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BUREAU OF ECONOMIC GEOLOGY
The University of Texas at Austin
Austin, Texas 78712
W. L. Fisher, Director

Report of Investigations—No. 72

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VAN HORN SANDSTONE, WEST TEXAS: AN ALLUVIAL FAN MODEL FOR MINERAL EXPLORATION

J. H. McGowen and C. G. Groat

ABSTRACT

The Van Horn Sandstone is an ancient alluvial-fan system with a northern highland source area of rhyolite, granite, metamorphic and sedimentary rocks. Sediment ranging in size from silt to boulders was transported southward through canyons by high-gradient mountain streams. South of the mouths of the canyons, sediment was transported by less confined braided streams.

The fan was deposited on a surface of faulted, folded, and highly dissected Precambrian sedimentary, metamorphic, and intrusive basic igneous rocks. Topography of the subjacent erosional surface was rugged and characterized by deep canyons that controlled the distribution of gravel downfan beyond the termination of high-gradient mountain feeder systems.

Three principal facies of the Van Horn area are, from north to south, (1) proximal, chiefly gravel; (2) mid-fan, alternating gravel and sand; and (3) distal, dominantly coarse and very coarse sand. The proximal facies is 300 to 600 feet thick in the northern outcrop area and consists of lower thick, massive cobble and boulder beds and upper thin to thick, horizontally bedded pebble, cobble, and boulder gravels. It grades southward and vertically into alternating gravel and sand of the mid-fan.

Mid-fan deposits are up to 300 feet thick in the northern outcrop area and about 30 feet thick in the central area where the facies plunges southward into the subsurface. Mid-fan gravels occur as lenses of parallel-bedded depositional units with flat bases and convex upper surfaces and as channel-fill deposits. Sands associated with the mid-fan occur either as broad channel-fill deposits or as lenses deposited in low areas flanking gravel lenses (or bars). Two stratification types, foreset and trough crossbeds, dominate these sands.

The distal facies consists chiefly of coarse and very coarse sand; the mid-fan facies grades southward downfan into distal facies, which also overlies mid-fan deposits throughout the fan. Maximum outcrop thickness of distal facies is about 700 feet. Three distal fan subfacies (main braided stream, braided distributary, and braided interlobe) have been differentiated. Main braided stream deposits occur as foreset and trough crossbeds; relative abundance of each crossbed type is variable. Scale of foresets and trough crossbeds decreases upward in the section and to the south. Braided distributary deposits are characterized by a relatively high content of muddy sand units, well-preserved channel-fill deposits, some ripple cross-laminated sand units, foreset- and trough-crossbedded sands (locally the facies may be dominated by small trough crossbeds), and units displaying soft sediment deformation and injection structures. Braided interlobe deposits consist of thick sand sequences composed almost exclusively of trough crossbeds. Muddy sand is uncommon and trough laminae are accentuated by heavy mineral placers. This subfacies contains the greatest heavy mineral concentration within the Van Horn Sandstone.

Facies relationships, textural trends, succession of sedimentary structures, and dip direction of crossbeds indicate a southerly sediment transport direction. Depth of flow, slope of the fan surface, stream velocity, and competence decreased southward. Proximal facies developed under confined, rapid flow conditions; surges were common events within the feeder system and within the canyons. Mid-fan deposits were laid down by braided streams; both rapid and tranquil flow conditions are indicated by longitudinal gravel bars and by flanking transverse bars with dunes, respectively. The distal fan was the area of lowest physical energy. Tranquil flow conditions dominated, slope of the surface was extremely low, and sediment remained saturated for relatively lengthy periods following a depositional event.

The Bliss Sandstone (Ordovician) is the oldest sedimentary rock sequence that overlies the Van Horn. In places the contact between Bliss and Van Horn is discordant, but in others the contact is conformable.

Although placer gold had been reported in the

Van Horn Sandstone, laboratory analyses of 71 samples revealed no significant amounts. Despite the absence of gold, the concentration of other heavy minerals in the braided interlobe subfacies of the distal-fan facies and the detailed descriptions of the facies relationships should contribute to a prospecting model that will be applicable to similar but ore-bearing alluvial fan systems.

INTRODUCTION

The Van Horn Sandstone in southwestern Culberson and southeastern Hudspeth counties, Texas (figs. 1, 2) was studied in cooperation with the United States Geological Survey in order (1) to determine the gold-bearing potential of this terrigenous rock body, (2) to ascertain the geological conditions which influenced deposition of the Van Horn, (3) to correlate heavy metal occurrence or concentration with particular facies of the Van Horn, and (4) to derive a process-defined depositional model with which areas of heavy metal occurrence could be predicted and to which similar terrigenous rock bodies may be compared.

Composition of the Van Horn conglomerates was determined from field pebble counts. Thin sections of sandstones and matrix of conglomerates from the various facies were examined to determine any vertical or lateral variations in composition. In addition to studies of conglomerate and sandstone composition, clay-sized ($< 2\ \mu$) materials for some of the muddy sandstones were analysed by X-ray diffraction.

Samples from each textural and structural type within each facies were analysed for gold by atomic absorption method. Heavy mineral separates were made from sandstones and matrix of conglomerates of each of the facies; separates were studied by standard petrographic methods.

Critical reading of the manuscript was done by W. L. Fisher, L. F. Brown, Jr., and C. V. Proctor,

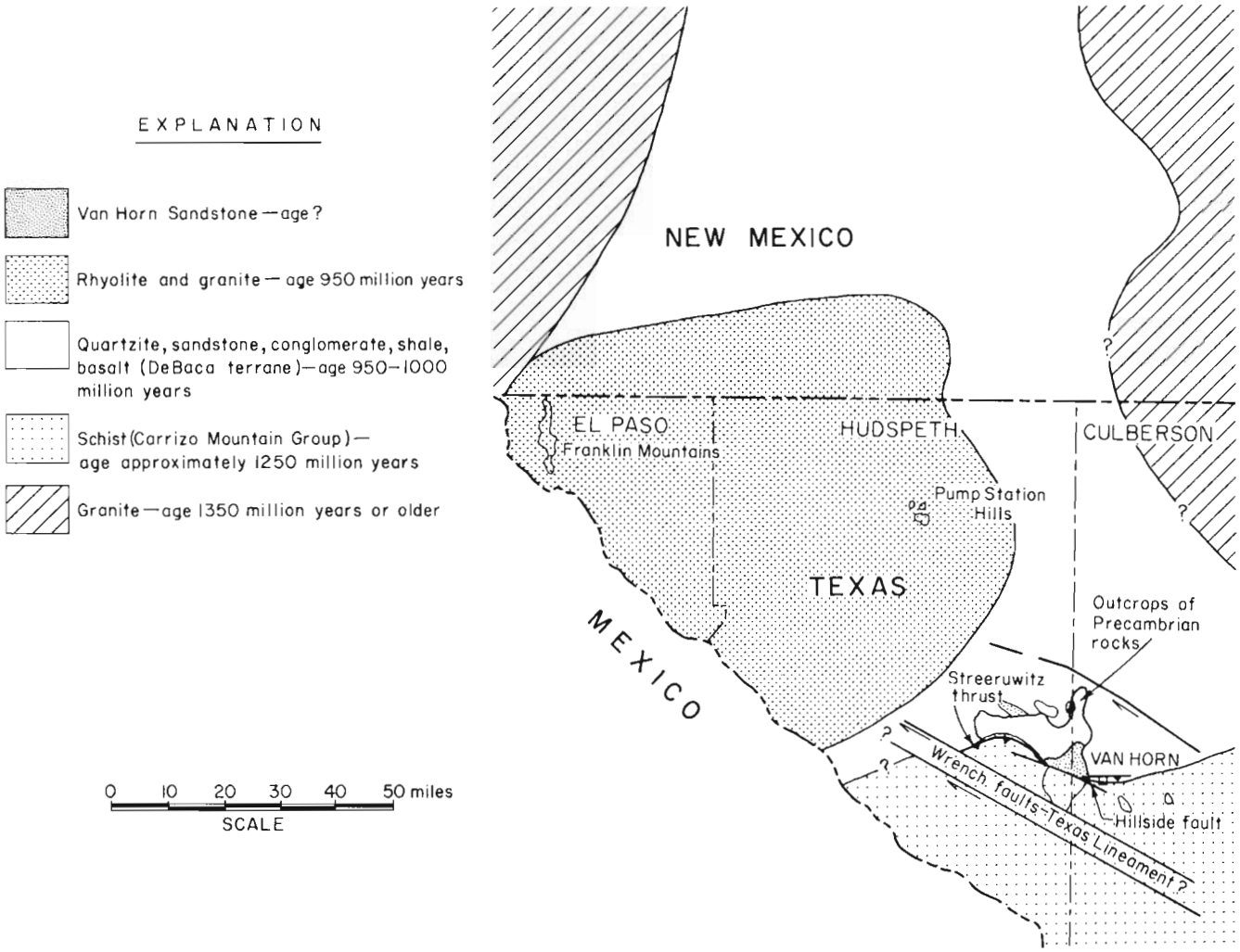

FIG. 1. Map showing location of Van Horn Sandstone outcrop, its source terrane, and related structural features. Modified from Denison and Hetherington (1969).

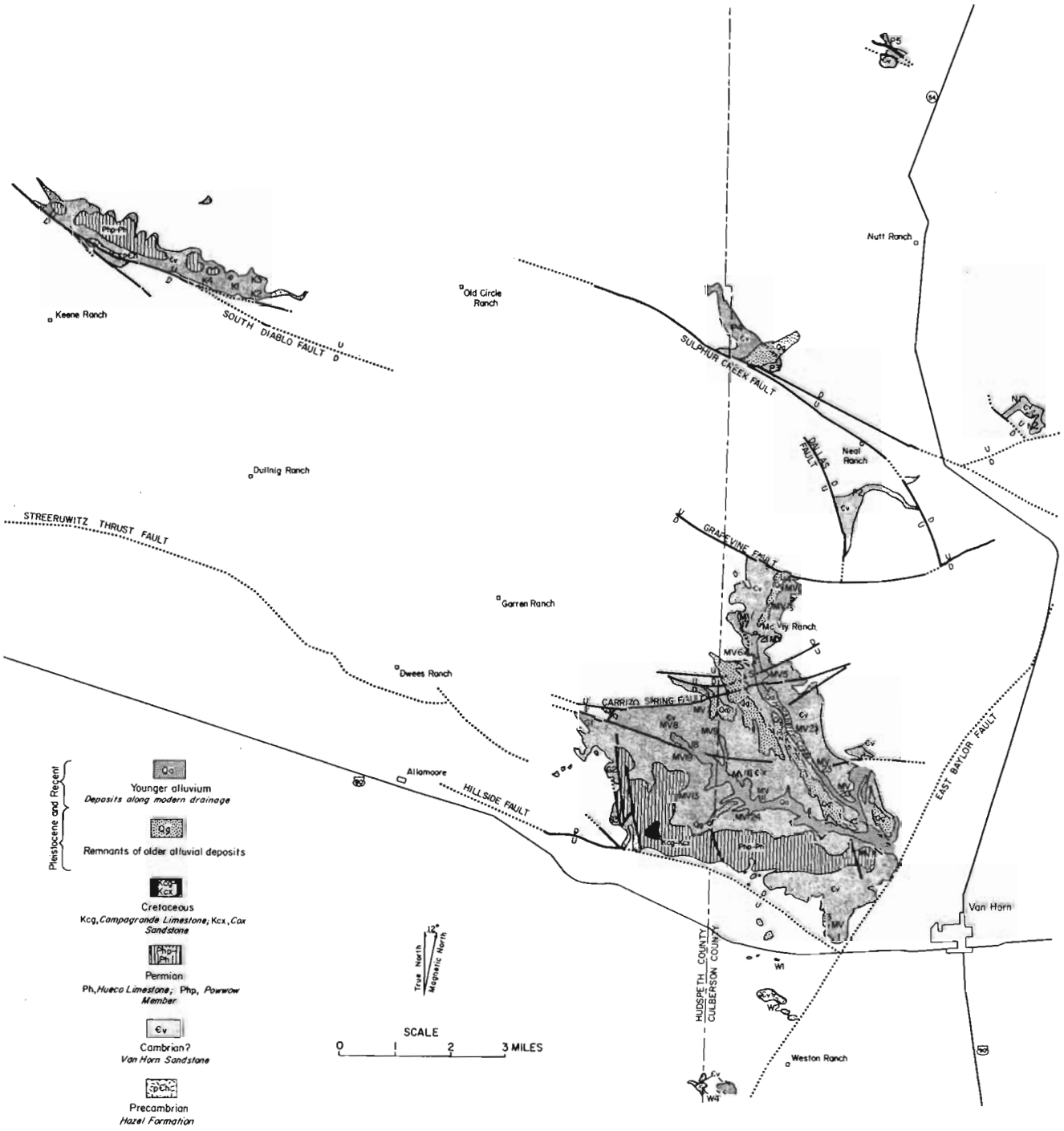

FIG. 2. Outcrop and locality/section map of the Van Horn Sandstone, Hudspeth and Culberson counties, Texas. Modified from King (1965).

Jr., of the Bureau of Economic Geology, and Professor A. J. Scott, of the Department of Geological Sciences, The University of Texas at Austin. Testing and analysis of samples were performed in the Bureau of Economic Geology's Mineral Studies Laboratory by D. A. Schofield, Chemist-in-Charge, and J. T. Etheredge, Chemist. Illustrations were prepared under the direction of J. W. Macon. Josephine Casey and Elizabeth Moore edited and typed the manuscript. Special thanks are extended to Bill McVay, Johnny Garren, Buddy Neal, Elmo Weston, and Mrs. Rodway Keene for permitting access to outcrops of Van Horn Sandstone on their properties.

GENERAL DESCRIPTION

The red massive sandstone and conglomerate of the Van Horn Sandstone crop out most extensively in the Red Valley northwest of the town of Van Horn, Culberson County, Texas. The "redrock," as it is called by area residents, is also exposed in the Baylor Mountains, at the northwest corner of Beach Mountain, along the southern margin of Sierra Diablo on the Keene ranch, and in the eastern Carrizo Mountains (fig. 2). Excellent exposures from a few feet to several hundred feet are numerous in steep cliff faces along extensive escarpments and in outliers. Outliers are most common in the Red Valley area, occurring as large blocks in which patterns and trends in sedimentary structures can be observed in three dimensions.

The Van Horn consists of conglomerate with varying amounts of interbedded sandstone in the northern areas grading southward to sandstone. The lower part of the exposed Van Horn is dominantly conglomerate; the conglomerates grade upward into abundant sandstone that characterizes the upper part of the formation. Outcrops in the southern two-thirds of the Red Valley on both sides of Threemile Mountain are sandstone with very little or no conglomerate. Conglomerate increases northward; excellent exposures of interbedded conglomerate and sandstone occur around the old Yates ranchhouse on the McVay ranch, on the Neal ranch, and along the southern face of Sierra Diablo on the Keene ranch.

The Van Horn Sandstone is predominantly red, dark red, and reddish brown; yellowish-brown and orange-brown rock occurs in fault blocks and outliers in the Red Valley. In one area (McVay ranch, section MV18) a distinct change in color accompanies an increase in resistance to weathering; however, no obvious differences were observed in thin sections of the contrasting rocks. Variations in ground-water chemical composition or movement may account for some of the color variation.

Localities from which samples were collected and/or sections measured are shown on figure 2.

GEOLOGIC SETTING

The Van Horn Sandstone is an unconformity-bounded unit, a few feet to about 1,200 feet thick (exposed). No known correlative strata have been recognized in West Texas. The Van Horn was deposited on highly dissected Precambrian conglomerate and sandstone of the Hazel Formation, and on carbonate, metamorphic, and volcanic rocks of the Allamoore Formation (King and Flawn, 1953). The Bliss Sandstone (Ordovician) is the oldest rock overlying the Van Horn. The Van Horn is considered Precambrian by previous workers (King and Flawn, 1953), though it could be Precambrian, Cambrian, or Ordovician in age.

The Allamoore and Hazel Formations are complexly folded and faulted near the trace of the Streeruwitz overthrust (fig. 2). Farther north intensity of deformation in the Hazel Formation decreases and the Hazel displays low-angle dips. King (*in* King and Flawn, 1953) stated that the Streeruwitz overthrust and associated structures are probably major features on the border between a northern stable region and a southern mobile belt. These tectonic elements persisted at least through Cretaceous and probably into Tertiary time.

Tectonic events in the Van Horn area created a setting favorable for accumulation of a thick wedge of terrigenous sediment, that is, a highland and adjacent lowland. Alluvial fans (Denny, 1967) and fan deltas (Holmes, 1965; Burke, 1967; McGowen, 1971) presently form where similar conditions prevail. Development of alluvial fans or fan deltas depends on whether deposition is subaerial or into a body of water.

Conglomerate and coarse sandstone that comprise the Van Horn Sandstone are post-orogenic deposits interpreted by King (*in* King and Flawn, 1953) to be "almost certainly of continental origin." According to King (*in* King and Flawn, 1953), the original depositional area was an east-west trough that developed between deformed and uplifted Allamoore and Carrizo Mountain rocks on the south, and highlands of granite and rhyolite porphyry on the north. The Carrizo Mountain Group, the oldest rocks in the Van Horn area, consists of altered sedimentary rocks that have been intruded by large volumes of igneous rocks. Field evidence shows that the northern highlands were the exclusive source of the Van Horn sediments.

The Van Horn Sandstone was tilted and faulted prior to accumulation of younger deposits. The Bliss Sandstone is in erosional contact with the underlying Van Horn; the contact is for the most part one of very low-angle truncation (King, 1965); however, locally the discordance between the two sandstone units is not apparent.

VAN HORN SANDSTONE: A LARGE ALLUVIAL FAN SYSTEM

The Van Horn Sandstone was deposited as a widespread alluvial-fan system by high-gradient, short-duration peak discharge streams which transported sand, gravel, and minor amounts of clay and silt. Highlands to the north of the present outcrop, and perhaps local divides capped by volcanic and underlain by igneous, metamorphic, and sedimentary rocks, supplied debris that was transported by high-gradient streams through gorges or canyons which opened out onto an alluvial plain. Deposition within three physiographic segments of the fan--(1) proximal fan, (2) mid-fan, and (3) distal fan (fig. 3)--is normally represented by gravel, gravel-sand, and sand, respectively. Not all facies of the fan are preserved in outcrop; the most proximal and distal facies are missing.

Gravels, mostly cobbles and boulders, were deposited on the proximal fan, specifically in canyons cut by pre-Van Horn erosion. Mixed gravel and sand accumulated in the mid-fan zone where the canyon began to widen southward toward the open alluvial plain. The distal part of the Van Horn fan, by far the largest depositional area, was constructed primarily of coarse to very coarse sand dispersed downfan by a complex of braided streams. Only part of this segment of the Van Horn fan is preserved; therefore, it is not known whether the fan terminated in an inland basin or prograded into a marine environment.

The Van Horn differs from the well-known arid-region fans (Blissenbach, 1954; Bull, 1963; Beaty, 1970; Denny, 1967; Hooke, 1967; Lustig, 1965); its best analogies are humid-region fans, such as the giant Kosi River fan of India (Gole and Chitale, 1966) that is being constructed solely by fluvial processes. The Kosi River fan covers approximately 8,000 square miles; it is about 130 miles long and about 60 miles wide. Slope of that fan is only 5 feet per mile at the apex and slightly over 1 foot per mile at the base of the cone; this is low in comparison to arid-region fans whose slopes are as much as 500 feet per mile. The Kosi River fan has developed in a region where average annual rainfall is about 60 inches, most of which occurs in about 3 months. The fan is constructed of clay- to boulder-size material that is

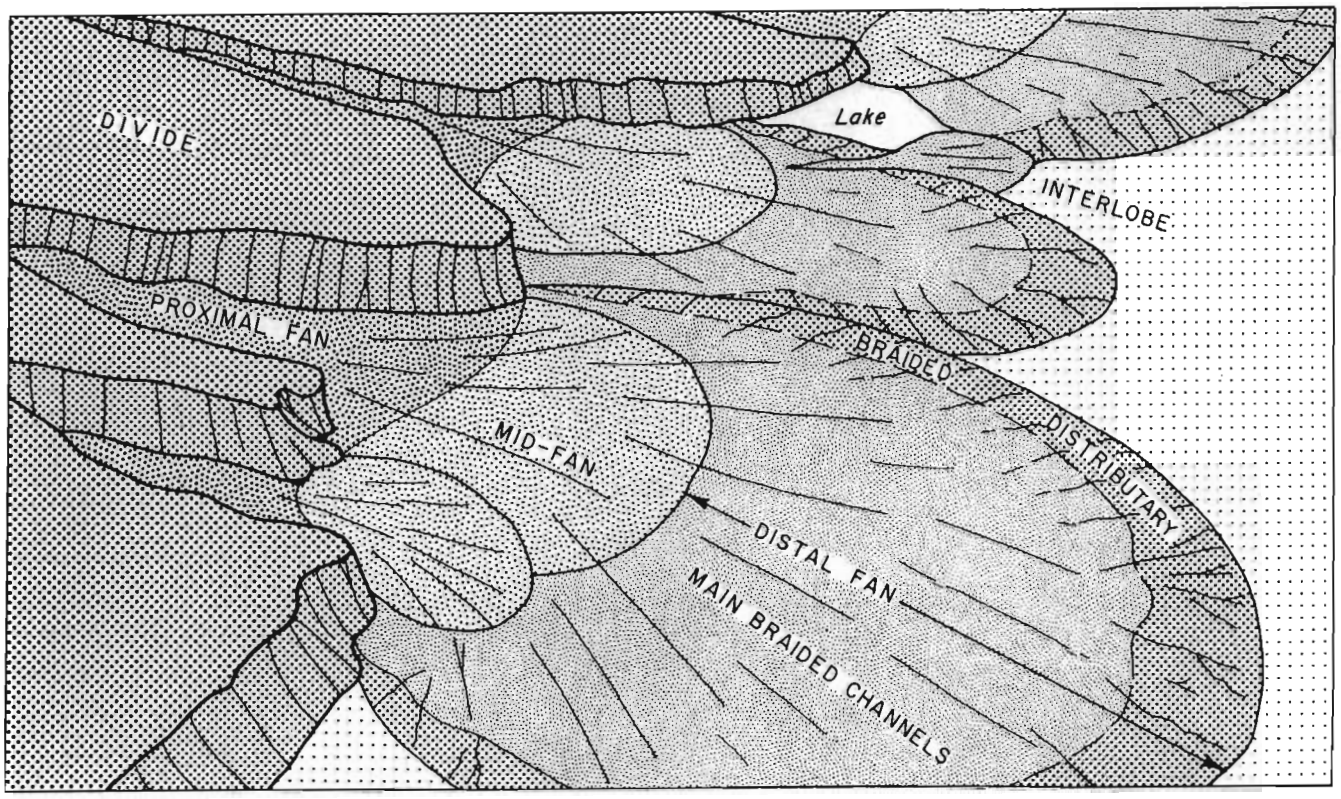

FIG. 3. Schematic plan of Van Horn facies. From nearest the source (north) to the most distal facies these are proximal, mid-fan, and distal. Distal facies includes main braided channels and braided distributary and interlobe subfacies.

dispersed across the fan by large floods having maximum discharge in the range of 20,000 to 860,000 cubic feet per second. In contrast, arid-region fans are constructed by debris flows and sieve deposition near the apex and by fluvial processes downfan in distal areas. Arid-region fans are characterized by poorly sorted debris with large angular clasts near the fan apex deposited by highly viscous debris flows. Because humid-region fans are constructed by streams, nearly all the sediments are better sorted and rounded than those in arid-region fan deposits. The Van Horn deposits are most similar to the Kosi River or humid type of alluvial fan.

Vegetation did not begin to influence erosion in the terrestrial environment until Devonian time (Schumm, 1968). Vegetation retards runoff and therefore promotes chemical breakdown of earth materials. During the time that the Van Horn was being constructed (sometime between Precambrian and Ordovician) there was virtually no terrestrial vegetation, lag between precipitation and runoff was brief, chemical weathering was negligible, and only a small quantity of clay minerals was produced in the source area.

The absence of vegetation and source sediment devoid of fines prohibited generation of debris flows, hence the Van Horn fan was constructed only by fluvial processes.

SEDIMENTOLOGY

FACIES

Characteristics of proximal, mid-fan, and distal-fan facies are presented in the following section. Textural features, thickness and lateral persistence of sedimentation units, and types of primary and deformational sedimentary structures are the field criteria used in delineating these facies. (*See* Appendix for descriptions of stratification types.)

In addition to the north-south succession of facies, proximal to distal, there is a similar vertical succession from proximal to distal facies. Complete vertical succession of facies exists only in the northernmost outcrop areas (Keene and Neal ranches). Facies regressed northward toward the source area as the canyons were filled and the slope of the fan surface decreased.

Proximal Facies

Proximal facies includes gravel or interbedded sand and gravel where 15 percent or more of the section is gravel (fig. 4). Maximum development of the facies is in the northern outcrops where the Van Horn is thickest (fig. 2; Keene and Neal ranches). Other exposures of the gravel facies are along the western limits of the outcrop (Garren ranch, section G1), in Red Valley (McVay ranch), and south of U. S. Highway 80 (Weston ranch). Exposures on the Keene ranch (fig. 5) indicate that gravel distribution was strongly influenced by pre-Van Horn topography, and coarse gravel on the Weston ranch indicates that gravel, at one time, extended a considerable distance south of the present outcrop. Gravel deposition was restricted chiefly to canyons where flow was confined; only in these areas were streams competent to transport boulders up to 3 feet in diameter.

High gravel concentration, as shown in outcrop, indicates at least four loci of gravel influx, mostly from the northwest. Directional features, as determined from foreset and trough crossbedding, and orientation of long axes of cobbles and boulders indicate a south to southwest transport direction (fig. 6). Gravel percentages alone are not reliable indicators of transport direction because in some areas faulting has exposed the gravel and erosion has removed most of the overlying finer grained material, giving local, anomalously high gravel percentages.

On the Neal ranch the lower 600 feet of the Van Horn is mostly gravel. To the west, on the Keene ranch, areas of the Van Horn dominated by gravel vary considerably in thickness over a lateral distance of about 1 mile (fig. 5). The largest clasts occur a few feet above the base of the Van Horn; maximum clast size observed was 3 feet (long axis). A possible explanation for the occurrence of larger clasts a few feet above the floor of the canyon is that the lowermost and finest material was deposited under rising flood conditions (such as described by Scott and Gravlee, 1968) and the larger boulders accumulated under conditions near peak discharge. The largest boulders observed were on the Keene ranch between 50 and 80 feet above the base of the Van Horn.

Lateral continuity of gravel units is limited in a direction perpendicular to sediment transport, but gravels commonly persist several hundred feet in a direction parallel to transport. Texture and thickness of gravel beds and the number of associated sand units vary considerably a few hundred feet laterally and a few tens of feet vertically. Locally, thick, massive boulder beds grade within a few hundred feet into alternating massive boulder beds and sand. The nature of the gravel facies is shown in a vertical sequence in figures 7, 8, and 9.

Massive boulder beds.--Some of the thickest units in the gravel facies are massive boulder beds about 15 to 50 feet thick. Boulder beds are in the lower part of the Van Horn Sandstone on the Keene, Neal, and Weston ranches. Subround to well-rounded, elongate to compact-elongate, pebble- to boulder-size clasts characterize these beds (*see* Sneed and Folk, 1958, for clast morphology); granular, coarse to very coarse arkosic sand fills interstices. Commonly, the clasts are in contact with each other, with no separation of gravel and sand into mutually distinct beds.

Faulting was contemporaneous with deposition of some boulder beds. Limited exposures 50 feet above the base of the Van Horn on the Keene ranch (section K1) display angular discordance between underlying thin cobble and boulder beds and overlying massive boulder beds. Apparent dip of thin-bedded gravel is to the south. Massive boulder beds rest unconformably on progressively older, thin gravel beds in a northerly direction. Long axes of clasts in the massive boulder bed have apparent dips to the north (fig. 10).

A few massive boulder beds are graded. Between 80 and 85 feet above the base of the Van Horn on the Keene ranch (section K2), a 20-foot massive gravel sequence is composed of cobble gravel which

coarsens upward into boulder gravel (fig. 9).

Alternating gravel and thin sand beds.--Massive boulder beds grade laterally and vertically into alternating gravel and thin sand beds. Massive boulder beds recur in the vertical sequence, but with each successively higher appearance both size of clasts and bed thickness decrease.

Thickness of alternating gravel and sand packages ranges from about 10 to 95 feet. Similar sequences higher in the section and south of the northernmost outcrops are thinner and clasts are smaller. As clast size and thickness of gravel beds decrease,

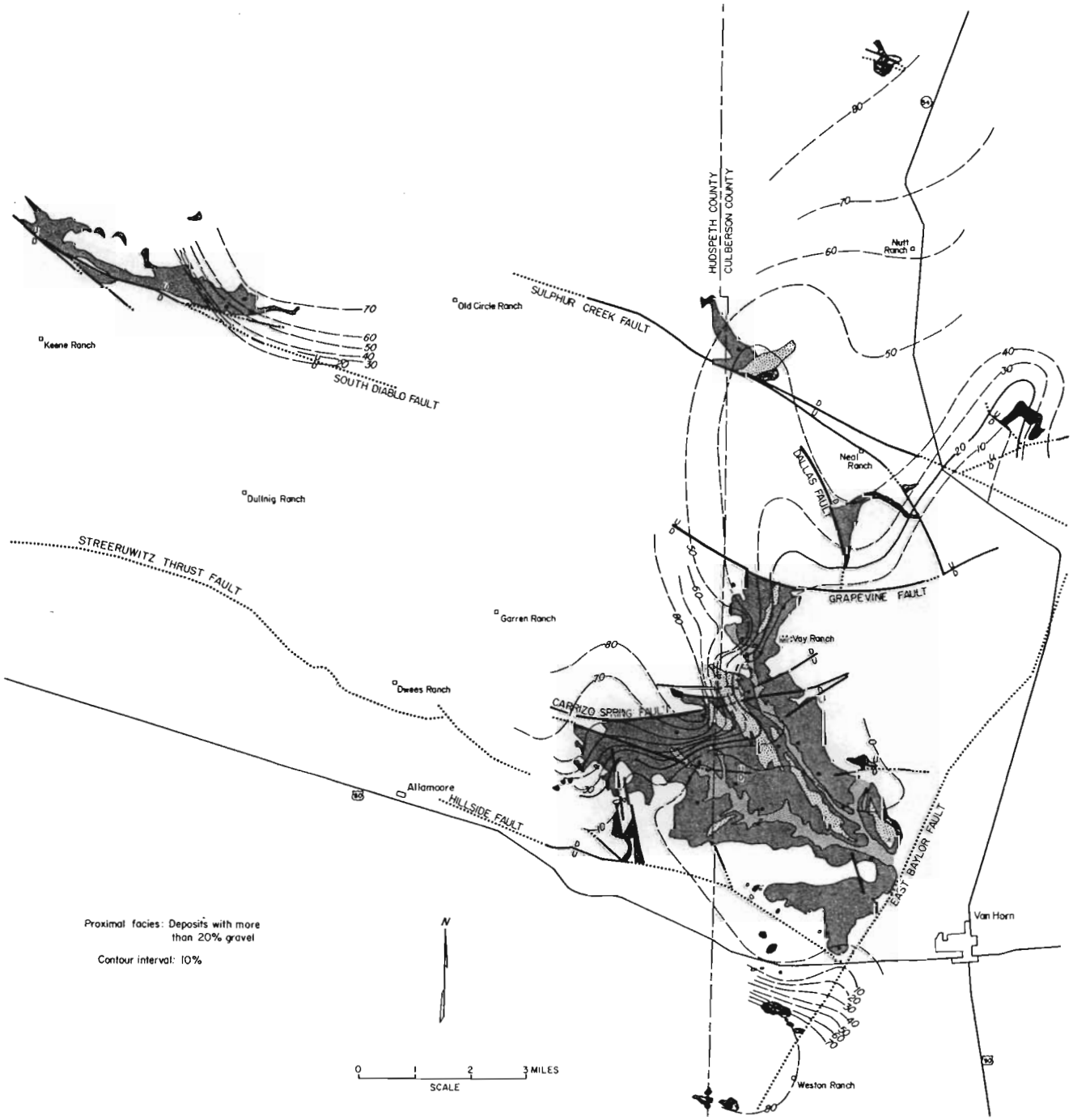

FIG. 4. Percent gravel in outcropping Van Horn Sandstone.

sand beds thicken. Range in thickness of sand beds is a few inches to about 2 feet; these sands are massive or parallel laminated. Commonly, the thicker beds are massive, granule- to pebble-bearing, coarse to very coarse sand, whereas the thinner beds are parallel-laminated coarse sand that commonly contains heavy mineral laminae. Vertical sequence through gravel facies and vertical distribution of gravel types are shown on figures 7, 8, and 9.

Neither gravel nor sand beds are uniform in thickness. Gravel beds commonly have a flat base and a flat to slightly convex upper surface, with gentle to abrupt slopes laterally and distally. Normally, sand units thicken toward distal and lateral parts of gravel beds where foreset crossbedding is common. Figure 11 shows the relationships of alternating sand and gravel beds approximately parallel to flow; figure 12 is a section approximately perpendicular to flow.

Thick sand and muddy sand of the proximal facies.--The sequences of alternating gravel and thin sand beds are underlain and overlain by sand units 10 to 30 feet thick. Foreset and trough crossbeds are the dominant primary sedimentary structures in the thick sand sequences; commonly, the vertical distribution of stratification types, from base upwards, is as follows: (1) foreset crossbeds up to 10 feet thick with individual foresets 1 to 3 feet thick; (2) foreset and trough crossbeds in which foresets are 0.5 to 2.0 feet thick with trough crossbeds commonly 0.5 to 1.0 foot thick and 5 to 8 feet wide; and (3) trough-crossbedded gravelly coarse sand with troughs 3 to 6 inches thick and 1.5 to 6 feet wide.

Grayish-red, muddy, muscovite-bearing, medium to coarse sand occurs either as a separate, distinct unit or interbedded with other units. As a distinct unit, it is as much as 10 feet thick and laterally grades into gravelly coarse sand. Stratification types are low-angle foreset and trough crossbeds. Foresets commonly grade into parallel-laminated bottomsets.

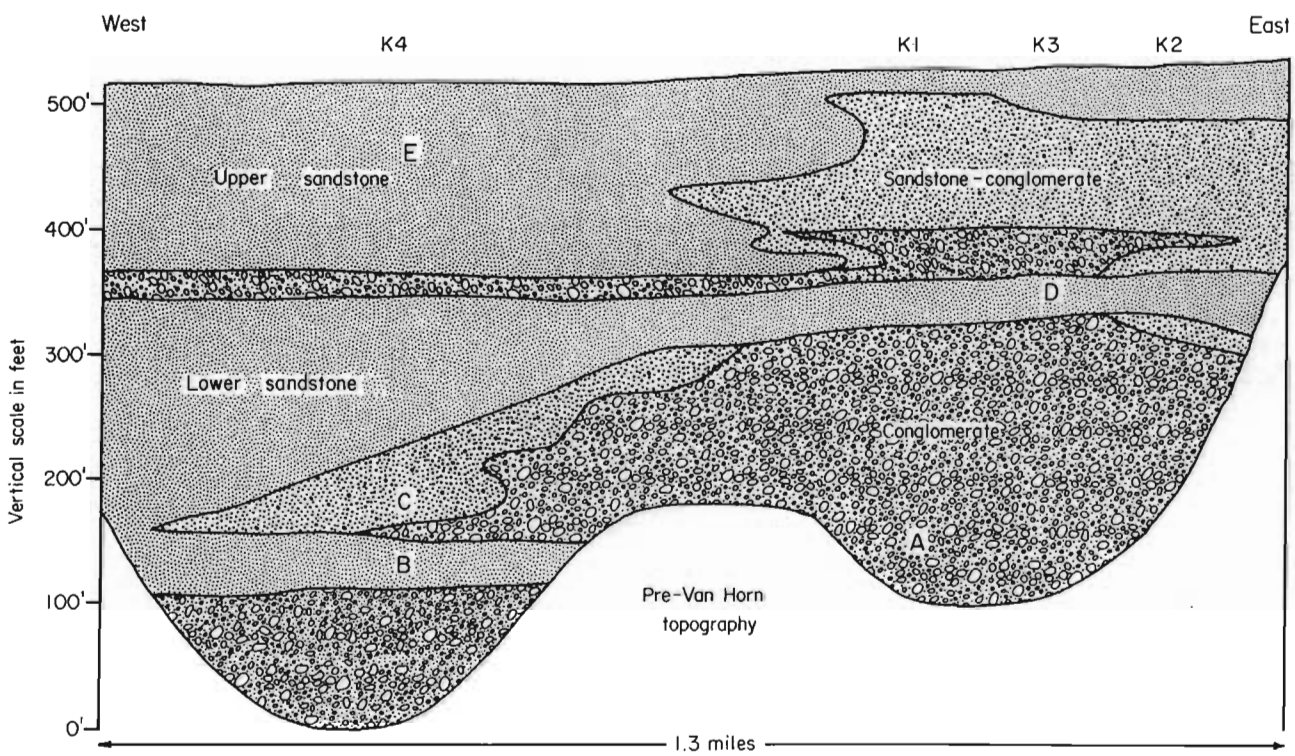

FIG. 5. Cross section through northernmost Van Horn Sandstone on the Keene ranch (localities K1-K4). The three facies (proximal, mid-fan, and distal) are represented by conglomerate, conglomerate-sandstone, and sandstone, respectively. Gravel (conglomerate) distribution is chiefly concentrated in the deeper parts of the canyons. Letters A through E are referred to in figures 10, 23, 24, 25, and 26.

Near the upper part of the proximal facies, muddy sand is interbedded with pebble and cobble gravel lenses and thin beds of gravelly sand. These sequences are lower energy deposits than most of the other parts of proximal facies and were deposited in depressions between major fan lobes; the fines are both underlain and overlain by coarser gravel and sand units. Commonly, these sequences of interbedded muddy sand and gravel are 10 to 15 feet thick. Individual foresets of muddy sand are a few inches to 1 foot thick and cosets are composed of as many as six foreset units. In a downcurrent

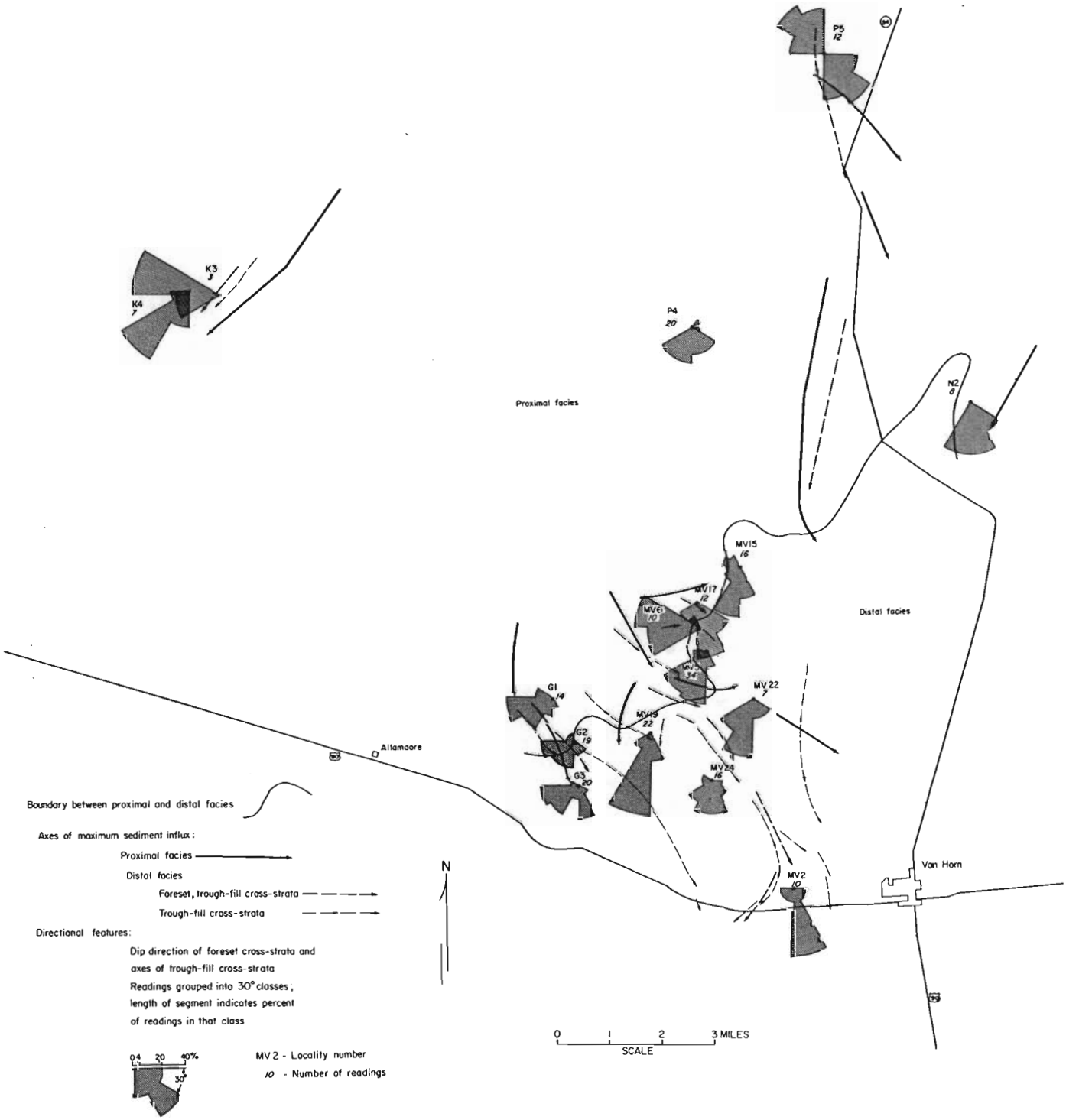

FIG. 6. Depositional trends of the Van Horn Sandstone.

direction foresets grade into thin beds of either parallel-laminated or homogeneous muddy sand. Lenses of gravel and gravelly sand about a foot thick and a few tens of feet wide are interspersed within the sand.

Other features of the proximal facies.--Large depositional features such as gravel lobes, filled interlobe depressions, and large scour-and-fill features are common but because of their large size are not immediately obvious in limited outcrops.

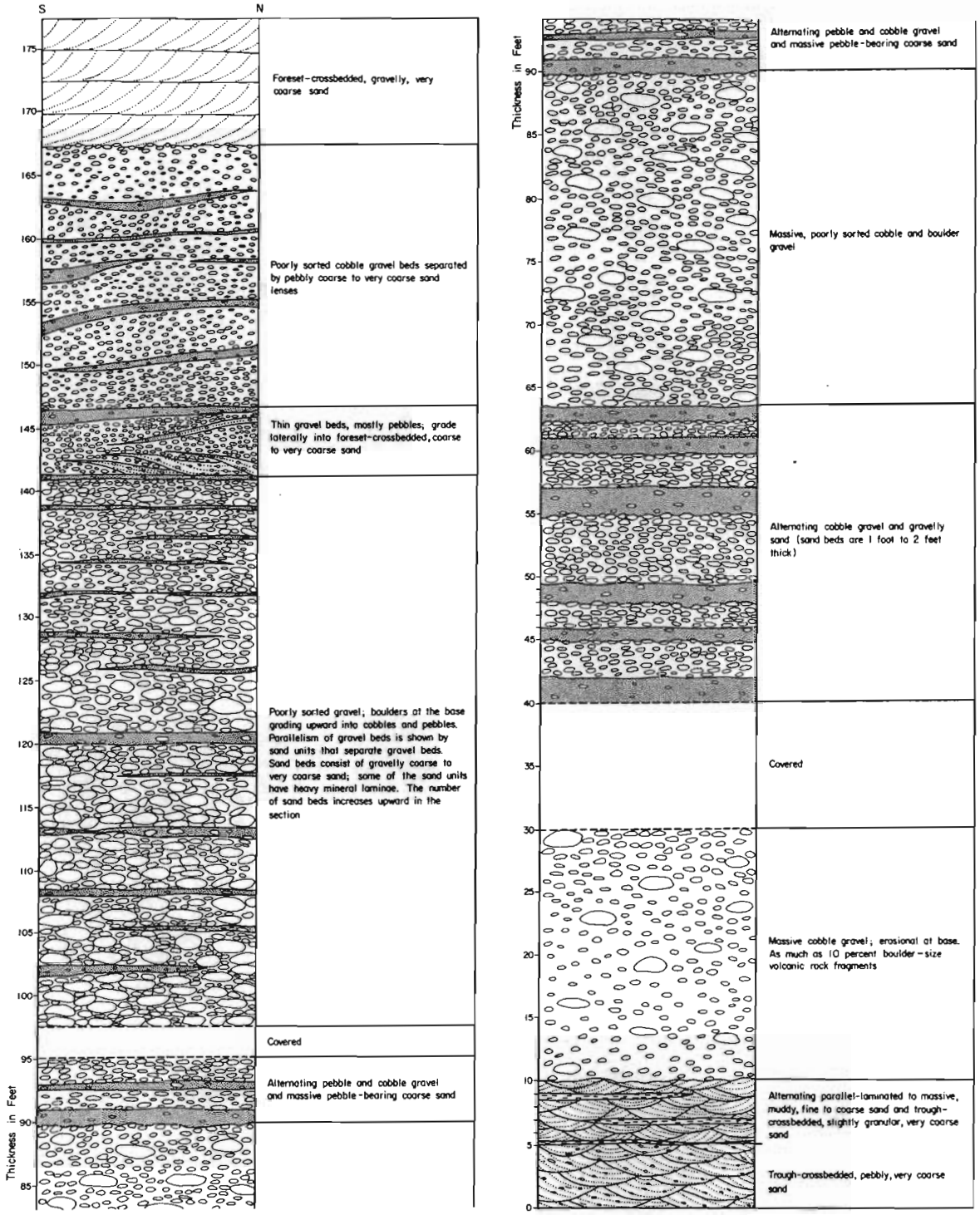

FIG. 7. Characteristics of the proximal facies on the Neal ranch (section P4; *see* fig. 2 for location). This section begins 300 to 400 feet above the base of the Van Horn Sandstone.

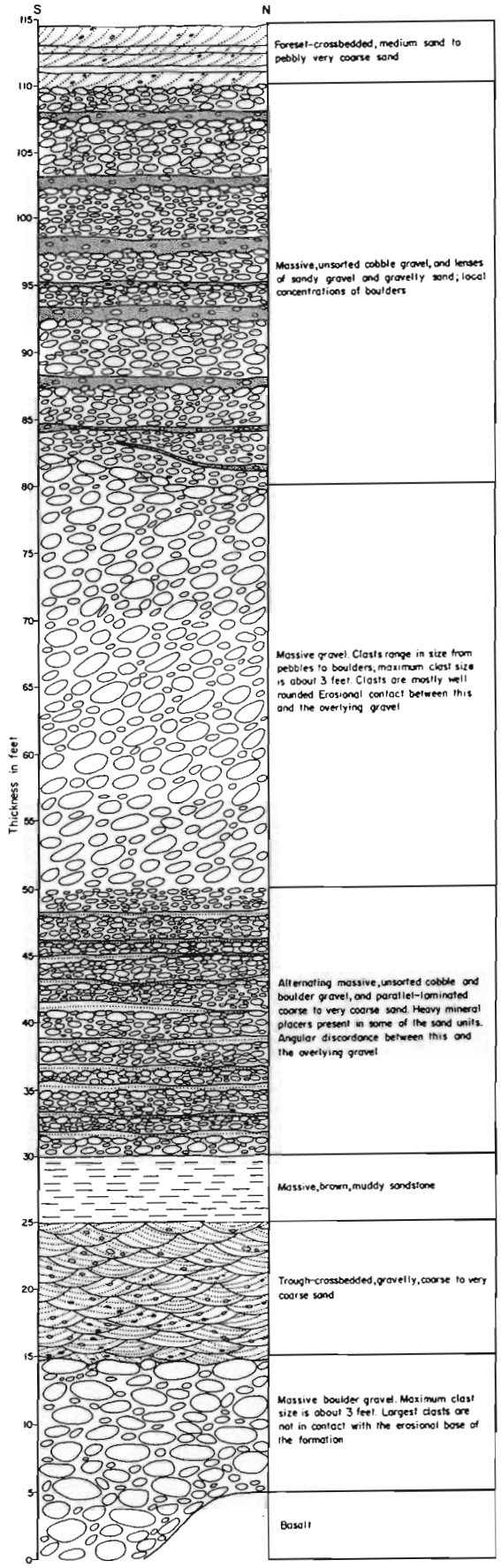

FIG. 8. Characteristics of the proximal facies on the Keene ranch (section K1; *see* fig. 2 for location). Cobbles and boulders of the basal Van Horn are in contact with Precambrian basic igneous rocks.

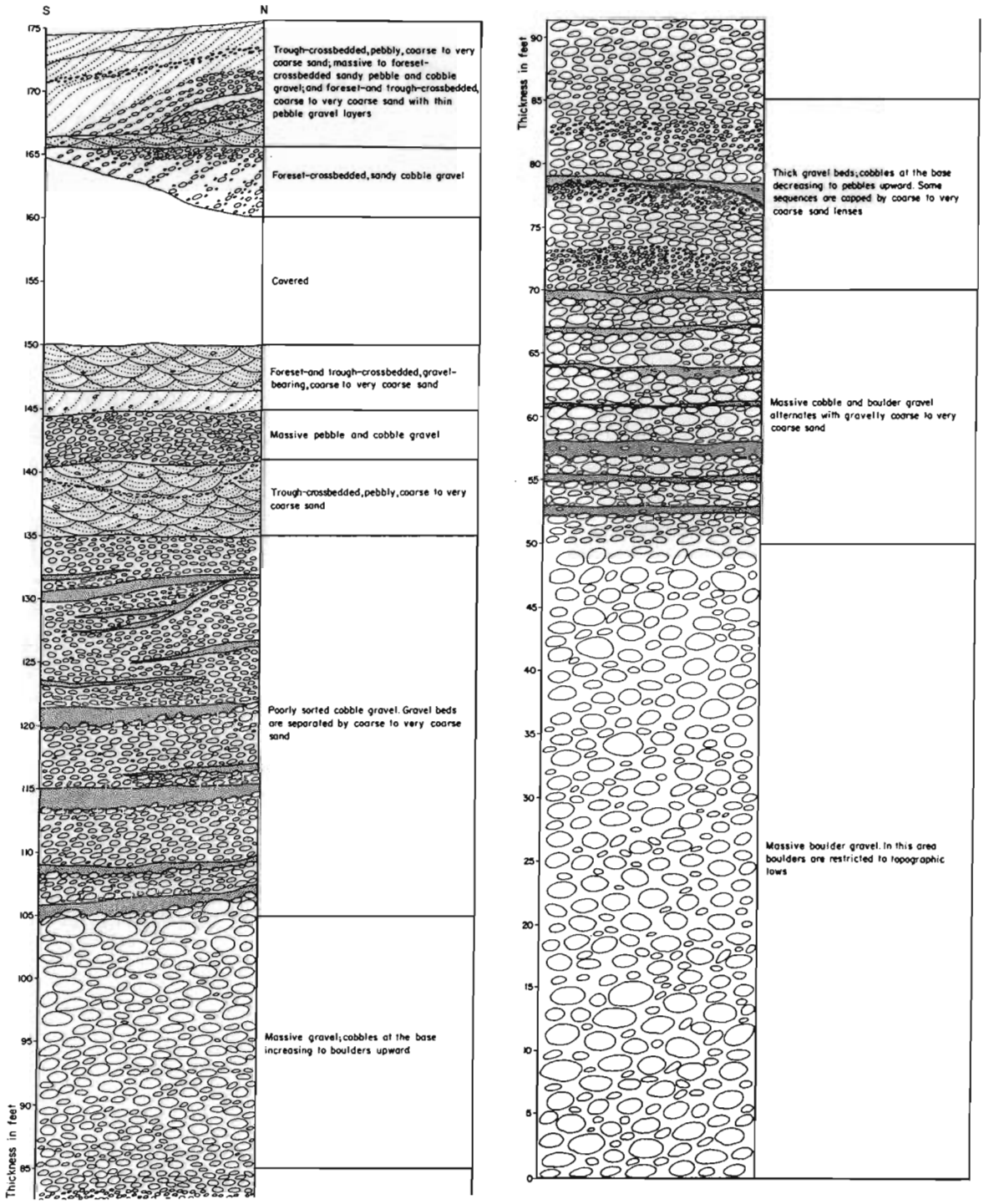

FIG. 9. Characteristics of the proximal facies on the Keene ranch (section K2; *see* fig. 2 for location). Cobble and boulder gravel are in contact with Precambrian carbonates that have been intruded with basic igneous rocks. Gravel units display both normal and reverse graded bedding in this area.

The full cross section of narrower channels can be observed in some vertical cliff faces. Interlobe depression fills are inferred on the basis of lateral relationships of gravel and sand where exposures are laterally extensive. One such depression was recognized in the proximal facies (Neal ranch, locality P4) and undoubtedly many more occur. This interlobe depression occurs about 400 feet above the base of the Van Horn with an estimated width of about 0.5 mile. Sediment fill is 25 to 30 feet of reddish-brown, coarse to very coarse sand with a few gravel lenses (one or two pebbles thick). Deposition of gravel and sand was contemporaneous and as the east and west flanks of the fill are approached, the scale and number of gravel units increase until gravel becomes the dominant textural type. Primary sedimentary structures are almost exclusively trough crossbeds from 2 to 4 inches thick and 2 to 3 feet wide. Sand that fills the interlobe depression is underlain and overlain by gravel.

Scour channels associated with gravel facies are normally shallow. Among the deepest channels are those in the Neal ranch area which are on the order of 8 to 20 feet deep. The most common channel fill is unsorted gravel or a combination of massive gravel and gravel-bearing, very coarse, trough-crossbedded sand (fig. 13). Other channels, up to 5 feet deep, are filled with foreset-crossbedded muddy coarse sand. Lateral extent of this muddy sand could not be determined; in some instances the muddy sand may have been deposited in lows between gravel or sand lobes.

Mid-fan Facies

The mid-fan facies is made up of interbedded gravel and sand; gravel comprises up to 15 percent of the facies. Gravel in the mid-fan facies occurs in scour channels and as longitudinal bars with relatively flat bases and convex upper surfaces. Longitudinal bar deposits are parallel bedded in their central parts. Parallel bedding, in some bars,

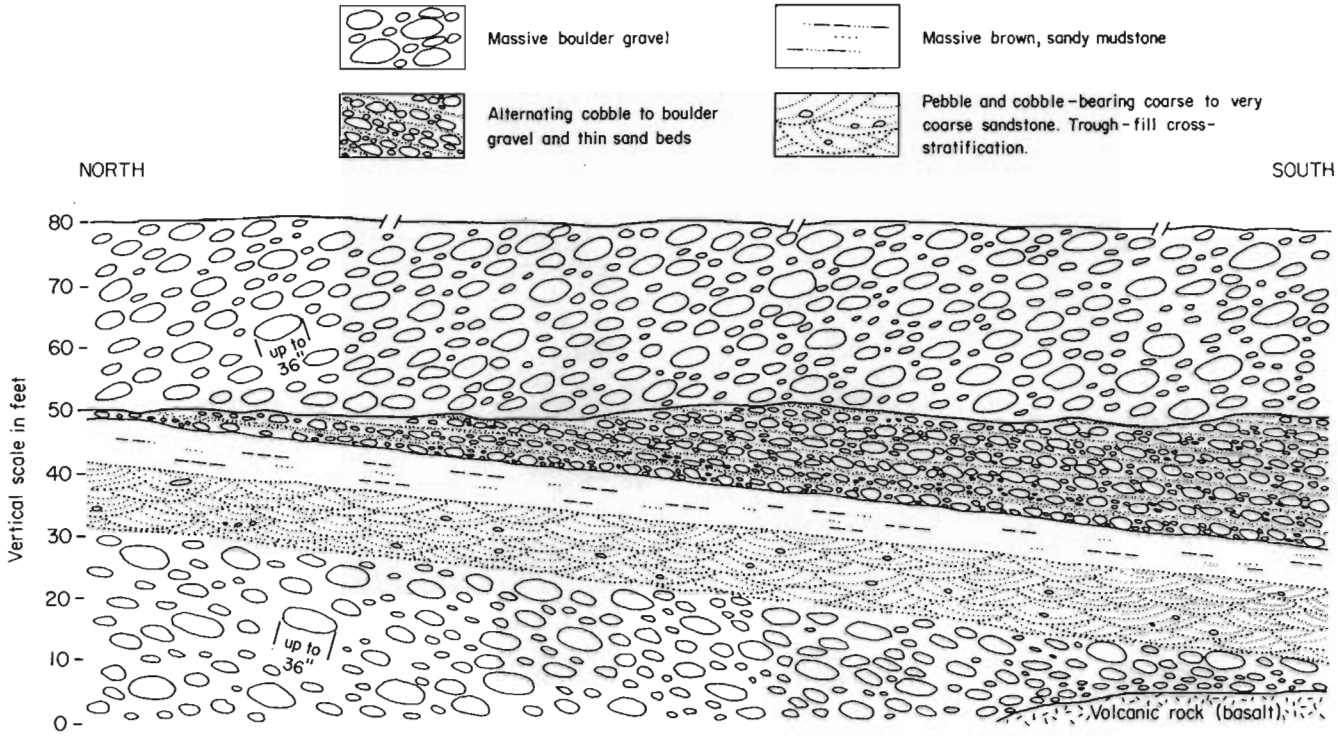

FIG. 10. Characteristics of the basal proximal facies on the Keene ranch (section K1; *see* fig. 5, section A, for stratigraphic position). Lowermost massive gravel has clasts up to 36 inches in diameter; clasts are in contact and interstices are filled with coarse sand to granule gravel. Next above the gravel are about 5 feet of trough-crossbedded gravelly coarse to very coarse sand. Massive, brown, sandy mudstone is the next stratigraphic unit. Overlying the mudstone is a sequence of alternating sand and gravel units. Unsorted cobble and boulder beds, 1.0 to 1.5 feet thick, are separated by thin beds (2 to 3 inches thick) of parallel-laminated sand with heavy mineral placers. There is discordance between this and the overlying massive boulder bed. The boulder bed is comprised of round to very round clasts 10 to 36 inches in diameter.

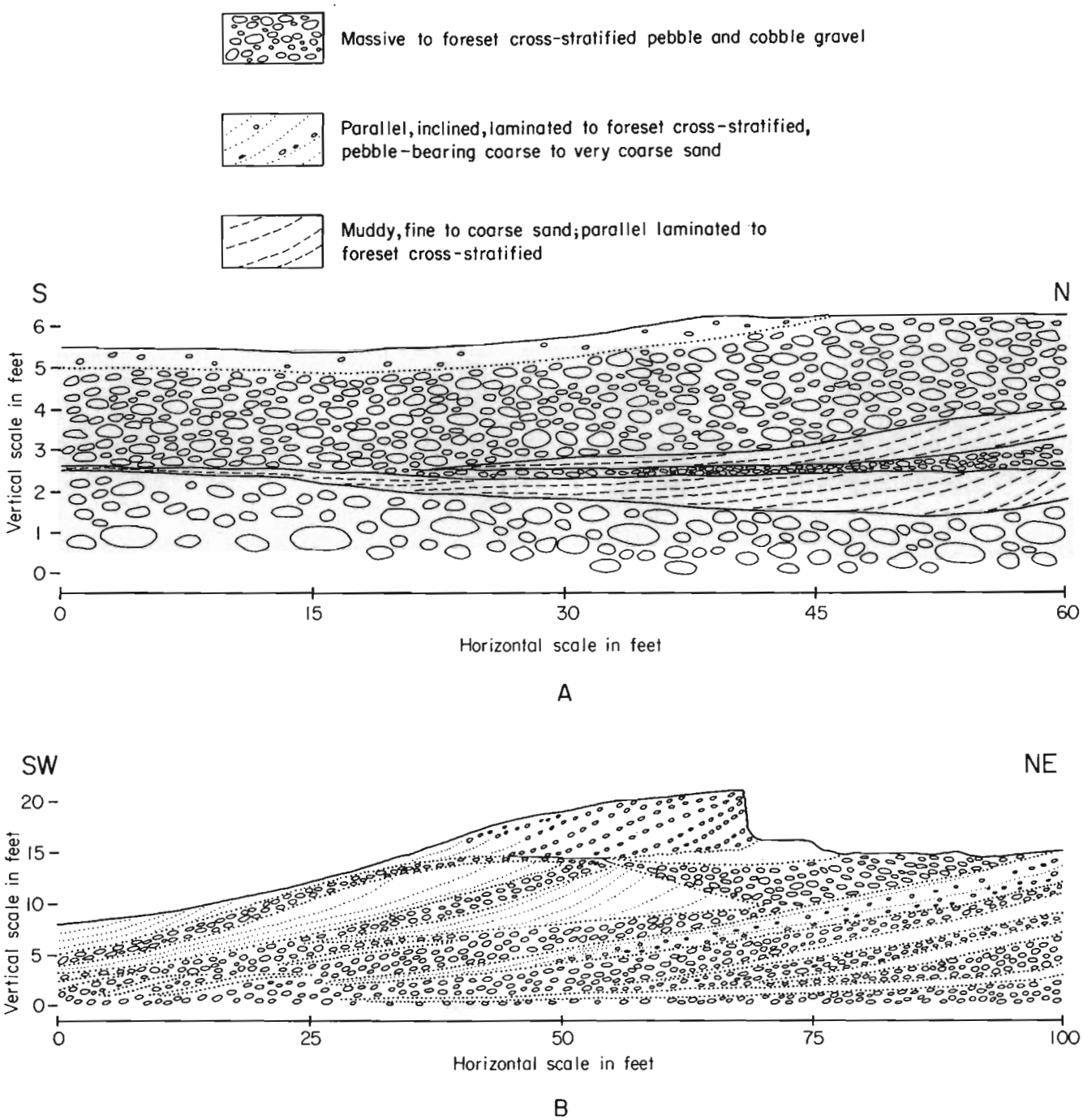

FIG. 11. Characteristics of some of the upper parts of the proximal facies on the Neal ranch (section P4).

A. Alternating gravel and muddy sand representing longitudinal gravel bars and channel-fill, respectively. Lowermost gravel unit consists of pebbles, cobbles, and boulders; uppermost gravel unit consists of pebbles and cobbles. General transport direction was from north to south.

B. Westward-accreting gravel bars and flanking shallow channels are represented by pebble to cobble gravel foresets that in places grade laterally into sand foresets and finally into parallel-laminated sand. This sequence, about 20 feet stratigraphically higher than (A), grades southward into dominantly foreset-crossbedded sand. General transport direction was from north to south.

grades laterally into low- to high-angle foresets. These bars were constructed by braided streams. Gravel occurs as thick foresets adjacent to some channel banks, and gravel units are lens-shaped near channel centers; these lenses are commonly flanked by sand. Channel-fill gravels are most common in the northern and stratigraphically lower parts of the facies (McVay ranch, sections MV16 and 17).

Sand makes up the remainder of the mid-fan facies and occurs in lows flanking gravel lenses that it commonly succeeds vertically in well-defined, broad, shallow channels, and as thick sand masses, up to several tens of feet thick, in which channel boundaries are not recognizable. All sand deposits are characterized by foreset and trough crossbeds. Relative abundance and scale of these two sedimentary structure types are variable, and locally

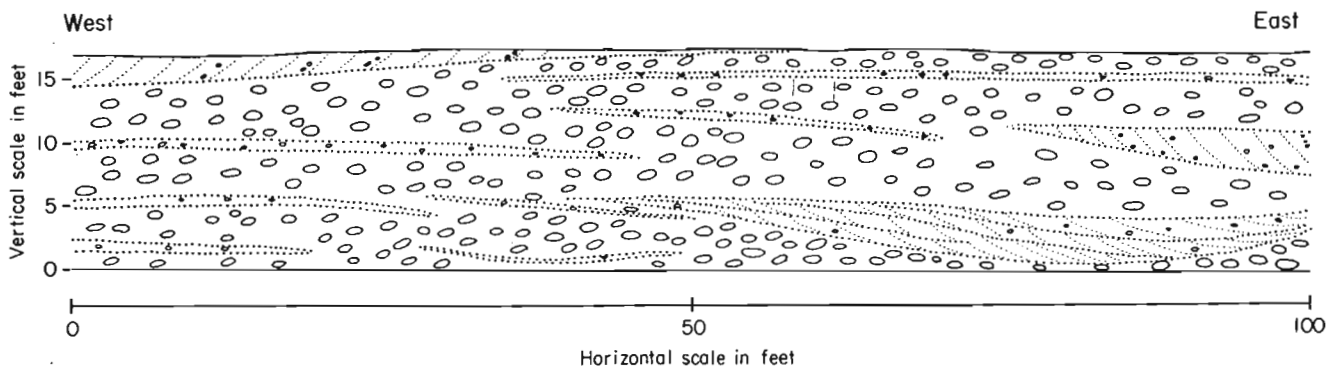

FIG. 12. Longitudinal gravel bars and flanking sand-filled channels near the southern limits of the proximal facies (McVay ranch, section MV17). Gravel beds, made up of pebbles and cobbles, range from about 1 foot to 5 feet in thickness. Sand beds, which separate some of the gravel units, are thin near bar crests and thicken and display foreset crossbedding in areas flanking the bars. General transport direction is toward the observer.

FIG. 13. Gravel-filled channel near the upper part of the proximal facies (Neal ranch, section P4). Channel-fill, shown by dashed lines, is a lens about 6 feet thick and about 60 feet wide. Thick gravel foresets overlie the channel-fill. View is west.

one type may dominate.

Gravel and sand of the mid-fan facies were deposited contemporaneously. Gravel accumulated as elongate bodies (longitudinal bars) parallel to transport direction. Sand occurs as thin sand sheets atop gravel beds, as shallow channel fill within the gravel sequence, and as thicker braided-stream deposits (transverse bars and dunes) lateral to or downstream from the gravel mass. Vertical recurrence of either gravel or sand does not necessarily indicate a change in sediment availability, stream gradient, or discharge; it records only the lateral migration of contemporaneous facies.

Individual channels are more apparent in mid-fan deposits than in either proximal or distal facies because of diverse textural types. Channels cut into gravel are commonly deeper and narrower than those cut into sand (fig. 14). Width/depth ratio of channels cut into sand ranges from about 10 to 125, whereas channels cut into gravel have ratios of about 13 to 20.

Maximum thickness of the mid-fan facies, where both lower and upper boundaries are exposed, is about 300 feet (Neal ranch, P4). Elsewhere only the upper or lower parts of the facies are present and thickness of the exposed facies is about 30 to 190 feet. In a few areas mid-fan and distal facies alternate in the vertical sequence; for example, on the McVay ranch (MV22) about 35 feet of mid-fan deposits are underlain and overlain by distal-fan sediment in the lower 100 feet of the outcrop.

Best exposures of mid-fan alternating gravel and sand units are on the Neal and McVay ranches. On the Neal ranch a complete vertical succession of the facies crops out just north of Sulphur Creek fault (P4), and on the McVay ranch there are good exposures along Hackberry Creek (MV17 and MV-5).

Facies description.--On the Neal ranch (P4) the mid-fan deposits are about 300 feet thick and consist of lower and upper gravel-rich sequences separated by a middle, dominantly sand sequence.

The lower gravel sequence is about 100 feet thick and the upper one is approximately 50 feet thick; both gravel-rich sequences consist of alternating gravel and sand. Pebble and cobble gravels are up to 7 feet thick; these consist of beds up to 3 feet thick with thin interbedded sands that are commonly less than a foot thick. Most of the gravels are parallel bedded but locally show scour bases and low-angle foresets. Sands more than 5 feet thick occur within the gravel sequences. These sands consist of trough and foreset crossbeds; locally, one stratification type dominates. Foresets are 1 to 3 feet thick and trough crossbeds are 8 feet wide.

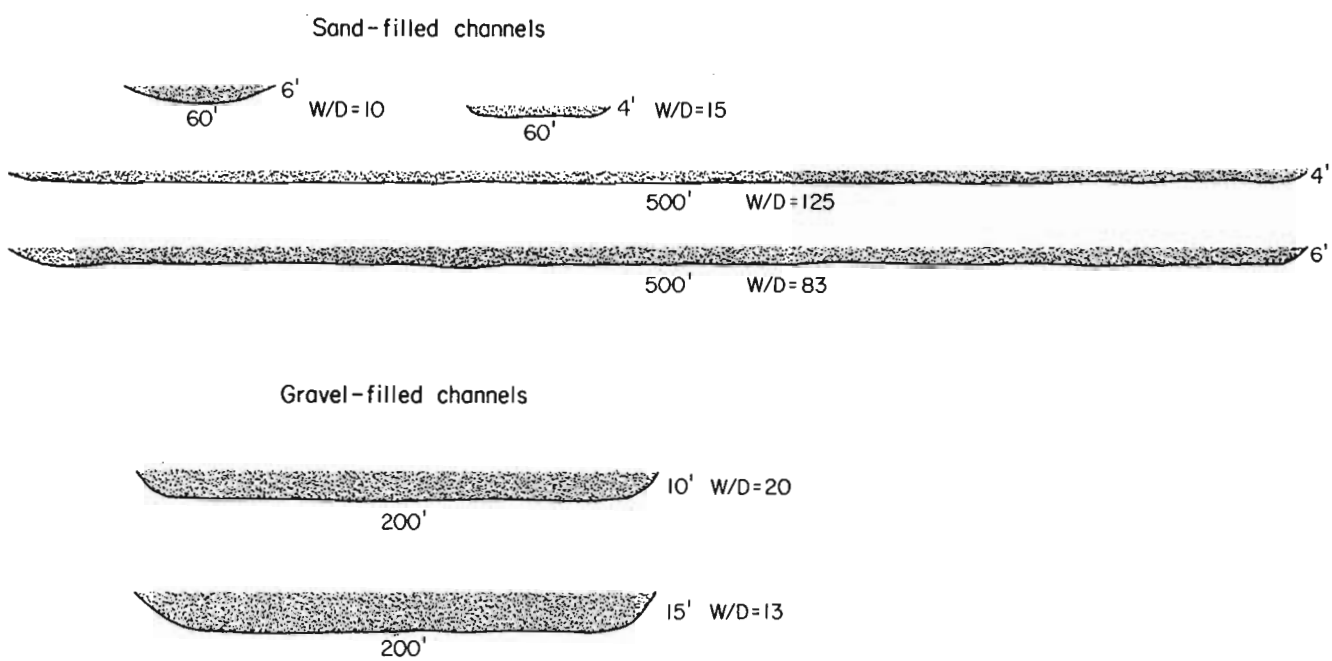

FIG. 14. Channel profiles generalized from gravel- and sand-filled channels of the mid-fan facies. Gravel-filled channels normally have a small width/depth ratio as compared to sand-filled channels.

Although the middle 150 feet of the mid-fan facies at section P4 is mostly sand, it does contain some gravel. Gravel commonly fills scours up to 6 feet deep, or it occurs as a veneer lining the scour floor; it rarely occurs as parallel beds. These scour-and-fill sequences of lag gravel and trough- and foreset-crossbedded sands are up to 15 feet thick; units resulting from a single depositional event are 2 to 5 feet thick. Remainder of the sand sequence is mostly trough and foreset crossbeds. Within the dominantly sand sequence are some exceptionally thick foreset units up to 8 feet thick. At least one thick foreset unit was deposited along the banks of a scour channel that directly underlies the upper gravel-rich sequence of section P4 (fig. 15).

Several areas on the McVay ranch are also representative of the mid-fan facies; for example, northwest of the McVay ranchhouse (MV17) about 120 feet of mid-fan deposits is exposed. In this area approximately equal amounts of sand and gravel occur. The thickest gravel sequence, 13 to 20 feet, is in the upper 30 to 40 feet of the section. Pebble and cobble gravel occurs as channel fill and relatively thin sheetlike bodies. The uppermost gravel sequence consists of beds 0.5 to 5 feet thick; most are on the order of 1 to 2 feet. Gravel beds are commonly separated by thin sands. Along gravel bar crests, sands are thin (2 inches to 1.5 feet), but they thicken gradually or abruptly along bar flanks. Maximum thickness of sands flanking these gravel bars is about 4 feet; primary sedimentary structures are foreset crossbeds (fig. 16).

Locally, on the McVay ranch (MV17) both gravel- and sand-filled channels are exposed. Relatively deep (up to 15 feet), dominantly pebble-gravel-filled channels directly underlie the thick gravel sequence (fig. 17). Gravel units are about 2 inches to 3 feet thick and lenticular but persist across the width of the channel. Sand beds that are part of the gravel channel fill are 2 inches to 2 feet thick. Texturally these are muddy, coarse sand to pebbly, very coarse sand. Most sand beds are foreset crossbedded. Sand-filled channels as much as 6 feet deep and 500 feet wide are characterized by trough- and foreset-crossbedded sand (fig. 18). Trough crossbeds are confined to the basal channel and foresets represent lateral fill from each bank.

Some dominantly sand sequences in the mid-fan deposits on the McVay ranch are up to 20 feet thick. Individual channels are not distinguishable in the thick sands that alternate with gravels since channel form was not preserved under conditions

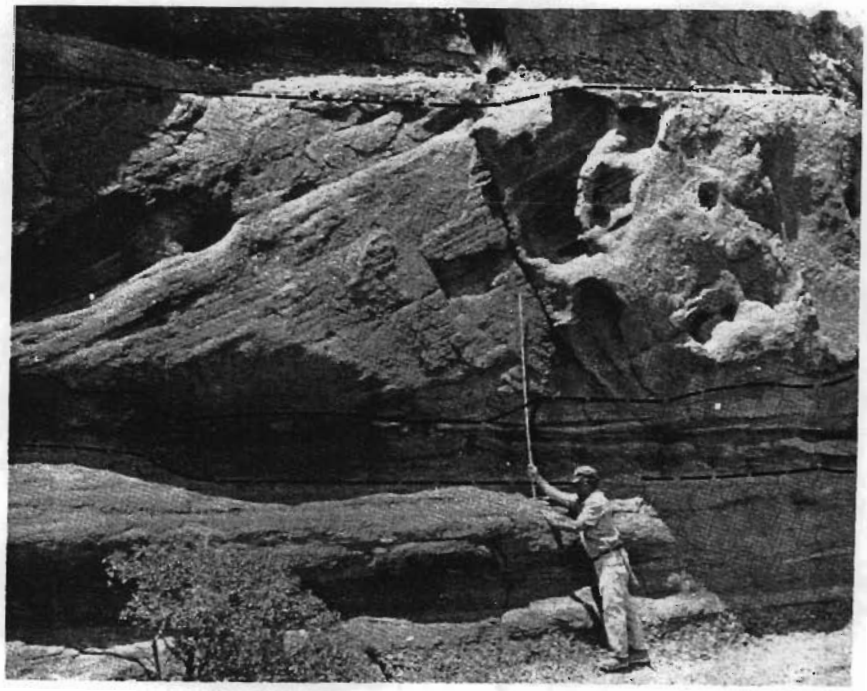

FIG. 15. Thick foreset crossbeds of granular very coarse sand (Neal ranch, section P4). Foreset unit is about 9 feet thick; it overlies about 3 feet of alternating coarse sand and muddy sand. Locally, the muddy sand has been injected into overlying coarse sand. View is southwest.

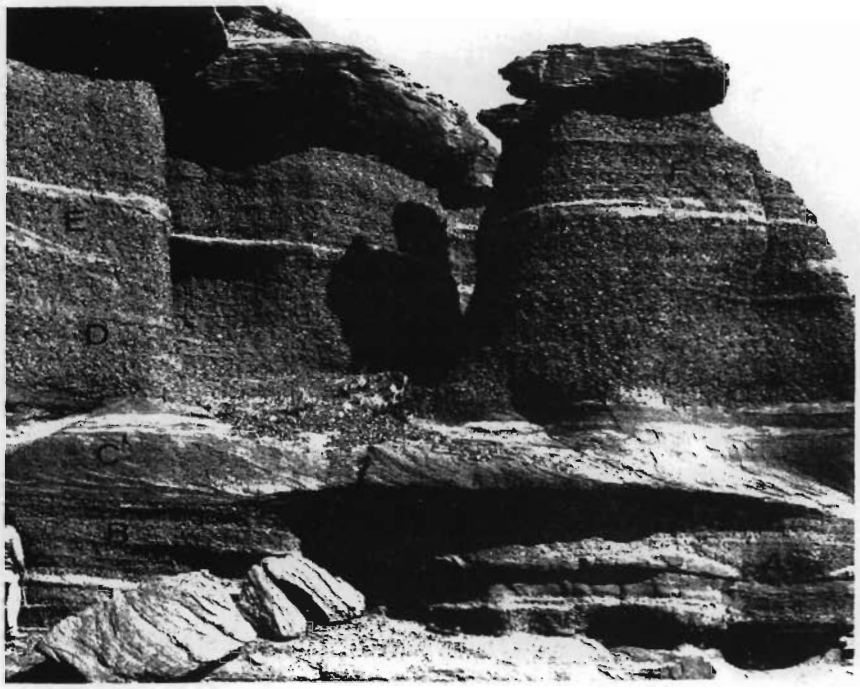

FIG. 16. Characteristics of the mid-fan facies (McVay ranch, section MV17). In the lower part of the section are small, gravel-filled channels (A), thin gravel bars (B), and thick foreset-crossbedded sand (C). The upper part of the section consists of thin gravel bars (D), shallow, gravel-filled channels (E), and thin sands along bar crests that grade laterally into thick foreset crossbeds (F). View is east.

FIG. 17. Gravel-filled channel of the mid-fan facies (McVay ranch, section MV17). Thickness of the channel-fill, outlined by dashed lines, is about 6 feet. Fill of this channel did not occur immediately after scour, as indicated by parallel-laminated muddy sand (A) that locally floors the channel. Floods of varying intensities moved through this channel, as indicated by gravel and some trough-crossbedded sand lenses (B). View is north.

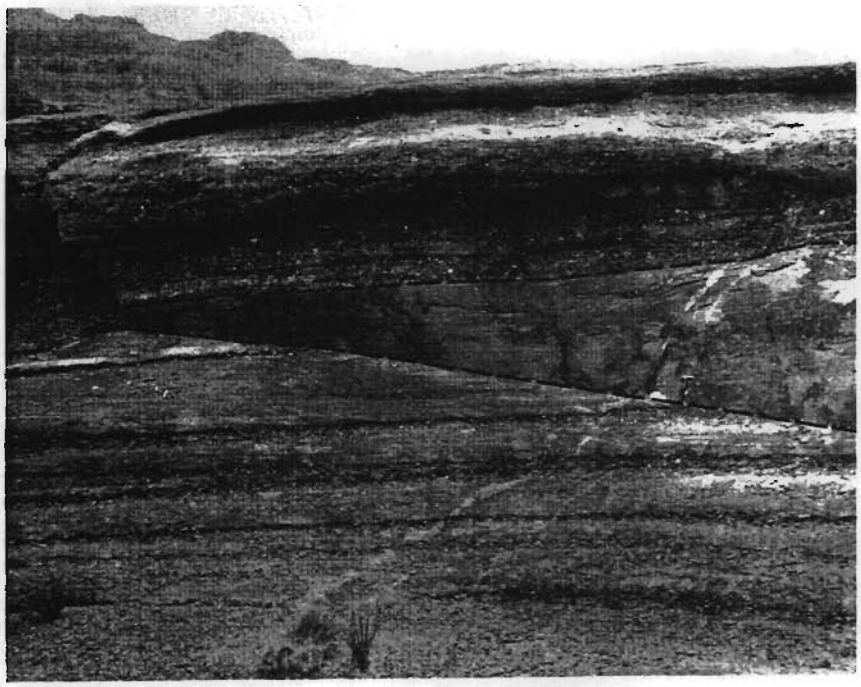

FIG. 18. Sand-filled channel of the mid-fan facies (McVay ranch, section MV17). Only the fill near the left channel bank is shown; the channel was scoured into alternating thin horizontally bedded gravel and foreset and trough-crossbedded sand. View is south.

FIG. 19. Compound foreset crossbeds (McVay ranch, section MV14). Ten sedimentation units, with a combined thickness of 2 feet, are outlined by dashed lines. Sediment transport was from left to right; each sedimentation unit thickens downcurrent. View is north.

of continually shifting, braided streams. Primary sedimentary structures typical of the sand section are foreset and trough crossbedding. Both simple and compound foreset units occur in the mid-fan deposits (*see* Appendix, p. 55). Simple foreset units commonly have planar bounding surfaces that converge upcurrent. Foreset laminae are either straight and make high-angle contacts with bounding surfaces, have low-angle contact with the lower bounding surface and high angle with the upper surface, or assume a sigmoidal shape with low-angle lower and upper bounding surfaces. The compound foresets are similar to structures in longshore bars and beaches (McKee and Sterrett, 1961) and within dunes in New Mexico (McKee, 1966). Bounding surfaces of this foreset type are inclined and are commonly convex upward. Thickness of individual cross-sets and degree of convexity commonly increase in the transport direction. Compound foreset crossbeds are 3 to 5 feet thick, consist of coarse to very coarse sand, and occur alone or grade downcurrent or upcurrent into simple foreset units (fig. 19).

Other stratification types associated with thick sands are trough crossbeds and parallel laminae. Trough crossbeds are locally dominant and sands comprised entirely of trough crossbeds are up to 10 feet thick. The scale of troughs ranges from 1.5 to 8 feet wide and 0.1 to 1.0 foot thick; they are commonly replaced laterally by foreset crossbeds. Parallel-laminated sands are rare; the most common occurrence is above gravel beds. Less commonly, parallel laminae succeed foresets and some parallel laminae grade downcurrent into foresets (fig. 20).

The southernmost outcrop limit of the mid-fan facies is near MV5, located south of the McVay ranchhouse and just west of Hackberry Creek, where only the upper 20 feet or so of the mid-fan deposits are exposed. This section is characterized by (1) parallel-bedded pebble and cobble gravel, (2) thin massive sand beds, (3) thick sand sequences comprised of foreset and trough crossbeds, (4) shallow scour channels that are sand filled, and (5) relatively thick sands consisting of compound foresets (fig. 19). The lower 13 feet or so consists of parallel-bedded gravel beds 0.5 to 1.5 feet thick separated by gravelly coarse sands less than 4 inches thick. In the upper part of the gravel section clast size decreases and locally a few beds of pebble gravel are foreset crossbedded. Relatively thick sands, characterized by foreset and trough crossbeds, overlie the gravels. These sands have been scoured locally with base of the scour reaching almost to the underlying gravel sequence. Succeeding the scour-and-fill sequence is a sand unit 3 to 5 feet thick consisting entirely of compound foresets (fig. 19).

Distal Facies

Mid-fan deposits of gravel and sand are succeeded vertically and to the south by distal fan deposits of coarse and very coarse sand. Greatest development of distal fan deposits generally lies south of the 20 percent gravel contour (fig. 4). Locally, gravel occurs as distinct beds a foot or so thick, as thin gravel veneers overlying sand units, or as scattered granules and pebbles within foreset- and trough-crossbedded sands.

Because of incomplete preservation in outcrop, it is not possible to delineate depositional variations in thickness of the facies. In the northern part of the area of Van Horn outcrop (Neal ranch, P4) the facies is about 400 feet thick. Maximum preserved thickness of the distal facies, about 700 feet, is on the McVay ranch east of Hackberry Creek (MV5, fig. 2). Sections of the facies thin southward toward the Hillside fault, and near U. S. Highway 80 at the south end of the McVay ranch (MV1 and 2) the facies is only about 200 feet thick.

Dominant stratification types within the distal facies are foreset and trough crossbeds. Locally, there are thin, discontinuous, muddy sand beds that are either parallel laminated or foreset crossbedded. Muddy sand comprises no more than 5 percent of the facies. Trends readily detected from field observations are a vertical and distal decrease in scale of primary sedimentary structures and an increase in the ratio of trough to foreset crossbeds. As abundance of trough crossbedding increases, so do the number of muddy sand units.

Distal fan deposits were laid down by braided stream systems that were probably comparable in size to the Kosi River (Gole and Chitale, 1966). The Kosi River of India is braided for about 100 miles with a width of about 10 miles, but during extreme floods width increases up to 20 miles (Inglis, 1967). Within this braided belt streams shift back and forth. At present the belt is migrating westward across the alluvial fan. Rates of migration for the past 200 years have ranged from 0.1 mile to 1.7 miles per year. As the river migrates it corrades laterally, eroding fan deposits along its right bank and depositing as much as 6 feet of sedi-

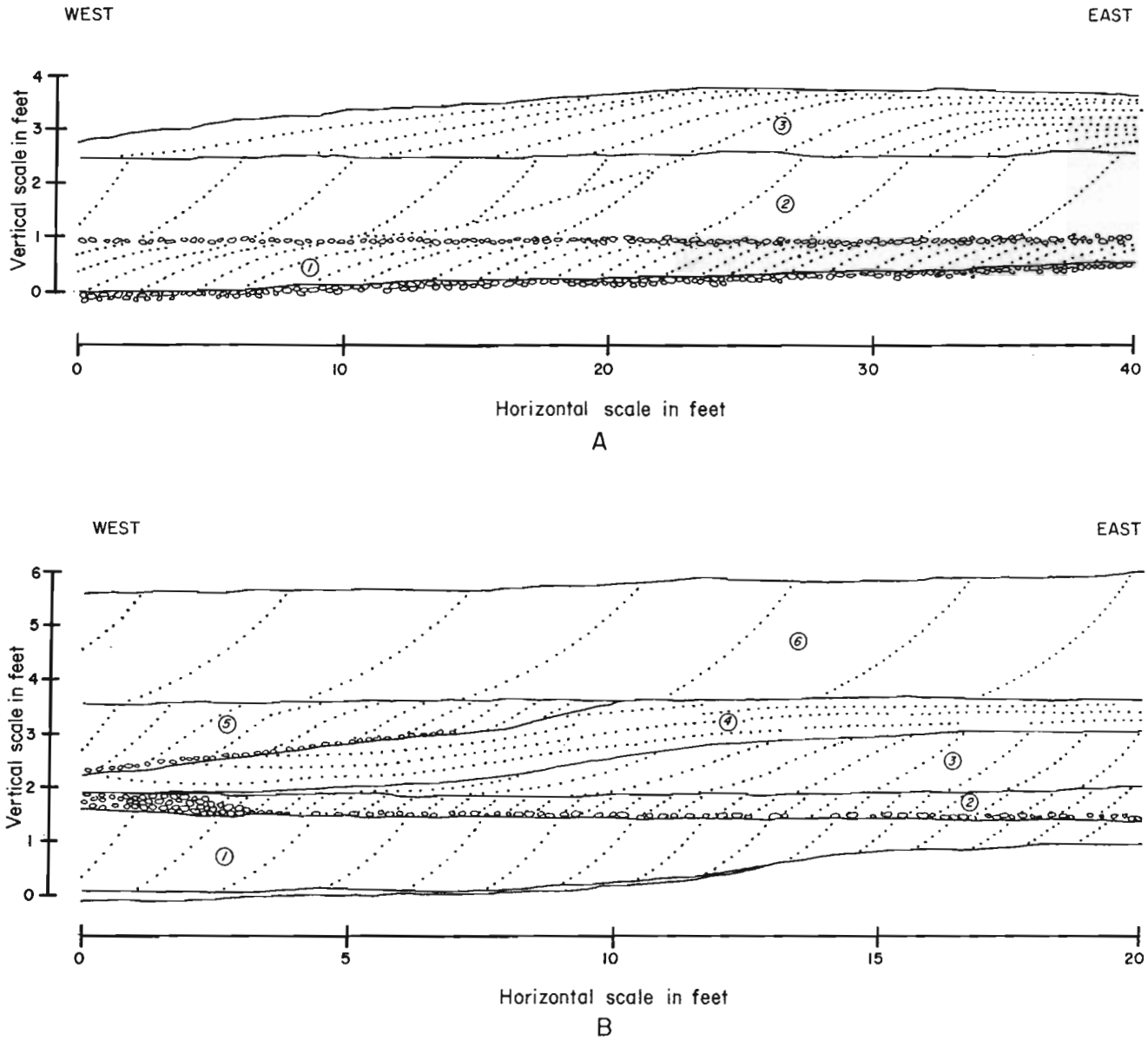

FIG. 20. Stratification in sands of the mid-fan facies (McVay ranch, section MV15).

A. This section shows some changes in stratification within individual sedimentation units. (1) Compound foreset crossbeds; underlain by pebble gravel (undetermined thickness) and overlain by gravel veneer 1 or 2 pebbles thick. (2) Simple foreset crossbeds; shows overlapping of at least two transverse bars. (3) Convex upward foreset crossbeds that grade westward into parallel laminae with low westward inclination. Transport direction generally to the west.

B. This section is east of and about 150 feet stratigraphically higher than (A). Sedimentary structures are chiefly foreset crossbeds that range in thickness from 0.5 foot to 2.5 feet and that have laminae that may have high-angle upper and lower contacts (units 1, 2, and 6) or well-developed toesets (unit 3). Both sections (A) and (B) are representative of broad shallow channels filled with transverse bars; thin gravels commonly represent channel-floor deposits, and muddy fine sand (such as that underlying unit 1) accumulated in residual channels.

ment along its left bank (erosion along the left bank and deposition along the right bank occur when migration is to the east). Maximum deposition is just below mid-fan, about 50 to 60 miles below the fan apex.

During construction of the Van Horn, depth of scour and depth of flow controlled the scale of sedimentation units and thickness of sands (consisting of one or more sedimentation units) deposited by a single depositional event. Sands deposited by a single flood constitute a "genetic package." Depth of scour in braided streams during deposition of the Van Horn alluvial-fan system decreased southward. Where fill of individual channels is observed, for example, at the upper end of the distal facies, maximum depth of scour is about 6 feet. Farther south (from section MV17 southward) it is not possible to identify individual channels, though depth of scour can be determined from thickness of units laid down by single depositional events. These units are bounded above and below either by a thin muddy sand or by a gravel lag unit. Depth of scour is on the order of 4 to 6 feet at the upper part of the facies and only 1 to 4 feet near the southern outcrop limit. Depth of flow also decreased to the south, as indicated in the decrease in scale of sedimentation units.

Downfan decrease in depth of scour and depth of flow, accompanied by lateral shift of the braided stream system, produced three distinct subfacies of the distal fan (fig. 3). First, in the area of the main braided stream, and particularly just downslope from the mid-fan, the distal facies is characterized by a few well-preserved channels and two types of primary sedimentary structures--foreset and trough crossbeds (main braided channel subfacies). Second, adjacent to and downfan from the main braided stream where depth of scour and flow decreased, there were minor braided streams through which relatively sluggish water flowed; here some small scour channels, 1 to 2 feet deep, are preserved with dominantly foreset crossbeds alternating with thin parallel-laminated muddy sands (braided distributary subfacies). Third, where lobes of adjoining fans coalesced, a relatively persistent low developed in which thick sand sequences composed of dominantly trough crossbeds accumulated up to 100 feet thick (interlobe braided subfacies).

Main braided channel subfacies.--Outcrop distribution of the main braided channel subfacies is shown on figure 21. Maximum development of the facies trends south-southeast across the McVay ranch. This trend occupies approximately the same position as one of the axes of thick gravel accumulation (fig. 4), suggesting that one of the canyons, cut into the Precambrian section, underlies this area.

Lateral and vertical relationships of the several Van Horn facies filling canyons are shown on the Keene ranch (fig. 5), where the distal facies of the Van Horn is divided into two unconformable sequences displaying distinctive bedding features. A lower sequence (fig. 5, section K4) was deposited contemporaneously with gravel lenses of the mid-fan facies. In the lower sequence, beds are not laterally persistent, whereas the upper sequence is composed of beds that are relatively uniform in thickness and display lateral persistence. Upper beds pinch out and to the west locally overlap progressively younger beds (fig. 22). A typical sequence of stratification types in the lower sand sequence is shown in figure 23; it is overlain by mid-fan deposits. Figure 24 illustrates some mid-fan sediment characteristics in the lower few feet of the section.

Just above the thickest mid-fan gravel deposit (fig. 5) 20 to 30 feet of muddy sand represents the top of the lower distal sand sequence; it has a lateral extent of 0.25 mile and grades westward into coarse, resistant beds. Figure 25 illustrates some characteristics of the upper 8 to 9 feet of the muddy sand and the basal part of the resistant sand. Genetic packages (1 to 4 feet) are recognized by bounding thin, almost planar, muddy sand units that accumulated in broad, shallow, scour channels (fig. 26).

On the Garren ranch, the succession of facies from north to south (G1 through G3) is proximal, mid-fan, and distal fan. The G3 area (fig. 2) is typical of the distal facies along the southwestern outcrop; there are rare occurrences of channels up to 200 feet wide and 4 feet deep. Recognition of channels is possible since the channel fill consists of sandy granule and pebble gravel that is texturally distinct from the coarse sand in which the channel was scoured. In most exposures single genetic packages (defined on p. 26) cannot be traced extensively, but thickness of a single genetic package--and hence approximate depth of a channel--can be determined by observing thickness of the sediment bounded by either thin gravel or muddy fine sand units. Thickness of genetic units is commonly 3 to 4 feet. Within one of these channels (on the Garren ranch, section G3) there is (1) a basal massive pebble gravel bed a few inches to 1 foot thick, (2) trough crossbeds (up to

FIG. 21. Percent of Van Horn Sandstone comprised of foreset and trough-fill cross strata.

FIG. 22. Upper part of Van Horn Sandstone on the Keene ranch. Sandstone packages of rather uniform thickness show progressive offlap to the west. About 150 feet of Van Horn Sandstone is exposed here. View is north.

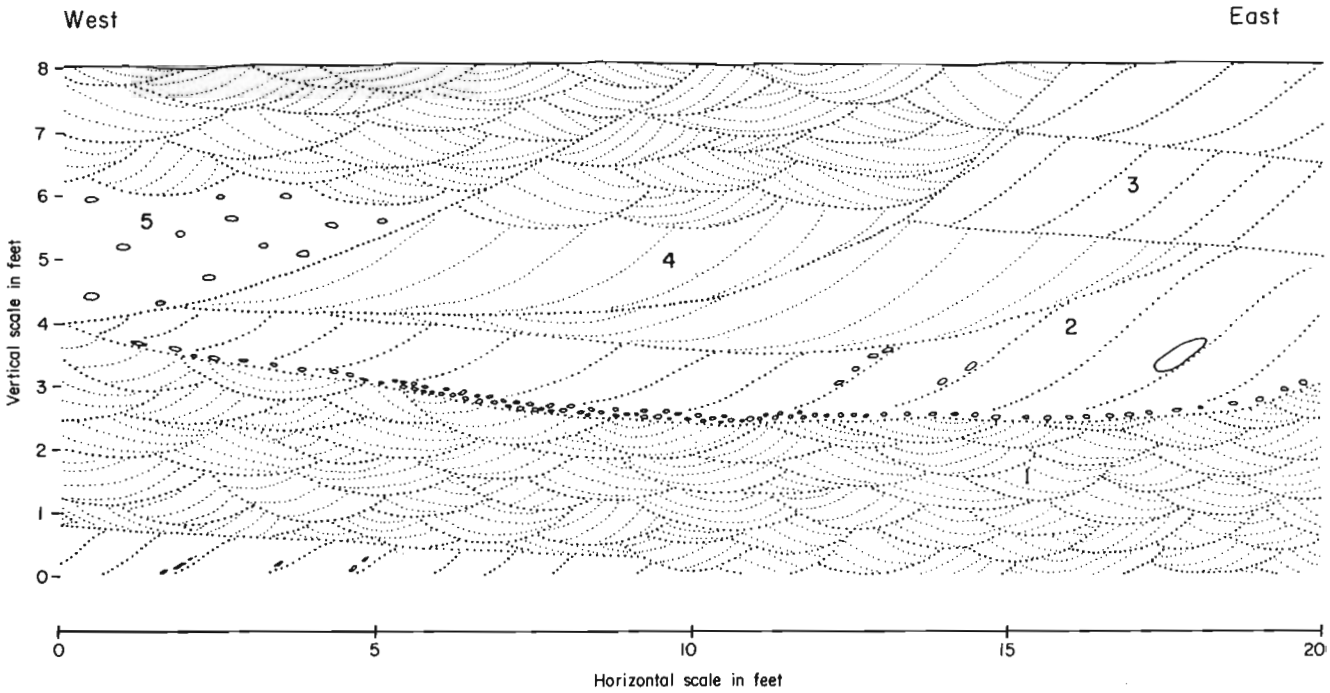

FIG. 23. Stratification types representative of distal facies deposits in the northernmost Van Horn outcrops (*see* fig. 5, section B, for stratigraphic position). Trough and foreset crossbeds are dominant. At least five depositional events are recorded by these deposits. Unit 1 and upper parts of units 4 and 5 are dominated by trough crossbeds. Lateral discontinuity of sedimentation units is typical of main braided channel deposits of the distal facies.

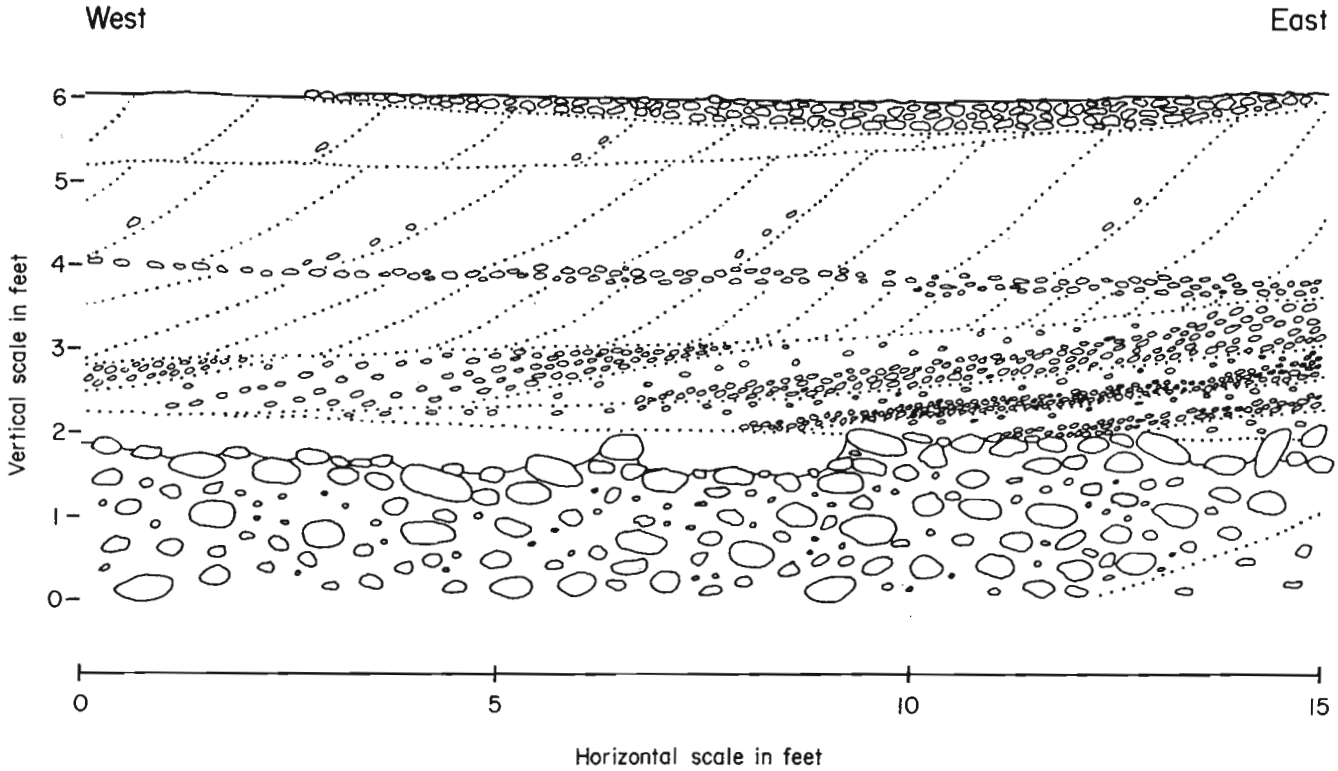

FIG. 24. Details of some mid-fan deposits that are interbedded with distal-fan deposits (*see* fig. 5, section C, for stratigraphic position). Two textural types, gravel and sand, are shown in this section. Gravels appear to have been deposited as bars, and most sand deposits (that is, the thicker ones) appear to flank the bars and to represent deposition in shallow braided streams during waning stages of a flood. The lower gravel bed is poorly sorted with the largest clasts (cobbles and boulders) occurring in the upper foot or so. Alternating pebble gravel and massive gravelly sand, next above the lower gravel unit, accumulated along bar flanks. The upper foreset-crossbedded sand units are transverse bar deposits. Some of the gravel units are fine at the base and coarse at the top, suggesting surge deposits.

5 inches thick and 3 feet wide) consisting of very coarse sand to granule gravel, and (3) two types of foreset crossbeds, low angle with bottomsets and high angle with only foresets preserved. Other channel-fill sequences (section G3) consist of a basal muddy sand followed by foreset crossbeds and finally trough crossbeds.

Braided distributary subfacies.--The braided distributary subfacies occurs in stratigraphically higher and more southerly parts of the distal facies. This subfacies is well exposed in the southwest part of the McVay ranch where it is underlain and overlain by main braided channel deposits. Where the fan surface and slope of the main channel floor intersect and sands in this subfacies were deposited, depth of scour and depth of flow suddenly decreased. This was an area of very low physical energy, and muddy sand content is higher here than in any other Van Horn facies.

Braided distributary subfacies can be divided into two groups based on degree of preservation of channel-fill deposits. Each can be characterized by relatively high muddy sand and by the dominance of trough crossbeds.

One group of braided distributary deposits on the McVay ranch is composed of small channel-fill deposits preserved within a 100-foot thick vertical section. Scour channels are 1 to 1.5 feet deep and are from 10 to 30 feet wide (most are 10 to 15 feet wide); the entire section consists of a series of overlapping channels. Commonly, a scour channel of the braided distributary subfacies is floored

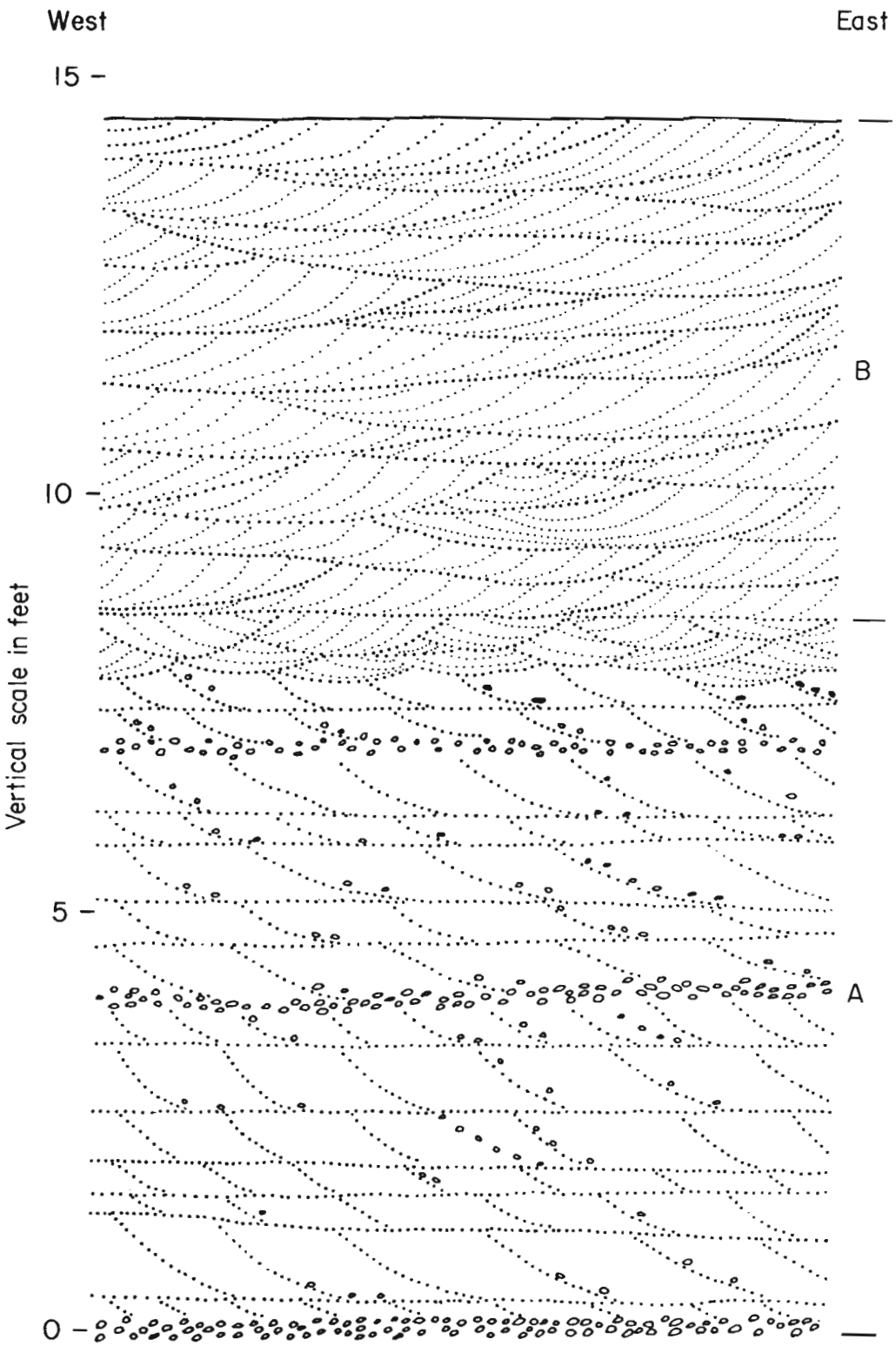

FIGURE 25

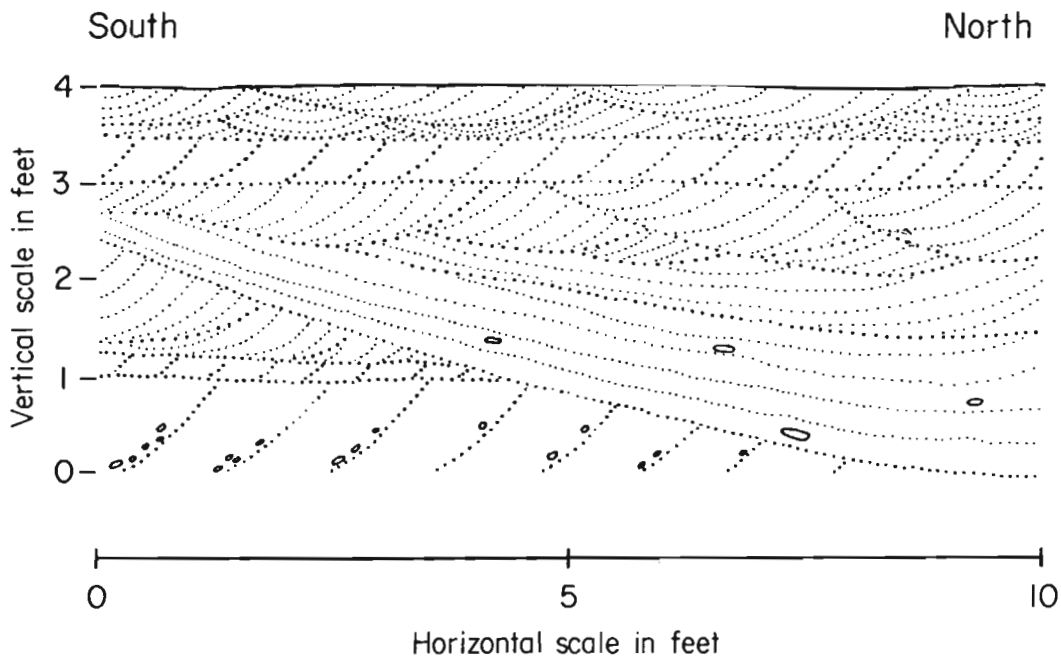

FIG. 26. Some characteristic features of the upper Van Horn Sandstone (*see* fig. 5, section E, for stratigraphic position). Sand of this section accumulated in broad, shallow channels, and thickness of genetic packages is in the range of 1 to 4 feet. Channel-fill is dominated by trough-crossbedded sand; foreset crossbeds are minor.

FIG. 25. Distal fan facies of the northern outcrop at locality K3 on the Keene ranch (*see* fig. 5, section D, for stratigraphic position). Thickness of sand lying between gravel deposits is about 30 feet; only the upper 15 feet or so is exposed. Two units, defined on the basis of texture and stratification types, make up this section.

A. The lower unit consists of muddy coarse sand and granule gravel. Primary sedimentary structures are dominantly foreset crossbeds with rare pebbles along foresets, and trough crossbeds, which are confined mostly to the upper 1.5 feet of the unit. Three depositional events account for this unit; the base of each genetic unit is a thin gravel layer that is 1 to 2 pebbles or cobbles thick.

B. Trough-crossbedded, slightly granular coarse sand. This unit, about 6 feet thick, is a ledge former and is traceable throughout the outcrop.

with muddy sand, with soft-sediment deformation structures succeeded by trough crossbeds (fig. 27).

A second group of braided distributary deposits consists of relatively small trough crossbed units (1 to 3 inches thick and 6 inches to 2 feet wide) and thin muddy sand units (1 to 6 inches thick). Maximum observed thickness of a sequence of these deposits is about 75 feet (MV19). Individual channels are not recognizable in this part of the subfacies, but channel depth, based on the thickness of a single genetic package, must have been between 1 and 4 feet. A single package consists of a lower trough-crossbedded sand and an upper parallel-laminated to low-angle foreset-crossbedded muddy sand. Lateral continuity of a trough-crossbedded unit is broken in many places by injection of underlying muddy sand (fig. 28). Similarly, this part of the subfacies is also underlain and overlain by main braided channel deposits.

Braided distributary deposits accumulated on a relatively low gradient surface where depth of scour and flow were less than for other distal subfacies. These conditions favored accumulation of the muddy sand; because the relatively impermeable muddy sand hindered internal drainage, injection structures developed in the saturated deposits.

Interlobe braided subfacies.--Relatively thick sections of trough-crossbedded, coarse to very coarse sand comprise the interlobe braided subfacies which commonly overlies, underlies, and grades laterally into main braided-stream deposits. This facies is best developed on the McVay ranch where locally (MV11) it is overlain by braided distributary facies. On the Garren ranch (G2) interlobe facies grades northward into braided distributary subfacies.

Trough-crossbedded sand is concentrated along a narrow belt on the McVay ranch (MV21, 5, 11, and 3, fig. 29). Along this trend, thickness of the subfacies ranges from about 30 to 100 feet. Where several hundred feet of distal facies are exposed (for example, MV5 more than 700 feet and MV3 more than 500 feet) interlobe deposits are separated upward in the section by progressively thinner main braided-channel deposits; as many as three interlobe units occur in each section.

Although trough crossbeds are by far the most common stratification type in the interlobe subfacies, foreset-crossbedded coarse sand and some parallel-laminated muddy sand are present. Commonly, the thickest interlobe deposits occur in the lower parts of the distal facies where depositional relief on the lobes was most pronounced. Scale of individual trough crossbeds in the lower, coarser parts of the subfacies are from 3 to 6 inches thick and 1 to 4 feet wide. Smaller scale structures and finer grained sand (medium sand) occur in stratigraphically higher parts of the subfacies. The smaller trough crossbeds approach the lower size limit of dunes (Kennedy et al., 1966); grain size ranges from medium to coarse sand.

DEPOSITIONAL TRENDS

Several techniques may be employed in deducing depositional trends or determining direction of currents operative during deposition of a terrigenous rock sequence. Nilsen (1968, 1969) showed a correspondence between trends in maximum clast size, sphericity, imbrication of clasts, and dip direction of tabular crossbeds (foreset crossbeds as used in this report) in Devonian fanglomerates

FIG. 27. Representative sedimentary structures of the braided distributary subfacies. A, B, and C are from the braided distributary subfacies and D is from the underlying main braided channel subfacies. A and B are sections roughly parallel to general transport direction (flow was southward). A is from an east-facing outcrop and B from a west-facing outcrop. C is a view of sedimentary structures perpendicular to general transport direction.

A. Three genetic packages are shown, each floored by muddy sand. Primary sedimentary structures are (1) simple and compound foresets, (2) trough crossbeds, and (3) parallel-laminated or structureless muddy sand.

B. About 10 depositional events are recorded in this section. Primary sedimentary structures are (1) foreset crossbeds, (2) trough crossbeds, and (3) parallel-laminated or structureless muddy sand. Gravel lag and muddy sand mark the floors of individual channels. Large foreset units completely fill some of the channels.

C. The upper diagram shows some details of deformation in muddy sand that floors many of the braided channels. Note the poorly preserved ripples at the top of the diagram.

The lower diagram shows a partial channel cross section. Muddy sand that floored the channel was locally removed by the next flood event. Sedimentary structures are small trough crossbeds and foreset crossbeds. The basal trough crossbed unit contains mud clasts derived from the channel floor.

D. Upper 5 feet or so of main braided channel subfacies. General sediment transport direction is toward the south. Primary sedimentary structures are (1) small trough crossbeds, (2) parallel-laminated muddy sand, (3) compound foresets, and (4) simple foresets.

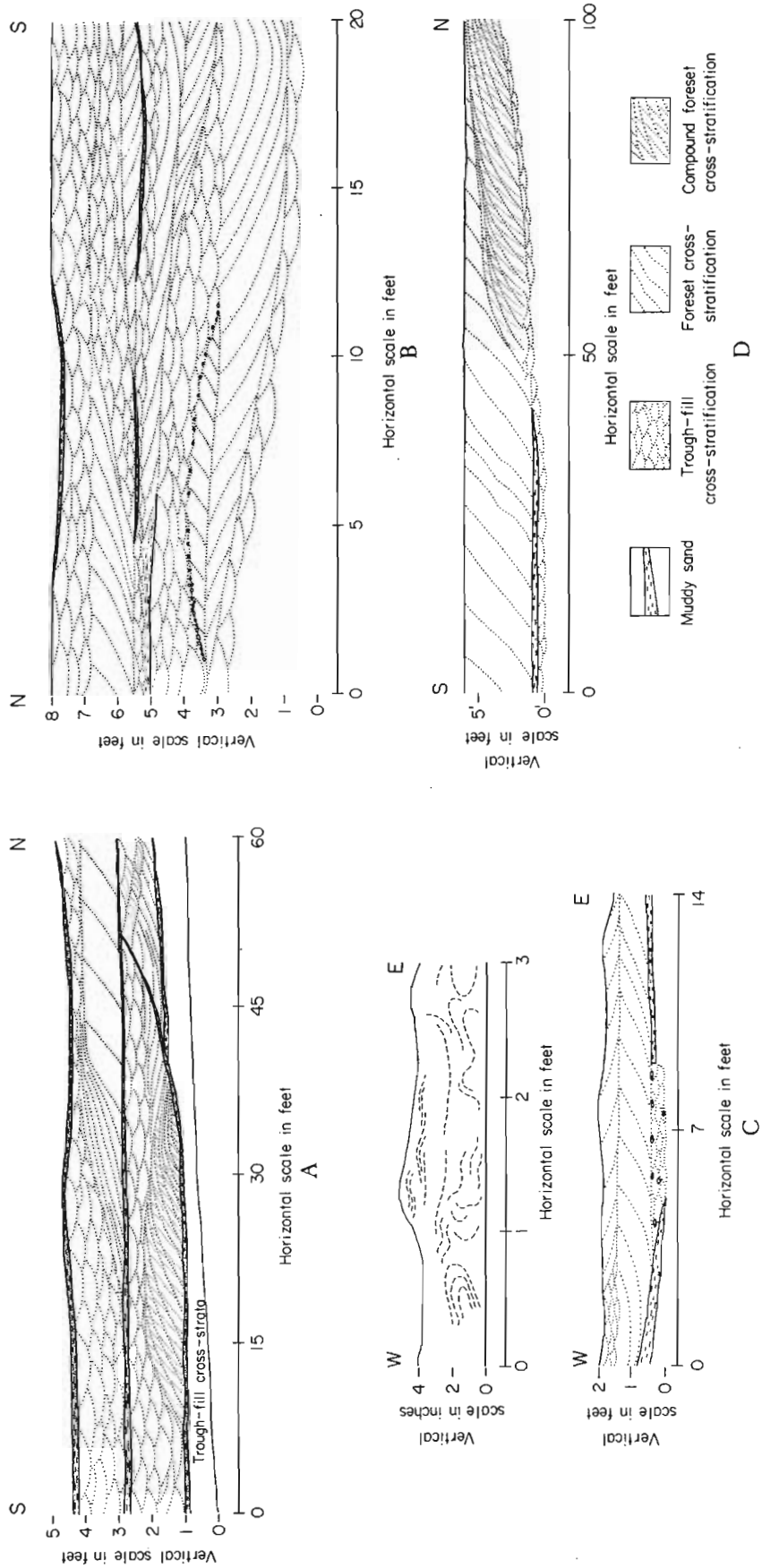
S
N
Vertical scale in feet
Horizontal scale in feet
A
Trough-fill cross-strata
B
C
D
W
E
scale in inches
scale in feet
Muddy sand
Trough-fill cross-stratification
Foreset cross-stratification
Compound foreset cross-stratification

FIGURE 27

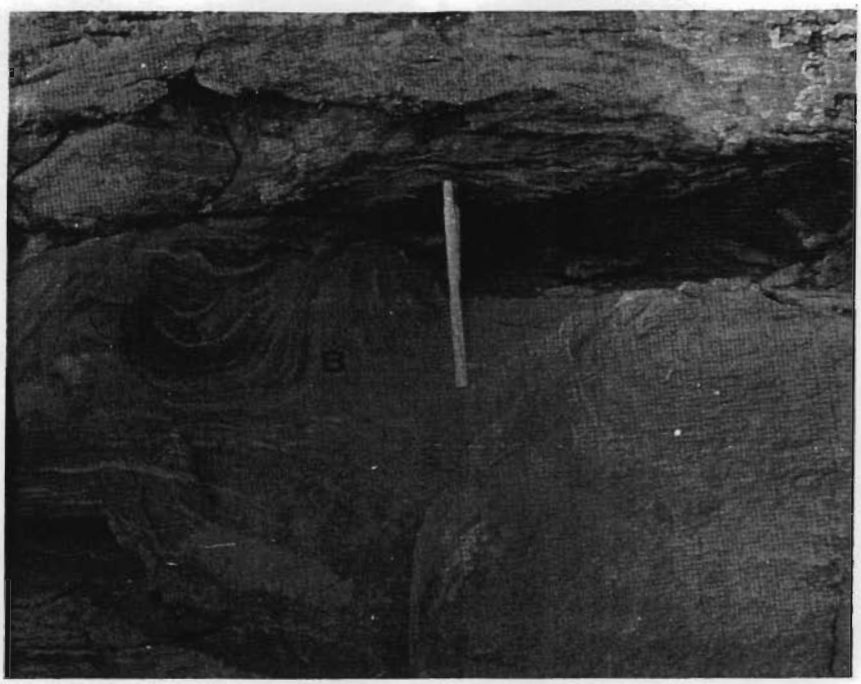

FIG. 28. Convolutions and injection features of the braided distributary subfacies (McVay ranch, section MV4). Convolution of trough-crossbedded sand (A) and injection of muddy sand (B) into overlying trough units are common in this subfacies. View is east.

of southwestern Norway. He found that rounding decreases in the direction of sediment transport; decrease in roundness was accompanied by a decrease in grain size.

Van Horn depositional trends are indicated by textures and primary sedimentary structures. Maximum boulder size (36 inches longest dimention) occurs on the Keene ranch (fig. 2); there is a southward decrease in maximum boulder size. The gravel fraction of the Van Horn consists of subangular to well-rounded pebbles, cobbles, and boulders. There is no apparent trend in roundness or shape; most clasts are compact-elongate, with the exception of a few platy to very platy pebbles (clast shape after Sneed and Folk, 1958). Imbrication of cobbles was observed in the proximal facies on the Neal ranch (section P4). Imbrication was not measured, but cobbles were inclined toward the north; this agrees with directional features obtained by other methods. Preferred direction of longest clast axes was measured at one locality (P5); these values are illustrated on figure 6.

Local current directions were determined by measuring dip direction of foreset crossbeds, axes of trough crossbeds, and long axes of clasts. These values are displayed as rose diagrams for each locality (fig. 6). The dominant crossbed trend is southward; however, a few readings fall in the northeast and northwest quadrants. Alignment of long axes of cobbles and boulders (on the Neal ranch, P5) in a northwest-southeast direction could indicate a current flowing in either direction (Nilsen, 1968, 1969), or according to Lane and Carlson (1954) elongate clasts are aligned perpendicular to flow; in this situation current direction at P5 would have been either southwest or northeast. Regardless of which view is accepted, evidence from other sources (dip direction of foresets and trough axes, textural trends, and lateral succession of facies) indicates an overall southerly transport direction.

Gravel percentages alone are adequate to indicate that the general transport direction was south. Axes of gravel highs may approximate the track along which high physical energy was operative; however, some of these axes reflect the faulting or eastward tilting that exposed the lower gravel, or they indicate high gravel percentages resulting from removal of overlying finer grained material. Consistency of flow direction, as indicated by cross-

bedding, probably reflects a relatively high gradient surface across which Van Horn sediment was transported.

There are exceptions to the overall southward sediment transport direction. On the McVay ranch (section MV6) plunge of trough crossbed axes and dip direction of foreset crossbeds are westward. Sand and gravel in the area of MV6 were deposited in a notch or channel cut through a divide separating areas of Van Horn deposition. A canyon

FIG. 29. Percent of Van Horn Sandstone comprised of trough-fill cross strata.

lying to the east of MV6 was filled and deposition was shifted through a notch to a lower area to the west.

DEPOSITIONAL PROCESSES AND ENVIRONMENTS

The Van Horn Sandstone is interpreted to be a large alluvial fan system that was probably comparable in size to the large fan being built today by the Kosi River of India (Gole and Chitale, 1966). Like the Kosi River fan, the Van Horn fan was constructed entirely by fluvial processes. There is no evidence in the Van Horn of debris-flow deposits (Kesseli and Beaty, 1959; Hooke, 1967; Beaty, 1970) or sieve deposits (Hooke, 1967) that characterize arid-region alluvial fans. Laming (1966) likewise did not recognize debris-flow deposits in the New Red Sandstone of England, and Gole and Chitale (1966) did not report debris flows on the Kosi River fan.

No modern alluvial fan has been described that provides a precise depositional model for the Van Horn. Interpretation of the Van Horn Sandstone as a large alluvial fan is based on several examples: (1) modern arid-region fans (Kesseli and Beaty, 1959; Hooke, 1967; Beaty, 1970); (2) modern humid-region fans (Gole and Chitale, 1966); ancient fans (Laming, 1966; Nilsen, 1968, 1969; Wilson, 1970); (4) characteristics of braided streams (Ore, 1963; Smith, 1970); (5) fluvial processes (Simons and Richardson, 1961; Harms and Fahnestock, 1965; Williams, 1967); and (6) flood-surge deposits (Scott and Gravlee, 1968). Recognition of the significance of downfan succession of textural and stratification types was greatly facilitated by the work of Scott and Gravlee (1968), Smith (1970), and Wilson (1970).

Sedimentary Processes and Facies

Facies characteristics such as clast size, bedding thickness, and sedimentary structures reflect the intensity of physical processes operating during construction of the Van Horn fan. Indications are that depth of flow, confinement of flow, and slope of the fan surface decreased from north to south or from proximal to distal parts of the fan system.

Proximal fan.--Gravels were deposited mostly in canyons where flow was confined. Canyons extended at least 20 miles in a north-south direction as judged by gravel distribution in the preserved Van Horn outcrop. Unconfined flow (fluvial processes) across the surface of a typical alluvial fan would not have the competence to transport boulders and cobbles for any great distance. Lowermost massive gravel deposits of the Van Horn accumulated as surge deposits within the canyon. Gravel deposits higher in the section accumulated under more shallow and less confined conditions where sorting was accomplished; these occur as longitudinal bars and have horizontal bedding characteristic of some modern braided streams (Ore, 1963; Smith, 1970).

Gravel deposits, particularly the cobble and boulder beds, are probably surge deposits similar to those of the Rubicon River of California (Scott and Gravlee, 1968) and might have been deposited in several feet of water. Gole and Chitale (1966) reported that the Kosi River is subjected to sudden spate, sometimes rising more than 30 feet in 24 hours; the Rubicon River has a depth of flow of about 45 feet during flood (Scott and Gravlee, 1968). During the 1964 flood on the Rubicon River, average velocity was about 22 feet per second. Some gravels deposited during this surge were up to 7 feet thick. These Rubicon deposits had steep fronts transverse to the channel trend, and movement of material along the channel floor probably was in the form of large gravel waves.

Some gravel sequences in the Van Horn, consisting of several gravel and sand units, have foresets on the order of 5 to 10 feet thick (fig. 11, B). Foresets in these Van Horn gravels are less than the angle of repose and are coarser along upper parts of foresets; a few foresets grade into bottomsets of gravelly coarse sand. Clasts coarser than cobbles are uncommon in these foresets, and gravels with foresets occur a few tens to several hundred feet above the base of the Van Horn. These gravel deposits (bars) probably developed under flow conditions less vigorous than those reported for the Rubicon River. Where gravel deposits crop out over a considerable distance it can be shown that some of these are longitudinal bars (Ore, 1963; Smith, 1970). Thin sand beds at the tops of bars accumulated during waning flood stage when water depth was probably on the order of a few inches; parallel laminae are the only stratification type in the sand because grain size precluded development of ripple bed forms (Williams, 1967).

Sand and muddy sand deposits that are associated with the proximal facies accumulated in residual lows flanking the gravel bars and in lows between two adjacent fan lobes. Sand-size sediment filled many broad, shallow, anastomosing channels that flanked gravel bars. Deposition of sand oc-

curred (1) during waning stages of floods that laid down gravel bars, (2) when lesser floods were not competent to transport gravel, or (3) when the locus of maximum discharge had shifted. Locally, within the proximal facies, particularly near the transition from proximal to mid-fan facies, there are sections of muddy sand with a composite thickness of 10 to 15 feet. These muddy sands consist of sedimentation units with topsets, foresets, and bottomsets. These units coarsen upward from muddy, medium and coarse sand to granular, very coarse sand; they represent infilling of local ponds on the fan by small, Gilbert-type deltas.

No terrestrial vegetation existed at the time the Van Horn alluvial fan system was developing, and significant soil-forming processes were probably nonexistent. Schumm (1968) has speculated on the role played by vegetation on terrestrial erosion and sedimentation through geologic time. In the absence of a vegetation cover there is little resistance to runoff, lag between precipitation and runoff is extremely short, and peak discharge duration is short. Thus, prior to evolution of terrestrial plants, optimum conditions existed for development of alluvial fans, fan deltas, and braided streams. There was also a paucity of clay-size material, and streams were characterized by a high bed-load/suspension load ratio. With high bed-load/suspension load ratio, short lag between precipitation and runoff, and short duration peak discharge, the rounding of gravel-size material might have proceeded at a more rapid rate than at present; rounding of volcanic and igneous rock clasts in the Van Horn is probably a first-cycle feature.

Mid-fan.--The proximal facies grades upward and southward to the mid-fan facies. Associated with decrease in clast size of the gravels is a corresponding decrease in bedding thickness. A mixed facies of sand and gravel resulted from the widening of the canyon to the south (figs. 30 and 31). As the canyon opened out southward, depth of flow, stream competence, and stream gradient all decreased and a braided-stream system was developed.

Below the point where the canyon opened southward, the braided-stream system migrated across a broader area than in the confinement of the canyon. The braided stream occupied a given area within this section of the fan system less frequently than it did in the upper parts of the canyon. This factor allowed frequent rapid, lateral shifts in channels resulting in preservation of entire channel-fill deposits. Braided streams were deeper and narrower where gravel content was high, particularly where cobbles were the dominant sediments. Channels associated with high sand content were wider and broader because sand banks were less resistant to erosion (Mackin, 1956).

Gravel beds, characterized by thin to thick parallel beds that grade laterally and downcurrent to low- to high-angle foreset crossbeds, accumulated in braided streams as longitudinal bars similar to those described by Ore (1963) and by Smith (1970). As gravel and sand deposits aggraded, a convex upward surface transverse to flow resulted and frequently the fluvial system was diverted suddenly eastward or westward across a surface with a higher gradient. Channels were scoured into the underlying sediment at the onset of diversion of flow. These channels are judged to be analogous to fanhead trenches (Denny, 1967; Hooke, 1967). The channels are commonly filled with gravel with high-angle foresets adjacent to steep banks and with alternating massive gravel beds and foreset- and trough-crossbedded sand along the central parts of the channels.

Longitudinal gravel bars were probably formed by rapid flow conditions during flood crest. Because the flow regime concept (Simons and Richardson, 1961; Harms and Fahnestock, 1965) was developed for bed forms produced only in medium sand, and because of the paucity of discharge/bed-form data for streams transporting coarse sand and gravel material, stratification types in the Van Horn Sandstone are not classed as products of either upper or lower flow regime. With a decrease in discharge, sand was transported transversely across the crests of longitudinal gravel bars, and it accumulated as transverse bars under tranquil flow conditions in the flanking shallow braided channels. With a further decrease in discharge, gravel bars became emergent and flow was then confined entirely to the shallow braided streams. Sand moved down these channels as continuous crested transverse bars or as short, discontinuous crested dunes. Stratification types produced by these bed forms are foreset crossbeds and trough crossbeds.

Distal fan.--Distal fan facies of the Van Horn alluvial fan system is characterized by coarse and very coarse sand with some granule and pebble gravel and by a dominance of two stratification types, foreset and trough crossbeds. The distal facies represents the lowest physical energy deposit of the Van Horn Sandstone (figs. 30 and 31). Sand accumulated in the area south of the canyons

where the slope of the fan surface was considerably less than the slope of the proximal and mid-fan areas. Because flow across the distal fan was virtually unconfined, depth of flow, velocity, and stream competence were all less than on the proximal and mid-fan. Flow across the distal fan was accommodated by numerous, shallow, braided streams.

Distal-fan deposits are divided into three subfacies based upon the relative abundance of foreset and trough crossbeds, number of thin muddy sand beds, and degree of preservation of channel-fill deposits. The subfacies, described in a previous section, are: (1) main braided channel, (2) braided distributary, and (3) braided interlobe. On the distal fan, the bed-load/discharge ratio, depth of flow, velocity, and stream competence were less than on the mid-fan. These less intense physical processes are reflected in the distal facies by sediment characteristics such as texture (fine grain sizes), suites of sedimentary structures (dominantly troughs and foresets), and smaller scale of sedimentation units.

MAIN BRAIDED CHANNELS.--Braided streams deposited the facies characterized by the combination of foreset and trough crossbeds. It is postulated that both tranquil and rapid flow produced bed forms that fluctuated between discontinuous crested and continuous crested transverse bars (Williams, 1967; McGowen and Garner, 1970). Either transverse bars or dunes will develop under these discharge conditions depending upon the bed-load/discharge ratio. Transverse bars (foreset crossbeds) probably formed when bed-load/discharge

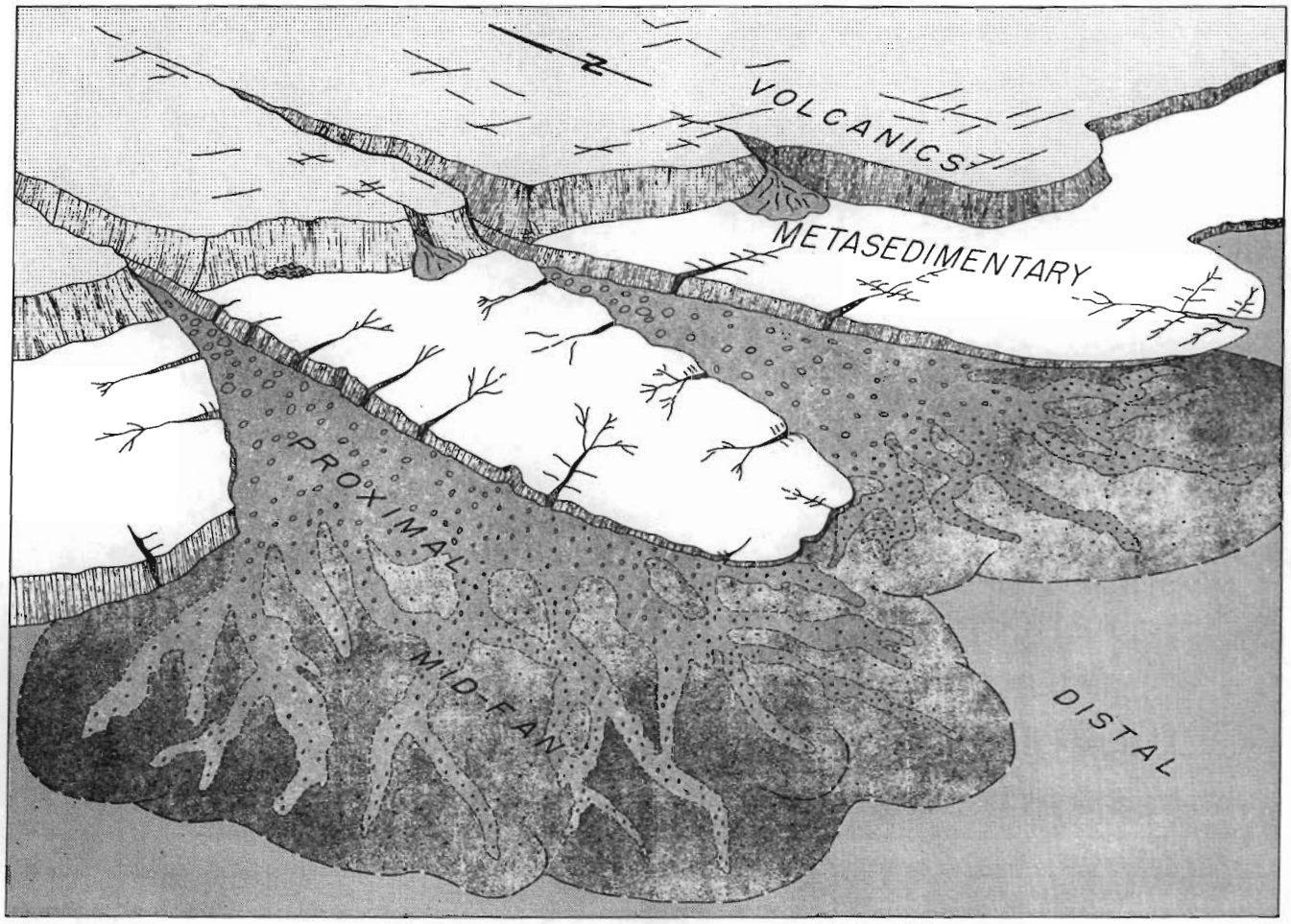

FIG. 30. Interpreted Van Horn paleogeography. Highlands to the north capped by volcanics; not shown is the granitic source terrane that is interpreted to lie somewhat farther north than the volcanics. Canyons were cut through volcanics into underlying metasedimentary and sedimentary rocks that also form divides between canyons. Coarsest material is confined to the canyons, and finer material is spread to the south beyond the canyon mouths.

ratio was highest. Angle of foresets (fronts of advancing transverse bars) was high at the onset of an individual depositional event, and the angle decreased as flood intensity increased.

Minor surges are recorded in deposits of this facies by compound foreset crossbeds, which developed as water depth increased. Compound foreset crossbeds grade upcurrent and downcurrent into simple foresets. Where compound foresets are downcurrent from simple foresets, a trans-

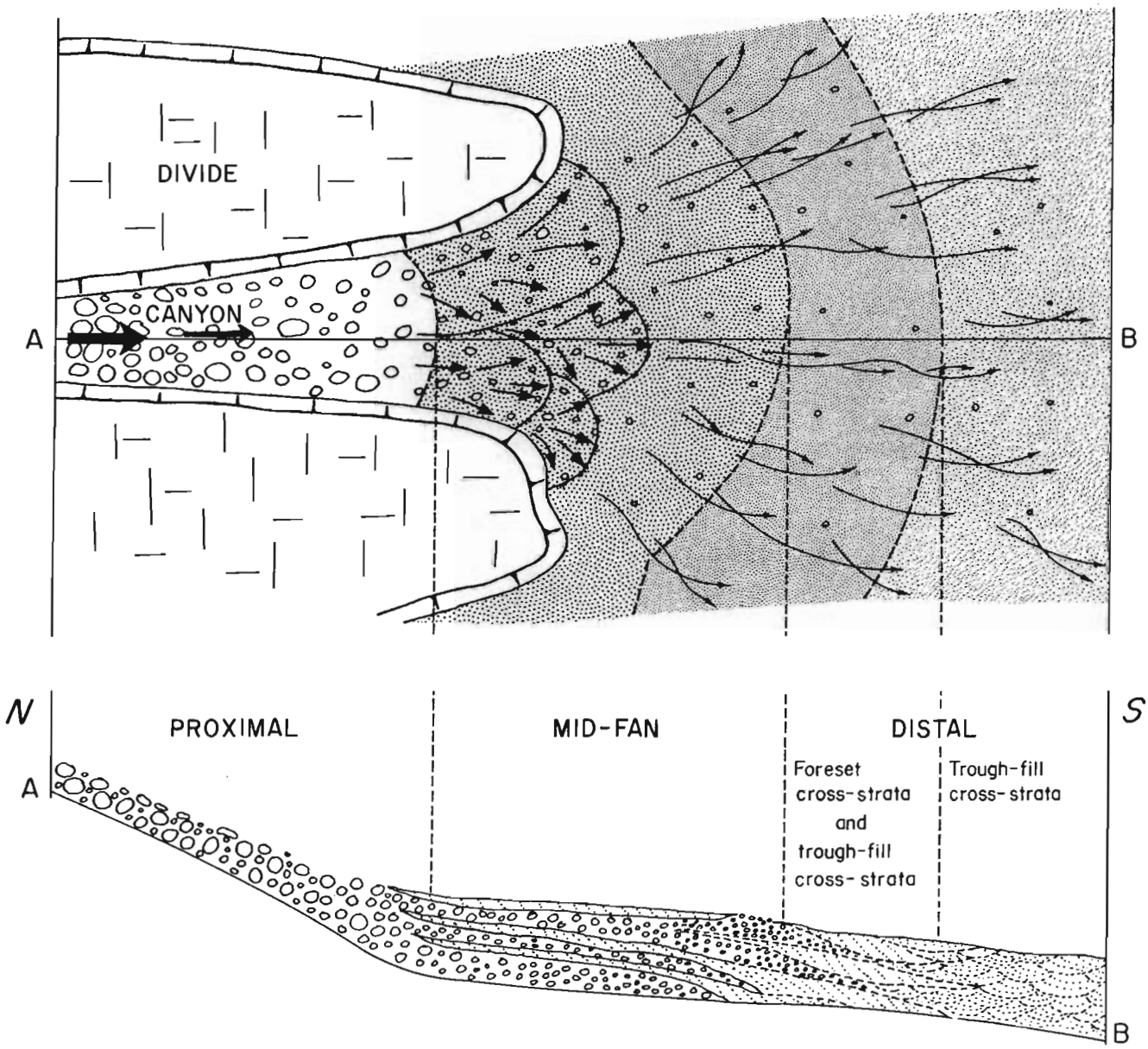

FIG. 31. Plan and cross section of a single canyon and fan. Width of arrows, in plan view, indicates relative intensity of fluvial processes. Cross section shows downfan decrease in slope and grainsize and the following general north-south succession of stratification types: (1) proximal-massive gravel, (2) mid-fan alternating gravel and trough- and foreset-crossbedded sand, and (3) distal trough- and foreset-crossbedded sand.

verse bar (simple foresets) was accreting downstream under constant velocity and water depth conditions when water depth was suddenly increased. Deposition of sand as a transverse bar with a low avalanche face would be initiated upcurrent from the position of the face of the bar prior to rise in water level. Continued flow at this new depth would move the newly formed transverse bar downcurrent and finally avalanche over the previous bar. A combination of avalanching sand and granule gravel and suspension deposition of similar material would develop the convex upward foreset units as flow separated across the front of the underlying transverse bar. Several sudden but slight rises in water level would produce relatively thick sequences of compound foresets (*see* Appendix, block diagram F, fig. 36).

Dune bed forms developed contemporaneously with transverse bars but generally downcurrent from the bars where bed-load/discharge ratio was lower; Harms and Fahnestock (1965) described the mechanics of dune formation in fine to coarse sand. Dunes also formed in deeper parts of Van Horn braided streams during flood stage after transverse bars had become emergent. Unlike modern braided streams studied by Ore (1963) and Smith (1970), there is no evidence that longitudinal bars developed along distal segments of the Van Horn alluvial fan. Parallel-laminated sand deposits, characteristic of longitudinal bars, are rare in this facies. Ore (1963) believed that braided streams with high bed-load/discharge ratio would be characterized by a dominance of transverse bars over longitudinal bars. He noted that Pleistocene braided stream deposits were characterized by dominance of foreset and trough crossbeds over parallel laminae.

BRAIDED DISTRIBUTARIES.–Continuing downfan, from the main braided channels (fig. 3), the slope of the fan surface and depth of flow continued to decrease. At about the point where slope of the fan surface and slope of the main braided channels were the same, flow broke up into numerous, small, braided channels and radiated outward across the toe of the fan. This is the area where braided distributaries developed. Many small channels, 10 inches to 1.5 feet deep, were floored with muddy sand which was succeeded by foreset and trough crossbeds.

Flow through braided distributaries was sluggish in comparison to the main braided stream. Channels were not always scoured and filled during the same depositional event, as indicated by the common occurrence of a muddy sand floor suggesting that sluggish to stagnant conditions often occurred following scour of a channel. In deposits of the Van Horn fan, ripple cross laminae were observed only in muddy sand units that floor these scour channels; ripple cross laminae were commonly obliterated by soft sediment deformation. Other stratification types, foreset and trough crossbeds, suggest tranquil flow conditions; the deformational structures indicate prolonged saturation periods.

In parts of the braided distributary subfacies, channel-fill deposits are not preserved, and the facies is characterized by alternating muddy sand and sand consisting of small trough crossbeds. Within this part of the braided distributary subfacies, injection structures are common. These structures resemble quicksand injection structures described by Laming (1966). These are the lowest physical energy deposits of the distal facies. Small dunes (trough crossbeds) migrated downcurrent during flood conditions and muddy sand accumulated during waning flood and stagnant conditions.

BRAIDED INTERLOBE AREA.–A topographic depression was created in areas where distal parts of two adjacent fans overlapped. This low served to collect flow from overlapping distal fan areas and to increase locally the velocity and depth of flow. Tranquil flow conditions probably dominated this area since the bed forms were almost exclusively dunes (trough crossbeds). Sediment deposited in interlobe fan areas is dominantly trough-crossbedded, coarse sand and granular, very coarse sand. Heavy mineral placers are common in trough-crossbedded sand of this subfacies. Heavy minerals were concentrated because movement of bed-load material was sufficiently slow as to allow for preferential sorting.

SUMMARY

Van Horn Sandstone, composed of gravel and sand, is thickest in the northernmost outcrops (up to 1,200 feet) and thins irregularly to about 100 to 200 feet near its southernmost outcrop limit.

Gravel-size material is confined primarily to the northern outcrop area and stratigraphically to the lowermost sections of the Van Horn. Maximum size clasts, up to 3 feet, occur a few feet to a few tens of feet above the base. Beds consisting of boulder-size clasts are massive and are the thickest deposits of gravel-size material. Clast size decreases upward in the section, as well as toward the south; accompanying the decrease in clast size is a decrease

in bedding thickness of gravels and an increase in the number and thickness of sand beds.

The lower section dominated by gravel is replaced vertically and to the south by alternating gravel and sand beds. Packages of gravel beds are thickest in the north; these thin and ultimately pinch out southward where coarse and very coarse sand becomes dominant.

Genetically related packages, whether gravel, gravel and sand, or sand, show a decrease in scale upward and southward. There is also a succession of stratification types from north to south coincident with the decrease in clast size and bedding thickness. At a particular moment in time, the Van Horn surface displayed the following features from north to south: (1) thick, massive boulder beds; (2) alternating, thick, horizontally stratified cobble to boulder beds and thin, massive, or parallel-laminated sand beds; (3) alternating thin to thick, horizontal to foreset-crossbedded pebble to cobble beds and thin to thick, parallel-laminated and foreset- and trough-crossbedded sand; (4) coarse to very coarse sand characterized by foreset and trough crossbeds; (5) coarse to very coarse sand and muddy coarse sand dominated by foreset and trough crossbeds with minor ripple cross laminae and soft sediment deformational structures; and (6) coarse sand, granular very coarse sand, and muddy coarse sand consisting for the most part of trough crossbeds or alternating small trough crossbeds and thin parallel-laminated muddy sand (quicksand structures common).

In general, the three Van Horn facies--(1) proximal, (2) mid-fan, and (3) distal--are regressive facies. This can be demonstrated in the northernmost sections where in vertical succession the facies are proximal, mid-fan, and distal. With filling of the canyons, confined flow was virtually eliminated, gradient on the depositional surface decreased, and the entire facies tract shifted northward toward the source area.

COMPOSITION AND MINERALOGY

GRAVEL COMPOSITION

The composition of Van Horn conglomerates was determined by making pebble counts at localities throughout the area of gravel occurrence (fig. 32). At each locality approximately 100 clasts larger than 1 inch were counted in the area immediately surrounding a randomly selected point in a conglomerate bed. Roundness estimates were made for each lithologic group.

Volcanic rock fragments are most common in the conglomerates; in most areas quartzite is second in abundance followed by vein quartz. Lesser quantities of chert and miscellaneous fine-grained siliceous rock, metamorphic rock, and clasts derived from the underlying Hazel Formation are also present. The percentage of each constituent varies within the area, but the general pattern of relative abundance of each of the lithologic types is persistent throughout the Van Horn conglomerate.

Volcanic rock fragments constitute 50 to 75 percent of the gravel clasts. Clasts vary in texture from aphanitic to very porphyritic. Most are dark red or dark reddish brown; however, some are dark gray and various shades of purple. King (*in* King and Flawn, 1953) classified these volcanics as rhyolites and pointed out their similarity to volcanic rocks cropping out in the Pump Station Hills (fig. 1). C. S. Ross examined rocks from both areas and agreed that rhyolite clasts in the Van Horn conglomerate are probably related to the Pump Station Hills volcanic rocks (King and Flawn, 1953). Roundness varies from subangular to well rounded; most clasts are at least moderately well rounded.

Quartzite clasts, 10 to 25 percent of the gravel fraction, are brown, tan, and medium gray. Where grain size is discernible in the quartzite, it is medium to fine sand. Quartzite plus milky and honey-colored vein quartz comprise the most rounded fraction of the conglomerate; nearly all clasts are well rounded and many are very well rounded.

Sandstone and siltstone clasts derived from the underlying Hazel Formation comprise 1 to 3 percent of most Van Horn conglomerate gravel clasts. Clasts derived from the Hazel are most abundant near the base of the Van Horn. On the Neal ranch, for example, Hazel clasts comprise approximately 10 percent of the gravel clasts in conglomerates near the Hazel-Van Horn contact but decrease to 1 to 3 percent a few feet above the contact. The roundness of Hazel clasts is highly variable.

Chert and miscellaneous fine-grained siliceous rock constitute 4 to 19 percent of the gravel clasts. A wide variety of siliceous rock is included in this group. Some resembles chert from the Allamoore Formation, but most is of unknown origin and source. The siliceous clasts range from subangular to moderately well rounded.

Metamorphic rock fragments compose a minor constituent of the conglomerates in some places and are absent in others. They comprise less than 6 percent of the gravel at most localities and most commonly only 1 to 2 percent. Their roundness is highly variable.

Most Van Horn conglomerate has a mean and modal size in the large pebble to small cobble range (16 to 128 mm); clasts coarser than 6 inches are not common. Coarser conglomerate, with boulders up to 3 feet in diameter, is present, however, near the base of the formation on the Keene, Neal, and Weston ranches. In these areas pink or red granite comprises 80 to 90 percent of the clasts larger than 6 inches; the remaining 10 to 20 percent is quartzite and volcanic rock fragments. Granite clasts smaller than 4 to 5 inches are not common in these outcrops. Thus weathering characteristics of the granite source rock or processes active during transport are factors that limit the occurrence of granite to the coarsest conglomerate. This suggests that caution be exercised when determining provenance from counts of pebbles or even from sand grains.

Current indicators in the Van Horn show a general north to south transport direction; based on what is known about the Precambrian terrane north of the Van Horn area (fig. 1), pebble composition reinforces other directional data (fig. 6). Denison and Hetherington (1969) described this terrane as consisting of quartzite, shale, rhyolites, and granites old enough to have been possible source rocks for the Van Horn conglomerates. The pebble types in the conglomerate reflect this general source area. Though variations in percentages of various pebble types occur in the Van Horn, the number of counts made and the geographical area represented by the Van Horn are not sufficient for interpretations of the pattern nor for interpreting the extent of outcrop of the various rock types in the large source area to the north.

SANDSTONE PETROGRAPHY

The Van Horn sandstones are arkoses; the miner-

alogy places them in the arkose and lithic arkose groups in the classifications of McBride (1963) and Folk (1968). Point-counted samples (fig. 33) from throughout the area of outcrop are near the approximate mean composition of 55 percent quartz, 35 percent feldspar, and 10 percent rock fragments.

The various framework constituents are discussed separately below; the data presented are based on point counts of 20 thin sections and examination of 30 additional thin sections.

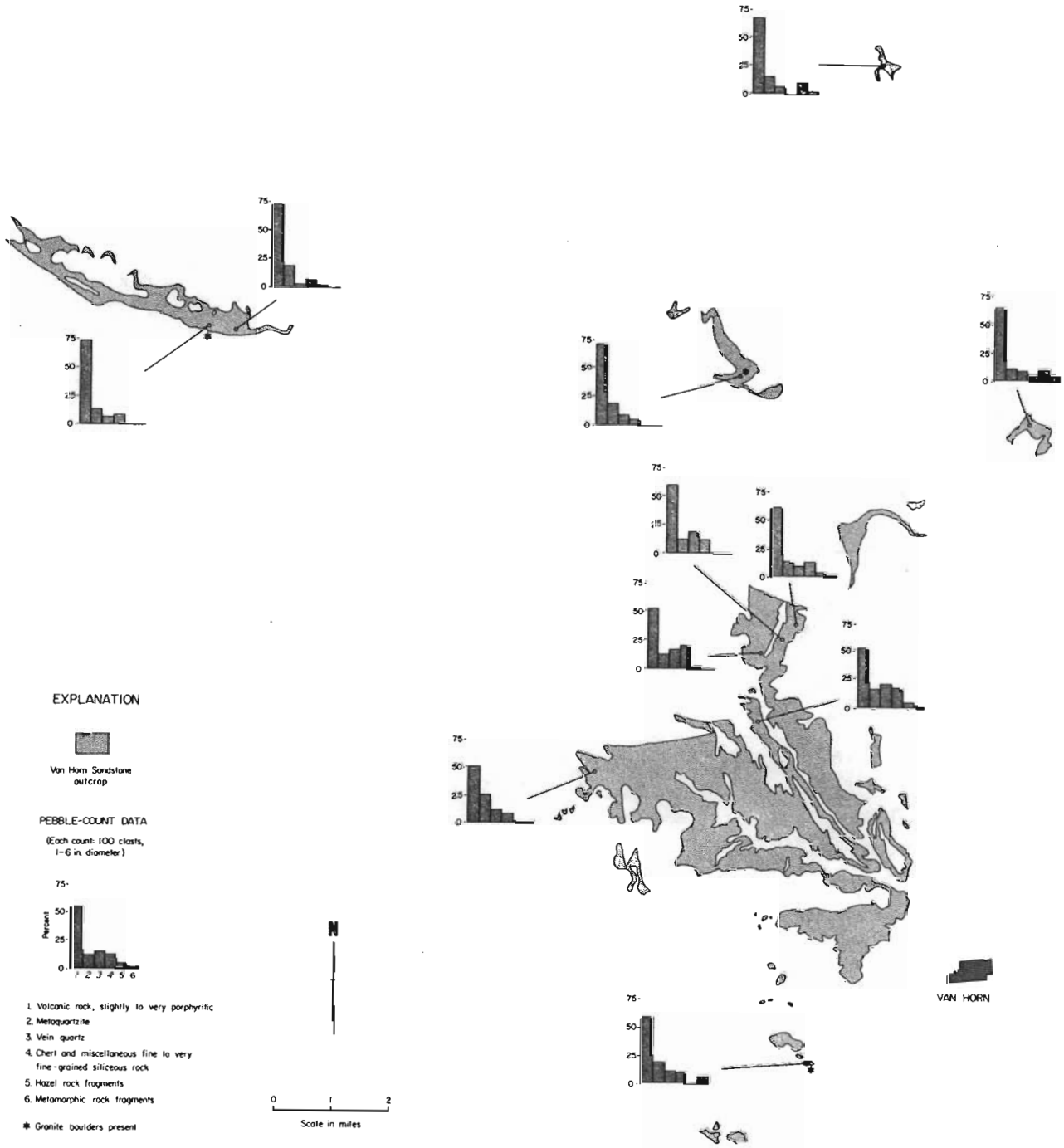

FIG. 32. Composition of gravel in the Van Horn Sandstone.

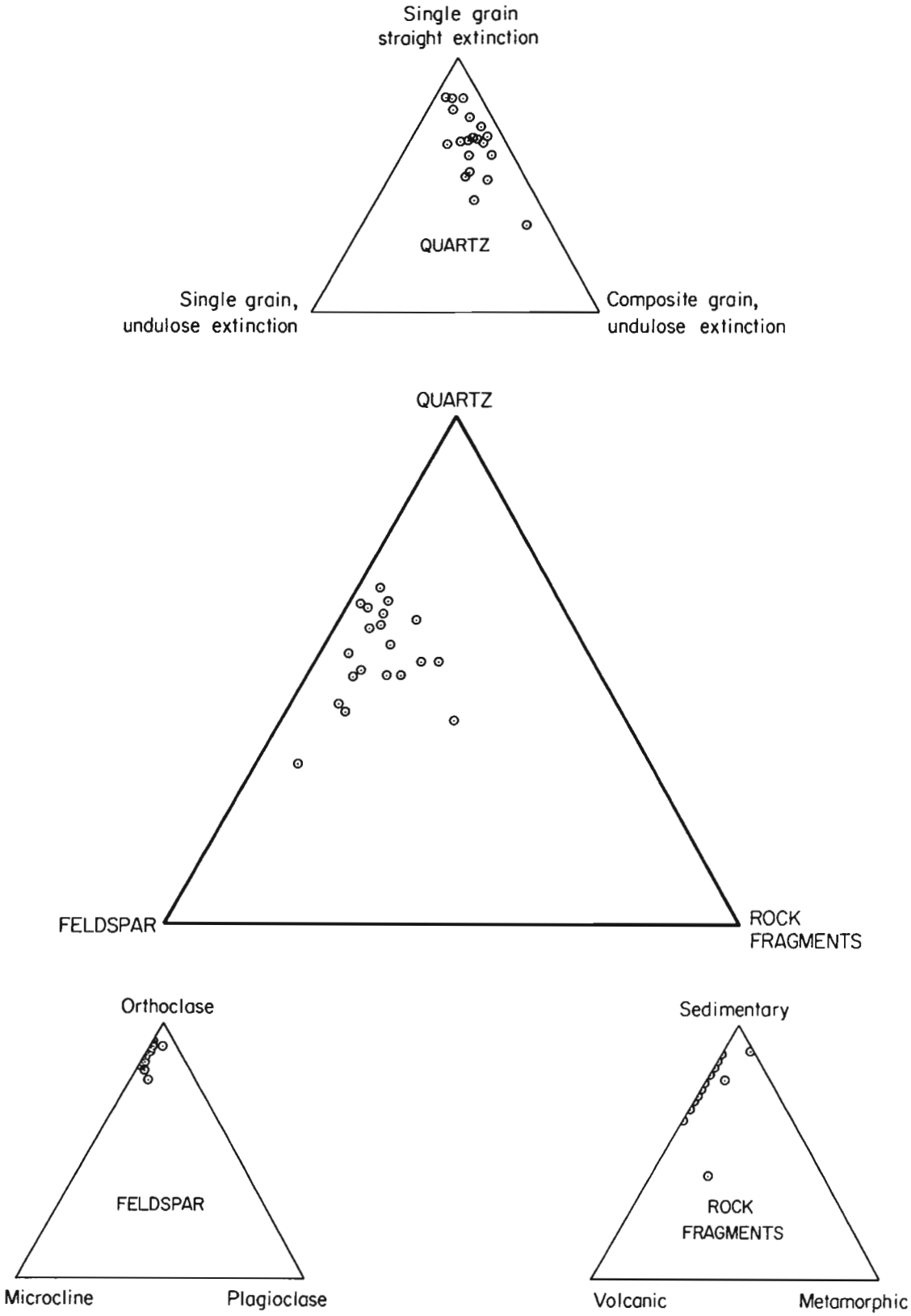

FIG. 33. Composition of the Van Horn Sandstone.

Quartz.--Quartz comprises 30 to 65 percent of the framework grains. Strained and unstrained single grains with few to moderately abundant vacuoles account for 60 to 95 percent of the quartz grains; the majority of these have straight extinction. Elongate, compound, vein quartz grains with abundant vacuoles and slightly undulose extinction constitute up to 30 percent of the quartz grains. Metamorphic quartz is 5 to 40 percent of the quartz; these grains are composite with crenulated or sutured boundaries and undulose extinction. The majority of quartz grains are angular to subangular; a few well-rounded and a few to several subrounded single quartz grains were observed. Two thin sections contain quartz grains with abraded overgrowths.

The angular and subangular metamorphic and vein quartz composite grains are probably first cycle and reflect the presence of metamorphic and igneous rocks in the source area. The single quartz grains indicate an ultimate igneous source for some of the sediment, but the presence of rounded grains suggests that more than one cycle is involved for at least a portion of the clasts.

Feldspar.--Twenty-five to 50 percent of the framework grains are feldspar. Orthoclase is most abundant comprising 80 to 95 percent of the feldspar, and microcline is present in all thin sections examined in amounts ranging from 5 to 20 percent. Plagioclase is present in three thin sections and in these it is less than 7 percent of the total feldspar. Some of the orthoclase is perthite.

As much as 85 percent of the orthoclase is vacuolized, but in most sections examined 45 to 70 percent was altered in this way. Five to 30 percent of the orthoclase is kaolinized or seriticized and 15 to 20 percent is unaltered. In most, 70 to 80 percent of the microcline is vacuolized; however, the range is from 27 to 100 percent; the remainder is unaltered. All the plagioclase observed is vacuolized.

Calcite has preferentially replaced feldspar in many of the sections studied. Hematite, present throughout the rock, tends to be concentrated in vacuolized feldspar, as well as in rock fragments and matrix.

Most feldspar grains are subangular; in a few of the freshest ones cleavage faces are intact and grains are angular to very angular. Some of the larger, vacuolized grains are moderately well rounded and approximately 5 percent of the altered grains are subround.

Rock fragments.--Two to 20 percent of the framework grains are rock fragments. Most of these are sedimentary and volcanic clasts; only three thin sections contain metamorphic rock fragments and they are not abundant. The sedimentary rock fragments, 60 to 100 percent of all rock fragments, are sandstone (quartz arenite) and chert. Sandstone clasts are the most common; they range from fine sandstone to siltstone and from well sorted and clean to poorly sorted and muddy. Quartz grains in the sandstone fragments range from subangular to moderately well rounded. Volcanic rock fragments are aphanitic and porphyritic; they comprise 0 to 40 percent of the total rock fragments.

Rock fragments are commonly the coarsest grains in the sandstone. They are most commonly subround to well rounded. In a few thin sections, squeezed and indented muddy sandstone clasts indicate that some of these fragments are autoclasts. Other sandstone clasts, particularly those with coarser, better rounded grains, are well cemented and were so when deposited.

Hematite.--Hematite is present in most but not all of the Van Horn Sandstone; the amount varies from 0 to 13 percent in point-counted thin sections. Hematite is concentrated in vacuolized feldspars, rock fragments, and matrix, in that order. It replaces feldspar and corrodes the edges of quartz grains in a few places. Hematite is either a cementing agent or a component of the cement in a few thin sections and coats grains in several. The origin of the hematite and stage of diagenesis at which it obtained its present distribution are not completely clear. Ilmenite and magnetite, which are common throughout the rock, show some evidence of alteration to iron oxide; thus some of the iron probably was derived from these heavy minerals. The association of hematite with cement and as a replacement of quartz cement suggests that iron may have been mobile at various stages of diagenesis; there has been sufficient time for a complex history of hematite development.

Cement and matrix.--Hematite or hematite material is the cementing agent in some of the Van Horn Sandstone. The other cements are quartz, calcite, and in two thin sections, chert. Quartz cement comprises 0 to 5 percent of the rock, calcite 0 to 10 percent, and chert 0 to 3 percent. Quartz and calcite cement are present together in several thin sections and in these the calcite has replaced quartz. Cement is a very minor constituent of several thin sections, some of which are tightly packed; others have a matrix binder.

Matrix is 0 to 15 percent of the sandstone; in most samples it is 1 to 5 percent. Matrix material is mud that contains platy sericite flakes oriented around framework grains, indicating flowage during compaction or perhaps orientation by growth of sericite plates during diagenesis.

Provenance.–Rock fragments, like pebble composition, give the most direct evidence of the kinds of rocks exposed in the source area. Sedimentary rock fragments (excluding those that may represent reworked contemporaneous deposits), volcanic rock fragments, and the few metamorphic rock fragments indicate a diverse, mixed terrane. The abundant feldspar reflects the presence of plutonic igneous rocks.

The presence of both altered and fresh feldspar, according to Folk (1968), indicates an uplifted or fault-block igneous terrane of high relief that furnished both fresh feldspar from canyons cut into plutonic rocks and altered feldspar from the weathered zone. This interpretation could be complicated by a condition of deuteric alteration of some feldspars in some parts of the igneous body and none in others. Regardless of the details, the presence of plutonic igneous rock in the source area is strongly indicated.

Quartz grains of diverse origin are present throughout all of the sandstone. Angular grains of definite metamorphic origin (composite, strained, sutured boundaries), angular and subangular vacuolized compound vein quartz, and both angular and rounded simple quartz, like the rock fragments, indicate a diverse terrane. A few well-rounded quartz grains, some with abraded overgrowths, are present in most thin sections. Other single quartz grains are angular to subangular and are probably first-cycle deposits derived from the same igneous rocks that produced the feldspar.

Grain types present in the sandstone, as well as pebble types in conglomerate units, indicate a source area of diverse composition, probably dominated by volcanic and granitic or siliceous plutonic igneous rocks but also including sedimentary rocks, quartzite, and foliated metamorphic rocks. Directional features demonstrate that the source area was to the north. Studies by Denison and Hetherington (1969) delineated a Precambrian terrane complex in eastern New Mexico and northern West Texas that includes extrusive and intrusive igneous rocks dated at 950 my to 1350 my and older, and sedimentary rocks and quartzite dated at 950 to 1000 my. Thus, all the rock types present as clasts in the Van Horn Sandstone and conglomerate are present in a provenance area of similar age that directional features indicate to have been the source.

CLAY MINERALOGY

Clay is not abundant in the Van Horn Sandstone, but matrix material from some of the coarse clastics and fine to very fine sandstones contains some clay in addition to silt. The term "muddy" used herein refers to sediment containing silt and some clay. The rock judged in the field to be the most mud-rich contained 24 percent clay, 25 percent silt, and 51 percent sand; the amount of clay in most fine-grained Van Horn rocks is considerably less.

Twenty-seven samples of the less-than-4-micron fraction from conglomerates, sandstones, and muddy very fine sandstone were analysed by X-ray diffraction. Illite or sericite is present in all samples analysed. The 10Å and 5Å peaks are diagnostic and in most samples they are sharp and distinct, indicating that the mica is well crystallized. Illite is the only clay mineral that is exclusive or strongly dominant in any of the rocks; nine of the samples contain illite with either no other clay mineral evident or only a trace of kaolinite. No clear relationship exists between this dominance and any particular rock texture, mineralogy, or location.

Seven samples of conglomerate, sandstone, and very muddy sandstone contain only kaolinite in addition to illite. The presence of kaolinite is indicated by a sharp 7Å peak and by the absence of any related peaks for spacing greater than 10Å.

The remainder of the samples examined contain illite, kaolinite, and chlorite. Chlorite is indicated by a sharp, moderate to weak 14Å peak and by a stronger 7Å peak that is present in samples lacking chlorite but containing kaolinite. In three of the samples the large-spacing peak is broad and centered nearer 13Å than 14Å, suggesting the presence of mixed-layer clay minerals, perhaps the result of degradation of illite or chlorite by weathering.

The well-crystallized clay minerals in the Van Horn fit the general pattern that Paleozoic and older rocks contain distinct, well-ordered clay minerals. The only relationship between clay-mineral assemblages and texture is that the finest grained rocks analysed contain only illite and kaolinite in the clay fraction. However, this is also true for some of the coarse clastics, and no other tie, such as similar geographic or stratigraphic position, correlates the two rock types; this makes it difficult to consider that this clay-mineral

assemblage is meaningful. The absence of a relationship between clay-mineral assemblages and textural, stratigraphic, and geographic factors is true for all of the Van Horn samples analysed.

HEAVY MINERALS

Heavy minerals were separated from more than 70 samples of conglomerate matrix and sandstone from all facies and at localities throughout the Van Horn outcrop. Representative stratification types of each facies were sampled; samples of heavy mineral placers, or laminae, were also analysed. Only matrix material was collected from conglomerates so that weight percent is based on the less-than-4-mesh fraction of all samples. Separation of heavy from light minerals was accomplished by heavy liquids; heavy minerals were further separated into two groups, ilmenite plus magnetite and miscellaneous nonmagnetic heavies, with a Franz Isodynamic Separator.

Ilmenite and magnetite are the most abundant heavy minerals; with altered ilmenite they comprise more than 95 percent of the heavy mineral fraction. No attempt was made to separate ilmenite from magnetite nor to group the various degrees of altered ilmenite that range from brown grains with slightly translucent rims around opaque centers to lighter colored, leucoxene-like grains. Most of the altered ilmenite is sufficiently ilmenite-like in magnetic susceptibility and morphology to be considered true ilmenite.

Heavy mineral placers occur within sand-size material from each of the Van Horn facies. Heavy mineral concentrations are expressed as parallel laminae of magnetite and ilmenite in thin sand units overlying gravel beds in gravel and gravel and sand sequences, as placers along foresets, and in the bottoms of troughs. Heavy mineral distribution was apparently controlled by the hydraulic regime. A plot of mean size against weight percent of heavy minerals (fig. 34) indicates that the greatest amount of heavy minerals occurs in that part of the Van Horn which had a mean size of coarse sand (0.0 to 1.0 ϕ). Most heavy minerals, then, are the hydraulic equivalents of coarse sand-size quartz, feldspar, and rock fragments.

The heavy mineral suite of the matrix material of the proximal facies consists of magnetite, ilmenite, leucoxene, apatite, zircon, tourmaline, garnet, chloritoid, epidote, rutile, anatase, and hornblende. Leucoxene ranges from a trace to about 15 percent of the magnetic fraction; all gradations of ilmenite alteration are present ranging from ilmenite with brown, translucent rims to white leucoxene. Apatite is, with exception of one sample, the dominant nonmagnetic mineral. Zircon is the second most abundant nonmagnetic mineral and in one sample it is dominant. Thin sections of heavy mineral placers show that magnetite grains commonly have a rind of iron oxide.

The mid-fan facies has mainly the same heavy mineral suite as the proximal facies. Leucoxene, the same types as in the proximal facies, ranges from a trace up to 10 percent of the magnetic fraction. Apatite is the dominant nonmagnetic mineral in all but two samples; anatase is the dominant mineral in one sample and in another zircon is dominant.

Leucoxene consistently comprises 5 to 10 percent of the magnetic fraction of the distal facies. Apatite and zircon are the dominant minerals in the nonmagnetic fraction; apatite is dominant in about 60 percent of the samples; and zircon is dominant in the remainder.

Mudstone and very muddy sandstone associated with each of the Van Horn facies contained magnetite, ilmenite, and leucoxene. Leucoxene, with exception of one sample, comprises less than 5 percent of the magnetic fraction. The nonmagnetic fraction is characterized by a dominance of apatite and zircon and a sporadic occurrence of weathered muscovite and biotite.

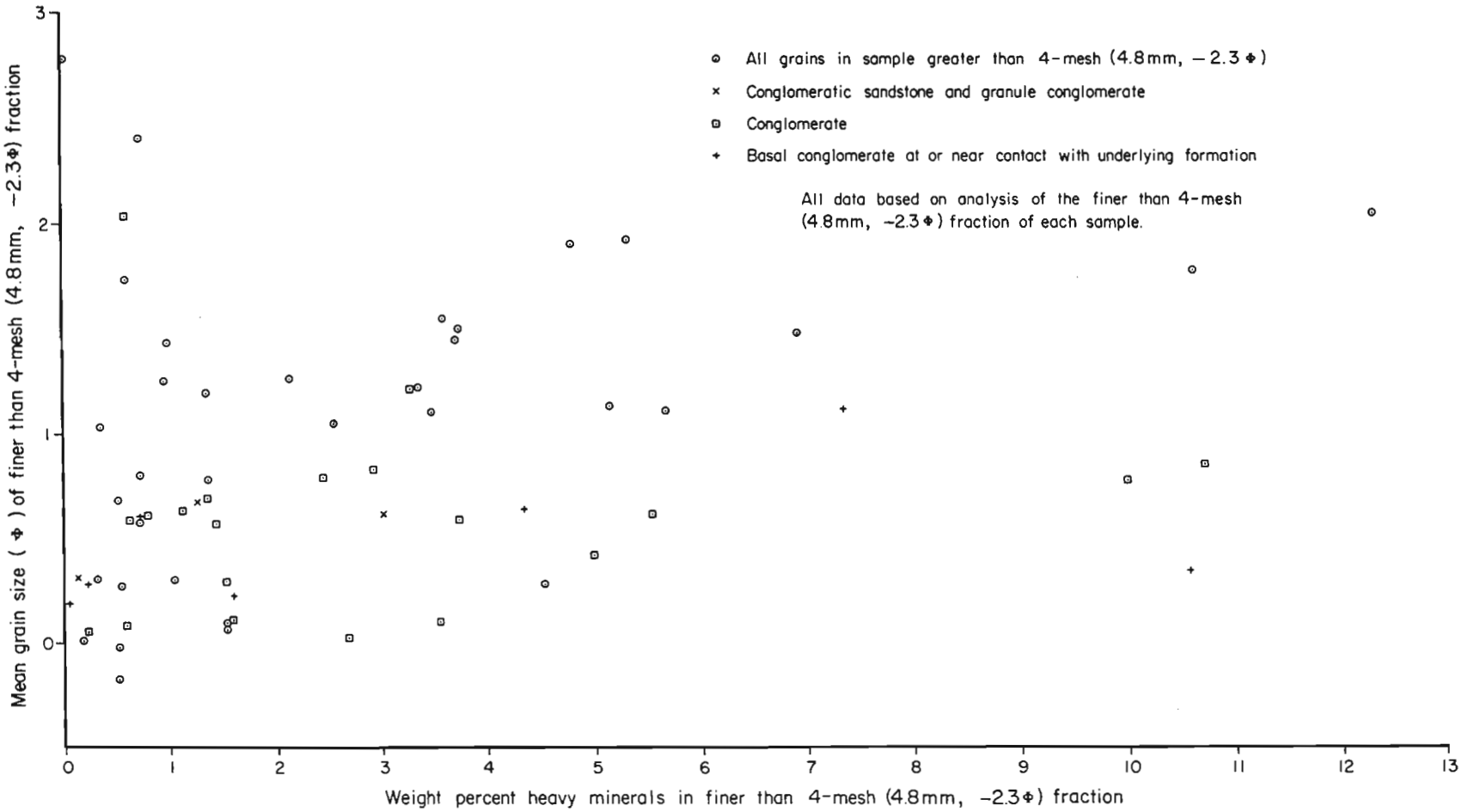

FIG. 34. Plot of mean size vs. weight percent of heavy minerals. Mean size of the sample (ordinate) is plotted against weight percent of heavy minerals (abscissa) contained in that sample.

ECONOMIC GEOLOGY

Economic resources derived from fluvial deposits are diverse--they include sand and gravel, uranium, and a suite of metals extracted from detrital heavy minerals concentrated as placers in various parts of the deposits. Of these heavy minerals and heavy metals, gold has received the greatest attention from prospectors. In the process of searching for gold, technology has developed for the production of other heavy concentrates from alluvial deposits. Important among these are ilmenite (titanium), magnetite (iron), cassiterite (tin), monazite (rare earths and thorium), platinum, and diamonds.

An unconfirmed report of gold in modern stream alluvium near the area of Van Horn outcrop and the abundance of heavy minerals in the sandstone were important factors leading to the present study. Aside from the possible direct economic potential, the investigation was designed to obtain an understanding of heavy mineral distribution in a fluvial complex in order to provide a prospecting model for other similar ancient fluvial systems.

The types of heavy minerals present and the relationship of zones of concentration to particular parts or facies of the Van Horn Sandstone have been previously discussed. Although ilmenite and magnetite are abundant in several sections, the deposits are not presently economic.

GOLD

Seventy-one samples of conglomerate matrix and sandstone from all areas of Van Horn outcrop were analysed for gold by D. A. Schofield, Chemist-in-Charge, and J. T. Etheredge, Chemist, at the Mineral Studies Laboratory of the Bureau of Economic Geology. The analytical technique, cyanide-atomic absorption, is described by Huffman et al. (1967); the limit of detection was 0.05 parts per million. Detectable gold was present in only one sample and the amount was only 0.15 parts per million--far from economic proportions. Other samples from the same area and from similar deposits in other areas yielded no gold.

An effort was made during the sampling program to include samples not only from all geographic areas but also from the types of deposits that have yielded placer gold in other areas. These deposits include the following:

1. Conglomerate at and near the bottoms of channels cut into the underlying Hazel Formation. Deposits of this type have yielded most of the placer gold from Tertiary gravels in California (Clark, 1965; Lindgren, 1911).

2. Sandstone and conglomerate where the concentration of heavy minerals is high. These include the toes of foreset cross strata and especially small troughs in the distal facies where the greatest concentrations of heavy minerals occur. Tertiary placer gold in the once rich California gold fields is always associated with black sands composed mostly of magnetite (Clark, 1965).

3. Matrix material from conglomerates throughout the outcrop area.

The absence of gold in the Van Horn samples can be attributed to at least two factors, one or both of which may be relevant: (1) The terrane from which the Van Horn was derived did not contain significant gold and (2) gold-bearing parts of the formation were not sampled or are not exposed.

Pebble counts and sandstone petrography indicate a source terrane composed predominantly of granitic and volcanic rocks with lesser amounts of metaquartzite, which may have been reworked from older rocks, and sedimentary rocks. The relation of placer gold to metamorphic terranes and to gravels in which metamorphic rocks are a significant constituent has been well documented by Lindgren (1911) and by Bateman and Wahrhaftig (1966). Lindgren stressed that in the California gold-bearing gravels gold occurs only in gravels in which quartz and metamorphic rocks are principal components. He also indicated that granitic terranes were barren except near contacts with metamorphic rocks. Thus, the composition of the source terrane may have been an important factor in the absence of gold from the Van Horn.

The possibility that gold is present in deposits that are not exposed is worthy of consideration, because the absence of metamorphic rocks in the gravel, for example, may be related to the lack of preservation of the more proximal parts of the fluvial deposits where these relatively fragile clasts would be most likely to be found. The Van Horn fan complex was a very large system of which only a small portion is preserved in outcrop; the amount of very coarse, proximal gravel that was present between present outcrop areas and the source area may have been large. Likewise, the present outcrop of the basal part of the Van Horn is limited in extent; it may be that the deepest part of the canyon system is beneath the surface or has been eroded from upthrown fault blocks in another area, removing the most suitable sites for placer gold.

PROSPECTING MODEL

Although heavy minerals of commercial value were not found in the Van Horn Sandstone, an outgrowth of this study was the recognition of the association of heavy mineral concentration with facies of the distal fan. From this association it is possible to construct an alluvial-fan model depicting areas favorable for heavy mineral accumulation that can be applied to rocks similar to the Van Horn Sandstone.

Heavy minerals occur throughout the Van Horn Sandstone but are concentrated in the distal-fan facies where grain size is dominantly coarse sand and where sedimentation units are thin. There is also a close association between opaque, heavy mineral placers and trough crossbeds. Concentration of heavy minerals in the distal fan, particularly in that part of the facies dominated by trough crossbeds, is explained by a process-defined model (fig. 35, A and B).

Whereas physical energy, grain size, and scale of sedimentation units all decrease in a downfan direction (fig. 35, B), heavy mineral concentrations increase downfan.

Smith (1970), in a study of modern and ancient braided stream deposits, demonstrated that there is a downstream succession of bar types. In the proximal (upstream) reaches where grain size is at a maximum, longitudinal (gravel) bars are dominant. These decrease in abundance downstream, and transverse bars become more numerous until in distal (most downstream) reaches transverse bars are the dominant bar types. Longitudinal bars, studied by Smith, consist mostly of gravel with varying admixtures of sand and finer materials and are characterized by horizontal stratification; transverse bars are chiefly sand and display planar crossbedding (foreset crossbeds of this report). Although scour troughs, and hence trough crossbedding, were observed by Smith, he could not detect any preferred occurrence of these features with a particular position along the river.

In order to develop this model, it is necessary to consider the Van Horn alluvial fan during a single depositional episode and to consider the characteristics of braided streams described above. Figure 31 shows the fan in cross section and plan during one of these events.

Maximum depth of flow was in the canyon cut into the uplands; flow was rapid, confined, and surging (fig. 35, B). This was the area of most intense physical energy, very much like that of the Rubicon River (Scott and Gravlee, 1968), and, therefore, the site of gravel accumulation. Because flow was rapid and confined, most of the finer particles (sand and smaller gravel) were transported high in the water column and moved through the canyon onto the piedmont to the south. Under flow conditions that prevailed in the canyons there was little opportunity for segregation of grain sizes or compositions, hence most of the heavy minerals that accumulated in this area were randomly distributed through the gravel body.

As the canyon opened out to the south, flow was less confined and depth of flow and slope of the water surface decreased (fig. 35, B). Here, flow was still rapid but unconfined and not surging; the intensity of the fluvial process decreased as flow was distributed over a much larger area. Grain-size segregation increased in this segment of the fan and two principal textural types, that were temporally distinct, occur here. Gravel accumulated as longitudinal bars during the flood crest, and sand accumulated during waning stages of flow in lows flanking the elongate gravel bodies, chiefly as transverse bars of coarse sand to granule gravel; some scour troughs developed contemporaneously with these bars (*see* Harms and Fahnestock, 1965). There was little opportunity for heavy minerals to be concentrated in this fan segment; however, a few heavy mineral concentrations developed along steeper avalanche faces of some transverse bars and in some scour troughs.

Farther downfan depth of flow diminished and the slope of the water and fan surfaces decreased even more. In this area flow was tranquil and unconfined (fig. 35, B). This was an area of least intense fluvial activity; velocity decreased as flow was spread over a very large area. Bed forms here are predominantly transverse bars and dunes. Along the most distal parts of the braided stream complex, where depth of flow was extremely shallow, overbanking occurred (fig. 35, A). Some of the finest material in the fan accumulated lateral to the distal braided stream; here dune-bed forms were the smallest of any associated with the Van Horn. Depth of flow was extremely shallow, and there was sufficient time for heavy minerals to be segregated from other terrigenous material. Along the most distal segments of the fan, where both transverse bars and dunes developed simultaneously, there was an increase in dune bed forms. Heavy minerals were concentrated along slip faces

of dunes.

Heavy-mineral laminae in trough crossbeds provide the greatest concentrations of heavy minerals in the Van Horn Sandstone. The model (fig. 35, A) shows in plan areas that are favorable for development of dunes; trough crossbeds, the stratification type produced by migrating dunes, are guides to heavy mineral concentrates rather than heavy minerals themselves. Areas favorable for maximum development of dunes are (1) where adjacent fans coalesce (fig. 35, A, 1), (2) where depth of flow in distal braided streams is extremely shallow and overbanking occurs (fig. 35, A, 2), and (3) near the distal part of the fan where flow is shallow yet con-

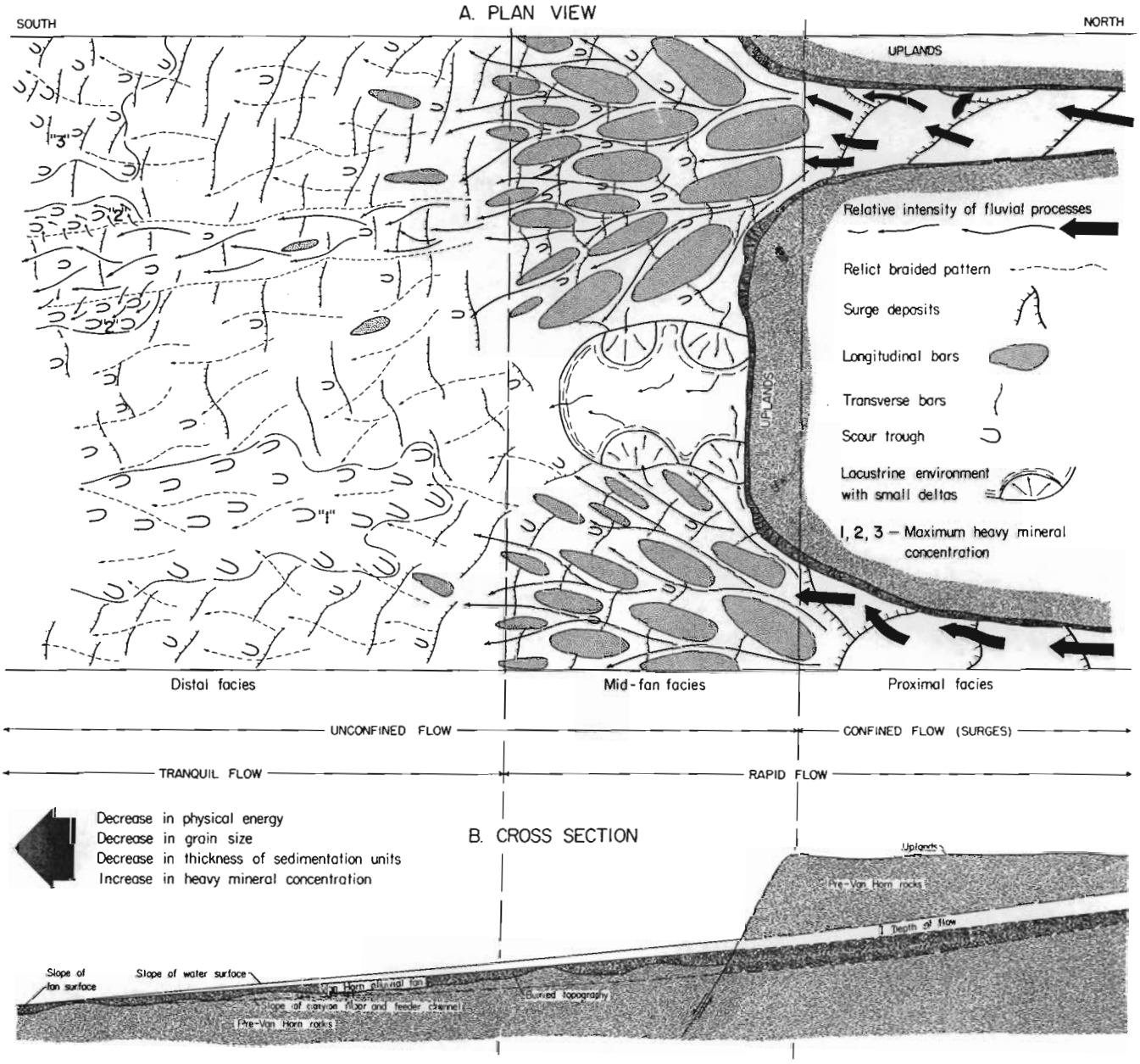

FIG. 35. Alluvial fan prospecting model.

fined to a definite channel (fig. 35, A, 3). Sequences of trough crossbedded sand are thickest in area 1 (fig. 35, A), and areas such as this should yield the largest quantity of heavy minerals. The next largest volume of sediment composed of trough crossbeds is area 2 (fig. 35, A) where cosets of trough-crossbedded sand are 1 to 4 feet thick and are interbedded with muddy sand units a few inches to 1 foot thick. The least favorable area (fig. 35, A, 3) occurs where both transverse bars and dunes developed. The ratio of these two features is variable and trough crossbeds may be either sparse or abundant.

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APPENDIX

BED FORMS AND STRATIFICATION TYPES

As defined (Middleton, 1965, p. 247), bed form is "any deviation from a flat bed, generated by flow on the bed of an alluvial channel." Bed forms include features of small magnitude, such as ripples, as well as larger features, such as bars.

Stratification types, their thickness, and the geometry of sedimentation units within the Van Horn Sandstone indicate the following bed forms were present during deposition of the Van Horn: longitudinal gravel bars, transverse gravel and sand bars, dunes, plane beds, and ripples.

Longitudinal bars are elongate depositional features with their axes aligned along the channel in the direction of flow (Ore, 1963). Stratification of these bars is predominantly parallel bedding, but foreset crossbedding may occur at the distal and lateral parts of the bar. Longitudinal bars in the Van Horn are composed of gravel.

Transverse bars are continuous-crested features with crests oriented across the channel perpendicular to flow direction. These bars occupy nearly the full channel width. They occur both as isolated and periodic forms along a channel and move downstream (Kennedy et al., 1966). Steep avalanche faces, often at the angle of repose, mark the downstream terminus of a bar. Internally these bars consist of one or more types of foreset crossbeds.

Dunes are bed forms smaller than bars but larger than ripples that are out of phase with any water surface gravity waves that accompany them. Dunes generally occur at larger velocities and sediment transport rates than do ripples. The large lee eddies that occur in dune troughs often cause surface boils of intense turbulence and high-sediment concentration to occur above and slightly downstream from dune crests (Kennedy et al., 1966). Stratification produced by dunes is trough crossbedding.

Ripples are small bed forms with wave length less than approximately 1 foot and heights less than approximately 0.1 foot. Ripples occur at flow velocities slightly higher than those required for initiation of sediment motion. Crests of ripples may be discontinuous or continuous. Stratification produced by ripples is small-scale crossbeds; these are termed small trough sets by Harms and Fahnestock (1965). Ripples rarely occur in sediment coarser than 0.6 mm (Kennedy et al., 1966), and small trough sets are rare in the Van Horn Sandstone.

Plane bed is a surface devoid of bed forms. Stratification produced by a plane bed is parallel bedding in gravels or parallel laminae in sands.

The term flow rēgimē is not employed in this paper because as initially defined it was restricted to bed forms comprised of medium sand; in the Van Horn grain size ranges from coarse sand to boulders. Within the Van Horn there are foreset-crossbedded gravel deposits that, in terms of flow rēgimē, are the products of lower flow rēgimē, yet these deposits are capped by coarse sand (deposited during the same depositional event but during waning flood stage) that is parallel laminated and therefore indicative of upper flow regime conditions. There is no doubt that a greater amount of physical energy was expended during deposition of gravel than was expended during deposition of the sand; therefore, to speak of the gravel as a lower flow rēgimē deposit and the sand as an upper flow rēgimē deposit is confusing.

Common primary sedimentary structures are enumerated below under a dominantly gravel and a dominantly sand textural type. Sedimentary structures of the Van Horn Sandstone are mostly large scale, and some of the characteristics of gravel deposits, for example, graded bedding, may occur vertically through a few or several tens of feet.

(A) Massive boulder gravel. Clasts are aligned approximately parallel to current, and a few clasts are inclined upcurrent. Smaller clasts at the base of the massive boulder bed represent sediment deposited during rising flood stage.

(B) Graded gravel deposit; boulders at base grading to cobbles upward. Graded beds are up to 40 feet thick in the proximal facies. Grading is normally the upward-fining type; however, there are gravel deposits in the Van Horn that are fine at the base and become coarser grained upward.

(C) Gravel and sand representing sediment that accumulated as longitudinal and transverse bars (large bed forms) are characteristic of the proximal and mid-fan facies. Longitudinal gravel bars are parallel bedded; individual bars can be distinguished because there commonly is a thin sand unit marking the top of the bar. Some channels adjacent to longitudinal bars are filled with sand that accumulated as transverse bars. Scour channels, such as the one shown at the base of the diagram (fig. 36), are relatively narrow and deep.

(D) Thick gravel foresets are present in the proximal facies; these are most common near the upper part of the facies. Foresets of this scale, up to 10 feet, represent lateral

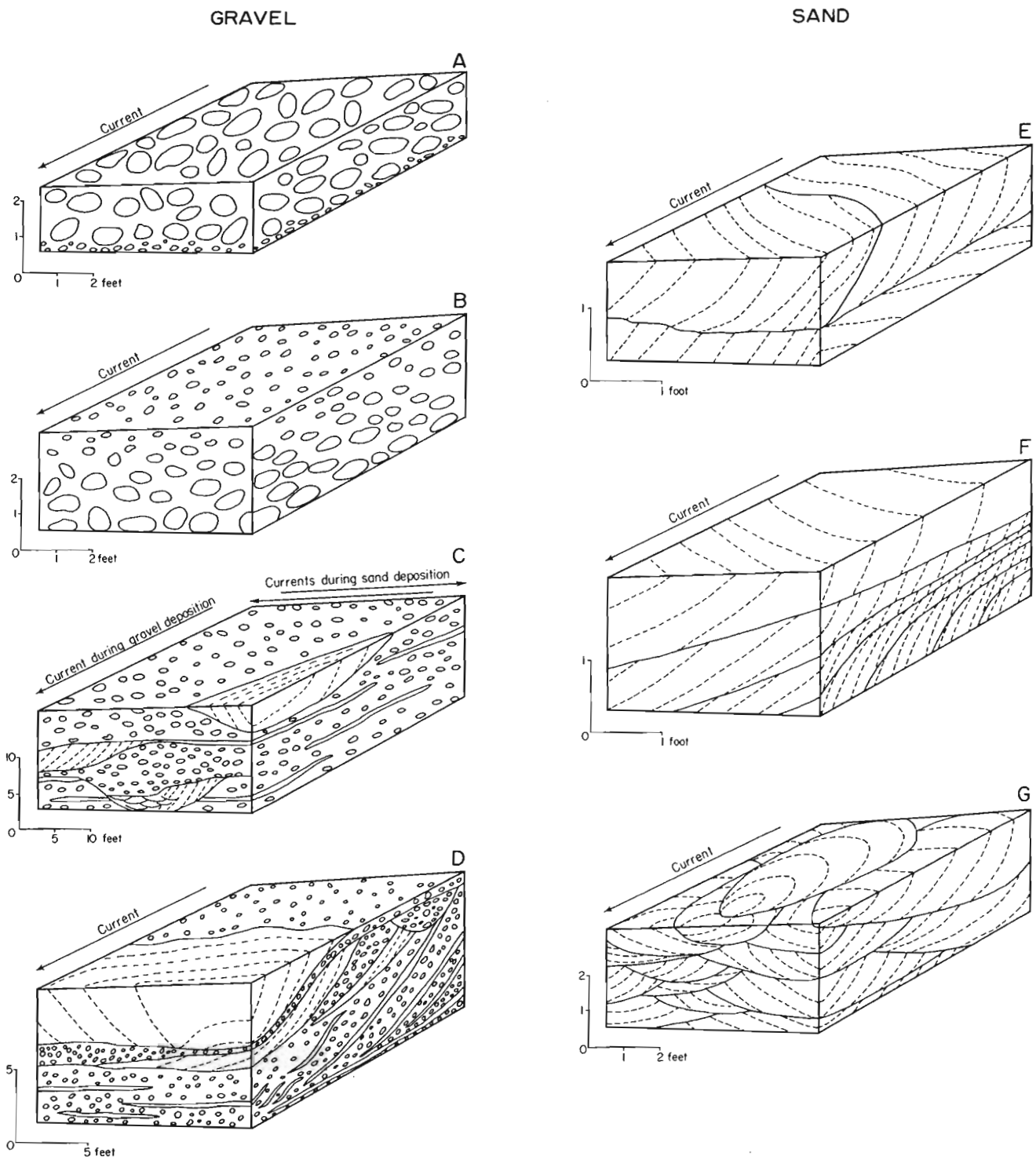

FIG. 36. Characteristic bed forms and stratification types in the Van Horn Sandstone.

accretion of longitudinal gravel bars into flanking channels. Several depositional events account for these deposits; this is shown by the alternating gravel and sand units. A single gravel foreset unit is commonly coarser near the top and becomes finer grained toward the toe. During its development, a longitudinal bar may be scoured along its crest by transverse currents; gravel filling the scour in the upper right of figure 36 represents fill of one of these transverse channels. The lateral channel was ultimately filled by sand moving downcurrent as a transverse bar (foreset crossbeds).

(E) Foreset crossbedded sand represents stratification produced by particles avalanching down the slip face of a transverse bar. Some foresets, such as those of the lowermost sedimentation unit, have high-angle upper and lower contacts; these represent relatively low velocity flow conditions, allowing sand to move down the slip face under the influence of gravity. With increased velocity some grains are carried in suspension short distances beyond the slip face; under these conditions foresets are built by suspension load plus gravity sliding, and the angle of foresets decreases; for example, the sedimentation unit in the upper right of figure 36.

(F) Compound foresets. In a direction parallel to flow, the upcurrent part of a sedimentation unit is a thin simple foreset unit with high-angle upper and lower contacts. Simple foreset units thicken downcurrent, and the bounding surfaces become inclined and convex upward. In a direction transverse to flow, sedimentation units tend to become wedge shaped. A simple foreset unit overlies the compound sequence.

(G) Trough crossbedded sand results from the fill of spoon-shaped scour features created in the lee of migrating dunes. Laminae of these crossbedded sands conform to the shape of the scour. Trough crossbeds may be symmetrical (flow parallel to trough elongation) or asymmetrical (flow at an angle to trough elongation).