the shelf lagoon by storm tides.

4. In addition to the enigmatic currents which deposited clastic fan-fringe flow units, submarine avalanche and mudflow deposits may be identified.

5. Detailed analysis of the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations in the Delaware Basin has revealed that they consist exclusively of deep-sea fan and fringe deposits. Clearly, the Delaware Basin remained a deep-sea basin throughout Guadalupian time. Therefore, the so-called Brushy Canyon onlap exposed in the Shumard Canyon-Bone Canyon area cannot possibly record filling-up of the basin as suggested by King (1948) and Newell and others (1953). This and other relationships in the Shirttail Canyon-Shumard Canyon-Bone Canyon area are easily resolved by postulating accumulation in a submarine canyon.

6. During times of falling sea level and lagoonal constriction, the reef tract and adjacent backreef areas became progressively subaerially exposed; permeable backreef carbonates became pisolitized (calichified). Constriction of the shelf lagoon is recorded by the upward succession of backreef carbonates, intertidal, algal flat, and supratidal deposits. Lagoonal expansion is reflected by the vertical sequence of supratidal, algal flat, intertidal, and backreef carbonate deposits.

7. The southern margin of the Persian Gulf represents a partial modern analogue to the Northwest Shelf during low and intermediate stands of sea level (see Illing, et al., 1965). Supratidal sebkhas are succeeded seaward by algal flats, intertidal flats, lagoons, and coral reefs.

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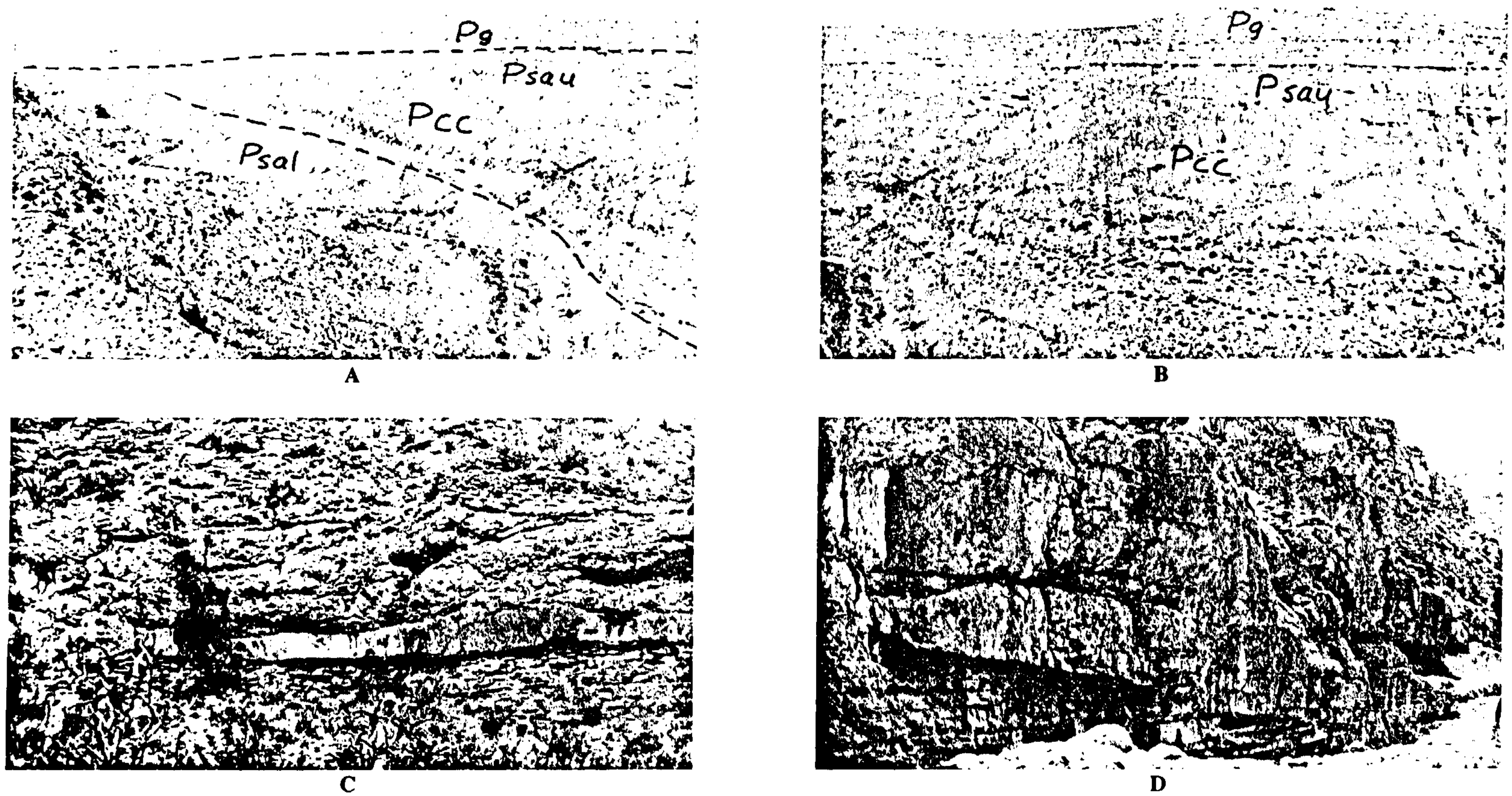


PLATE 1. Submarine canyon deposits in Last Chance Canyon.

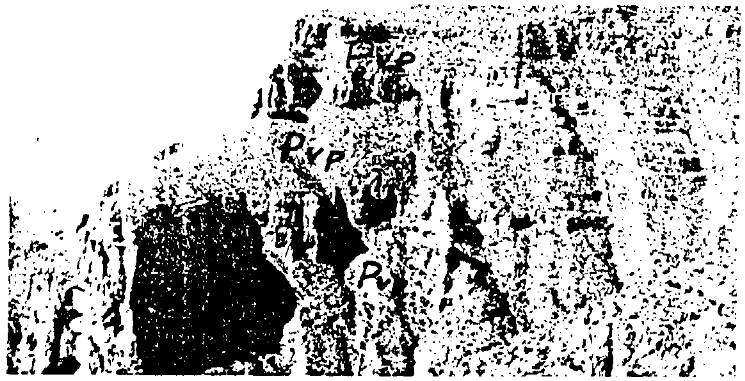
A and B. Longitudinal view looking northwest up Last Chance Canyon showing down-canyon wedging and shingling of upper San Andres (Psau), Cherry Canyon tongue (Pcc), and lower San Andres (Psal). By Grayburg (Pg) time depositional shoaling had converted the canyon into a shallow tidal inlet and reduced the gradient to less than 1°.

C. Conglomeratic lime mudstone with hummocky upper surface overlying thinly laminated shaly limestone in lower San Andres.

D. Erosional surface at base of conglomeratic lime mudstone shown in C.

PLATE 2. Submarine canyon-tidal inlet deposits in Last Chance Canyon.

A. Large groove cut into shaly limestone by conglomeratic lime mudstone shown in Plate 1, C and D.
B. Close view of conglomeratic lime mudstone depicted in Plate 1, C and D.
C. Intensively burrowed and churned interval in Cherry Canyon tongue.
D. Axial (longitudinal) view of tidal channel in Grayburg. Current ripple cross-bedded sets show 180° reversals recording tidal flood and ebb.



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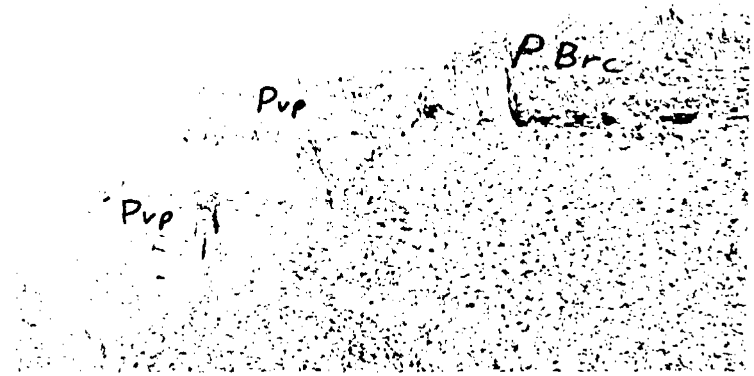

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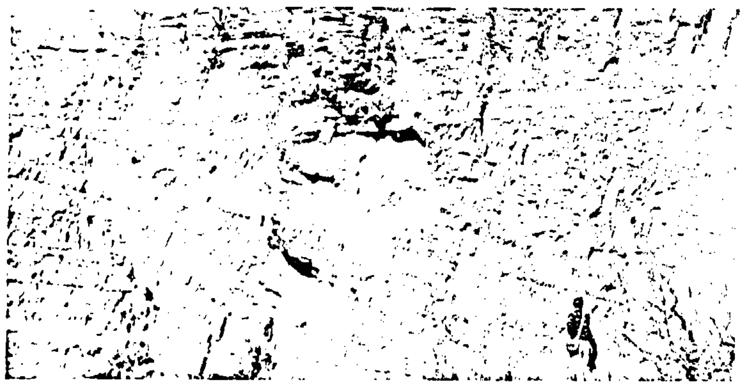


C

D

PLATE 3. Probable submarine canyon deposits in Shumard and Bone Canyons.

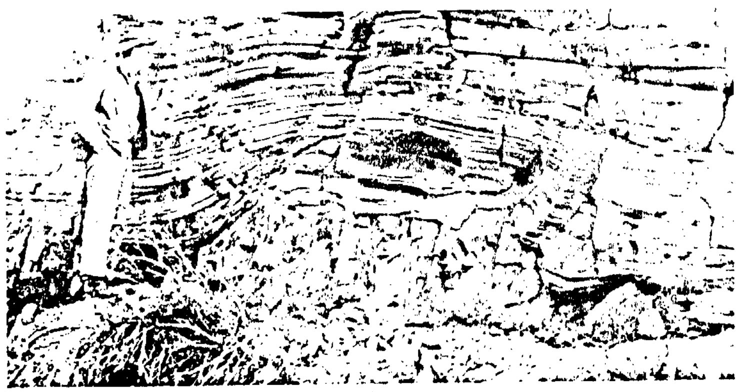
A and B. View toward northwest looking into Shumard Canyon from Bone Canyon. Transverse views of large cut-and-fill structures in Victorio Peak and Brushy Canyon Formations are shown.

C. One side of deeply incised channel cut-and-fill in Bone Spring Formation on north wall of Bone Canyon.

D. Thick boulder bed (submarine avalanche) deposit in lower Brushy Canyon filling channel cut into Cutoff Member, south wall of Bone Canyon.

A

B



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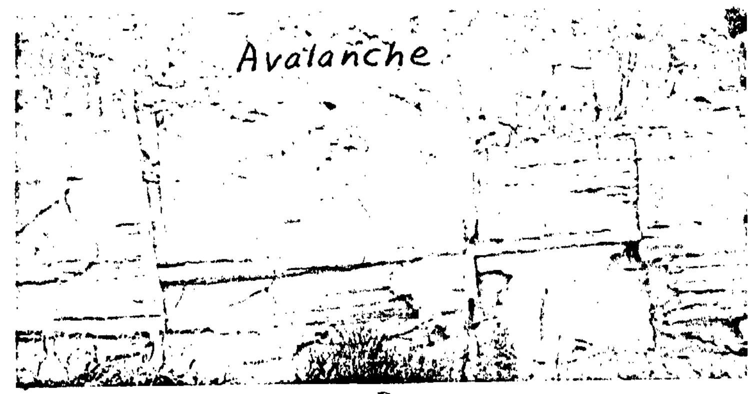

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PLATE 4. Probable submarine canyon deposits in Bone Canyon.

A. Thick, lenticular, conglomeratic mudstones intercalated with thinly bedded, laminated and small current-rippled sandstones in lower Brushy Canyon interval.
B. Upper portion of thinly bedded sand was contorted by drag as superjacent conglomeratic mudstone was emplaced.
C. Large boulder resting on conglomeratic mudstone deposit was overriden by sand flows.
D. Thinly bedded, current-rippled sand interval intercalated between two boulder beds deposited by submarine avalanches.

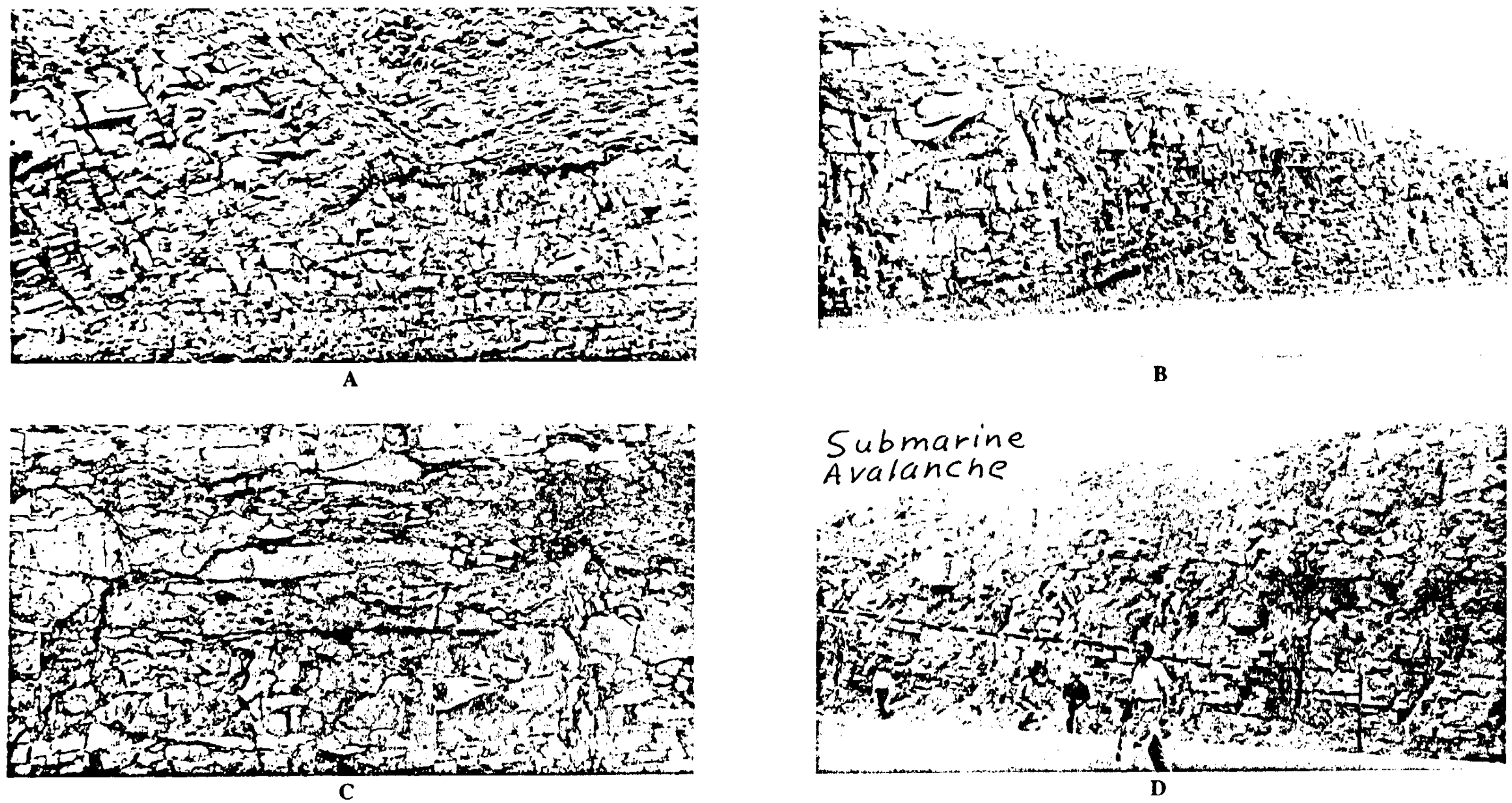
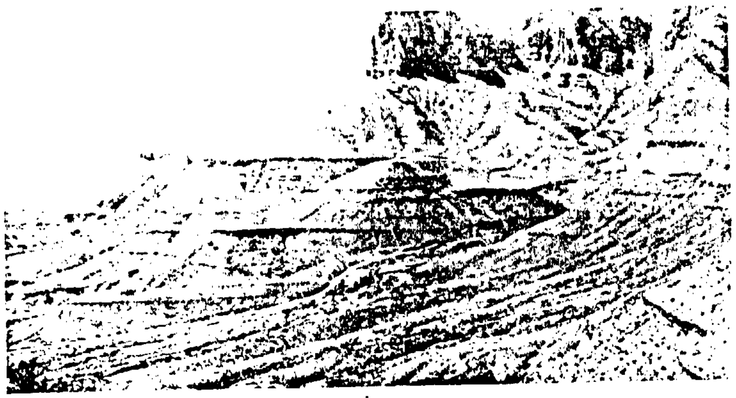


PLATE 5. Proximal fan deposits of Cherry Canyon and Bell Canyon Formations exposed along Highway 62. Proximal fan deposits consist of deeply incised channels filled with thinly bedded distal fan and fringe deposits, conglomeratic lime mudstones with hummocky upper surfaces (submarine avalance deposits), and submarine carbonate mudflows.

A and B. Cherry Canyon Formation, Guadalupe Pass.

C and D. A thick submarine avalanche deposit consisting of pebble-to-boulder sized limestone clasts in a sandy matrix. Rader Member of Bell Canyon Formation.



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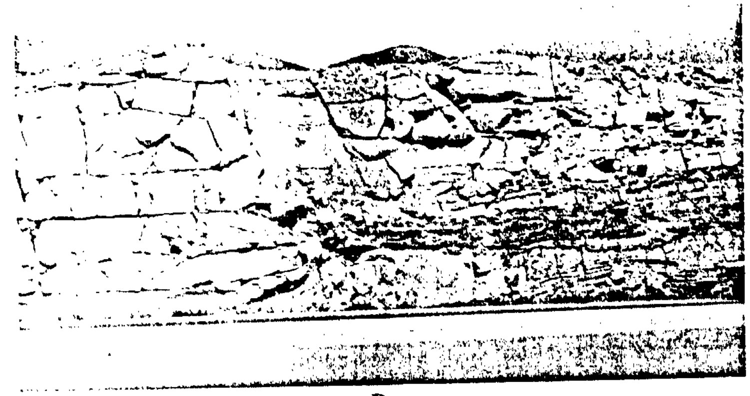

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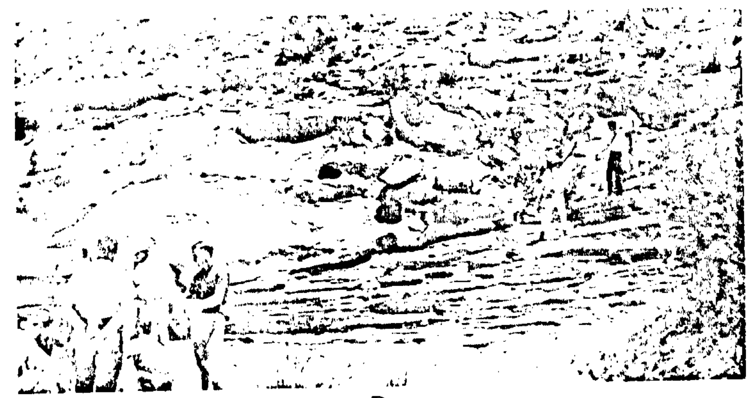

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PLATE 6. Intermediate fan deposits of the Brushy Canyon and Bell Canyon Formations showing intercalated channel-levee-overbank sediments.

A. View toward northwest from Delaware Mountains showing transverse views of Brushy Canyon channels.
B. Transverse view of Brushy Canyon channel flanked by levee and overbank deposits, Guadalupe Pass.
C. Large Bell Canyon channel 30 miles from basin margin.
D. Transverse view of Bell Canyon channel, Lamar Canyon.

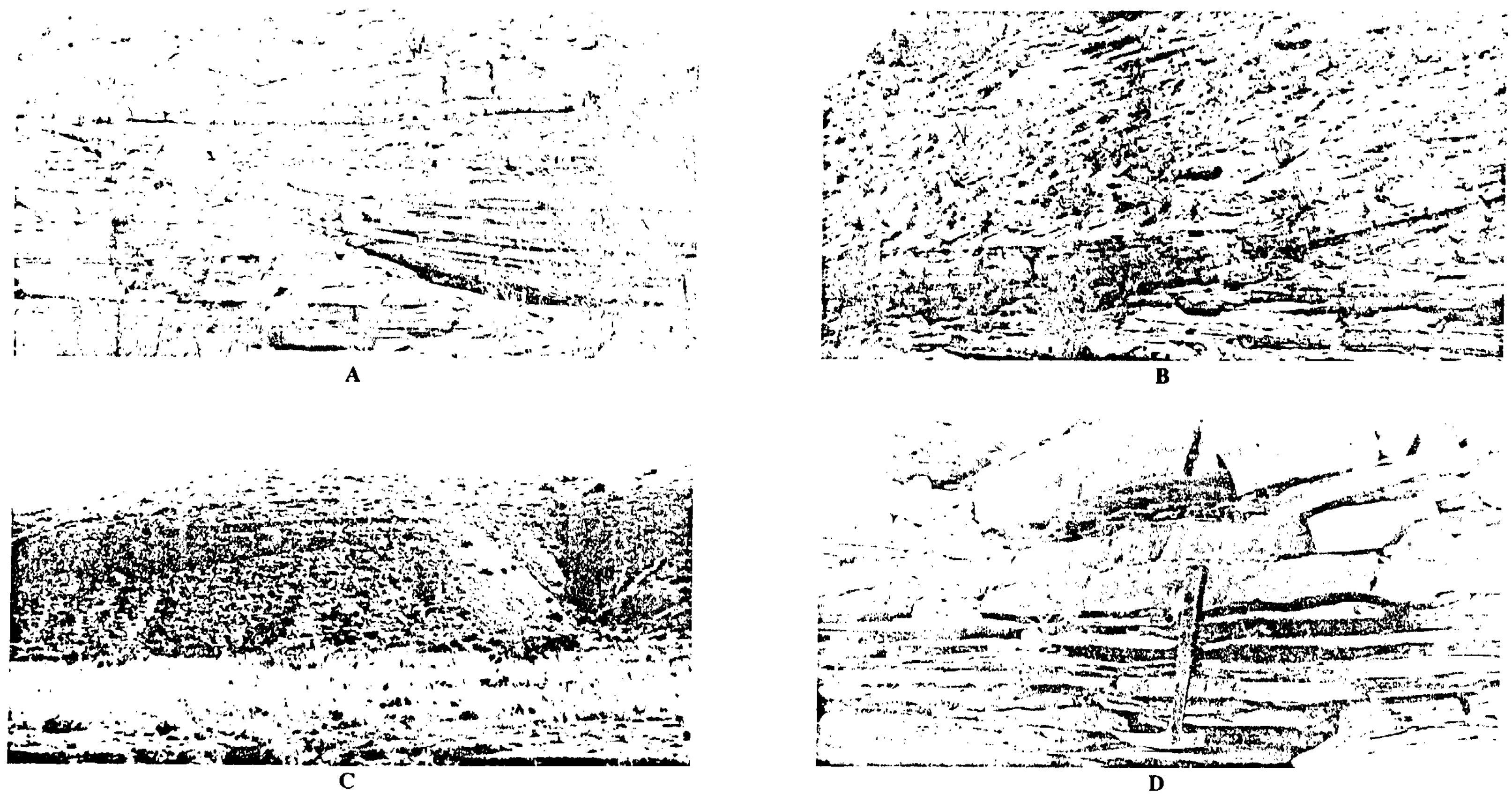
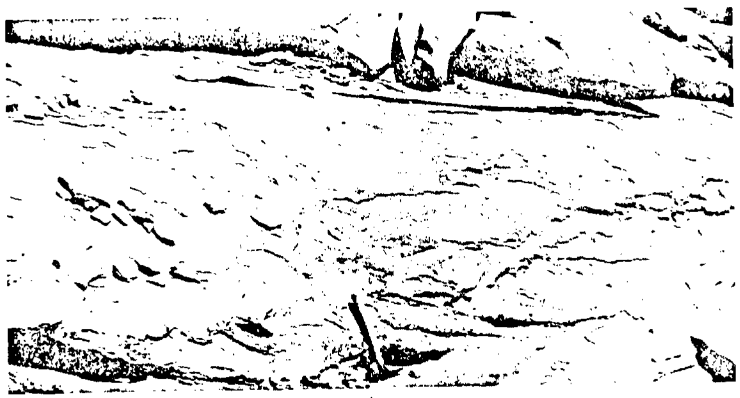
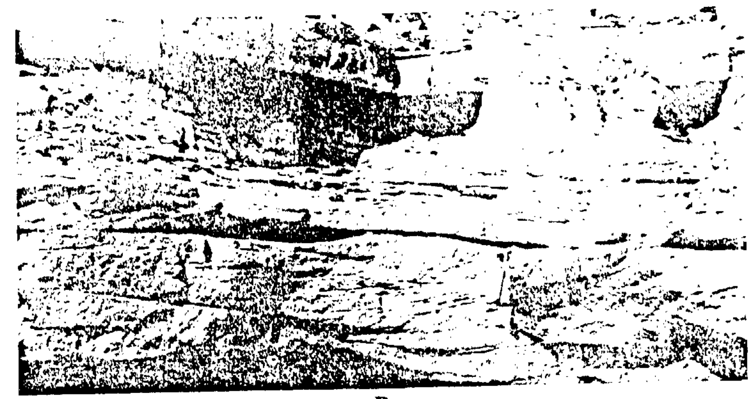


PLATE 7. **Distal clastic fan and carbonate fan deposits.**

A and B. Bell Canyon distal fan channels. Lamar Canyon.
C. Transverse view of large carbonate channel in Manzanita Member of Cherry Canyon Formation, Last Chance Wells.
D. Close view of minor flow units in carbonate channel, Pinery Member of Bell Canyon Formation, Lamar Canyon. Note groove casts as bases of beds.



A



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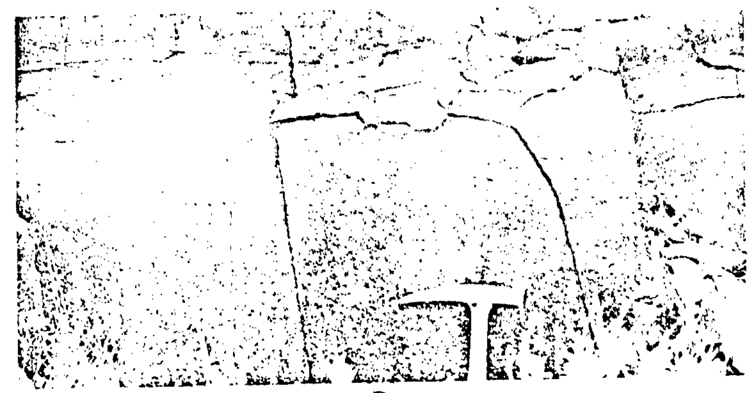

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PLATE 8.

A. Axial view of major flow unit showing upward sequence of: (1) massive, (2) large current ripples, (3) parallel-laminated sand, (4) small climbing ripples, and (5) laminated sand and silt, Lamar Canyon.

B. Axial view of Triassic point bar showing exact upward sequence found in A, Palo Duro Park.

C. Minor flow unit in Bell Canyon channel showing upward sequence of massive, laminated, small current rippled, and laminated intervals.

D. Conglomeratic lime mudstone with graded bedding, deposited by viscous mudflow, grades upward into laminated, small current-rippled interval. Carbonate channel in Rader Member of Bell Canyon.

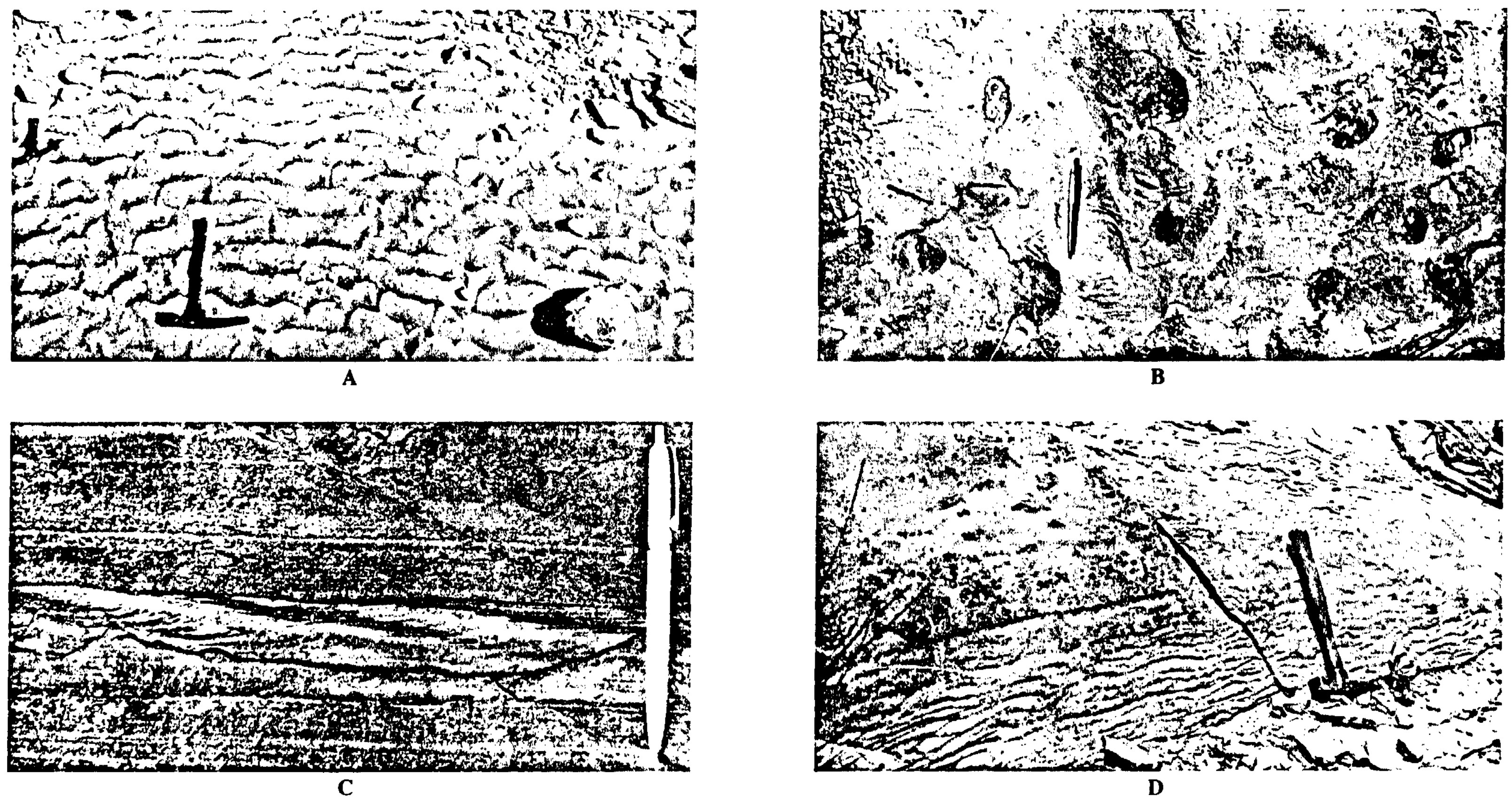
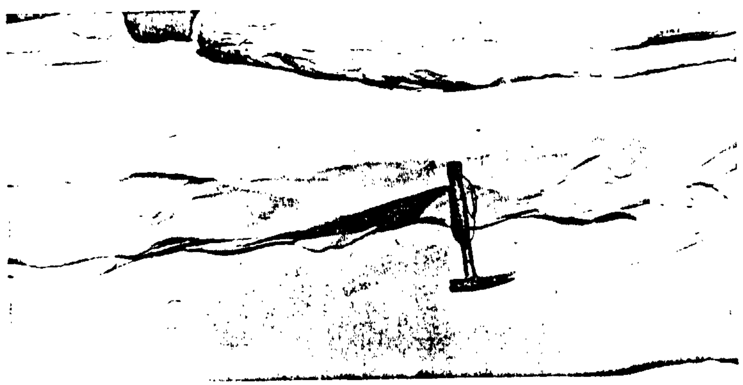


PLATE 9. Small current ripples in Delaware Mountain Group exposures.

A. Bedding-surface view of ripples in Bell Canyon channel.
B. Eroded bedding-surface showing rib-and-furrow structures in Bell Canyon channel.
C. Axial view of small climbing ripples in Brushy Canyon overbank deposit.
D. Frontal (transverse) view of small climbing ripples in Bell Canyon channel. Note how they resemble wave ripples.



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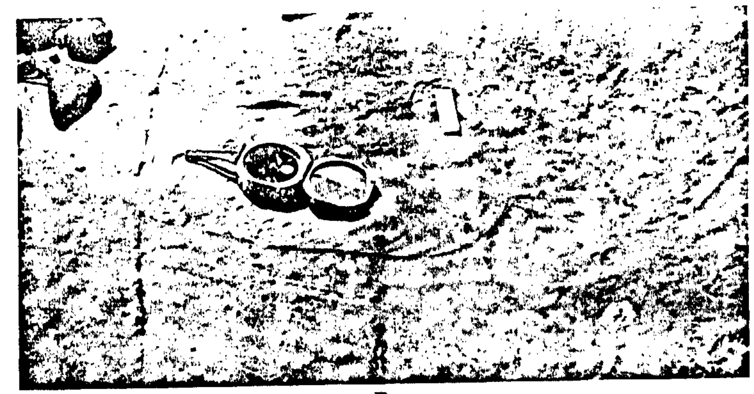

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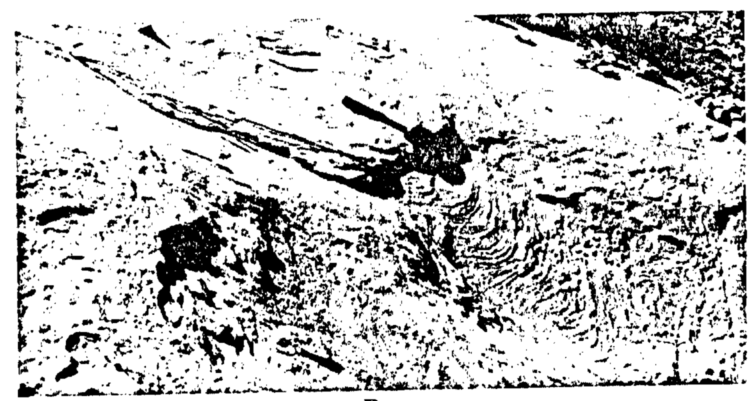

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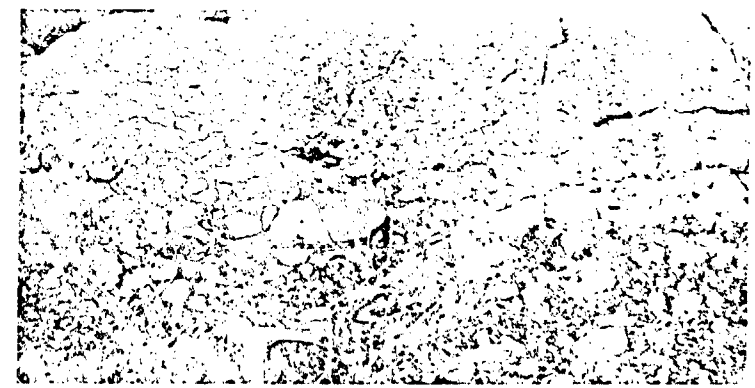
PLATE 10. Large current-ripple structures in Bell Canyon and Cherry Canyon channels.

A. Axial view of large climbing ripples in Bell Canyon channel. Ripples "climb" upward in the downcurrent direction — to the right.
B. Oblique axial view of large ripples in Bell Canyon channel. Current flow direction toward upper left corner.
C. Bedding-surface view showing large trough or rib-and-furrow structures in Bell Canyon channel. Current direction toward top of photo.
D. Oblique axial view of large climbing ripples in Cherry Canyon channel.

A



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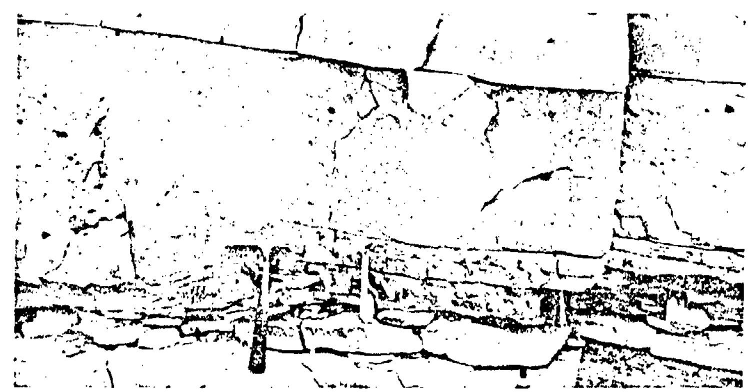

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PLATE 11. Conglomeratic lime mudstones deposited by highly viscous carbonate mudflows in Bell Canyon and Cherry Canyon carbonate fan channels.

A and B. Lithic clasts showing graded bedding in carbonate mudflow deposits of Rader Member of Bell Canyon, Lamar Canyon.
C. Graded mudflow in Getaway Member of Cherry Canyon, Delaware Mountains.
D. Viscous Getaway mudflow plowed through thinly bedded sands incorporating sand into the flow. Left end of hammer is on sandy dolostone and tape measure is on sandstone.

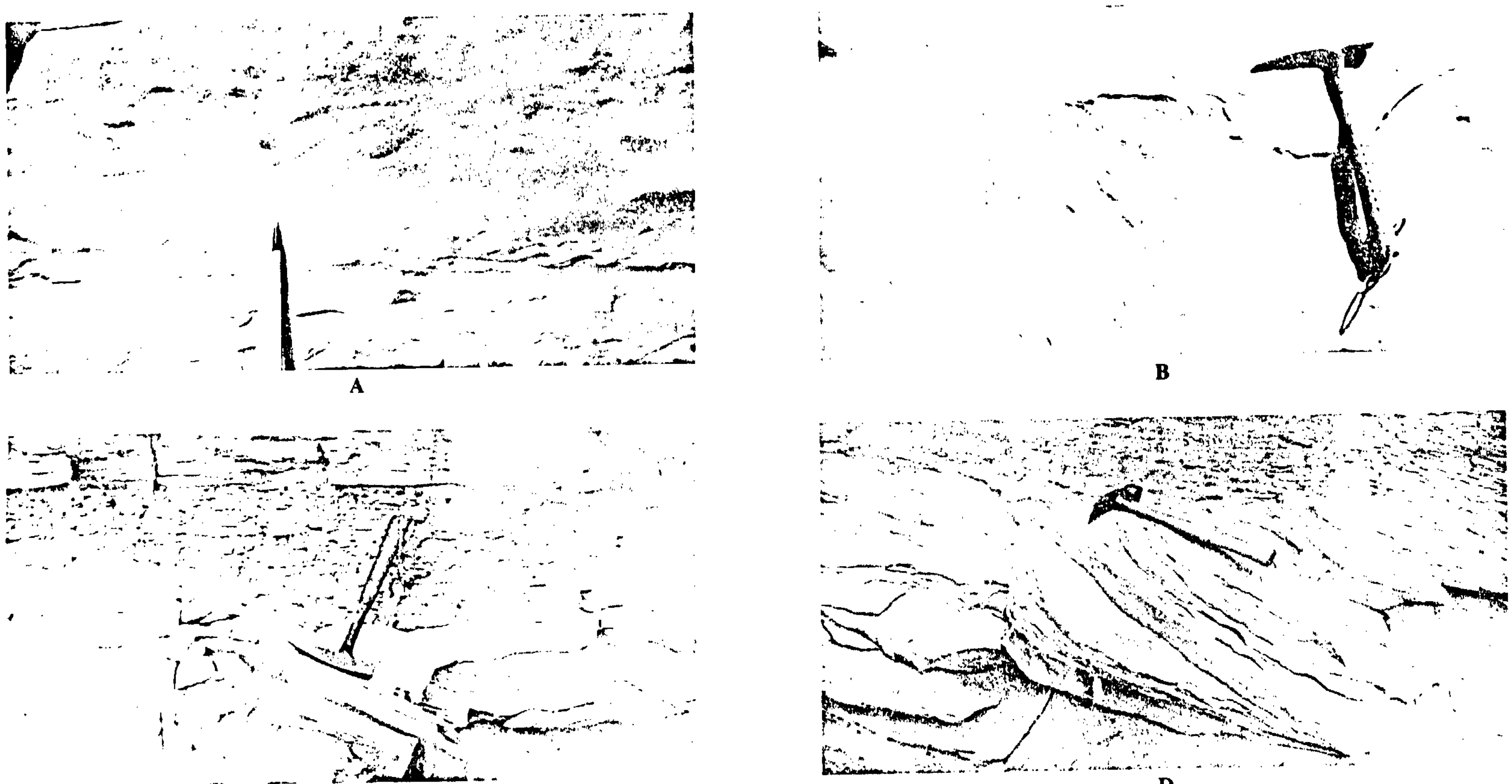
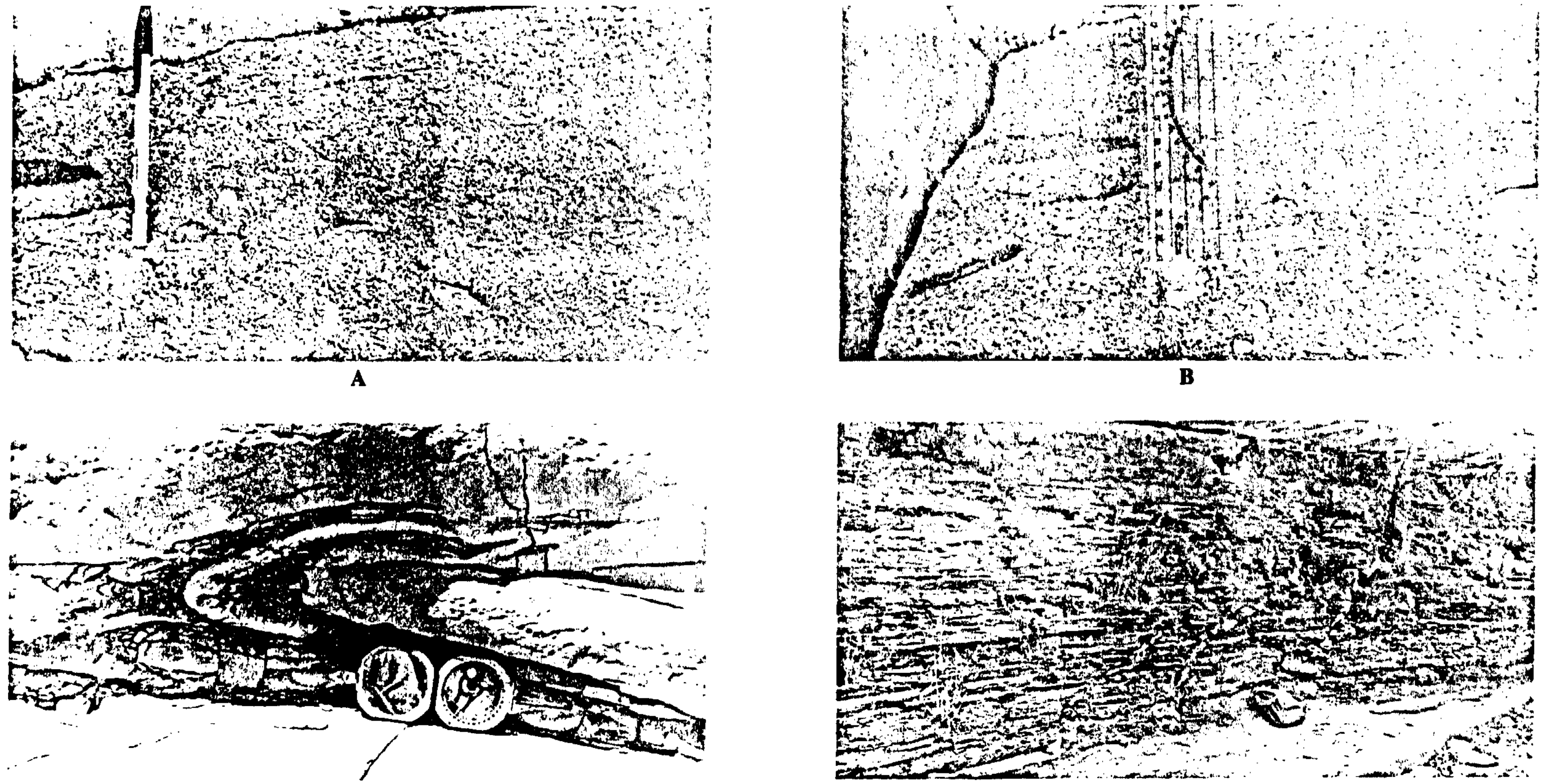


PLATE 12.

A and B. Convolute lamination in Bell Canyon channels, Lamar Canyon.
C and D. Lithic clasts imbricated downcurrent (southeast) in Bell Canyon channels.



A

B

C

D

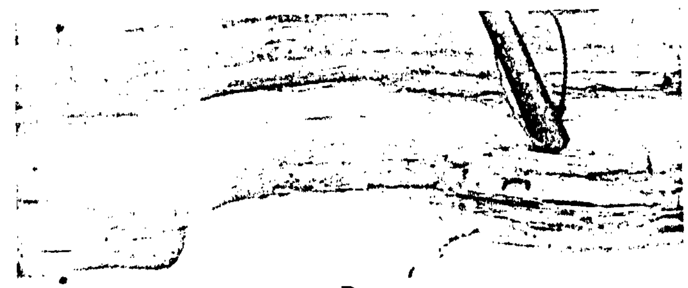
PLATE 13.

A and B. Aligned fusulines in Brushy Canyon channels. Current direction directly out of photo.
C. Pullover structure in Bell Canyon channel. A cohesive layer was overturned in the downcurrent direction.
D. Sand dikes, representing quicksand intrusions, in Bell Canyon overbank deposit.

A

B

C



D

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PLATE 14. Sole markings in Delaware Mountain exposures.

A. Slide marks at base of carbonate channel in Getaway Member of Cherry Canyon.
B. Load pockets and load waves (flame structures) in Bell Canyon channel.
C. Flute casts on base of Brushy Canyon float block.
D. Groove casts in carbonate channel, Pinery Member of Bell Canyon.
E. Groove casts in Brushy Canyon channel.

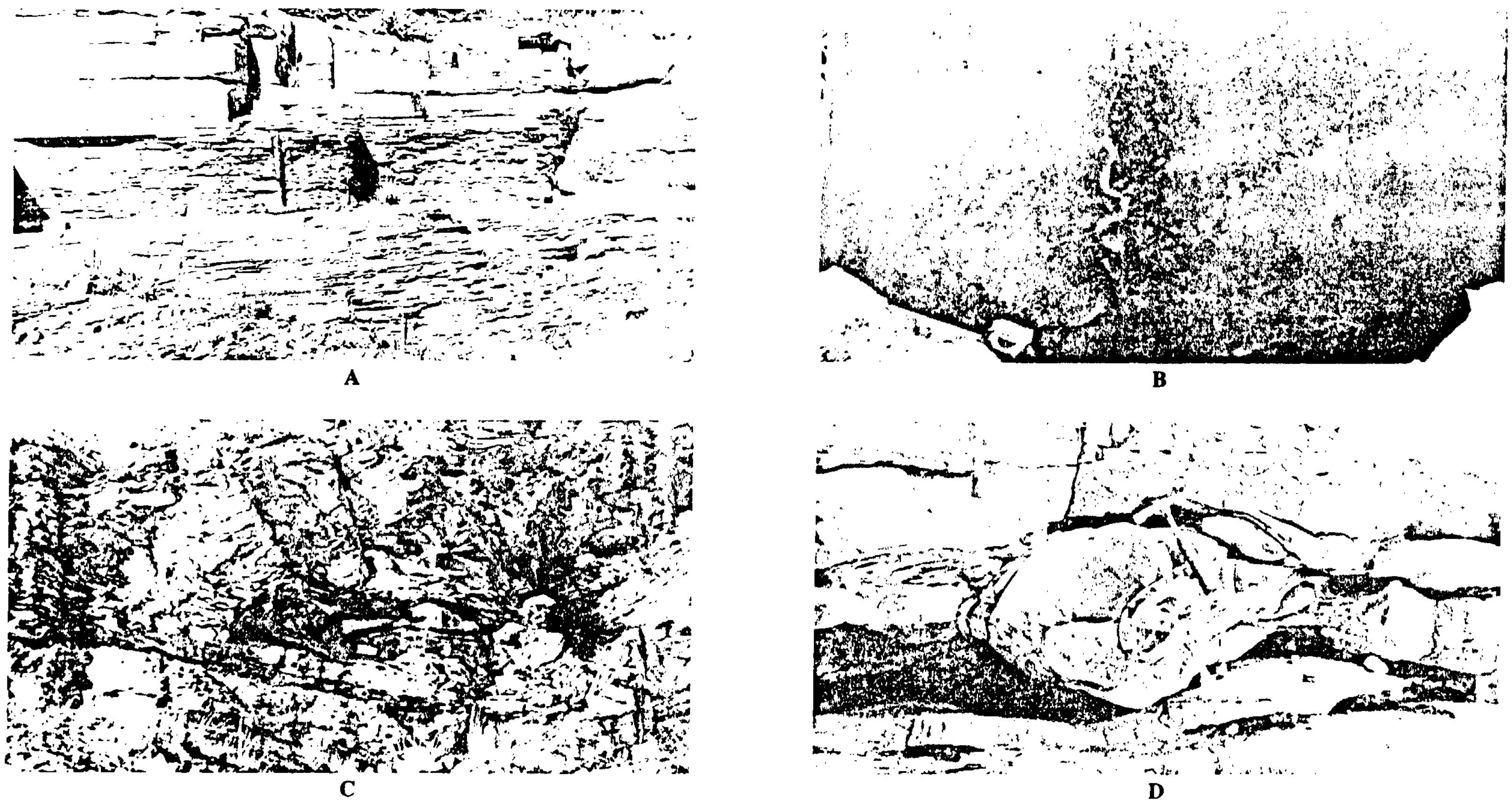
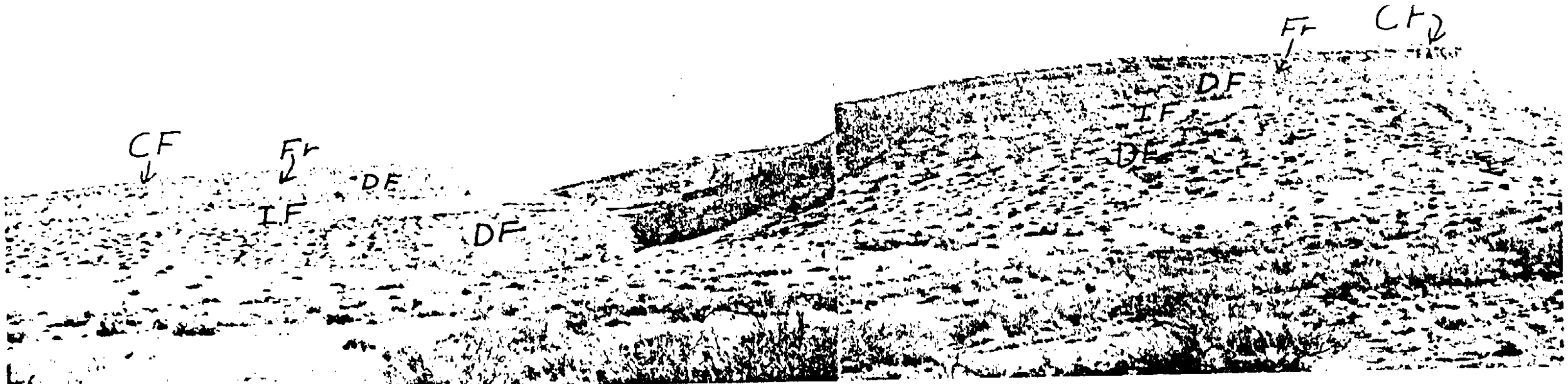


PLATE 15.

A. Parallel plane laminations in Bell Canyon overbank deposit.
B. Organic hieroglyphs at base of Cherry Canyon bed, Guadalupe Pass.
C and D. Post-depositional soft-sediment deformation in carbonate channels of Getaway Member of Cherry Canyon. C - Chico Ranch; D - Glover Canyon.



A

B

C

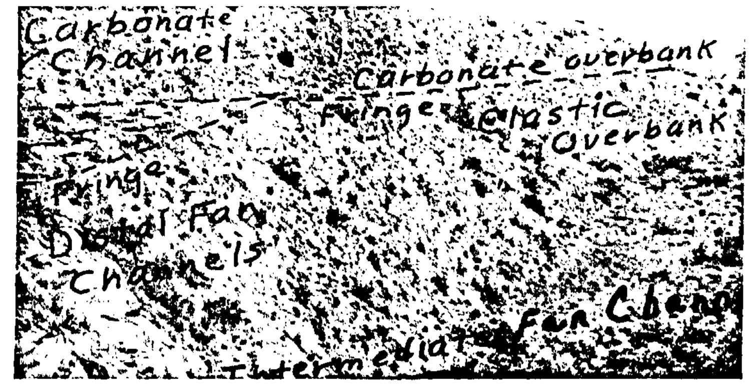
PLATE 16. Progradational-recessional fan-fringe cycles in Cherry Canyon and Bell Canyon Formations.

A. **Upward sequence of distal fan (DF), intermediate fan (IF), distal fan (DF), fringe (Fr), and carbonate fan (CF) (Manzanita Member) deposits in upper Cherry Canyon interval exposed on Long Point. This records a cycle of basinward progradation followed by "shrinking" of fans.**

B. **Vertical succession of intermediate fan (IF), distal fan (DF), fringe (Fr), and carbonate fan (CF) in upper Cherry Canyon (Manzanita) interval, Last Chance Wells.**

C. **Intermediate fan, distal fan, fringe sequence in upper Bell Canyon interval.**

A



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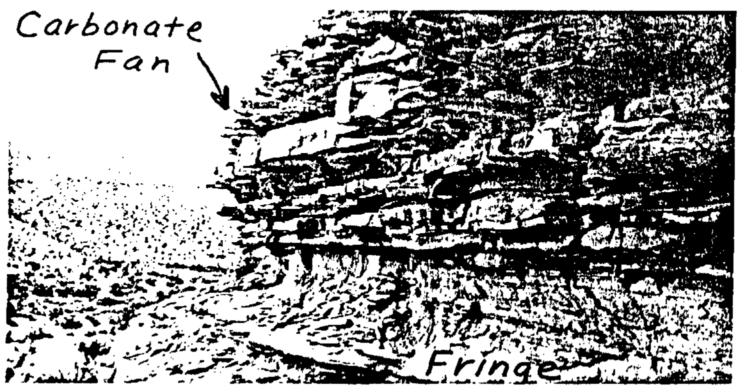
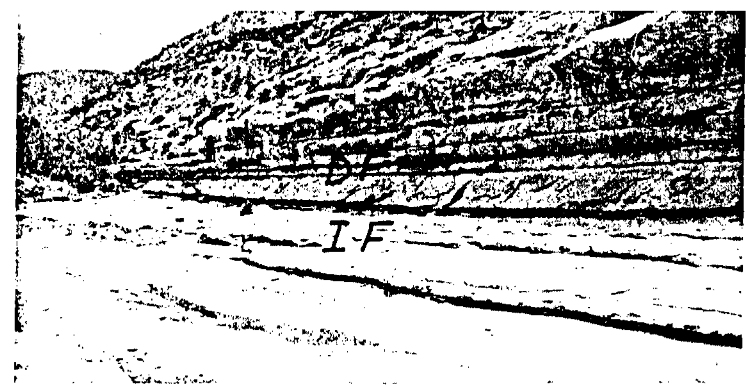


C



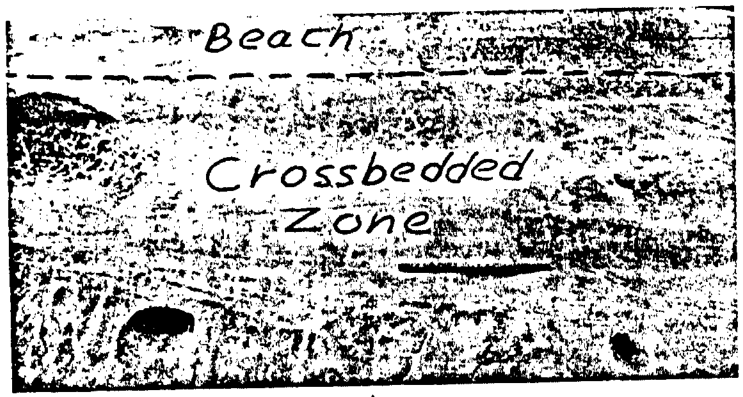
D

PLATE 17. Progradational-recessional fan-fringe cycles in subPinery-Pinery interval of Bell Canyon Formation exposed in Lamar Canyon.

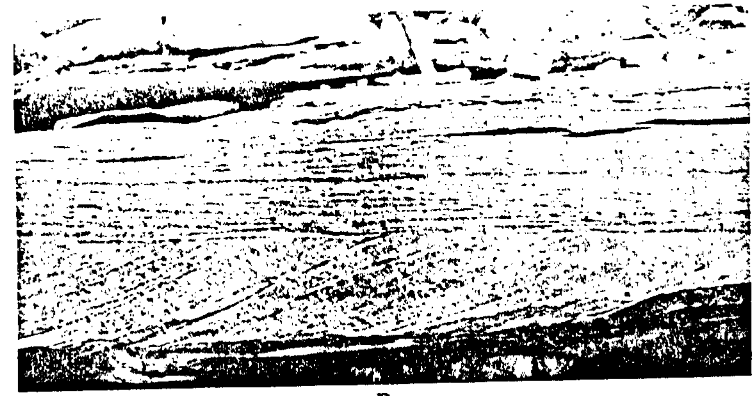
A and B. Transverse views of same exposure showing vertical sequence of intermediate fan (IF), distal fan (DF), fringe (Fr), and carbonate fan (CF). Note stacking of clastic and carbonate channels which pinch out to right in B and are flanked by overbank deposits.

C. Close view of A showing contact between fringe and carbonate fan.

D. Axial view showing thick-bedded intermediate fan (IF) channel overlain by distal fan (DF) channel.



A



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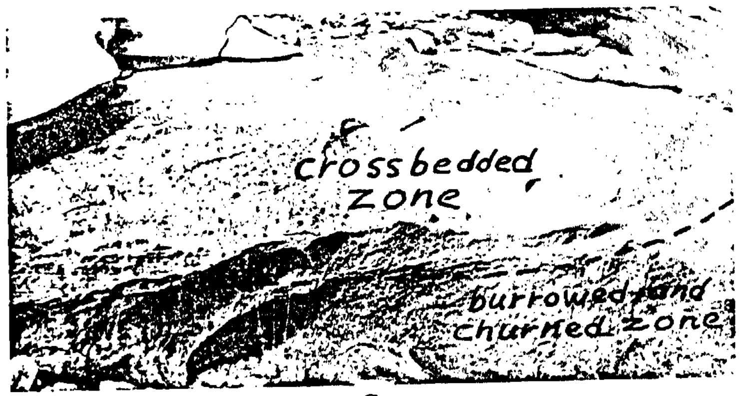

C

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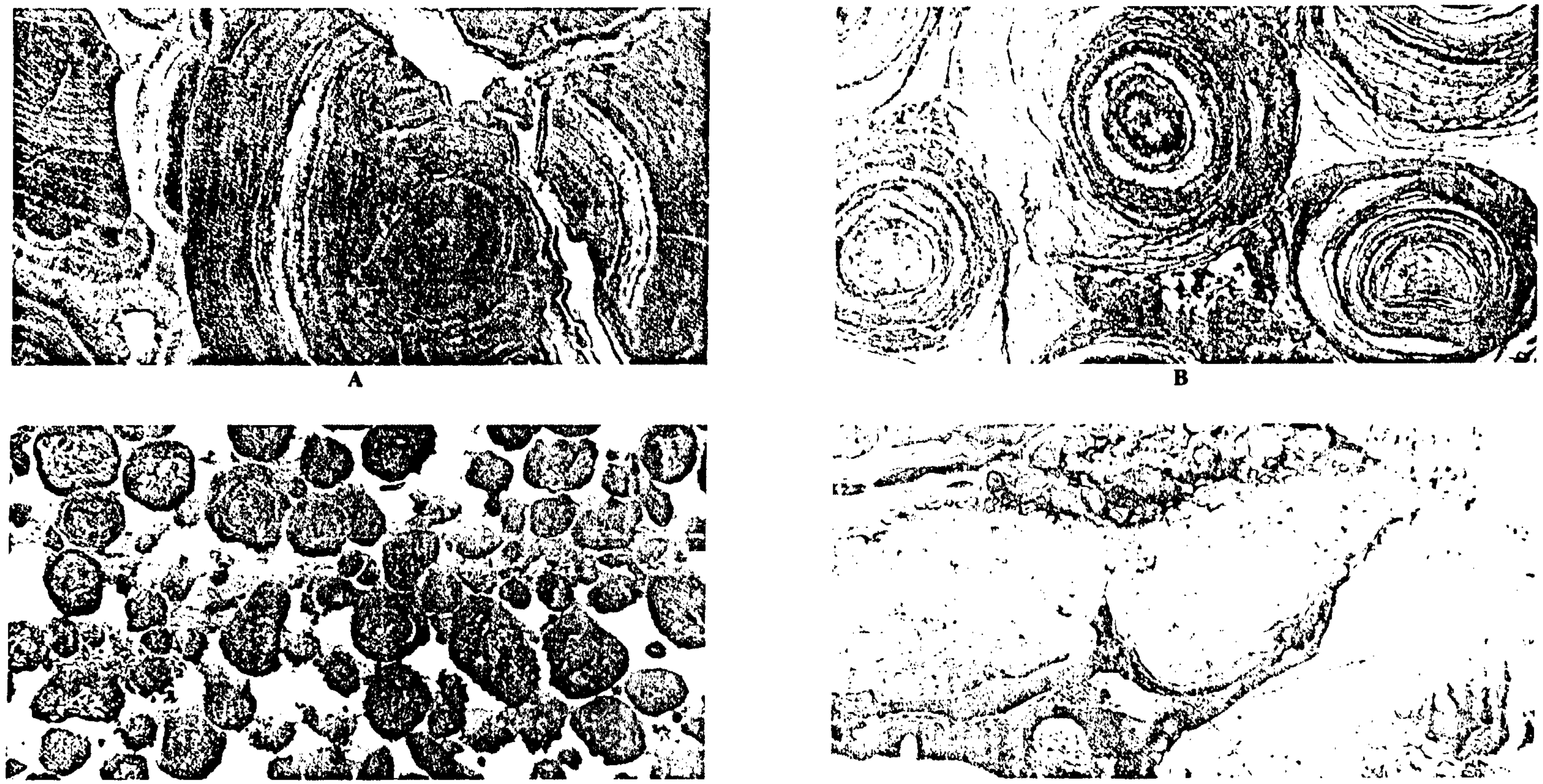
PLATE 18. Examples of Permian vadose caliche pisolites, Guadalupe Mountains. Yates Formation.

A. Photomicrograph (x10) showing fractures enlarged by solution. Numerous episodes of solution-truncation followed by deposition of laminar films are recorded.
B. Photomicrograph (x10) showing laminae growing together and eliminating interstitial space.
C. Photomicrograph (x10) showing voids between pisolites partly filled with internal sediment.
D. Oiled slab showing solution passages filled with dark laminar calcite films and sparry calcite.



A B C D

PLATE 19. Features displayed by Permian and modern caliche pisolites.

A. Former solution passages lined with dark laminar calcite films.
B. Modern caliche pisolites which formed in sandy soil. Notice composite forms and solution-truncation surfaces. x2.
C. Former solution passage filled with drusy calcite (Dr), laminar calcite films (LR), internal sediment (IS), and fibrous carbonate (F).
D. Tepee structure with brecciated core.

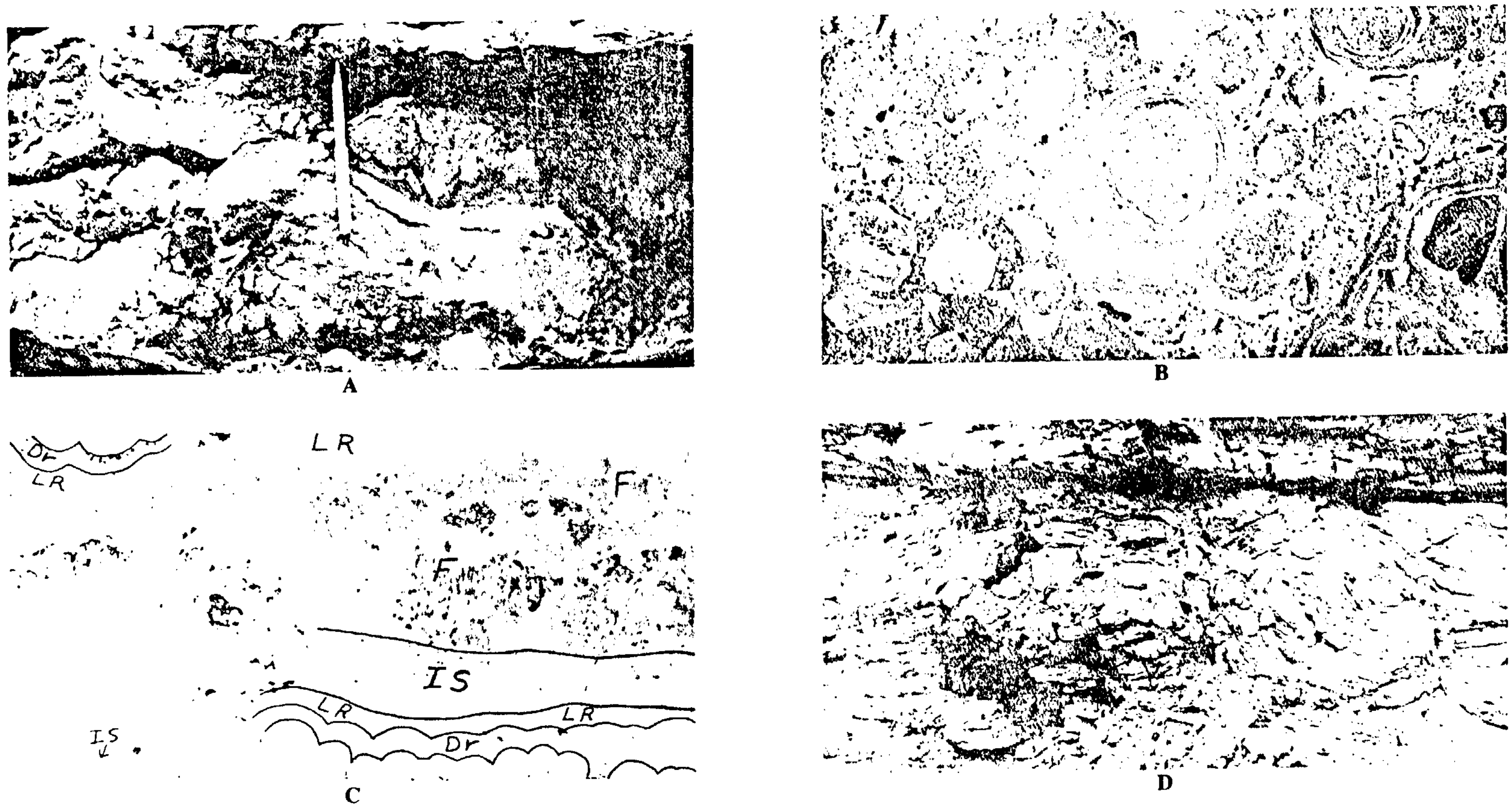
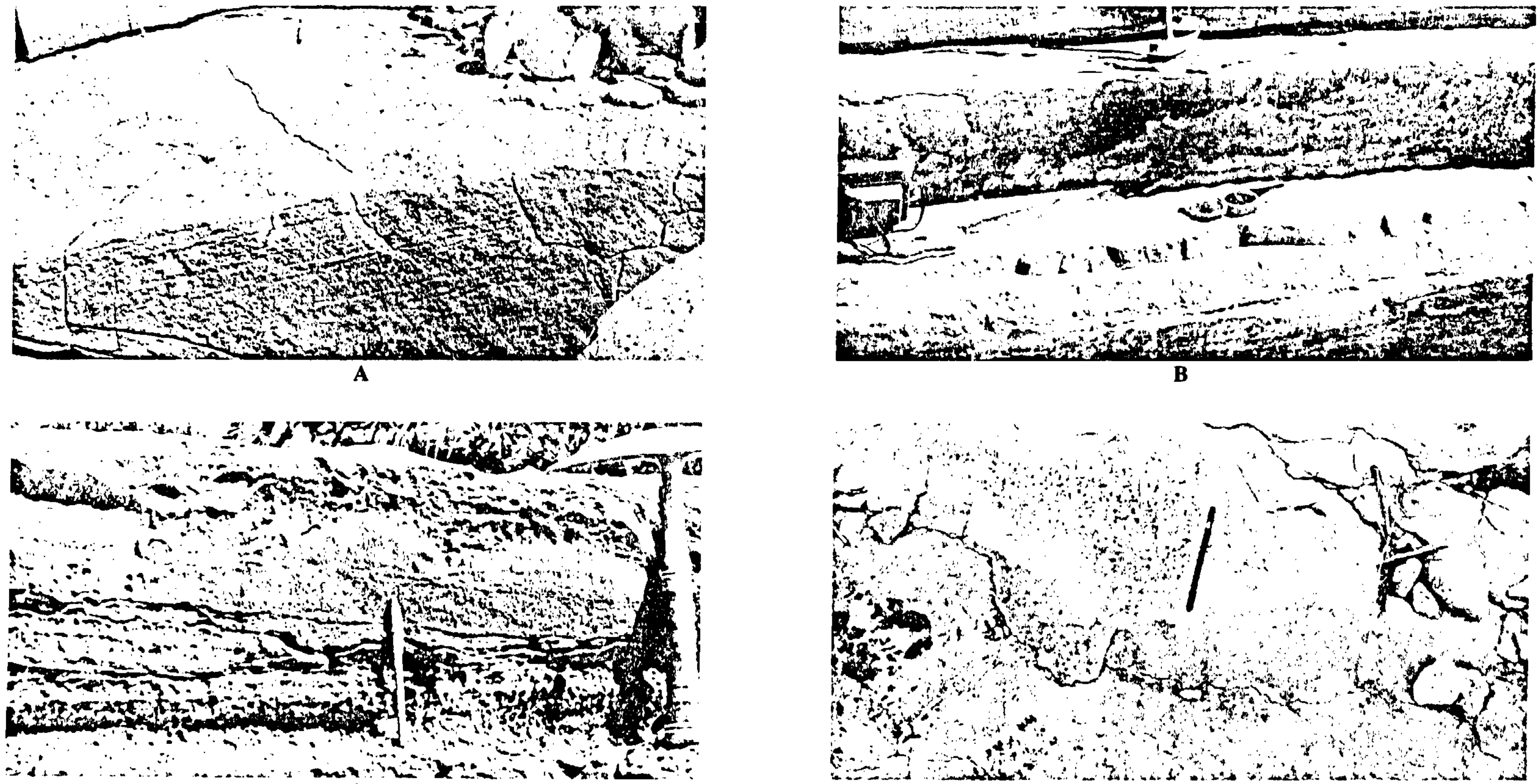


PLATE 20. Different views of shoreline-strike sand body, which probably represents a barrier island, in lower Queen interval exposed in Dark Canyon. The sand body, which parallels the NE-SW margin of the Northwest Shelf, displays an upward sequence of: (1) burrowed and churned zone, (2) current ripple cross-bedded zone recording reversing longshore currents, and (3) beach-washover fan deposits.

A and B. Contact between current ripple cross-bedded interval and beach.
C. Contact between lower burrowed and churned zone and crossbedded zone.
D. Washover fan at top of sand body.



A B C D

PLATE 21. Intertidal flat deposits in Grayburg exposures of Last Chance Canyon.

A. Wave ripples (upper right) on giant current ripple foreset.
B. Small current ripples and distinct lamination in interchannel flat.
C. Round-crested wave ripples formed by erosion of formerly sharp-crested ripples.
D. Burrowed and churned zone.

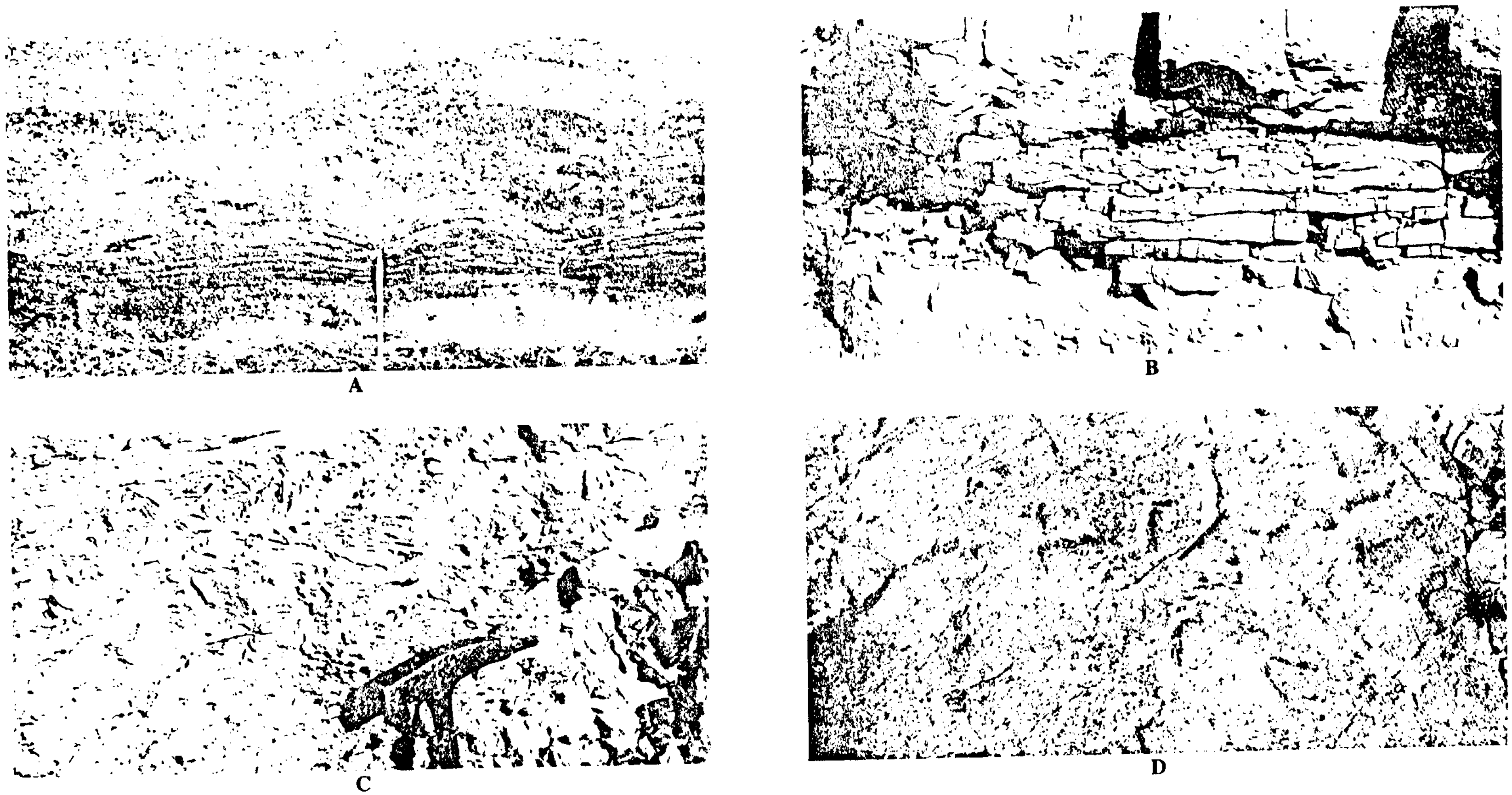


PLATE 22. Supratidal-algal flat deposits in Queen and Seven Rivers exposures.

A. Club-shaped stromatolites in Queen carbonate algal flat, Dark Canyon.
B. Laterally-linked hemispheroidal stromatolites in Seven Rivers algal flat, Rocky Arroyo.
C. Molds of gypsum blades and rosettes in Queen supratidal flat, Rocky Arroyo.
D. Mudcrack casts in Queen supratidal flat, Dark Canyon.