SEDIMENTOLOGIC AND STRATIGRAPHIC ANALYSIS OF THE POINT LOOKOUT SANDSTONE, SOUTHEAST SAN JUAN BASIN, NEW MEXICO

by

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In memory of my nephew,

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ABSTRACT

Detailed outcrop investigations of the Point Lookout Sandstone and adjacent parts of the underlying marine Mancos Shale and overlying continental Menefee Formation were conducted along the southeastern portion of the San Juan Basin, northwestern New Mexico. Units are described, five facies recognized and their environments of deposition interpreted on the basis of sedimentary-unit geometry, sedimentary structures, texture, mineralogy, and paleontology.

The lowest facies, regarded as a portion of the Mancos Shale, consists of thinly bedded, lenticular to moderately tabular, fossil-bearing, very fine grained, silty sandstones and interbedded brownish black to gray, fissile, generally silty shales. Sedimentary structures are dominantly subhorizontal lamination, small scale cross-lamination (mostly tabular and few undulatory or hummocky type), very poorly preserved small ripple marks, and abundant bioturbation. It represents a beach-offshore transition zone.

The next three facies comprise the Point Lookout Sandstone and their aggregate thickness varies from 23.5 to 65.5 meters. The lowest of these three facies, Facies B, consists of an upward coarsening sequence of very fine to fine grained, moderately sorted, laminated and cross-laminated to structureless, burrowed, and fossil-bearing sandstones either stacked vertically or separated by thin breaks of silty

shales. Sedimentary structures are dominated by small scale, shallow trough cross-stratification, some tabular cross-stratification, and megaripples. It contains the densest and most diverse fauna within the Point Lookout Sandstone. It was deposited in the shoreface environment.

The next facies of the Point Lookout Sandstone, Facies C, consists of massive and thin to medium well bedded, fine grained, moderately well sorted, moderately burrowed, sheet sandstones. It is characterized by subhorizontal stratification and/or low angle planar cross-stratification with relatively uniform, gently dipping interlaminae. Macroinvertebrates are very sparse but Ophiomorpha burrows are ubiquitous. It was deposited in the upper beach (foreshore-backshore) complex.

The upper facies of the Point Lookout Sandstone, Facies D, consists of very thick, fossil-barren, fine to medium grained, moderately well sorted sandstones with large scale wedge to trough cross-stratification. It contains carbonaceous debris, locally lignitic fragments, Teredo borings, and small to large mud clasts. It represents an estuarine-beach complex.

The upper facies, Facies E, regarded as a portion of the Menefee Formation, consists of variegated units of carbonaceous mudstone, organic-rich shale to humates, coal lenses, carbonaceous rooted muddy sandstones, and lenticular, thick to very thick, medium grained sandstones with large scale high angle wedge to trough cross-stratification. This variegated sequence represents a nonmarine coastal complex, where bay, lagoon, swamp, and fluvial subenvironments develop.

The prograding Point Lookout shoreline was developed due to a relatively balanced interrelationship between low to moderate energy coastal regime to the north-northeast and a steady supply of sediment from the southwest through small rivers across low-lying coastal plains characterized by humid conditions. Several lines of evidence indicate that the general trend of the Point Lookout paleoshoreline was northwest-southeast. The sequence of facies, and their diagnostic characteristics in the Point Lookout sequence correlate moderately well with those in some modern prograding shorelines, e.g., the Texas coast of the Gulf of Mexico.

The Point Lookout Sandstone exhibits adequate characteristics of a reservoir rock; production of hydrocarbons, mainly gas, has been established in several places. Its association with humate and coal-bearing units makes the understanding of its nature and distribution of great importance.

INTRODUCTION

General

The primary purpose of this study is to describe and interpret the stratigraphy and depositional environments of the Point Lookout Sandstone, Late Cretaceous, in the southeastern part of the San Juan Basin, northwestern New Mexico. The Point Lookout Sandstone comprises the lower unit of the Mesaverde Group, which consists, in ascending order, of: the Point Lookout Sandstone, Menefee Formation, and the Cliff House Sandstone, throughout most of the San Juan Basin. The Late Cretaceous sequence of the San Juan Basin is characterized by an alternation of transgressive and regressive intervals. The interval including the upper part of the marine Mancos Shale, the Point Lookout Sandstone, and the lower part of the coal-bearing Menefee Formation represents a major, well developed regressive sequence; this sequence is referred to as the Point Lookout sequence in this report.

In addition to providing a detailed description of stratigraphy, sedimentary structures, petrography and fossil content of the Point Lookout Sandstone, the objectives of the study are: 1) to establish and characterize depositional environments, and subenvironments within the Point Lookout sequence; and 2) to develop a model for deposition of the upper Mancos-Point Lookout-lower Menefee regressive sequence. The basic method used is detailed analyses of sedimentary-unit geometry, sedimentary structures, texture, mineralogy, and paleontology in surface stratigraphic sections of the Point Lookout Sandstone and associated portions of the adjacent units. The measured stratigraphic sections were selected at appropriate intervals along a trend generally perpendicular to depositional strike.

Although the regional stratigraphic relations of units in the Mesaverde Group are reasonably well known from surface mapping and subsurface oil and gas exploration, no detailed study of the petrology and sedimentology of the Point Lookout Sandstone has been published. A detailed study of the well developed and well exposed Point Lookout sequence is a great contribution to the understanding of ancient regressive sands which comprise an important type of sediment but have received little attention because of their relatively limited distribution in the sedimentary record.

This study, together with the work of Wallace (in progress) on the Menefee Formation and Mannhard (1976) on the La Ventana Tongue of the Cliff House Sandstone in the La Ventana area, provide a comprehensive detailed investigation of the Mesaverde Group in the southeastern San Juan Basin.

Location and Accessibility

The study was concentrated in the southeastern part of the San Juan Basin, mainly in the area between San Luis, Sandoval County, and Llaves, Rio Arriba County northwestern

New Mexico, U.S.A. The general location of the study area and the regional distribution of the Point Lookout Sandstone are shown in Figure 1, and the location of the measured stratigraphic sections is shown in Plate 1. The trend along the southeastern side of the San Juan Basin was chosen because 1) the Point Lookout and adjacent units outcrop fairly continuously with good exposure along this trend, 2) it is generally perpendicular to the strandline, and 3) no detailed surface work of the Point Lookout Sandstone has been done in this area.

The Point Lookout Sandstone forms the front cliffs and steep slopes of a series of northeast-southwest trending, northwest tilted cuestas and hogbacks formed by the sandstones of the Mesaverde Group. The thick Mancos Shale sequence forms low-lying surfaces below the Point Lookout resistant sandstones, and the Lewis Shale also forms low-lying surfaces above the resistant Cliff House sandstones. Exposures of the Point Lookout Sandstone, and the Mesaverde Group in general, are good due to relatively sparse vegetation. Relief in the area is generally less that 213 meters, with elevation ranging from 2390 to 1884 meters in the area occupied by the Mancos Formation and Mesaverde Group. The Rio Puerco, the major drainage in the southern part of the study area south of Cuba, N.M., flows south-southeastward; flow is generally very low, sometimes almost nonexistent, except after intense summer thunderstorms. The San Juan Basin area is in general arid, receiving less than 10 inches of precipi-

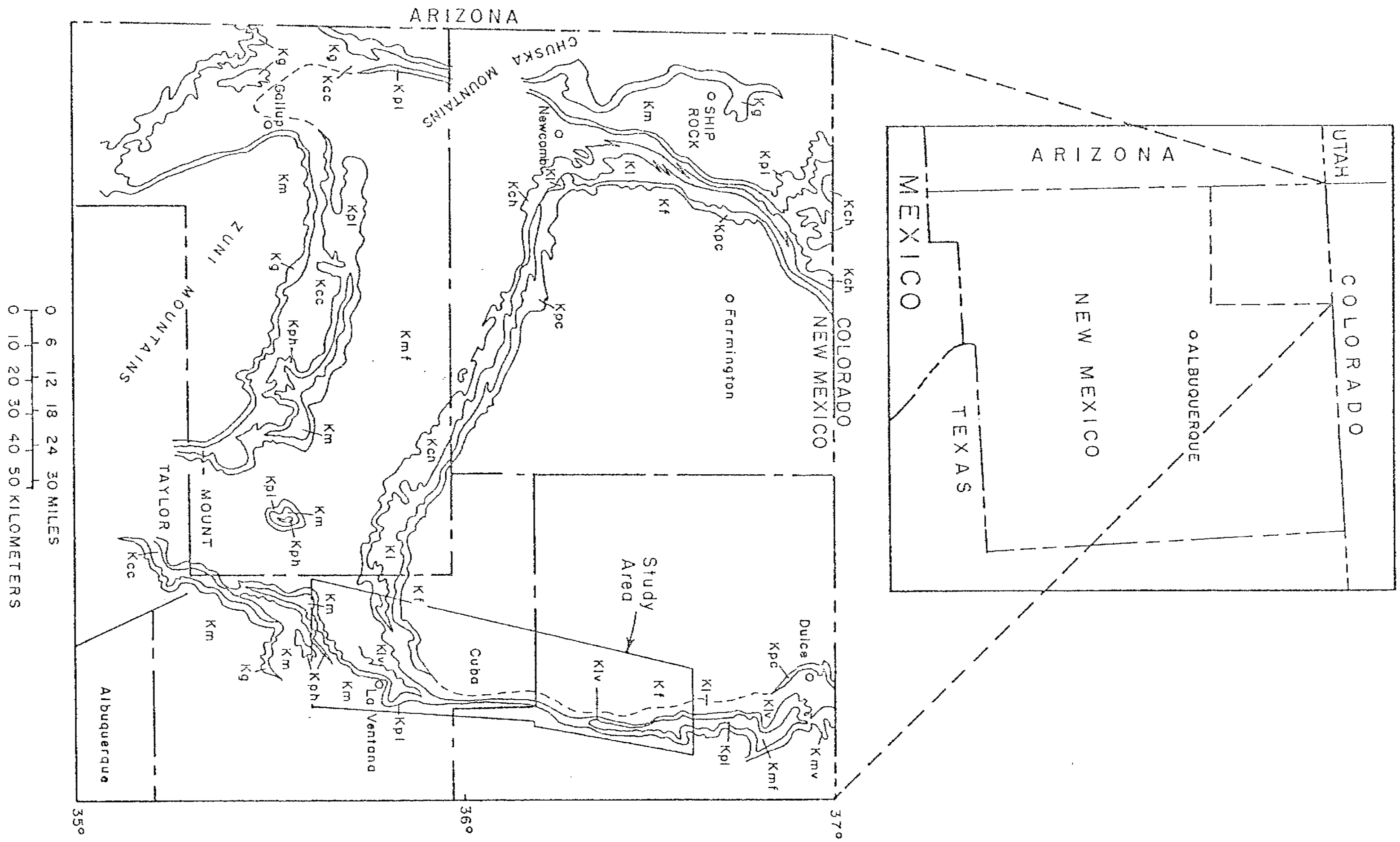

Figure 1. Map showing approximate location of study area, and outcrops of the Point Lookout Sandstone and other Upper Cretaceous units. Kf-Fruitland Formation and equivalent and younger beds; Kpc-Pictured Cliffs Sandstone; Kl-Lewis Shale; Kmv-Mesaverde Group undivided; Kch-Cliff House Sandstone, with La Ventana Tongue (Klv); Kmf-Menefee Formation; Kpl-Point Lookout Sandstone, with Hosta Tongue (Kph); Kcc-Crevasse Canyon Formation; Kg-Gallup Sandstone; Km-Mancos Shale and older rocks. Geologic map after Beaumont, Dane and Sears,(1956).

tation annually (Shomaker and others, 1971). But the eastern and southern parts, which include the study area, receive 12 to 16 inches, and the nearby higher areas to the east receive more than 20 inches of annual precipitation (Shomaker and others, 1971). Snowfall occurs during late autumn and wintertime; late afternoon showers and thunderstorms occur during summer and early autumn.

N.M. Hwy. 44, the old portions of highway 44 north of La Ventana, N.M., Hwy. 96, and N.M. Hwy. 112 are the major roads through the area. Several dirt and four-wheel drive roads exist throughout the area across the low-lying surfaces on the Mancos Shale. The Point Lookout Sandstone outcrops are generally easily accessible through the abundant dirt roads; however, the combination of wet conditions and the shale substrate make passage through those roads difficult.

Cuba is the major town in the area. The southern part of the area south of Cuba is sparsely populated. To the north, a few villages exist along N.M. Hwy. 96 and N.M. Hwy. 112, and more ranches are spread throughout much of the area north of Cuba, N.M. Land in the area is controlled partly by the Bureau of Land Management, and partly by private owners who use it mainly for ranching purposes.

General Geologic Setting

General structure of the San Juan Basin

The San Juan Basin is located in the southeastern part of the Colorado Plateau; it is mainly in northwestern New

Mexico and extends into southwestern Colorado (Figure 2). The structural aspects of the San Juan Basin have been described by Kelley (1950, 1951, and 1957). The central portion of the San Juan Basin is a roughly circular depression about 160 kilometers in diameter (Kelley, 1957); but the overall area that is usually referred to as the San Juan Basin extends east-west for about 217 kilometers and north-south for about 289 kilometers (Baltz, 1967). The central plains of the basin are underlain by almost horizontal strata (Shomaker and others, 1971). The basin is bounded on the east by the Nacimiento uplift and Archuleta arch, which includes the monoclines and anticlines north of the Nacimiento uplift; on the north by the San Juan uplift; on the west by the Hogback monocline and the Four Corners platform; on the south the Chaco slope forms an indistinct border, and the basin is commonly considered to extend to the more pronounced borders at the Zuni and Defiance uplifts. The monoclines, or hogback ridges, are the most striking structural features of the basin. They are generally continuous around the northwestern, northern, and eastern rims of the basin. The monoclines are caused by steep dips of the strata on the outer, basinward limbs of anticlines and the accompanying inner synclinal bends (Shomaker and others, 1971). The average structural relief is nearly 1524 meters; but against the Nacimiento uplift, it is about 4268 meters and reaches about 6098 meters against the San Juan dome to the north (Kelley, 1957).

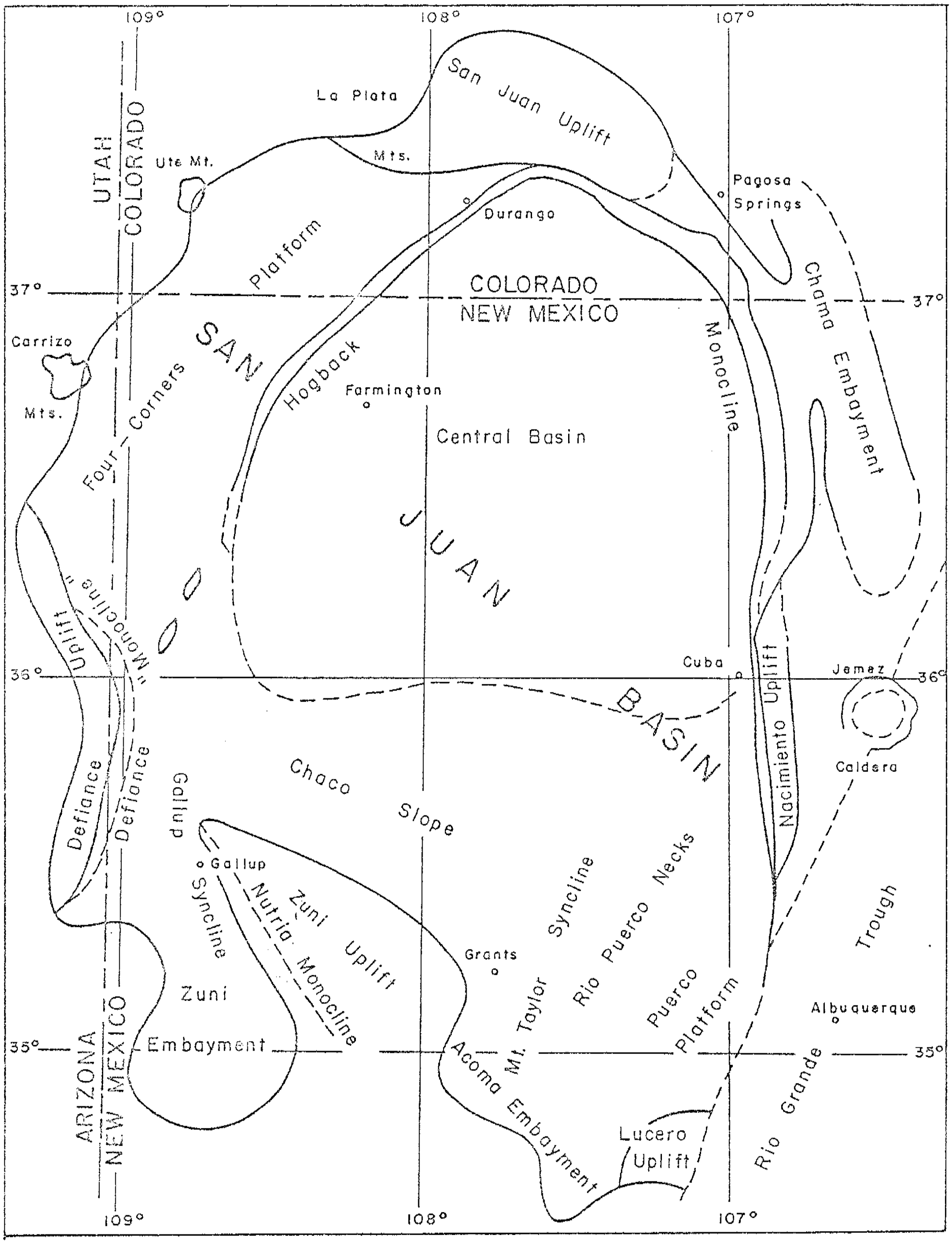

Figure 2. Structural elements of the San Juan Basin (modified from Kelley, 1950).

The tectonic evolution of the San Juan Basin might have begun earlier, but the present structural features, including domal uplifts, platforms, and monoclines, are mainly Laramide features (Kelley, 1950, 1951, and 1957; Woodward, 1974). The basin was mostly a byproduct of surrounding positive deformations, especially of the uplifts (Kelley, 1957).

The study area is part of the monocline along the southeastern rim of the basin where spectacular exposures of the Point Lookout and adjacent units occur in hogback ridges. The structural dip of the Point Lookout Sandstone ranges from only a few degrees at San Luis (measured stratigraphic section No. 7), but northward as the outcrop approaches the Nacimiento uplift, the dip increases to essentially vertical near the village of San Pablo, then declines again north of N.M. Hwy. 96 from Regina to Gallina where it is about 23° at measured stratigraphic section No. 5. Structural complexity and denser vegetation in the vicinity of the town of Cuba make measurement of a detailed stratigraphic section impractical.

The study area was mapped by Wood and Northrop (1946). Also Woodward and others mapped the La Ventana Quadrangle (Woodward and Schumacher, 1973), the San Pablo Quadrangle (Woodward, *et al.*,1973), and the Cuba Quadrangle (Woodward, *et al.*,1972). Despite the recentness of Woodward's and his coworkers' geologic mapping, they did not upgrade the stratigraphic detail of the Mesaverde Group; for example, north of Cuba they lumped units in the Mesaverde together, in spite of the fact the individual units, especially the Point Lookout Sandstone and Menefee Formation, maintain significant, certainly mappable, thicknesses. Also, placement of the Point Lookout Sandstone was imprecise in some places, probably due to lack of consideration of its transition and intertonguing relationship with adjacent units.

General stratigraphy of the San Juan Basin

General

The stratigraphy of the San Juan Basin, especially the Upper Cretaceous Series, is a complex, but very significant topic. The complexity of the Upper Cretaceous Series of the San Juan Basin resulted from the interplay between a shallow seaway in the northeast and supply of clastic sediment from the southwest across a low-relief area; Fassett (1974) described the San Juan Basin as being in the SCI-SWO ("sea came in, sea went out") zone. Such a depositional setting resulted in the development of a great sequence of marine shales and siltstones, marine and coastal barrier sandstones, and nonmarine deposits, with numerous intertonguing and lateral intermingling of sedimentary units and subunits. The significance of the Late Cretaceous stratigraphy of the San Juan Basin lies in: 1) preservation of an almost complete Upper Cretaceous section with excellent examples of regressive and transgressive deposits; and 2) its economic importance, especially for oil and gas, and coal.

Although the San Juan Basin is one of the most studied areas, due to its geologic and economic significance, its stratigraphic and sedimentologic aspects remain open for more detailed work. The complexity of its stratigraphy, especially in the southern part, and the different interests among the San Juan Basin workers lead to near confusion in terminology, especially at the member level. Figure 3 illustrates the time-stratigraphic nomenclature of the San Juan Basin units. This chart shows an up-to-date balanced summary of the Cretaceous stratigraphy of the San Juan Basin. It presents the stratigraphy and depositional history in a time sense without confinements of stratigraphic thicknesses.

Regional depositional setting

During Late Cretaceous time, the sea advanced to the present San Juan Basin area (Beaumont and Read, 1950 ; Silver, 1950), and this major transgression was recorded by the thick, widespread marine Mancos Shale sequence. The interplay between clastic sediment supply from the west and southwest (Beaumont and Read, 1950; Molenaar, 1977) and the shallow sea resulted in few major oscillations of the strandline which led to the development of the major stratigraphic units that form the thick Upper Cretaceous sequence, and in several other minor retreats and advances that resulted in the intertonguing and lateral intermingling of the different units. Strata deposited during these advances and retreats of the shoreline

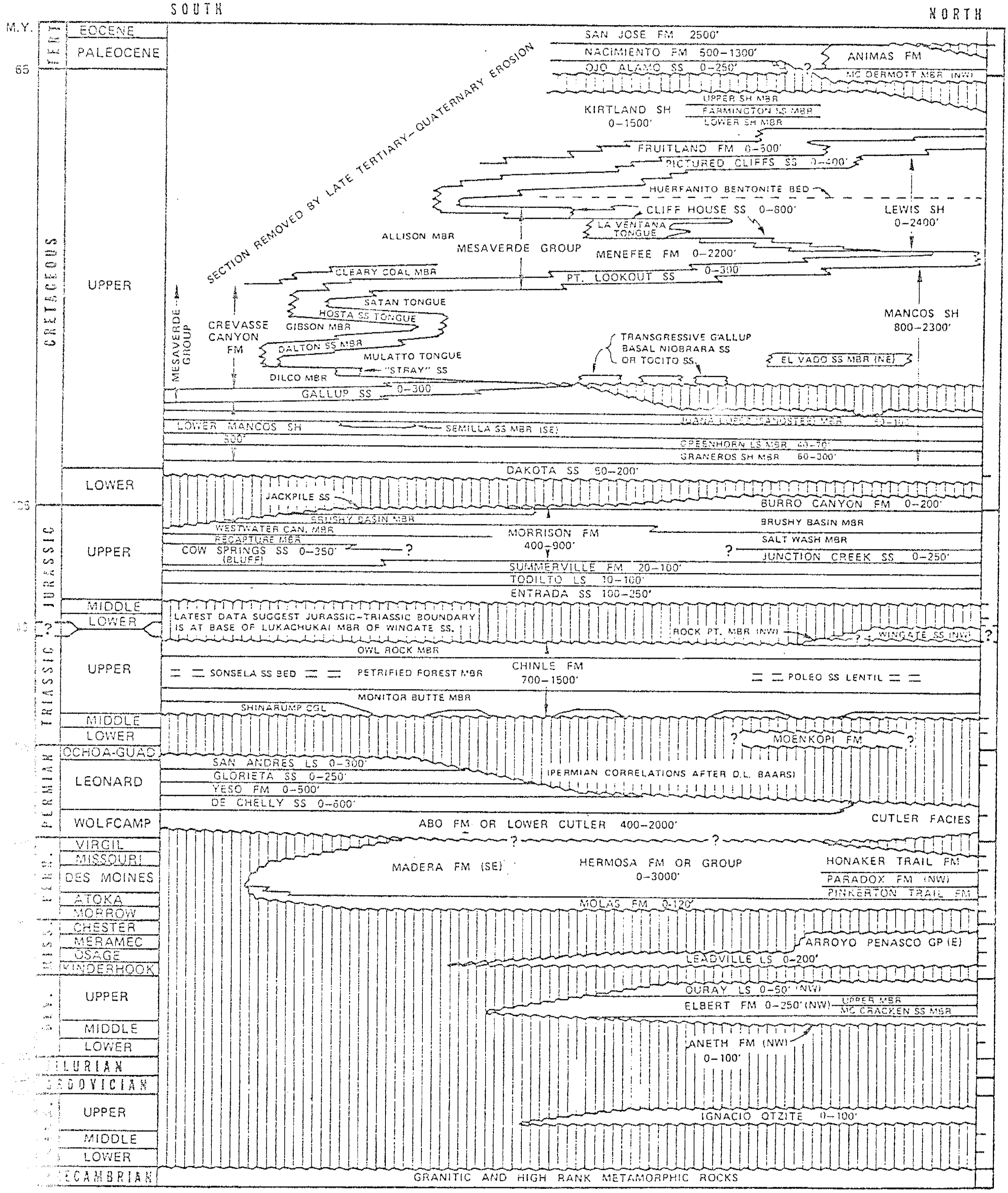

Figure 3. San Juan Basin time-stratigraphic nomenclature chart (from Molenaar, 1977).

are readily recognized as transgressive-regressive cyclic sedimentation units. The transgressive and regressive sequences and cyclicity of sedimentation of the Upper Cretaceous deposits in the San Juan Basin were described and discussed by Sears, Hunt and Hendricks (1941), Pike (1947), and Peterson and Kirk (1977). The regional stratigraphic setting and correlation was outlined and discussed by Weimer (1960).

During deposition of the Mancos Shale, the shoreline had a general northwest to southeast trend (Silver, 1950; Peterson and Kirk, 1977). This trend of the paleoshoreline was generally maintained in the area during Late Cretaceous time (Weimer, 1960); depending on the rates of regional subsidence and sedimentation, the shoreline either advanced southwestward (landward) or retreated northeastward (seaward). A great part of the deposition occurred during the intervals of regression, and subsidence and/or relative sea level rise in the area led to the development and preservation of a thick sequence of sediments, about 1524 meters of Cretaceous units (Fassett, 1974).

General stratigraphy of the Point Lookout Sandstone and adjacent units

Mancos Shale--. The Mancos Shale was named by Cross in 1899 from exposures in the Mancos River Valley and near the town of Mancos, southwestern Colorado (Pike, 1947). The term is being applied extensively to shales in the lower part of the Upper Cretaceous sequence in northern and western New

Mexico, western Colorado, eastern Utah, and northeastern Arizona (Pike, 1947).

The Mancos Shale occurs throughout the San Juan Basin, comprising the thickest marine unit of the sequence. It reaches a thickness of 671 meters in the northern part of the basin (Parker, 1957); Pike (1947) reported 668 meters of Mancos Shale in the Mesa Verde area about 8 or 10 kilometers from the type locality, and Landis, *et al.* (1947) reported a thickness of about 610 meters for Mancos Shale in the Tierra Amarilla area, Rio Arriba County. It is thinner in the southernmost part of the San Juan Basin; it is only about 122 meters thick in the southern part of the Zuni Mountains area, where the edge of the marine deposits are approached (Smith, 1957).

The Mancos Shale is divided into several members (see Figure 3); Molenaar (1977) described the different members of the Mancos Shale, also a very brief description is given by Fassett (1974). The intervals which contain calcareous sediments or sandstone are more resistant and form gentle relief on the generally low-lying surfaces above the Mancos Shale. In the area of this study, the Mancos Shale is generally poorly exposed, especially the less resistant shale intervals which form the bulk of the formation.

The Mancos Shale represents deposition in offshore quieter waters, to which generally only finer clastics were supplied and could settle out. However, in general, the sea was not deep during deposition of the Mancos Shale. Molenaar

(1977) proposed a possible depth of 91 to 122 meters at the most on basis of interpretation from foraminiferal data.

Point Lookout Sandstone--. The Point Lookout Sandstone comprises the lower unit of the Mesaverde Group. The Mesaverde Group was originally named by Holmes (1877) from exposures at Mesa Verde, Montezuma County, southwestern Colorado. He informally divided it into the Lower Escarpment sandstone, the Middle Coal Group, and the Upper Escarpment sandstone. Collier (1919) renamed the lower sandstone division the Point Lookout Sandstone from the typical exposures at Point Lookout on the northern rim of the Mesa Verde; he also renamed the middle division the Menefee Formation after Menefee Mountain southeast of the town of Mancos, and the uppermost sandstone division as the Cliff House Sandstone in relation to the presence of prehistoric cliff dwellings in this sandstone at Mesa Verde National Park. However, the term Mesaverde Formation rather than Group was used especially to the south (Pike, 1947); but Beaumont, Dane, and Sears (1956) raised the Mesaverde to group status everywhere in the San Juan Basin.

The Point Lookout Sandstone, which is the topic of this study, is the most laterally extensive sandstone unit of the Upper Cretaceous sequence of the San Juan Basin. It has been reported in the subsurface from wells throughout the basin, and in essentially all the hogbacks around the basin (see Figure 1). Its areal distribution and thickness variation are considered under the subsurface section in this report.

The Point Lookout Sandstone overlies the Mancos Shale conformably through a relatively thick transition zone, and underlies the Menefee carbonaceous and coaly sequence with a generally sharp conformable contact. Due to its stratigraphic position in the sequence, the Point Lookout Sandstone was interpreted as a regressive sandstone body developed in the littoral complex (e.g., Pike, 1947; Hollenshead and Pritchard, 1961), although no detailed studies of this unit and its depositional aspects were made.

Menefee Formation-. The Menefee Formation is the nonmarine middle unit of the Mesaverde Group, and also occurs throughout the San Juan Basin. The Menefee Formation is thicker in the southern part of the basin; it is about 518 meters thick near Torreon (Beaumont and Shomaker, 1974) and reaches about 610 meters at the southern extent of the overlying Cliff House Sandstone, but thins further south due to Late Tertiary to Recent erosion (Molenaar, 1977). It thins gradually northward and pinches out near the northern rim of the basin. In the study area, it occurs in considerable thickness forming relatively steep slopes between the hogback-forming overlying sandstone of the La Ventana Tongue of the Cliff House Sandstone and the front ridges of the underlying Point Lookout Sandstone; its thickness at measured section number 3 is 211 meters (Siemers and others, 1975).

The Menefee Formation is generally composed of complexly interlayered and laterally intermingled gray claystones, brown carbonaceous to humic shales (or humates), thin coal seams and lenses, thin and relatively tabular muddy sandstone, and lenticular fine to medium grained channel sandstones. The lithologic units forming the Menefee Formation reflect a nonmarine coastal complex where lagoon, bay, and swamp sediments associated with channel sandstone, overbank muddy sediments and splay sandstone developed (Siemers and others, 1975; Mannhard, 1976).

Beaumont, Dane, and Sears (1956) divided the Menefee Formation into a few members in the southern part of the San Juan Basin; a description of the Menefee Formation and its stratigraphic relationships is given by Beaumont (1974). A fairly detailed description of the upper part of the Menefee Formation in the La Ventana area is given by Mannhard (1976), and a more detailed study of the whole Menefee Formation in the La Ventana area is presently under study by Wallace (in progress). Shomaker and others (1971) provided a comprehensive description of the coal deposits in the Menefee Formation in the San Juan Basin, and the humate deposits have been recently studied by Siemers and Wadell (1977). The lowermost part of the Menefee Formation is included in this study in order to get a complete outline of the Point Lookout depositional system.

Method of Study

Field work for the present study consisted of measurement of seven stratigraphic sections, description of individual stratigraphic units including their fossil content, systematic sampling, and measurement of paleocurrent data. Seven stratigraphic sections were measured using a Jacob's staff; sections were selected about 8 to 10 kilometers apart, depending on the nature of the outcrop (see Plate 1). The measured sections included the transition zone above the typical Mancos Shale, the Point Lookout Sandstone, and the basal part of the Menefee Formation.

The sampling technique was intended to follow the lithologic variations; that is, representative samples were collected from each unit including thin ones. Thick units were sampled at average intervals of 2 meters. Representative samples of macroinvertebrate fossils were collected. Mean grain size of the sandstones was systematically estimated, using a hand lens and a transparent grid with standard pictures of grain-size classes. Format of the field notes consisted of a graph of mean grain size on the left side, a stratigraphic column to scale, and, to the right, comments on observed characteristics of individual units in the column. This format is similar to that shown in Plate 1. Comments on observed characteristics included descriptions of trace fossils, lithology, and sedimentary structures. Paleocurrent readings were taken on cross-stratification, ripple marks, and any other observed directional features. The approach for collecting data on cross-stratification was to record the direction and amount of dip, set thickness, nature of the basal boundary of the sets, and geometry of cross-strata within the sets. Stratification and cross-stratification were described according to the classification system of McKee and Weir (1953, see Appendix A) and Allen (1963). For ripple marks, their type, wave length, magnitude, crest orientation, and current direction were described and measured wherever possible.

Hand specimens were examined in the laboratory using a binocular microscope for textural and lithologic observations, and about 70 representative sandstone samples were selected for petrographic analysis. All thin sections were examined using standard transmitted light, and several were point counted for quantitative comparison. Several samples also were examined by Cathode luminescence for more petrographic observations. Eighteen samples from sandstone units in measured section No. 6 were disaggregated for mechanical grain-size analysis; some samples were treated by warm dilute hydrochloric acid because of the presence of carbonate and/or iron oxide cement. All samples were wet sieved to remove the mud (silt and clay) fraction prior to sieving; mud fractions of several of the analyzed samples were also analyzed using the pipette method. Several sandstone and shale or claystone samples from the different facies in measured section No. 6 were analyzed for the type and relative abundance of clay minerals by X-ray diffraction analysis.

Subsurface date (from scout cards on file at the N.M. Bureau of Mines and Mineral Resources) for one to three wells per township throughout the San Juan Basin in New Mexico were used to construct isopach and structure contour maps for the Point Lookout Sandstone. Several electric well logs were examined for significant lithologic variations within the Point Lookout Sandstone and to determine the variability in identification of the lower and upper contacts of the Point Lookout Sandstone among different workers.

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DESCRIPTION OF FACIES RECOGNIZED IN MEASURED SURFACE SECTIONS OF THE POINT LOOKOUT SANDSTONE AND PORTIONS OF ADJACENT UNITS

General

The Point Lookout Sandstone overlies the Mancos Shale conformably through a considerable transition zone, and underlies the Menefee Formation also comformably with intertonguing relationship. Such inter-relationship requires the consideration of a sequence, which includes the Point Lookout Sandstone and adjacent portions of the associated units, for a comprehensive study of the Point Lookout depositional system; this sequence will be referred to as the Point Lookout sequence to distinguish it from the Point Lookout Sandstone which is reserved for its formal usage. To avoid ambiguity in the application of some significant terms used in this study, brief definitions of sedimentary environment and sedimentary facies are worth mentioning.

A sedimentary environment is a part of the earth's surface which is physically, chemically, and biologically distinct from adjacent terrains (Selley, 1971). A sedimentary facies is a mass of sedimentary rock which can be defined and distinguished from others by its geometry, lithology, sedimentary structures, paleocurrent pattern, and fossils (Selley, 1971). A facies is regarded as the product of a specific sedimentary environment. These diagnostic parameters of a sedimentary facies are used in this study as a basic guide for describing the different facies in the Point Lookout sequence and interpreting their environments of deposition.

Five facies are recognized in the Point Lookout sequence, in ascending order: 1) Facies A consists of thinly bedded, tabular to lenticular, fossil-bearing, very fine grained silty sandstones and interbedded shales; 2) Facies B is an upward coarsening sequence of burrowed and fossil-bearing, very fine to fine grained sheet sandstones; 3) Facies C consists of fine grained, moderately burrowed sheet sandstones; 4) Facies D consists of fine to medium grained, thick to very thick sandstones with large wedge to trough cross-stratification and lacks fossils and burrows; and 5) Facies E is more diverse with gray claystones, brown carbonaceous shales, humate and coal beds, muddy carbonaceous sandstones, and fine to medium grained lenticular sandstone bodies. A detailed description of individual units in each measured stratigraphic section is given in appendix B.

The Point Lookout Sandstone along the eastern side of the San Juan Basin is dominated by a sequence of persistent very fine to medium grained, sheet sandstones interbedded with thin shales. The Point Lookout Sandstone is continuous throughout the area forming ridges and hogbacks, above low-lying surfaces of the less resistant underlying Mancos Shale marine sequence, and ranges in thickness from 23.5 meters at measured section No. 7 to 65.5 meters at measured section

No. 3 (Plate 1). These thicknesses are of the interval between the lower contact of Facies B and the upper contact of Facies D (as shown on Plate 1). Significant fluctuation in thickness among individual facies forming the sequence reflects local dominance of certain subenvironments. Maximum thickness of the Point Lookout Sandstone occurs in the area between measured sections No. 3 and No. 6. Its thickness declines gradually both southwestward and northeastward. (A detailed description of its distribution is given in the introduction and subsurface chapter.) To the south-southwest the Point Lookout Sandstone pinches out into the overlying humate and coal-bearing facies of the lower Menefee Formation; to the north-northeast it grades into the marine shale sequence of the Mancos Shale.

The rest of this chapter is devoted to detailed descriptions of each of the recognized facies in the Point Lookout sequence as it has been described in the measured stratigraphic sections. Individual stratigraphic units in the measured sections are referred to in the text by symbols, such as Kpl-6-9, where Kpl refers to the Point Lookout sequence, 6 is the number of the measured section as indicated on Plate 1, and 9 is the unit number shown on the left side of this stratigraphic section on Plate 1.

Facies A

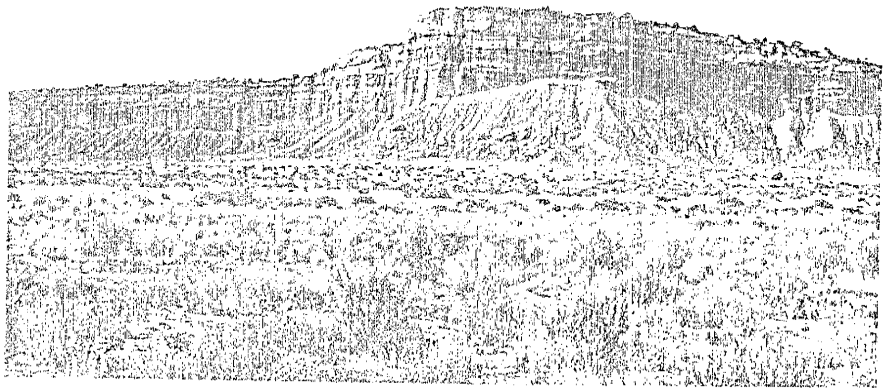
Stratigraphy-. Facies A is the lowermost part of the Point Lookout sequence. It is a transitional zone between the typical deep marine Mancos Shale below and the prominent sandstone units of the Point Lookout Sandstone above (Figure 4). It is laterally extensive throughout the area, and varies in thickness from a few meters to almost 20 meters. Units of this facies grade laterally into marine shales of Mancos Shale northward, and into Facies B of the Point Lookout Sandstone south-southwestward.

The upper and lower contacts of Facies A are arbitrarily defined, as required for consistent description and comparison of facies. The contacts are defined here on the basis of the thickness of individual sandstone units and their abundance relative to interbedded shales. The occurrence of individual sandstones one meter thick and a sandstone:shale ratio of approximately 3:1 define the upper contact of Facies A. The occurrence of individual sandstone units less than 1m thick (usually a few centimeters thick) and a sandstone:shale ratio of approximately 1:3 define the lower contact of Facies A.

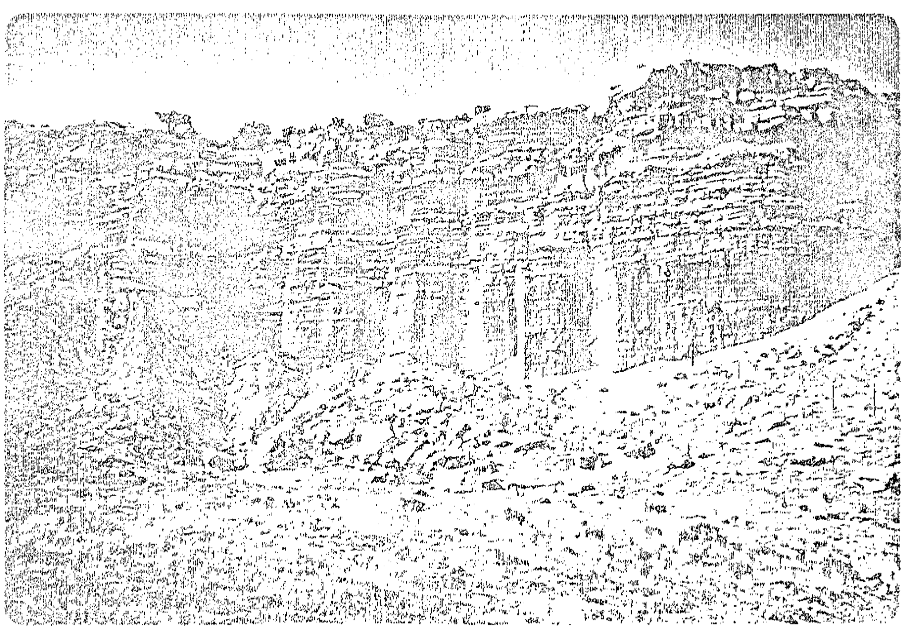
The occurrence of Facies A as a transition between the formally defined Mancos Shale and Point Lookout Sandstone provides a good argument against the use of pinpoint formation contacts. The transition is genetically related to both formally defined units. Because of the formal nomenclature and the importance of the Point Lookout Sandstone

Figure 4. Photographs of the Point Lookout Sandstone and upper Mancos Shale. A- Point Lookout Sandstone capping the Mancos Shale, with a thick transition zone (Facies A), near San Luis. B- Closer view (at the right part of A) showing interbedding and intertonguing between shale and sandstone intervals; note sandstone lenses pinch out within a short distance; thickness shown is approximately 35m.

A



B



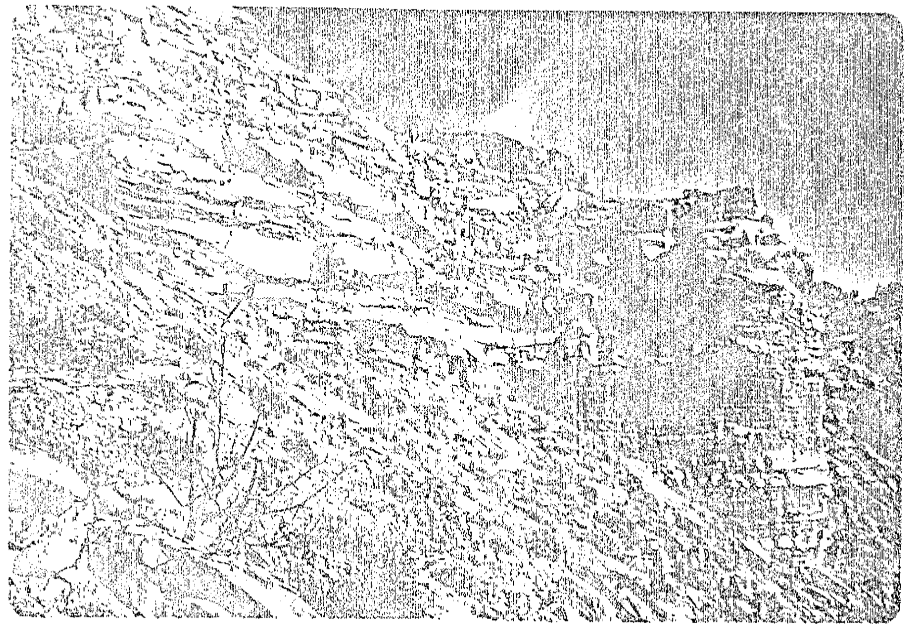
as a reservoir rock, Facies A can be excluded from the Point Lookout Sandstone and assigned to the Mancos Shale if it has to be assigned to one or the other formal lithostratigraphic unit.

Individual sandstone units and subunits in Facies A are generally less than one meter in thickness. Some of them are lenticular and pinch out within a few 10's of meters (see Figure 4); others are tabular and laterally continuous over 100 meters. Some sandstone lenses have a large scour-shaped basal surface (Figure 5). Lower contacts of the sandstone beds with the underlying shales are generally sharp, especially for the relatively thick, lenticular sandstones (see Figure 5); they are usually characterized by load casts. Upper contacts are fairly sharp for the relatively thick sandstone lenses, but are gradational into silty shales from thin sandstone beds.

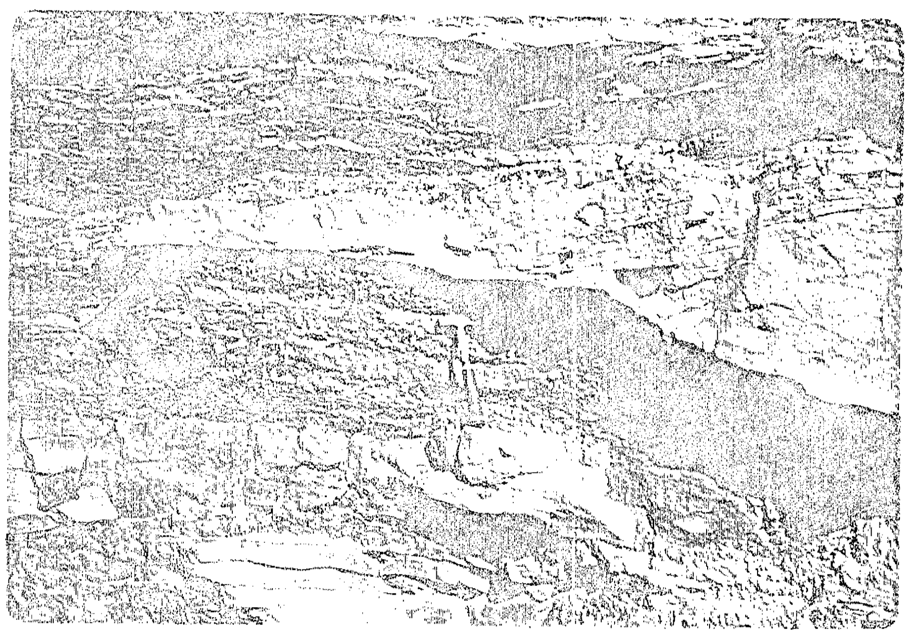
Lithology-. Facies A is characterized by interbedded and interlaminated sandy to silty shales and silty sandstones. The sandstones are typically yellowish-gray, very fine grained, poorly to moderately sorted, subrounded, friable, laminated and cross-laminated to bioturbated, silty sandstone. Some zones are slightly cemented by carbonate. Fine to coarse grained, brownish to black colored carbonaceous fragments are abundant, mainly between sandstone laminae. The shales are brownish black to gray in color, generally fissile, and mostly silty. Fine carbonaceous material is also abundant in some shale zones.

Figure 5. Photographs of sandstone lenses in Facies A. A- Sandstone lenses with a scour-shaped basal surface (arrow) in Facies A, at measured stratigraphic section Kp1-7. B- Close-up (left end of sandstone lens indicated by the arrow in A) showing the sharp and irregular basal contact.

A



B

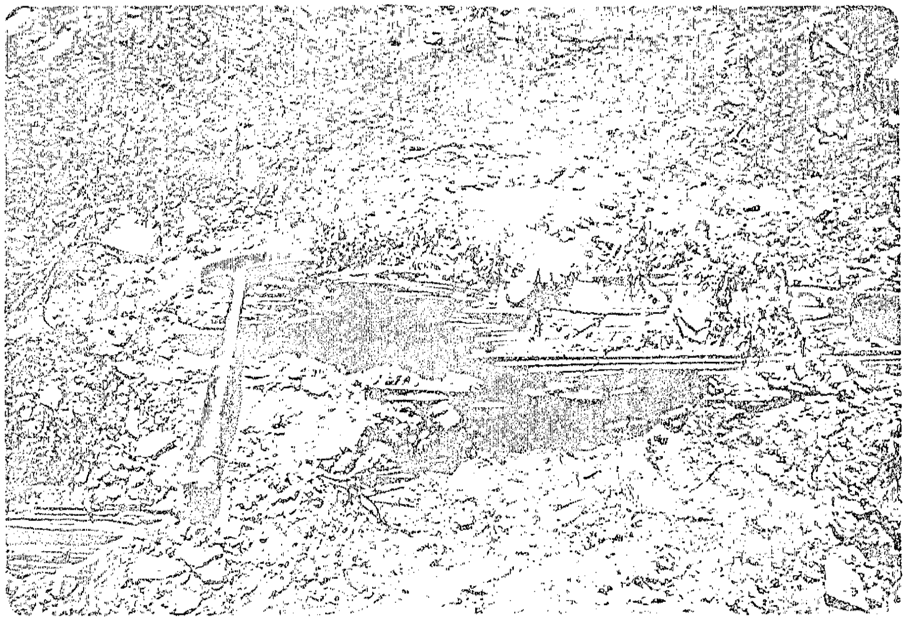


Very thin sandstone subunits are highly silty. Thick beds are less silty, better sorted, more indurated, and coarser, but may exhibit a slight decrease in grain size in the upper part. The range of mean grain size among sandstone of Facies A is very narrow; grain size is mostly less than 100μ (see grain-size plots, Plate 1). The relatively thick sandstones form small breaks in the gentle slopes.

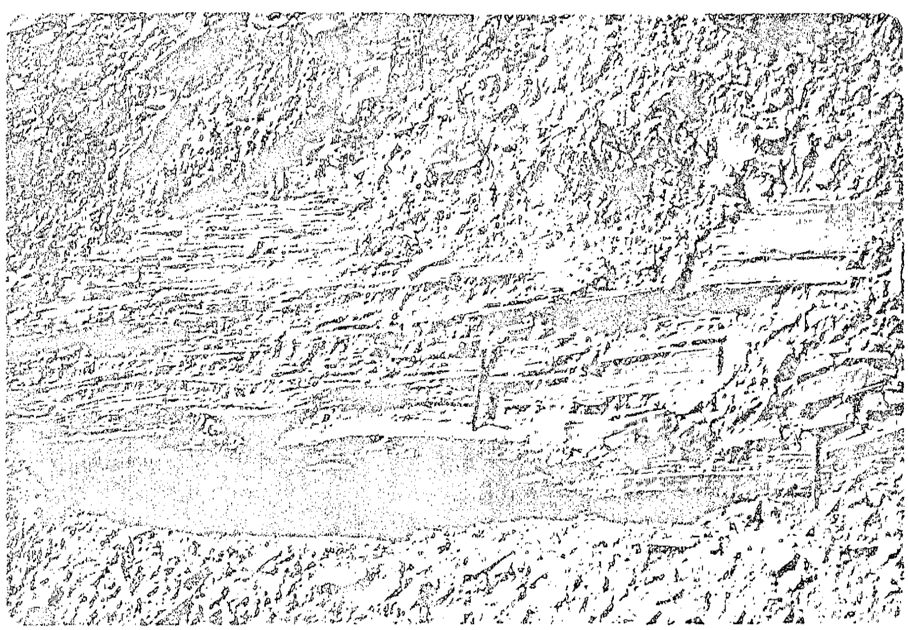
Sedimentary structures-. Sandstones in Facies A are generally characterized by subhorizontal lamination and small scale cross-lamination (Figure 6). Many sandstone units in Facies A show poorly preserved structure, a phenomenon which can be attributed to disturbance by organisms, during and immediately after deposition. The effects of bioturbation are moderately evident in units with disturbed stratification, abundant but poorly preserved burrows, and zones of muddy sandstones due to mixing of mud and sand.

In addition to subhorizontal lamination, another dominant sedimentary structure in sandstones of Facies A is a generally wavy (or undulatory) cross-lamination (Figure 7). These wavy or undulatory structures are characterized by: 1) gently curved lower boundary which is erosional based on its irregularity and truncation of underlying laminae; 2) the top of the set is generally planar; 3) set thickness is generally less than 25 centimeters, and extends laterally less than 1.5 meters; 4) laminae within the set are generally in accord with the bottom curved boundary of the set; 5) laminae within the set either retain a uniform thickness or thicken laterally

Figure 6. Photographs of lamination in Facies A sandstones. A- Laminated sandstone in Facies A, no well developed sets of cross-lamination, but some laminae wedge out laterally and apparent set boundary exist (arrow). B- Lamination in very fine silty sandstone in Facies A, wavy laminae (w), scale is 12cm; sandstone intervals in unit Kpl-6-1.



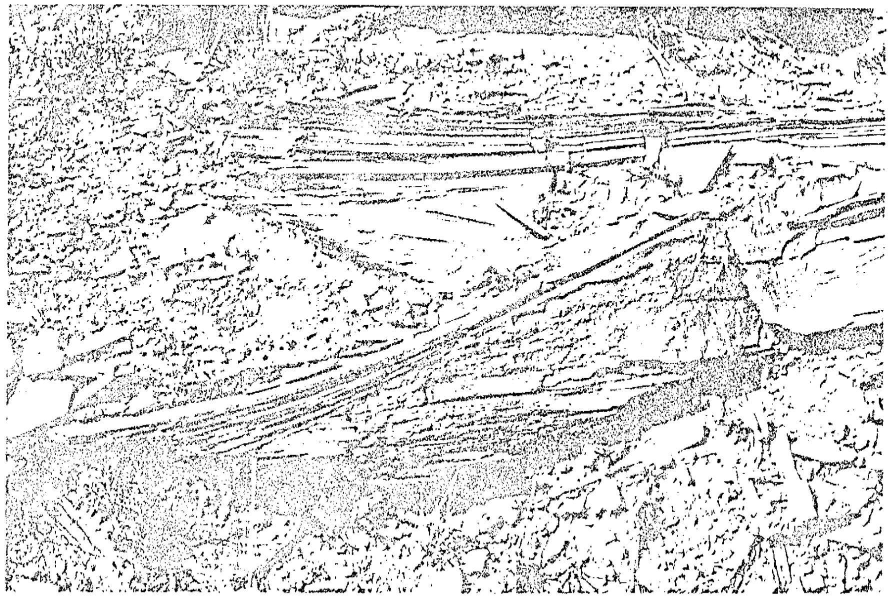
A



B

Figure 7. Photographs of undulatory or wavy cross-stratification. This structure exhibits gently curved, erosional lower boundaries; note internal laminae are in accord with bottom boundary (for description, see text). A- From upper part of Facies A at section Kpl-6, block in front at ruler (15 cm) is not in place but shows clearly the structure at the pencil. B- From lower part of Facies B at section Kpl-6 where this structure is well exposed. C- From lower part of Facies B at section Kpl-2; notice erosional basal surface near lower edge of scale (15cm).

A



B

C

and dip generally less than 10 degrees in variable directions.

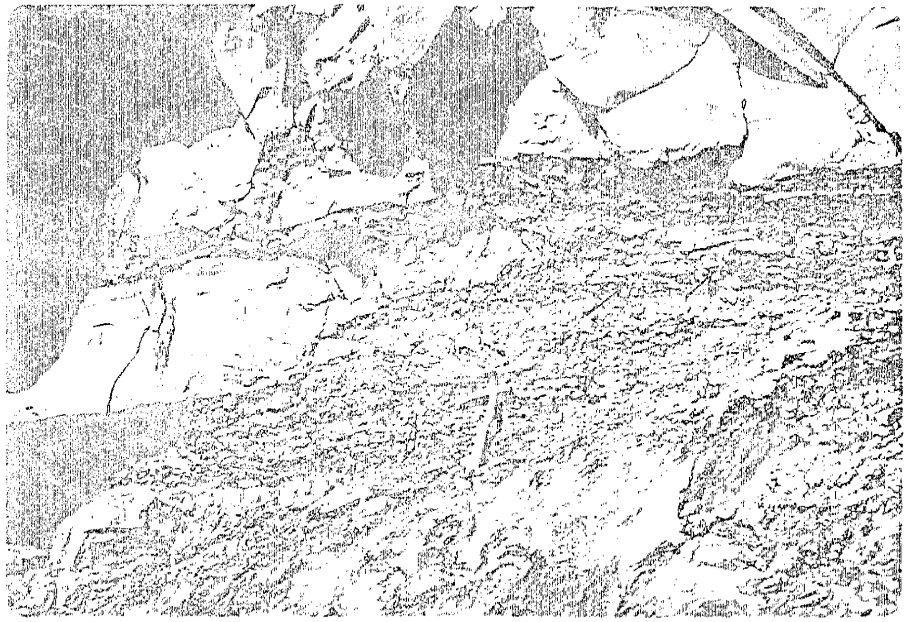
Very poorly preserved small ripple marks occur on the top surface of some sandstone beds. They appear to be symmetrical, but no measurements were made because of the poor development and preservation of these ripple marks. The lower surface of many sandstones is characterized by load casts into the underlying mud-rich zones.

Fossils-. Marine fauna are moderately abundant in Facies A. Macroinvertebrate fossils in sandy zones of Facies A are dominantly, in descending order, ammonites, bivalves (mainly pelecypods), and gastropods. The bivalves generally occur as small whole valves, or fragments. Gastropods are mostly small snails; ammonites are relatively large. A few shark teeth also occur in some units. Fossils are generally randomly oriented and moderately complete. They constitute a moderately diverse assemblage.

Trace fossils are also common in this facies. They are concentrated mainly on bedding surfaces of sandstone beds. Curved or sinuous trails are common on upper surfaces of some sandstone beds. Also smooth walled, generally branched, very thin (mostly less than 0.5 cm diameter) burrows (*Thallasinoides?*) are moderately common on bedding surfaces. *Ophiomorpha* is rare in Facies A units and does not exhibit knobby walls. Vertical to diagonal, sand and silt filled tubes (up to 1.5 cm diameter and several centimeters long) are moderately abundant in some shales underlying sandstones (Figure 8); mixing of sand and mud also occurs in some zones

Figure 8. Photographs showing interbedding of shale and sandstone, and burrows in Facies A. A- Interbedding of shale and sandstone in Facies A with mixing of the two lithologies by organisms, also lateral relationship between shale and sandstone intervals, sand and silt filled burrow tubes (at arrows) extending down through shales underlying sandstones. B- Close view of burrowed area shown in A, scale is 16cm, pictures from Kpl-1-4.

A



B

and is probably the result of bioturbation.

Facies B

Stratigraphy-. Facies B is a very prominent portion of the Point Lookout sequence throughout the area. It consists of a succession of tabular sandstone units with some thin silty shale breaks. Facies B conformably overlies Facies A, and grades upward into Facies C sandstones.

Units of Facies B grade laterally into Facies A toward the north-northeast and into Facies C sandstones south-southwestward. Facies B as a whole varies in thickness from 13 meters to as much as 34 meters (Plate 1). Individual sandstone units range in thickness from 1 meter, the limit used to distinguish between Facies B and underlying Facies A sandstones, to about 8 meters (Kpl-1-5, Plate 1). Sandstone units are typically laterally continuous; they may be traced for a few kilometers along a north to northeast - south to southwest trend. The lower contacts of sandstone units are sharp, commonly irregular, and exhibit load casts locally. Upper contacts are generally smooth and sharp; rarely they are slightly erosional (e.g., Kpl-1-5, and Kpl-6-9, Plate 1).

Sandstones of Facies B form a moderately sloping surface with zones of large sandstone concretions forming disconnected ledges, and shaley zones forming gentle breaks in slope. The shale breaks are generally thin and interbedded with silty sandstones. The shale breaks increase in thickness in a north to northeast direction, and pinch out into thick sandstone units in the opposite direction. However, a few shaley zones are not stratigraphically linked to Facies A; rather, they are confined to Facies B and may show an increase in thickness south to southwestward.

Lithology. Facies B consists mainly of a sequence of thick, tabular sandstone units either stacked vertically, forming a very thick sandstone interval, or separated by thin interbeds of silty shale. The sandstones are generally tan in color, weathering to orangish gray, very fine to fine grained, generally moderately sorted, subrounded to subangular, friable to moderately indurated, laminated and cross-laminated to structureless, and locally bioturbated, medium to very thick bedded, sublitharenite (modified Folk, 1974, classification).

Small iron-rich claystone pebbles occur in narrow zones in several sandstone units (see measured sections, Plate 1). They are commonly associated with, but not restricted to, erosional contacts. Sandstones of Facies B are moderately fossiliferous (e.g., units Kpl-3-5 & 8, Kpl-4-5, 7 & 9, Kpl-6-3 & 5). Sandstones are generally matrix bonded, but carbonate cement is very abundant in zones of large sandstone concretions. Carbonaceous material occurs in laminated zones.

Shale breaks are generally similar in lithology to those of Facies A, but are siltier, and some are sandy shales. The interbedded sandstone beds are finer and contain more mud than nearby thick sandstones.

Sandstones of Facies B range in grain size from about 80 microns to about 180 microns, mostly between 100 and 150 microns, and exhibit a progressive upward increase in grain size within Facies B (see grain-size plots, Plate 1).

Sedimentary structures-. Sandstones of Facies B exhibit a variety of sedimentary structures. Cross-stratification is a dominant feature in many units; it consists mostly of shallow trough type, and some tabular cross-stratification. Facies B also contains relatively thick sandstone intervals which lack sedimentary structures, probably the result of destruction of pre-existing structures by bioturbation.

Sedimentary structures in Facies B not only distinguish it from overlying sandstones of Facies C, but also can be used, to a certain extent, to divide it into two subfacies: 1) subfacies B_1, characterized by abundant shallow trough shaped cross-stratification (Figure 9); and 2) subfacies B_2, characterized by tabular cross-stratification and subhorizontal lamination (Figure 10).

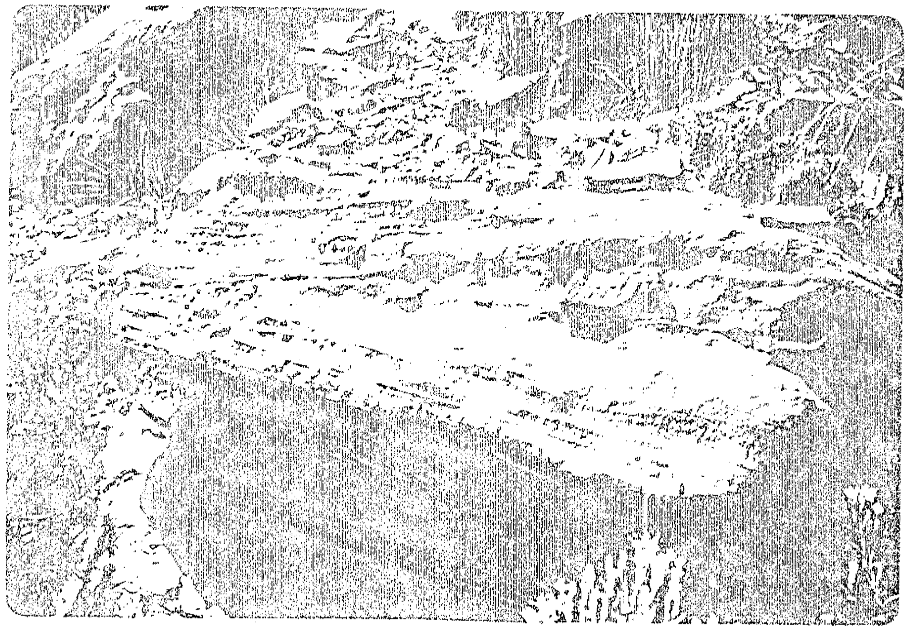
Subfacies B_1 constitutes a major portion of Facies B; its characterizing trough cross-stratification occurs in most sandstone units of Facies B in all the measured sections (see Plate 1), but with a variable degree of development and abundance. The shallow trough cross-stratification occurs as cosets of trough to wedge shaped sets, depending on the relative orientation of the outcrop surface (e.g., Figure 11). The lower boundary of the individual set is an erosional trough shaped surface (see Figure 11). The sets range in

Figure 9. Photographs of trough cross-stratification in Facies B. Well developed, small scale trough cross-stratification is abundant in Facies B (subfacies B_1) sandstones. A- From unit Kpl-2-2. B- From unit Kpl-2-4, ruler is 15cm, pen marks a set.

A

B

Figure 10. Photographs of tabular cross-stratification and subhorizontal lamination in subfacies B_2 sandstones. Lower boundary of set is generally planar; laminae within the set show tangential relationship with lower set boundary, but usually exhibit an angular relationship. A- From unit Kpl-6-2. B- From unit Kpl-6-3, scale is 15cm.

A 

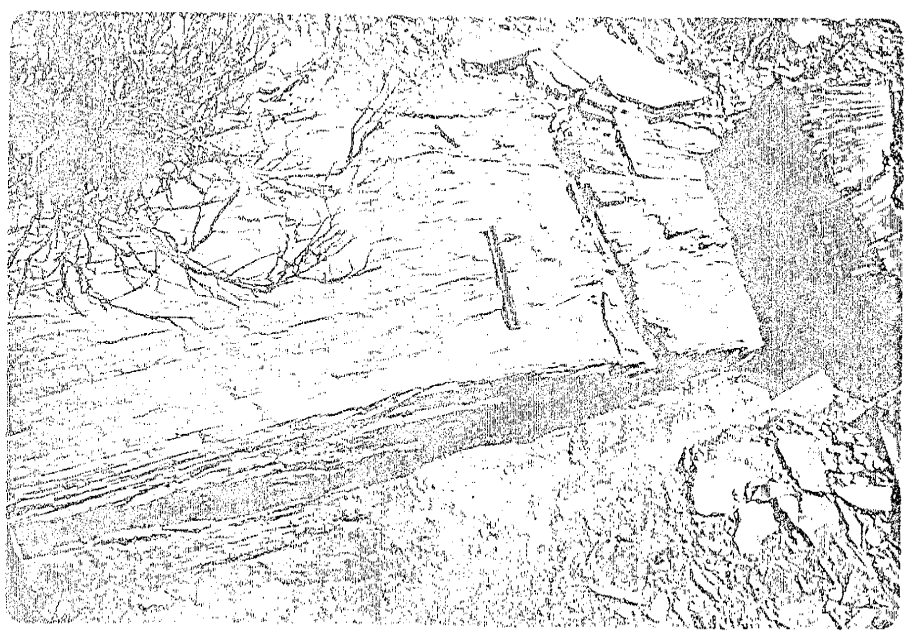
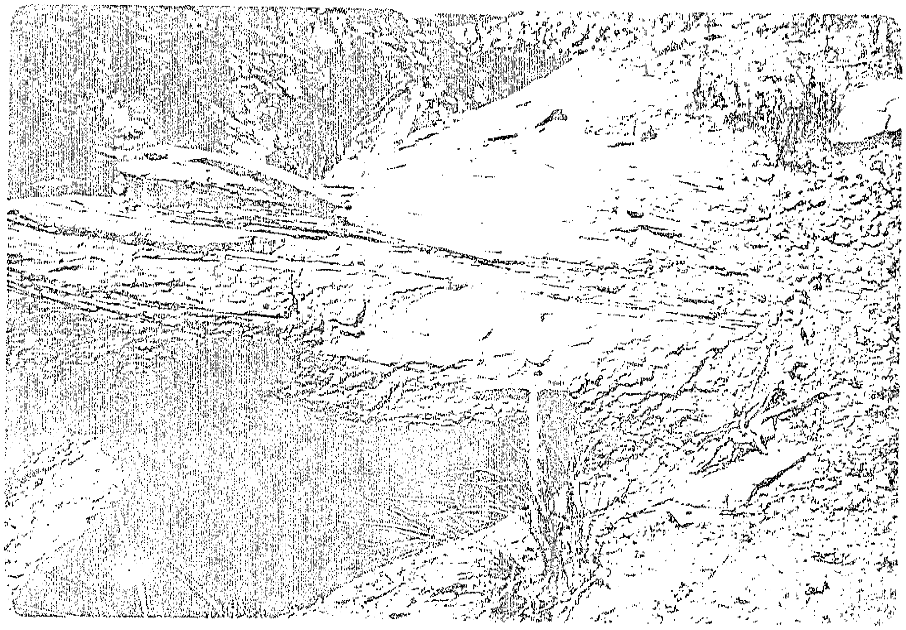
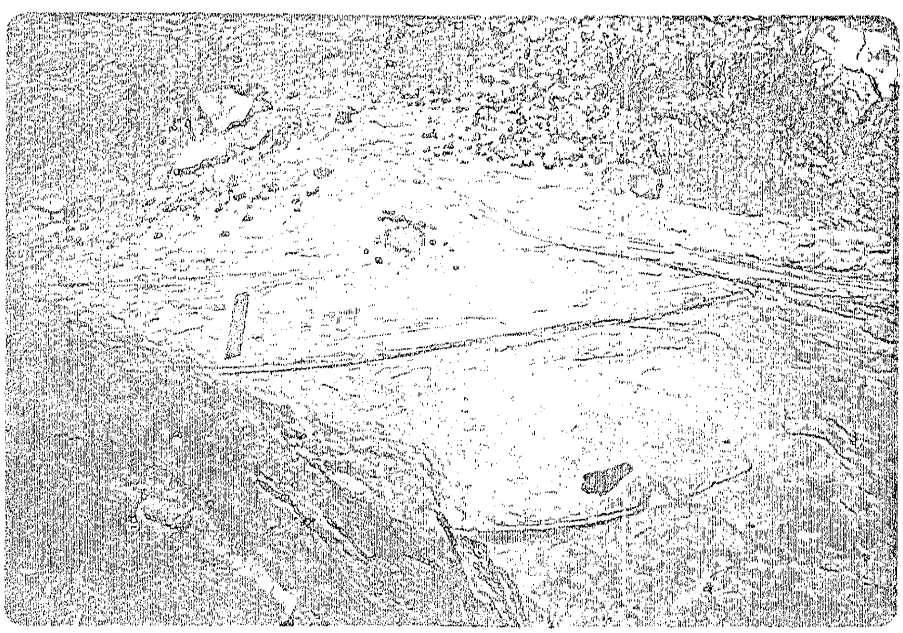
B 

Figure 11. Photographs showing the appearance of trough cross-stratification (from subfacies B_1) in different view sections. Trough cross-stratification may appear as long sets wedging laterally, Figure A, (surface parallel to the hammer), but on a view section perpendicular to it (at the ruler, 15cm) good troughs are well displayed; B is a close view of the troughs; scale is at the same place in A; pictures from unit Kp1-3-5.

A



B



thickness from 5 cm to 35 cm, mostly less than 25 cm; they are generally of small to medium scale. Cross-laminae within the set are almost concordant with the lower trough boundary in some views but highly tangential with the lower boundary in views which are perpendicular to the previous ones (see Figure 11). The views showing good troughs with cross-laminae concordant with lower set boundary are oriented perpendicular to flow direction; the other view is oriented parallel to flow direction (Harms, 1975).

Dip angle of cross-strata is generally less than 15 degrees, but can be as much as 39 degrees. A paleocurrent rose diagram (Figure 12A) indicates that dip directions are highly variable; it shows 84 degrees standard deviation, and a vector mean of N54° E, indicating that dominant transport was northeast. Other less dominant components suggest east, north, and northwest were also significant directions of sand transport.

Variability in cross-strata dip direction exists not only among the cumulative measurements of Facies B sequence but also in measurements within individual sandstone units (see paleocurrent plots, Plate 1).

Subfacies B_1 is also characterized by another type of cross-stratification (Figure 13) which does not occur in any of the other sandstone facies in the Point Lookout sequence. This cross-lamination consists of sets in which laminae truncate each other (see Figure 13). Away from the truncation point, laminae are less inclined forming a shallow

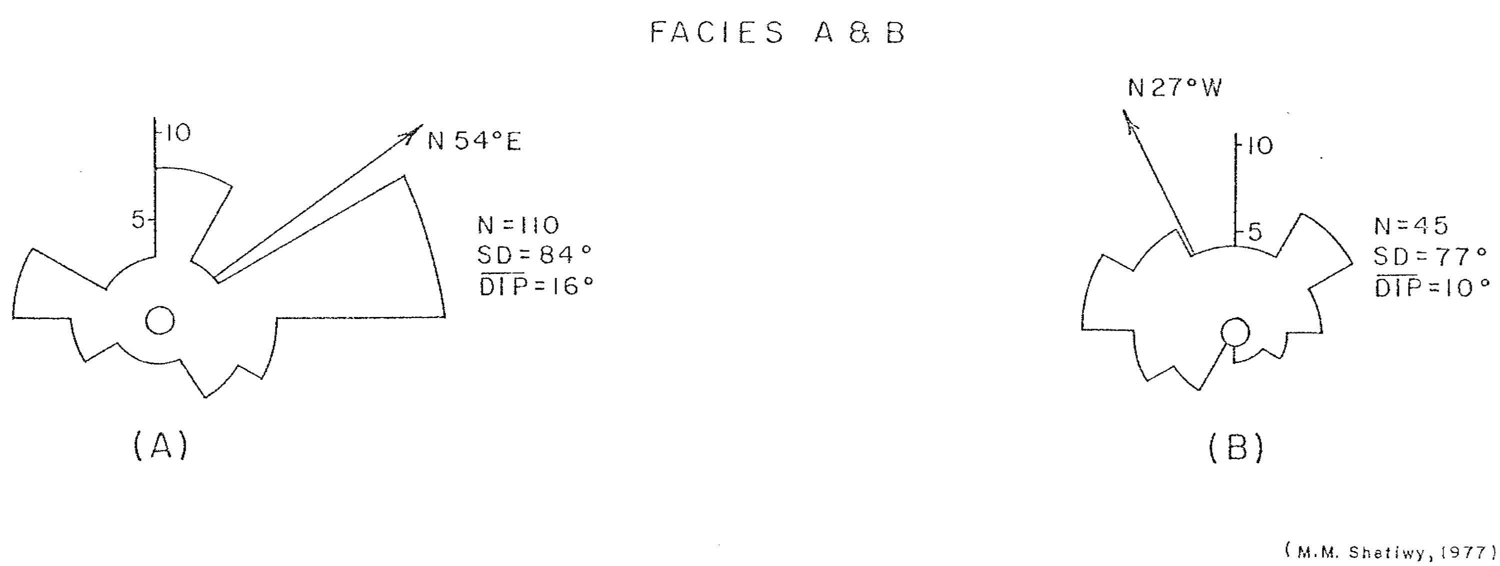
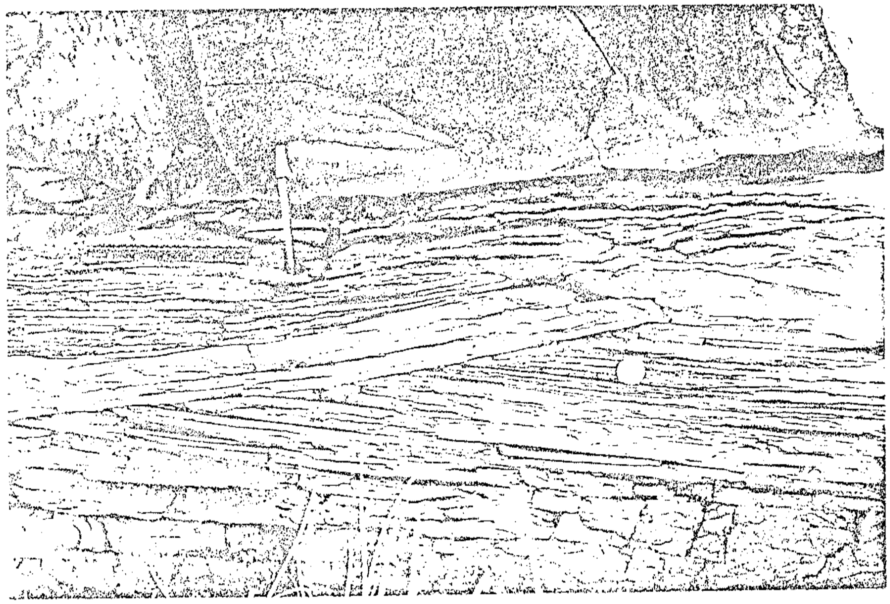
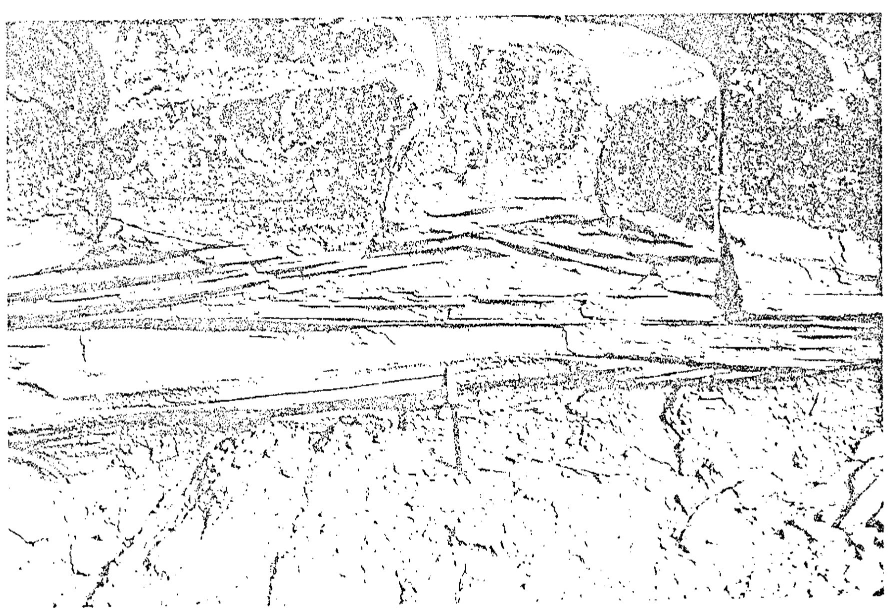


Figure 12. Paleocurrent rose diagrams showing dip directions in Facies A & B; (A) small to medium scale trough cross-stratification, from units Kpl-2-2, 4 & 5, Kpl-3-5 & 8, Kpl-5-3 & 5, Kpl-6-5, 9 & 10, and Kpl-7-7; (B) medium scale, mostly planar cross-stratification, from lower part of Facies B and Ss units in Facies A, (units Kpl-1-1 & 2, Kpl-3-1, 2 & 3, and Kpl-6-3).
N = number of readings; SD = standard deviation; $\overline{DIP}$ = arithmetic mean of dip angles of cross-strata.

Figure 13. Photographs of cross-lamination in subfacies B_1 sandstones. Laminae truncate each other; subparallel bedding surfaces seem to bound laminasets, for more description see text. Both A and B are from unit Kpl-2-5, ruler 15cm.



A



B

trough, then laminae ascend again toward the next truncation point. Distance between consecutive truncation points is about 2 to 4 meters, and amplitude at truncation points ranges from about 10 cm to 20 cm. Subparallel bedding surfaces seem to bound the laminasets.

Subfacies B_2 may form part of a sandstone unit and grade upward or downward to subfacies B_1 type sandstone. Sandstones of subfacies B_2 are generally finer, have less structure, and are more bioturbated than those of subfacies B_1. Its characterizing stratification is tabular to wedge shaped cross-lamination and subhorizontal lamination.

Tabular cross-lamination is relatively rare among the individual units, but occurs locally as isolated sets or small cosets. The lower boundary of the set is generally planar, and laminae within the set exhibit an angular relationship to the basal boundary (see Figure 10). Set thickness is generally in the same range as the trough shaped sets of subfacies B_1, but are slightly larger laterally, medium scale. Dip angles are slightly lower than trough sets values; dip directions are variable, similar to the trough cross-stratification distribution. Paleocurrent rose diagram (Figure 12B), which is based on cross-stratification types that are common in subfacies B_2 and some of Facies A sandstones, shows a vector mean of N27^{o}W and standard deviation of 77 degrees. Very shallow, irregular troughs with wavy (or undulatory) erosional lower surfaces occur locally (e.g., see Figure 7B); these resemble the undulatory shallow troughs described under

Facies A.

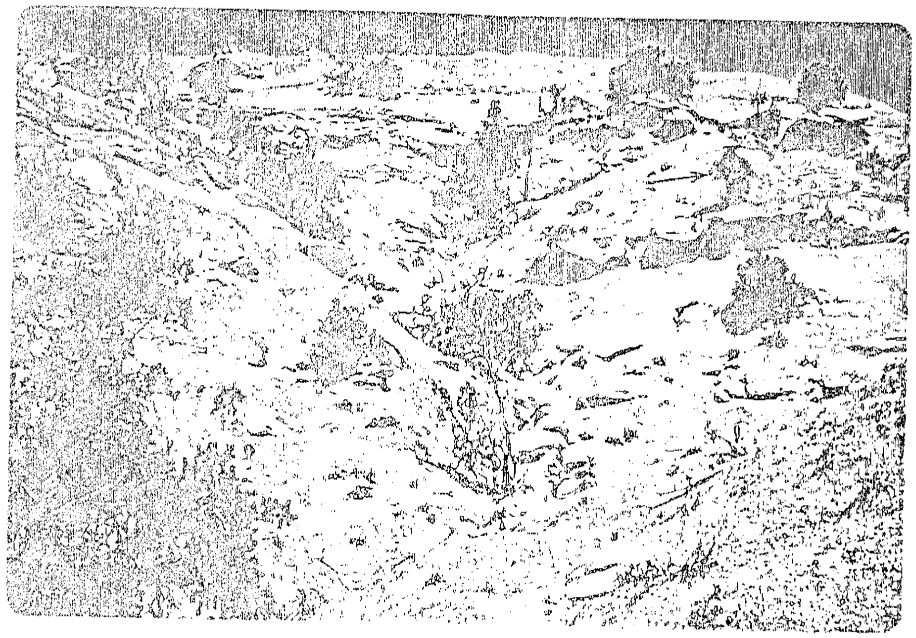
Megaripple type structure occurs in some sandstone units of Facies B (e.g., Kpl-3-3 & 5, Kpl-6-9, Plate 1). They occur either as a single zone or are stacked vertically and separated by discontinuous truncation surfaces, probably due to migration of the bedform. They are 15 to 20 cm thick and about 75 cm to 1.0 meter wide. Crestline (or trough axis) orientation ranges from N34°E to N51°W, but mostly in a NW direction. Cross-laminae within the megaripple troughs are curved and have a similar relationship with lower boundaries as that described for trough-shaped cross-stratification of subfacies B_1.

Large sandstone concretions are common in Facies B in almost all the measured stratigraphic sections (Plate 1). They are as much as 1.0 meter thick and about 2.0 meters across (Figure 14). They are highly cemented by carbonate and are the most consolidated sandstone in the Point Lookout sequence; they form prominent ledges in discontinuous horizons. The zones with large sandstone concretions are the best zones for fossil preservation.

Fossils-. Facies B sandstones contain the densest and most diverse fauna within the Point Lookout Sandstone. Macro-invertebrate fossils occur in sporadic zones within Facies B sandstones in most of the measured stratigraphic sections. Macro-fossils are either a thoroughly mixed assemblage concentrated in a very thin zone, few centimeters thick (e.g., Kpl-4-5, 7 & 9), or are a very limited assemblage distribu-

Figure 14. Photographs showing large sandstone concretion zones. A- General view of the Point Lookout Sandstone at section Kpl-3, with large sandstone concretions forming ledges in discontinuous horizons in units 5 and 8; tree at arrow is about 4 feet high. B- Large sandstone concretion in unit Kpl-6-9. Concretions are thoroughly cemented by carbonate, generally associated with trough cross-stratified sandstones of Facies B, and are the best zones for fossil preservation.

A



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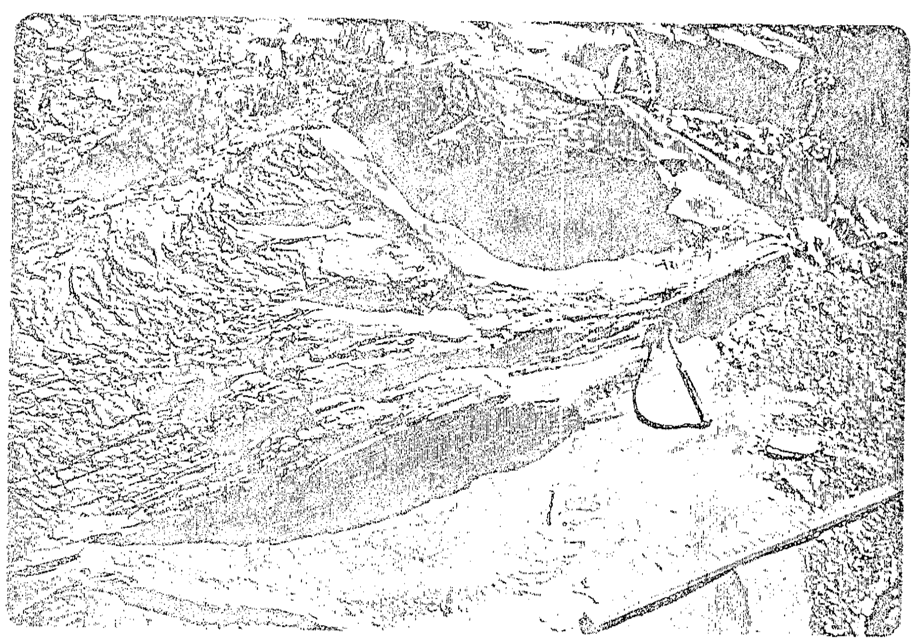
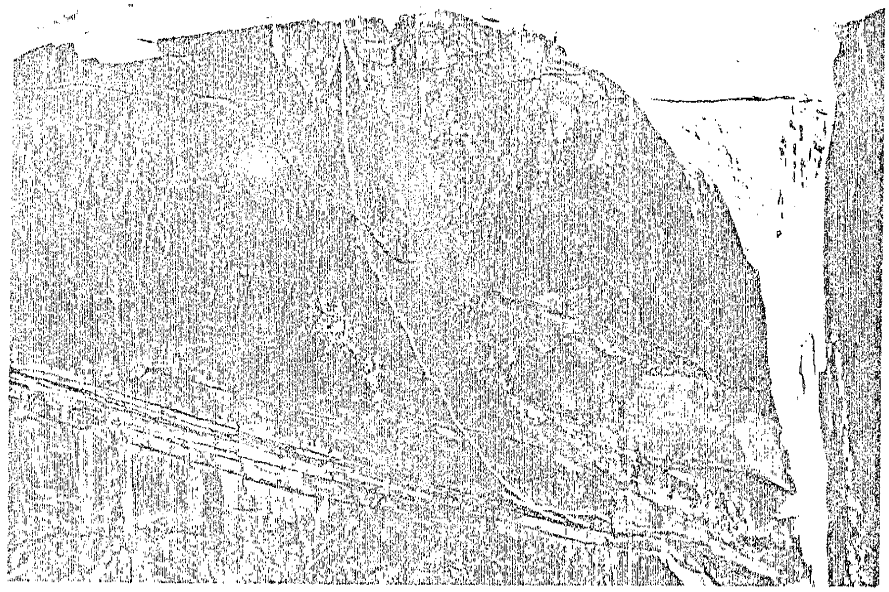


ted through moderately thick zones, commonly associated with large sandstone concretions (e.g., Kpl-2-5, Kpl-3-5 & 8, Kpl-6-5). Fossils in the thoroughly mixed, thin zones are dominated by bivalves, gastropods, and shark teeth; they are a mixture of fragments of large valves and shells, and fairly complete small shells.

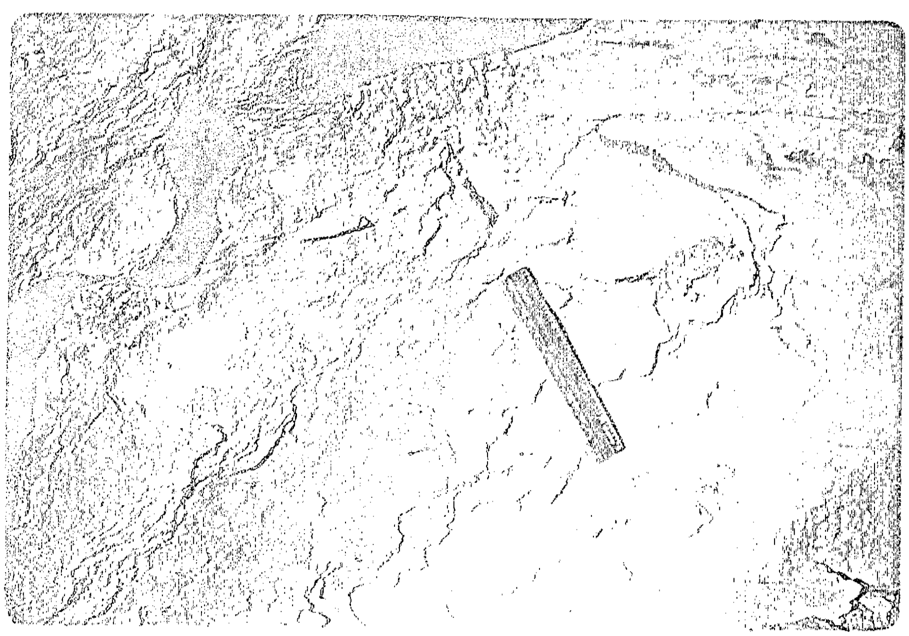
Trace fossils are also moderately abundant in Facies B sandstones, mostly in horizons with trough cross-stratification and large sandstone concretions. *Ophiomorpha* burrows are the dominant, or at least the best preserved, trace fossil in Facies B sandstones. It occurs as long tubes, generally less than 2.5 cm in diameter and as much as 70 cm or more in length (e.g., see Figure 15). In some units, the burrow wall is cemented by iron oxide which provides good preservation of the burrow. Some *Thalassinoides* also occur either separately or with *Ophiomorpha*; they are thinner, more branched than *Ophiomorpha*, and have smooth walls. The burrows are distributed sporadically throughout Facies B sandstones. They range from horizontal on bedding planes to vertically oriented; however, vertical to diagonal orientation is more common, especially in horizons with trough cross-stratification and large sandstone concretions. Bioturbation is moderately abundant in some horizons of Facies B (e.g., Kpl-3-8, Kpl-6-2, Kpl-7-5, Plate 1). Many parts of sandstone units within Facies B are devoid of trace fossils.

Figure 15. Photographs of *Ophiomorpha* in Facies B sandstones. A- Long tube of *Ophiomorpha*, with knobby and iron oxide-cemented wall, in unit Kp1-2-5. B- Small *Ophiomorpha* with well preserved knobby, iron oxide-cemented wall, scale 15cm.

A



B

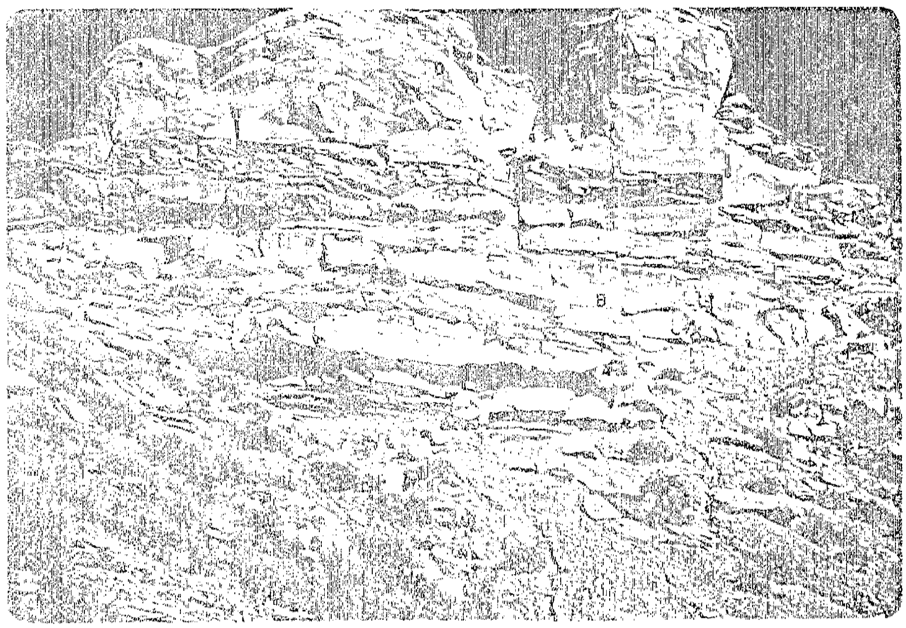


Facies C

Stratigraphy-. Facies C sandstones are overlain either by very thick, laterally extensive sandstones (e.g., sections Kpl-2, Kpl-3 and Kpl-4, Plate 1) or by thin to medium bedded, laterally extensive, tabular sandstones (e.g., sections Kpl-7, Kpl-1, Kpl-5, and Kpl-6, Plate 1). The very thick sandstones grade north to northeastward into Facies B, and south to southwestward into either the bedded units of this facies or into Facies D (e.g., section Kpl-3 and Kpl-4, Plate 1). The bedded, tabular sandstones grade north to northeastward into either the lower very thick sandstones (e.g., section Kpl-6, Plate 1) or into Facies B sandstones (e.g., section Kpl-1, Kpl-5, and Kpl-7); to the south to southwest they either change abruptly into Facies D (e.g., section Kpl-7, Plate 1, also see Figure 16) or wedge out into Facies E (e.g., section Kpl-1, Plate 1).

Facies C, as a whole, ranges in thickness from 3.2 meters (at section Kpl-7) to about 13.0 meters (at section Kpl-5, Plate 1). The well bedded sandstone units are generally less than 5 meters thick, and can be traced for about 2.5 kilometers along an approximately north-south trend. Individual very thick sandstone units are generally thick, mostly 4 to 8 meters thick, and can be traced along a north-south trend for a few kilometers. The sandstones of Facies C form either a cliff or a moderately steep slope. Lower contacts of the sandstone units with Facies B units are sharp, and locally

Figure 16. Photograph showing a general view of the Point Lookout Sandstone at section Kpl-7. Facies C consists of well bedded, burrowed sandstones, overlain by very thick sandstones of Facies D, and underlain by very thinly bedded to laminated muddy zone. B, C, and D refer to Facies B, C, & D; R.M. indicates ripple marks.



are irregular (e.g., unit Kpl-7, Plate 1). Upper contacts may be sharp (e.g., unit Kpl-6-12, Plate 1), sharp and irregular (e.g., Kpl-7-9), or gradational (e.g., unit Kpl-1-7).

Lithology-. Facies C consists of well developed, steep slope to cliff-forming, tabular sandstone units. The sandstone is generally tan in color, weathers to orangish gray, fine grained, moderately well to well sorted, subrounded to subangular, moderately indurated, very thin to thick bedded, laminated and cross-laminated sublitharenite to quartzarenite. Small lignitic fragments may occur (e.g., unit Kpl-1-7, Plate 1). The very thick sandstone units generally have more fine material content and are less indurated than the bedded units; they have more lignitic fragments, especially near the top (e.g., unit Kpl-2-8, Plate 1). Small iron oxide-cemented concretions (0.25 cm to about 4.0 cm in diameter) occur locally (e.g., units Kpl-6-11 & 12, Plate 1). The iron oxide in these concretions is mainly limonite; however, a few have pyritic centers indicative of incomplete oxidation. Facies C sandstones are generally devoid of body fossils, but burrows are moderately common though not abundant. Sandstones range in grain size from about 120 microns to 250 microns; they are generally slightly coarser than Facies B sandstones. A general trend of upward increase in grain size is typical in Facies C sandstones (see grain-size plots, Plate 1).

Sedimentary structures-. Some sandstone units of Facies C display subhorizontal stratification and/or low angle planar cross-stratification (e.g., see Figure 17). Poorly developed, or relicts of, planar cross-lamination is barely discernable in some parts of the very thick sandstone units of Facies C (e.g., units Kpl-2-8, Kpl-3-12, and Kpl-4-11 & 12).

The low angle planar cross-stratification, which characterizes Facies C sandstones, are tabular to wedge shaped sets. These tabular sets have planar, mostly nonerosional boundaries. They are generally less than 50 cm thick and can be traced laterally as much as 7 meters, large scale. Cross-laminae within the sets are relatively uniform in thickness, gently dipping (mostly less than 10 degrees) and subparallel with set boundaries. The rose diagram for cross-stratification that is common in the well bedded units of Facies C sandstones (Figure 18A) indicates that the dip direction of cross-laminae is dominantly in a northward direction, with a vector mean of N31°W. However, it also shows some measurements with a south to southwest trend; those sets dipping south to southwestward generally have higher dip angles than those dipping in the opposite direction. A rose diagram for the less bedded to massive sandstone units (Figure 18B) shows a vector mean of S27°E, and average dip angle of 15°.

Wave ripple marks are present in the lower part of unit Kpl-7-9 (Plate 1). They are oscillation type ripples with relatively flat topped crests. They are about 2 cm high and have a wave length of about 15 cm. Crest orientation from a few measurements range from 296 degrees to 307 degrees with

Figure 17. Photographs showing stratification in Facies C sandstones. A- From unit Kpl-6-11, shows subhorizontal stratification and low angle planar cross-stratification with cross-laminae subparallel with set boundaries; notice irregular, erosional contact (arrow) with unit 12 above, scale 15cm. B- From unit Kpl-6-12, well bedded, burrowed (*Ophiomorpha*) sandstones; also poorly expressed low angle planar cross-stratification with relatively uniform, gently dipping interlaminae subparallel with set boundaries occurs.

A

B

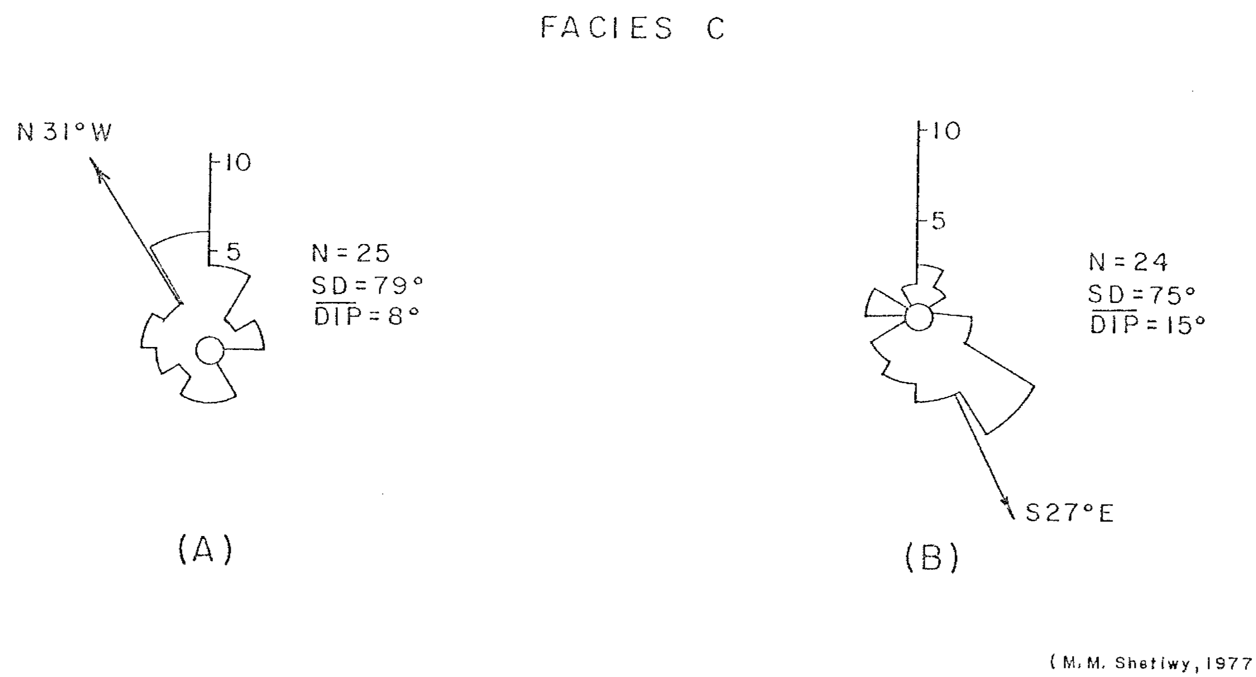


Figure 18. Paleocurrent rose diagrams showing dip directions of planar cross-stratification in Facies C; (A) units Kpl-5-4 (lower part), Kpl-6-12, and Kpl-7-9; (B) units Kpl-1-7; Kpl-2-8, and Kpl-5-4 (upper part).
N = number of readings; SD = standard deviation; $\overline{DIP}$ = arithmetic mean of dip angles of cross-strata.

an average of about 301 degrees (i.e., N59°W).

Fossils-. Body fossils are very sparse in Facies C sandstones, mostly poorly preserved bivalves in unit Kpl-4-12 (Plate 1). Trace fossils are rare but ubiquitous. *Ophiomorpha* is the most common type in Facies C sandstones. They are thin (generally less than 1.5 cm), rarely branched, mostly inclined to vertically oriented, but a few are horizontal (see Figure 19).

Vertical root structures occur at the top of unit Kpl-1-8, which is included in Facies C because of the transitional change from unit Kpl-1-7 sandstone.

Facies D

Stratigraphy-. Facies D consists of very thick, fossil-barren, cliff-forming, tabular sandstones (Figure 20). It is laterally extensive and occurs in most of the area (see Plate 1). Facies D is generally thick, ranging from about 6 meters at section Kpl-7 to about 25 meters at section Kpl-3; individual sandstone units are also relatively thick (see Plate 1).

Sandstone units of this facies overlie Facies C sandstones either with a sharp contact (e.g., sections Kpl-3 and Kpl-7), or gradationally through a zone of carbonaceous, muddy sandstone (e.g., section Kpl-2 and Kpl-4), or are locally separated from it by a carbonaceous to humic shale zone (e.g., section Kpl-6, Plate 1). Lower contacts of sandstone units are abrupt, locally irregular and sharp (e.g., units Kpl-2-

Figure 19. Photographs of *Ophiomorpha* in Facies C sandstones. They are generally rarely branched, range from about 1cm in diameter and more than 50cm long (A) to about 3cm in diameter (B), commonly with iron oxide-cemented wall and some exhibit knobby wall. Both pictures from unit Kpl-5-4, scale in A is 15cm and coin in B is a quarter.

A

B

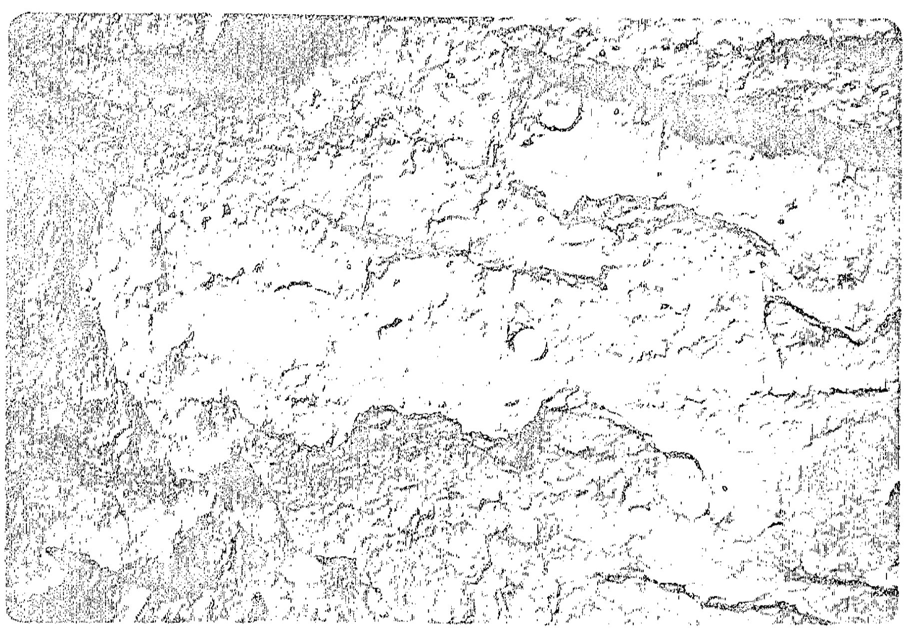
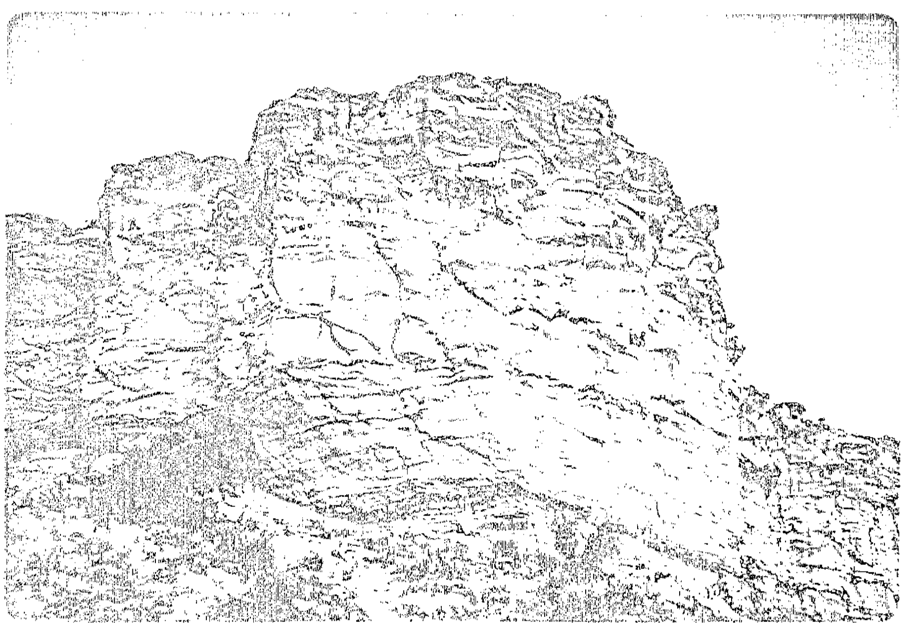


Figure 20. Photographs showing general view of the Point Lookout Sandstone. A- General view of section Kpl-2, person is near top of unit 2, higher ledge is of units 4 & 5; units 6, 7 and lower part of 8 form the overlying slope; cliff at top is shown in B. B- Upper part of unit Kpl-2-8, followed by units 9, 10 & 11, thickness of cliff shown is about 11m.

A

B



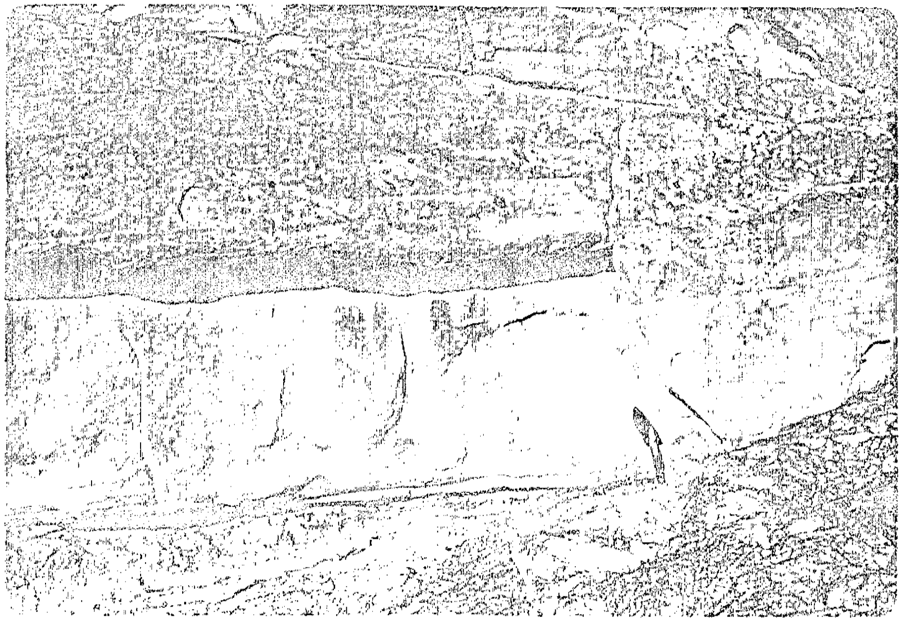
9 and Kpl-7-10); irregular, erosional, relatively shallow scour type contacts occur locally (see Figure 21). Two well developed channel shaped sandstone bodies exist in unit Kpl-3-15 (see Figure 21). Larger channel shaped sandstone bodies with moderately developed shallow scour basal surfaces also occur in units Kpl-3-17 & 19 (see Figure 21). Facies D sandstones are usually overlain by a succession of gray claystone, carbonaceous to humic shales, and humate and coal beds of Facies E; also they intertongue with Facies E units to the south-southwest. But north to northeastward they usually grade into Facies C sandstones.

Facies D sandstones represent a well developed sandstone body which forms a significant part of the Point Lookout sequence throughout most of the area; it represents the uppermost part of the Point Lookout Sandstone. Stratigraphically, Facies D represents a transition zone between the underlying finer, burrow and/or marine fossil-bearing sandstones of the Point Lookout Sandstone and the overlying humate and coal-bearing lower Menefee Formation.

Lithology-. Sandstones in Facies D are generally orangish light gray to tan in color, weathering to orangish tan, fine to medium grained, moderately well to well sorted, subangular to subrounded, moderately indurated, very thick, poorly cross-stratified, litharenite to sublitharenite. Small to fairly large clay clasts (some about 10 cm large) occur locally (e.g., units Kpl-2-9 and Kpl-6-14 & 15, Plate 1). Carbonaceous debris (or plant debris) occurs in thin,

Figure 21. Photographs of sandstone units in Facies D. A- Irregular, erosional shallow trough shaped (scour) lower contacts of sandstone units in Facies D; note thin lignitic lens just below lower sandstone unit (at scale, 27cm), from unit Kpl-3-17. B- Well developed lenticular (channel), medium grained, fossil-barren sandstone cutting through underlying poorly bedded, rippled, burrowed (*Ophiomorpha*) and fossil-bearing (shark teeth) fine sandstone (at stick, 150cm); another similar but thinner and shorter channel form exists just to the left, and a less developed one to the right, all of which pinch out laterally within 50m.

A



B

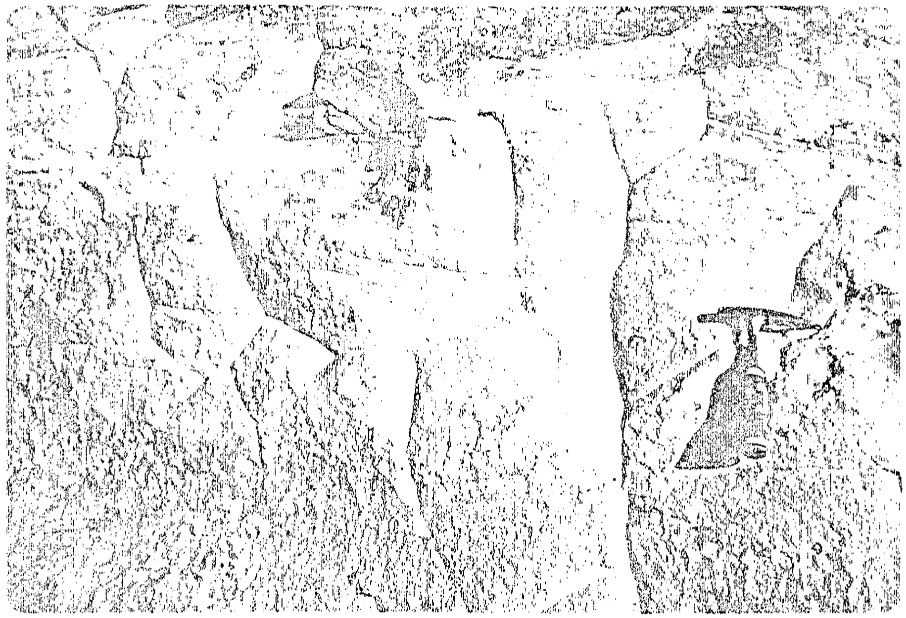
muddy zones (e.g., units Kpl-4-14 and Kpl-6-15, Plate 1); lignitic fragments and very thin lenticular coal pockets also occur in the muddy sandstone zone just below unit Kpl-2-9. Facies D sandstones grade upward into either coarser sandstone with large trough cross-stratification (e.g., units Kpl-7-11, Plate 1), or into finer, muddier, laminated and rippled, carbonaceous thin sandstone beds interbedded with very carbonaceous muddy zones (e.g., unit Kpl-6-15, Plate 1).

Grain size of sandstones in Facies D ranges from about 130 to about 360 microns, mostly between 200 and 300 microns (see grain-size plots, Plate 1). They contain the coarsest sandstones within the Point Lookout sequence. Although grain size within the Facies D sequence may progressively decline upward, or show no significant changes upward, it may also progressively increase upward (see grain-size plots, Plate 1); Facies D sandstones in general represent the uppermost part of the progressively upward increasing grain-size trend of the Point Lookout sequence.

Sedimentary structures-. Poorly developed cross-stratification occurs locally in sandstone units in Facies D. It is very shallow trough to wedge type, large scale cross-stratification (see Figure 22A & B). Moderately developed large trough cross-stratification occurs in units Kpl-2-11 and Kpl-7-11 (see Figure 22C). Thickness of individual sets ranges from 10 cm to about 65 cm, mostly between 25 cm and 5 cm, and range in lateral extent from a few meters for the trough type to several meters for the wedge type.

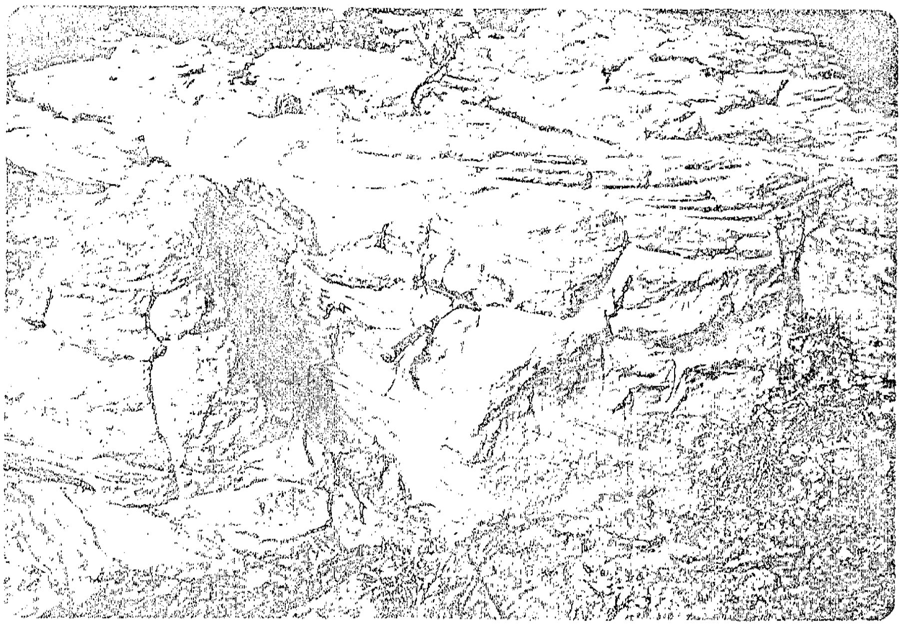
Figure 22. Photographs of cross-stratification in Facies D sandstones. A- Large scale, trough cross-stratification in unit Kpl-3-19. B- Large scale wedge cross-stratification in unit Kpl-3-19, with tangential to angular interlaminae (above the hammer); notice erosional surfaces. C- Moderately developed, large scale trough cross-stratification in unit Kpl-2-11.

A



B

C



Paleocurrent rose diagram (Figure 23A) shows current direction was mainly northward, vector mean of N7°E, for the wedge to planar type. But large trough cross-stratification is dipping dominantly northeastward (Figure 23B); vector mean is N55°E. Figure 23 shows southwest dipping components are almost absent.

Some ripple marks in the lower part of unit Kpl-2-11 (Plate 1) are slightly asymmetrical, with a wave length of 15 to 25 cm and an amplitude of 1 to 3 cm. Crest orientation is about 92-272 degrees, and current directions are approximately due north (N2°E). Some small ripple marks also occur in unit Kpl-6-15 (Plate 1); but they are poorly developed, and no reliable measurement was possible.

Fossils-. Neither macroinvertebrate fossils nor trace fossils, such as those in underlying Facies A, B, and C occur in Facies D sandstones. However, *Teredolithus* type burrows are common locally (e.g., units Kpl-2-9, Kpl-6-14, and Kpl-6-15, Plate 1). They are irregular, twisted, sand-filled tubes with brown carbonaceous material on the outer surface (Figure 24A). Other burrows with narrow, curved to branched, horizontally oriented tubes also exist in unit Kpl-6-14 (see Figure 24B). A well preserved log cast occurs near the top of unit Kpl-5-10 (see Figure 24C). It is oriented in a 46°-226° trend with its thin end pointing southwestward.

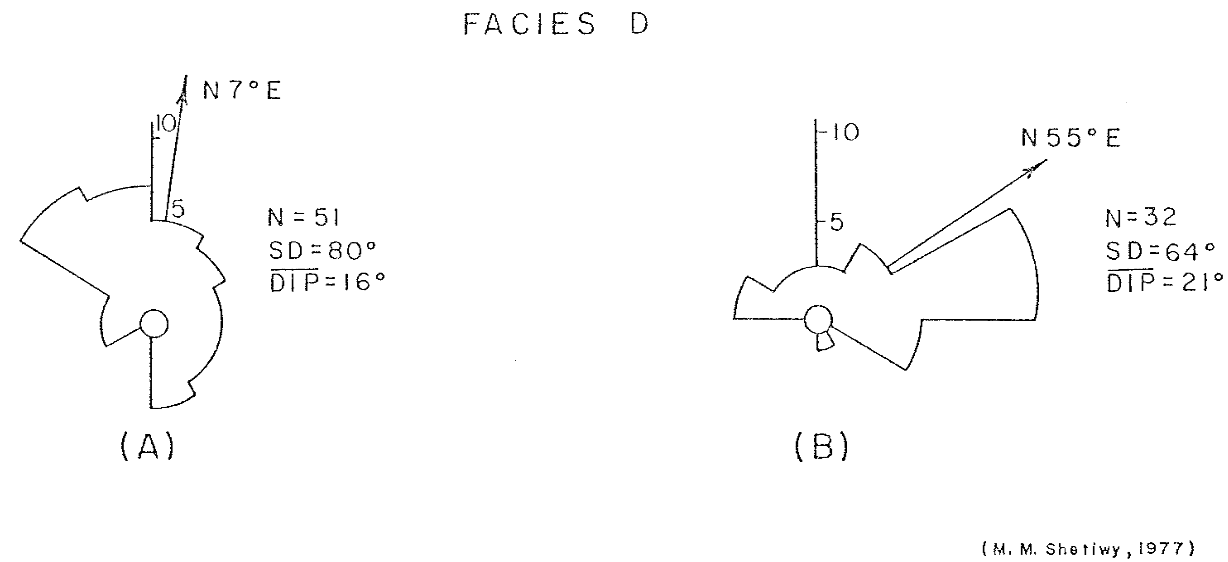
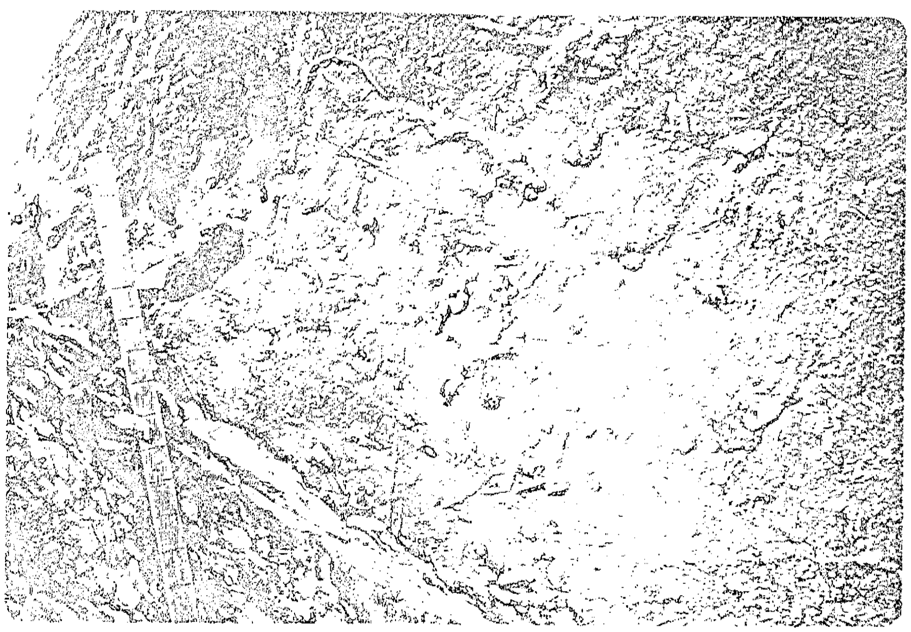


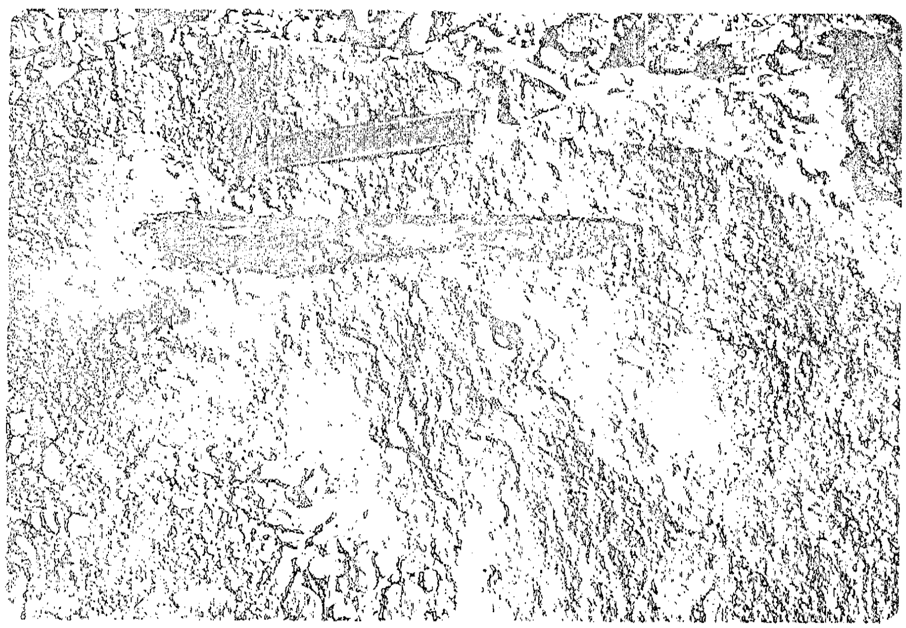
Figure 23. Paleocurrent rose diagrams showing dip directions in Facies D; (A) large scale planar to wedge cross-stratification, from units Kp1-2-9, Kp1-3-17 & 19, Kp1-6-14 and Kp1-7-10; (B) large scale trough cross-stratification, from units Kp1-2-11, Kp1-6-17 and Kp1-7-11.
N = number of readings; SD = standard deviation; $\overline{DIP}$ = arithmetic mean of dip angles of cross-strata.

Figure 24. Photographs showing trace fossils in Facies D sandstones. A- Samples of teredo structure from unit Kpl-2-8 (top) & 9, brown color on surface is carbonaceous material, scale is 15 cm. B- Branched, thin burrows (worms? and/or insects?) and teredo borings (at stick, each division is 5cm) in unit Kpl-6-14. C- Well developed log cast in unit Kpl-5-10, thin end pointing southwestward, scale 15cm.

A

B





Facies E

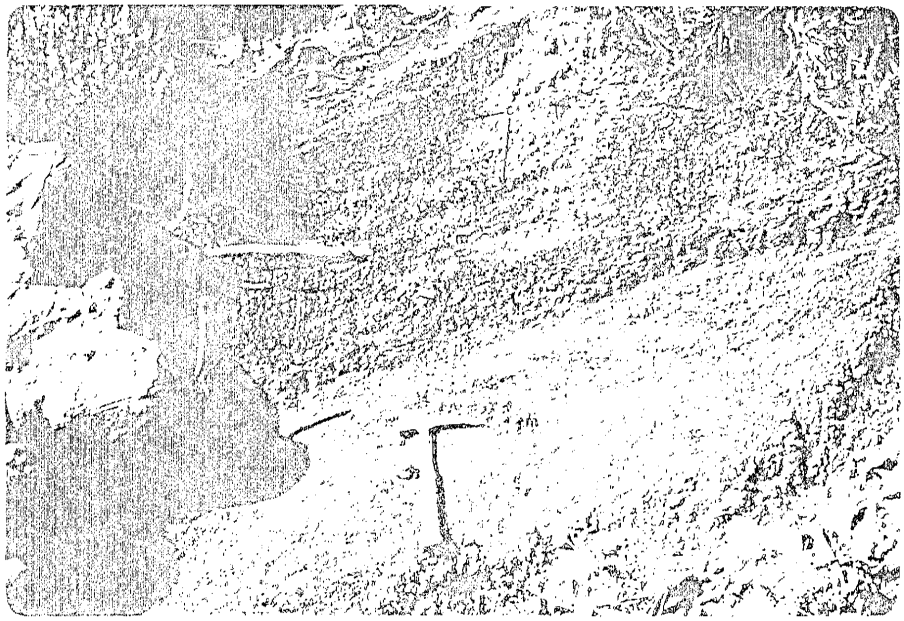
Stratigraphy-. Facies E consists of variegated units of mudstone, very fine grained carbonaceous silty sandstone, brown humic shale, humates and thin coal beds, and lenticular to tabular, medium grained sandstones. They are either interbedded or intertongue with each other; Figure 25 shows some of the units in Facies E sequence. Facies E as a whole occurs throughout the area, forming a gentler slope above prominent sandstone ledges of the Point Lookout Sandstone. Individual units in this facies vary in thickness laterally within a short distance; they either grade or pinch out laterally into one another or into top units of Facies D (e.g., at sections Kpl-1 and Kpl-6). Figure 26 illustrates the stratigraphic relationship of units from Facies E and Facies D at measured stratigraphic section Kpl-6.

At measured stratigraphic section Kpl-1, Facies E sequence contains a fine grained, well developed sandstone unit with *Ophiomorpha* and ripple marks (unit Kpl-1-12, Plate 1). At this locality Facies E sequence is also capped by prominent, cliff-forming sandstones with bivalve fossils and a few *Ophiomorpha* burrows in the upper part (unit Kpl-1-29, Plate 1).

Stratigraphically, Facies E units overlie Facies D or Facies C sandstones and maintain an intertonguing relationship with them laterally in a south to southwest trend. They also form the basal part of the typical Menefee Formation, which consists generally of similar units in repetitive

Figure 25. Photographs showing typical units of Facies E and lower Menefee Formation. A- Carbonaceous mudstone (m), followed by humate bed (h), highly carbonaceous mudstone (m), and coal lenses (c), from section Kpl-6. B- Prominent, thick to very thick lenticular sandstone bodies in the Menefee Formation, units typically pinch out laterally within 100-150m, notice repetition of slope-forming less resistant mudstones and humate zones and the more resistant channel sandstone bodies, from section Kpl-5.

A



B

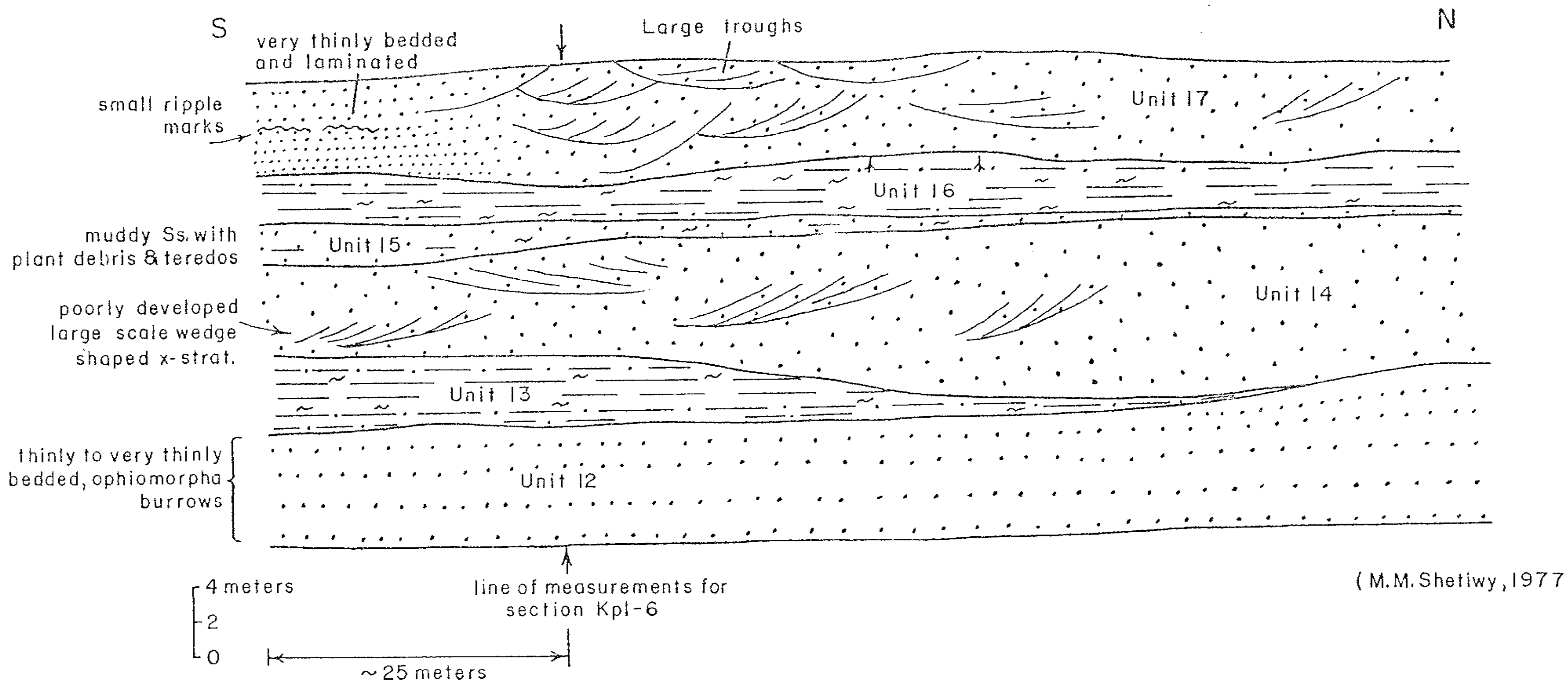


Figure 26. Schematic sketch illustrating the stratigraphic relationship between units from Facies C (unit 12), Facies D (unit 14), and Facies E (units 13, 16 & 17) at measured stratigraphic section Kpl-6. Vertical scale applies at line of section measurement, other parts are approximate.

sequences.

Lithology-. Mudstone (or claystone) units (e.g., units Kpl-1-17 & 23, Kpl-2-12, Kpl-6-13, Plate 1) vary in shades of gray, are moderately indurated in more silty zones, brownish gray and friable in zones with abundant fine carbonaceous matter. Siderite concretions which are partially to completely replaced by limonite occur in unit Kpl-6-13. These units may have sharp to gradational contacts with brown humic shales or silty sandstone units.

Silty sandstone units (e.g., units Kpl-1-10, 14, 18 & 20, Kpl-2-16, upper part of Kpl-6-16, Plate 1) are generally light gray, very fine grained, poorly sorted, friable, and muddy. They contain plant debris and impressions of small logs. Vertical root casts are moderately common, especially in the upper parts of the units. Silty sandstones may have abrupt contacts with brown humic shales (e.g., unit Kpl-1-14, Plate 1), but have more gradational contacts with mudstones (e.g., Kpl-6-16, Plate 1).

Brown humic shales (e.g., units Kpl-1-13 & 15, Kpl-6-18, Plate 1) are light to dark brown, fissile to friable, slightly to moderately silty, with abundant plant debris and carbonized wood material (see Figure 25A). Plant debris and wood material are oriented parallel to bedding surfaces but lack preferred directional orientation on the bedding plane. Several of these units are classic examples of humates.

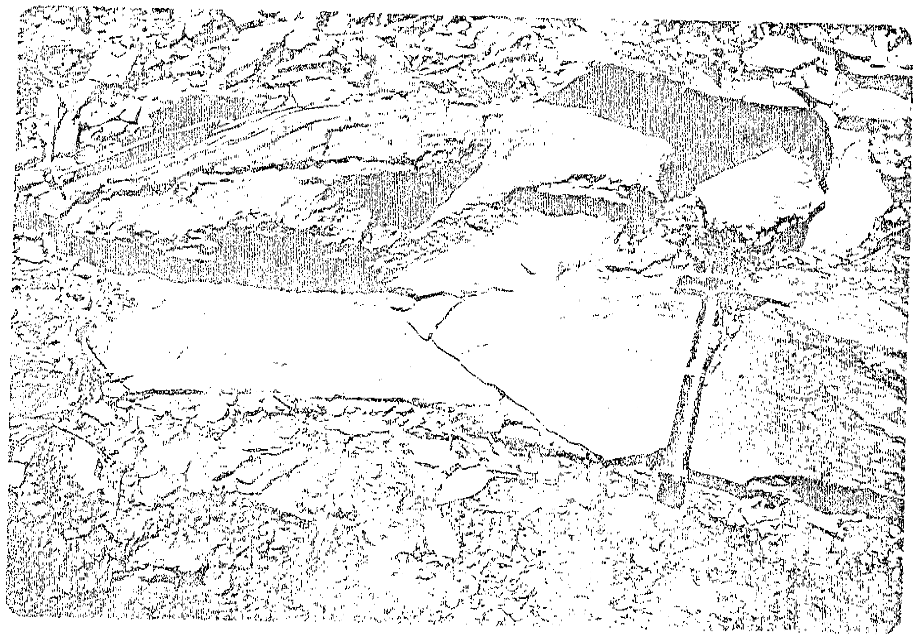
Coal seams occur in association or interbedded with humates (e.g., units Kpl-1-9, 11, 16, 22, & 25, Kpl-2-13, Kpl-

6-18, Plate 1). They range in thickness from a few centimeters to more than 1 meter. Surface samples indicate the coals are moderately dirty but appear to be high rank, most likely sub-bituminous coal.

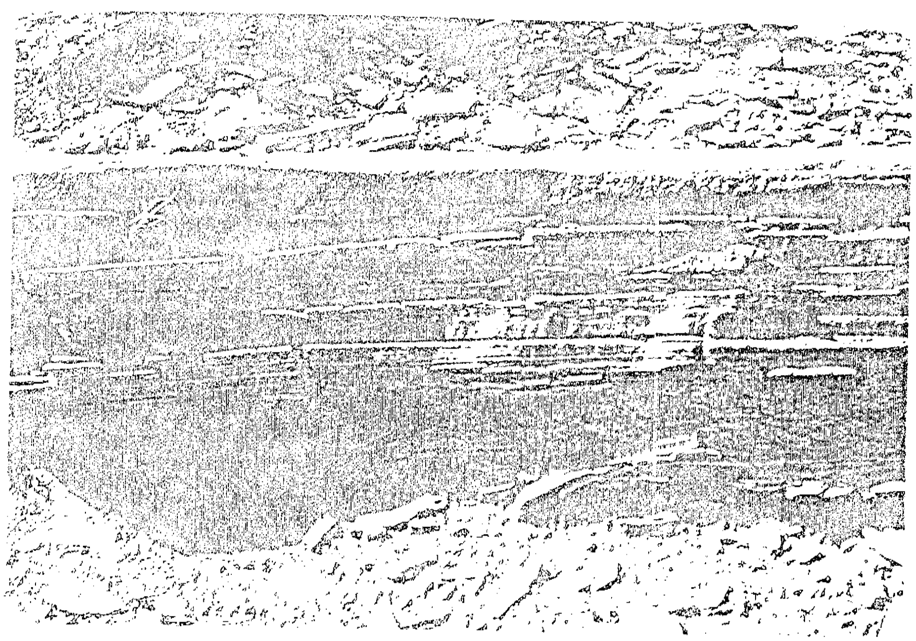
Prominent, very thick, moderately laterally extensive, lenticular sandstone bodies occur in Facies E (e.g., units Kpl-2-15, Kpl-6-17, Plate 1, also see Figure 25B). The sandstones are yellowish gray to tan, weather to slightly darker color, fine to medium grained, moderately sorted, subangular to subrounded (mostly subangular), moderately indurated litharenite. They are poorly, medium to very thick bedded with some large scale, wedge to trough type cross-stratification. The lower contact of units is well defined, sharp, irregular, locally erosional (e. g., units Kpl-2-15, and Kpl-6-17, Plate 1, also see Figure 27A). The upper contact ranges from moderately sharp, and nonerosional, to gradational into carbonaceous muddy finer sandstones (e.g., units Kpl-2-15 & 16, Plate 1). Grain size ranges from about 150 to about 220 microns. An abrupt increase in grain size, relative to underlying units, is a characteristic feature of these sandstones within the sequence (see grain-size plots, Plate 1). A slight to moderate upward decline in grain size may occur within individual sandstones. Carbonaceous debris is generally sparse in most of these sandstones; however, it is fairly abundant in finer silty sandstones.

Figure 27. Photographs of sandstone units in Facies E. A- Very thick, lenticular sandstone with poorly developed large scale trough cross-stratification and irregular erosional basal boundary, from unit Kpl-6-17. B- Sandstone unit in A changes laterally within about 30m into laminated to very thinly bedded, slightly finer sandstone with a few small nearly symmetrical ripple marks, scale 15cm.

A



B



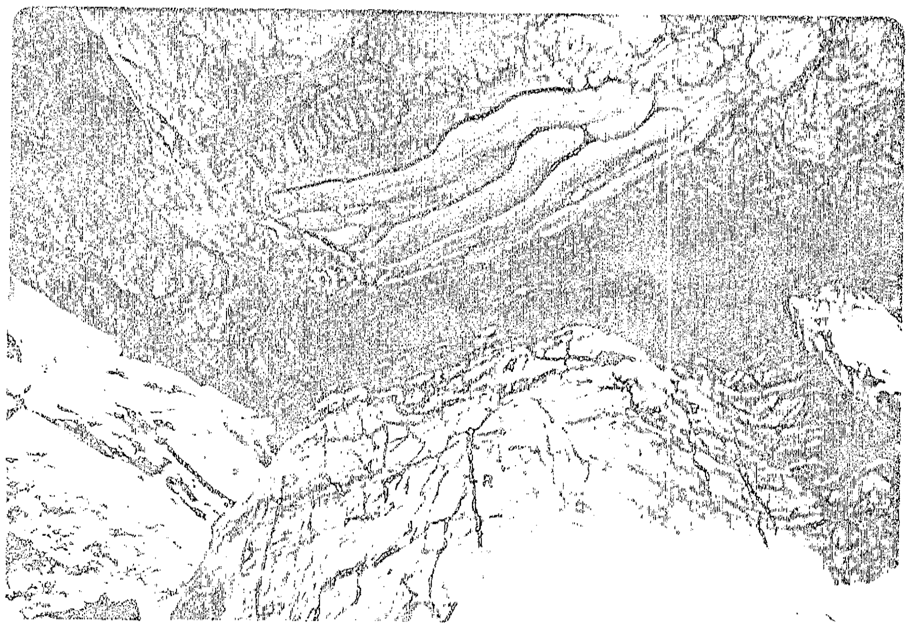
Sedimentary structures-. Except for the prominent thick sandstone units, sedimentary structures are rare in other units in Facies E. Very small scale cross-lamination (ripple cross-lamination) occurs in lenticular silty sandstones (e.g., units Kpl-1-14, Plate 1). Unit Kpl-1-18 exhibits poorly developed, nearly symmetrical small ripple marks and a few mud-cracks on muddy surfaces. Similar small scale ripple marks of interference type occur in unit Kpl-1-20 (Plate 1); they have 6 to 8 cm wavelength and 0.6 to 0.7 cm amplitude. A few measurements from these ripples show crest orientation between 48°-228° and 67°-247°, and the apparent current direction was due northwest (approximately N30°W).

The prominent thick sandstones are characterized by zones of large scale, high angle trough cross-stratification. The planar cosets are bounded by planar surfaces, and cross-strata within them exhibit tangential to angular relationship with lower boundaries. Trough type sets are also of large scale, and cross-strata within them show discordant tangential relationship with lower boundaries. Paleocurrent data plots are shown in Plate 1 (see units Kpl-2-15 and Kpl-6-17, Plate 1). Trends of trough axes from these sandstones indicate paleocurrents due northwest for the sandstone body of unit Kpl-6-17. Trough cross-stratified sandstone of unit Kpl-6-17 changes laterally (within about 30 meters to the south) into laminated, slightly finer sandstone with a few small ripple marks (see Figure 27B).

These ripples are nearly symmetrical with a wavelength of 5 cm or less and about 0.7 cm amplitude. Crest orientation is approximately 290°-110°, and paleocurrent is approximately N25°E. Interference ripple marks also occur at the bottom of unit Kpl-2-15 (Plate 1). Paleocurrent analyses of trough and planar cross-stratification from channel sandstone bodies in the Menefee Formation by Mannhard (1976) show dip directions mainly due northeast, with trough type showing a wider range.

Fossils-. No macroinvertebrate fossils occur in Facies E. Carbonized wood and plant fragments and debris are commonly abundant in many units (see Plate 1). *Thalassenoides?* burrows occur in units Kpl-1-20 and 26, and Kpl-2-15 (Plate 1). *Teredolithus* structure also exists in the upper part of unit Kpl-1-20 (see Figure 28). Vertically oriented root structures (see Figure 28) are fairly abundant in several units of Facies E; they destroyed some sedimentary structures in some units (e.g., unit Kpl-1-10, Plate 1).

Figure 28. Photograph of trace fossils in Facies E units. *Teredolithus* on basal surface of sandstone interval above a carbonaceous muddy zone in unit Kpl-1-18, vertical to oblique root structure (R) is shown in carbonaceous sandstone in lower part, scale 15cm.



PETROGRAPHY OF THE POINT LOOKOUT SANDSTONE

Textural Characteristics

Mechanical grain-size analyses

General

Grain-size analyses were conducted from representative samples from sandstone units through the stratigraphic section Kpl-6 (see Plate 1 for location) where all the recognized facies occur; a few more samples from some of the facies in other stratigraphic sections were added. The objectives of grain-size analyses are to: 1) validate the visual estimates shown on Plate 1; 2) describe the texture of the sandstones; and 3) define any significant differences in texture between the various sandstone facies. Observed textural variations are interpreted in terms of sorting processes that operated in the environment (or subenvironment) of deposition.

Three commonly used graphical displays of the results of grain-size analyses are used in this study to determine textural differences: 1) univariate analysis in which individual grain-size parameters of the various sandstone facies are compared; 2) bivariate analysis in which one parameter is plotted against another in the form of scatter diagrams; and 3) CM diagrams in which the coarsest one percentile (in phi) is plotted against median diameter (in phi).

Results

Table 1 shows the results of the grain-size analyses.

Table 1. Results of sieve analyses (mud fraction is not included)

	SAMPLE	1st %	Mo(ϕ)	Md(ϕ)	Mz(ϕ)	σ_I	SK_I	K_G
Facies A & B	6-2a	2.96	3.37	3.40	3.43	0.23	0.04	0.87
	6-2b	2.92	3.12	3.29	3.33	0.23	0.23	1.02
	6-3a	2.96	3.37	3.38	3.40	0.22	0.14	0.95
	6-5b	2.99	3.37	3.44	3.45	0.24	0.09	0.85
	6-5d	2.96	3.37	3.43	3.43	0.21	0.04	0.96
	6-7a	2.75	3.12	3.33	3.35	0.26	0.08	1.16
	6-9a	2.98	3.62	3.54	3.52	0.21	-0.15	1.02
	6-9c	2.83	3.62	3.53	3.52	0.23	-0.09	0.96
	6-10a	2.70	3.37	3.42	3.41	0.26	-0.05	0.92
	6-10c	2.72	3.62	3.54	3.51	0.25	-0.23	1.09
	(range)	(2.70-2.99)	(3.12-3.62)	(3.29-3.54)	(3.33-3.52)	(0.21-0.26)	(-0.23-0.23)	(0.85-1.16)
	(average)	(2.88)	(3.39)	(3.43)	(3.43)	(0.23)	(0.01)	(0.98)
Facies C	6-11a	2.75	3.12	3.19	3.26	0.14	0.22	0.81
	6-12a	2.20	2.87	2.90	2.95	0.37	0.26	1.34
	6-12b	2.31	2.87	2.94	2.99	0.31	0.27	1.30
	6-12d	1.80	2.87	2.83	2.84	0.38	0.08	1.32
	(range)	(1.80-2.75)	(2.87-3.12)	(2.83-3.19)	(2.84-3.26)	(0.14-0.38)	(0.08--.27)	(0.8-1.34)
	(average)	(2.26)	(2.93)	(2.96)	(3.01)	(0.30)	(0.21)	(1.19)

Table 1 cont'd.

Facies D

SAMPLE	1st %	Mo(ϕ)	Md(ϕ)	Mz(ϕ)	σ_I	SK_I	K_G
6-14a	1.75	2.37	2.48	2.49	0.44	0.12	1.21
6-14c	1.04	2.37	2.33	2.28	0.57	-0.01	1.20
6-15a	2.06	2.87	2.89	2.93	0.37	0.18	1.20
6-17c	1.14	2.37	2.31	2.29	0.46	0.02	1.19
(range)	(1.04-2.06)	(2.37-2.87)	(2.31-2.89)	(2.28-2.93)	(0.37-0.57)	(-0.01-0.18)	(1.19-1.21)
(average)	(1.50)	(2.49)	(2.50)	(2.50)	(0.46)	(0.08)	(1.20)

The tabulated data represent the graphic grain-size statistics following the procedure of Folk and Ward (1957) (see Appendix A). Mud content of the analyzed sandstone samples is not included in these size analyses because it was noticed that some lithic fragments disintegrate during even the most careful preliminary treatment. This pehnomenon was recognized by comparison of the constituents before and after sample treatment for sieve analysis, using a binocular microscope, and was confirmed by thin section analysis of a portion of the same hand specimen. However, in order to test the significance of the size-analysis approach with respect to the whole sample, mud fractions of several of the sieved samples were also analyzed using the pipette method. The combined sieve and pipette size data are shown in Table 2.

The grain size of sandstone units in the Point Lookout sequence ranges from very fine to medium; the sandstones are generally very well to moderately well sorted (Table 1) or moderately to poorly sorted (Table 2). The true sorting would lie somewhere between the estimate in Table 1 and that in Table 2 because of the addition of fines produced during sample preparation. Results of grain size analyses (Tables 1 and 2) indicate that no major textural differences exist between the various sandstone facies, especially adjacent facies, but slight differences occur between the various facies, especially in terms of mean grain size and standard deviation (M_Z and σ_I, Tables 1 and 2). Major textural dif-

Table 2. Results of mechanical combined sieve and pipette grain-size analyses

	SAMPLE	1st %	Mo(ϕ)	Md(ϕ)	Mz(ϕ)	σ_I	SK_I	K_G	Silt %	Clay %
Point Lookout Sandstone	6-5d	2.98	3.37	3.50	3.73	0.99	0.70	3.61	16.54	4.00
	6-9a	3.01	3.62	3.60	3.64	0.82	0.49	5.09	11.80	3.68
	6-9c	2.89	3.62	3.60	3.75	0.99	0.63	4.36	13.78	4.73
	6-10a	2.72	3.37	3.57	3.86	1.15	0.67	2.39	22.34	5.17
	6-10c	2.73	3.62	3.64	3.81	0.93	0.58	3.23	19.74	2.81
	6-11a	2.76	3.12	3.31	3.56	1.04	0.79	2.53	17.39	2.75
	6-12a	2.20	2.87	2.95	3.16	0.99	0.66	2.91	11.55	2.16
	6-12b	2.32	2.87	2.97	3.15	0.85	0.67	3.08	10.22	2.40
	6-12d	1.75	2.87	2.90	3.09	1.01	0.57	2.97	12.07	2.34
	6-14a	1.63	2.37	2.56	2.73	1.09	0.55	3.00	10.53	1.88
	6-14c	1.18	2.37	2.38	2.46	0.84	0.30	1.71	9.11	0.34
	(range)	(1.18-3.01)	(2.37-3.62)	(2.38-3.64)	(2.46-3.86)	(0.82-1.15)	(0.30-0.79)	(1.71-5.09)	(9.11-22.34	(0.34-5.17)
	(average)	(2.38)	(3.10)	(3.18)	(3.36)	(0.97)	(0.60)	(3.27)	(14.10)	(2.93)
Menefee Channel Sandstones*	1b-5b	2.11		2.63	2.76	0.94	0.67	6.42	8.3	2.8
	2-3a	2.54		3.17	3.49	1.24	0.69	3.19	13.6	6.6
	3-0	2.69		3.50	4.07	1.47	0.77	1.85	27.6	7.4
	3-2b	2.36		2.79	3.38	1.52	0.88	3.21	13.2	7.3
	4-2b	1.66		2.43	2.44	0.81	0.37	2.77	5.9	2.3

*Results from Mannhard (1976)

Table 2 cont'd.

Menefee Channel Sandstones

SAMPLE	1st %	Mo(ϕ)	Md(ϕ)	Mz(ϕ)	σ_I	SK_I	K_G	Silt %	Clay %
5-2d	1.16		1.75	1.91	1.07	0.66	4.66	7.1	2.1
5-6b	2.16		2.88	3.26	1.27	0.74	2.66	14.1	4.8
5-8e	2.67		3.69	5.11	2.53	0.79	1.01	26.4	18.4
6-2b	1.94		3.13	5.22	3.15	0.79	0.53	12.1	27.8
8-2c	1.94		2.60	3.28	1.76	0.80	3.26	11.8	8.7
8-6b	1.68		2.21	2.39	1.11	0.71	4.21	7.2	4.6
(range)	(1.16-2.69)		(1.75-3.69)	(1.91-5.22)	(0.81-3.15)	(0.37-0.88)	(0.53-6.42)	(5.9-27.6)	(2.1-27.8)
(average)	(2.08)		(2.80)	(3.39)	(1.53)	(0.71)	(3.07)	(13.4)	(8.0)

ferences do exist between the Point Lookout marine sandstones and the Menefee channel sandstones (Table 2).

Comparison of grain-size measurements from mechanical analyses with visual estimates of grain size (shown on Plate 1) shows that field visual estimates are in very close agreement with the laboratory results shown in Table 1, generally within a quarter phi interval. Accordingly, the grain-size representation along each stratigraphic section (Plate 1) is a reasonably accurate representation of the grain-size distribution.

Detailed visual estimates of grain size at the outcrop, though time consuming, are quite meaningful because: 1) they provide a comprehensive approach of comparison of units; 2) they clearly show grain size fluctuations within all the units; and 3) careful estimates reduce the need for extensive mechanical analyses in the laboratory.

Univariate analysis-. The distinction between the sandstone facies within the Point Lookout Sandstone, as well as its contrast from the Menefee channel sandstones on the basis of individual grain-size statistics, are illustrated in Figures 29 and 30. The distinction is clearest in terms of mean grain size and standard deviation. The results show some indicative trends of change in grain size parameters. Sandstones from Facies A are the finest and least sorted; Facies B, Facies C, and Facies D sandstones are progressively coarser and better sorted. Channel sandstones from the Menefee Formation are generally finer than Facies C and Facies D,

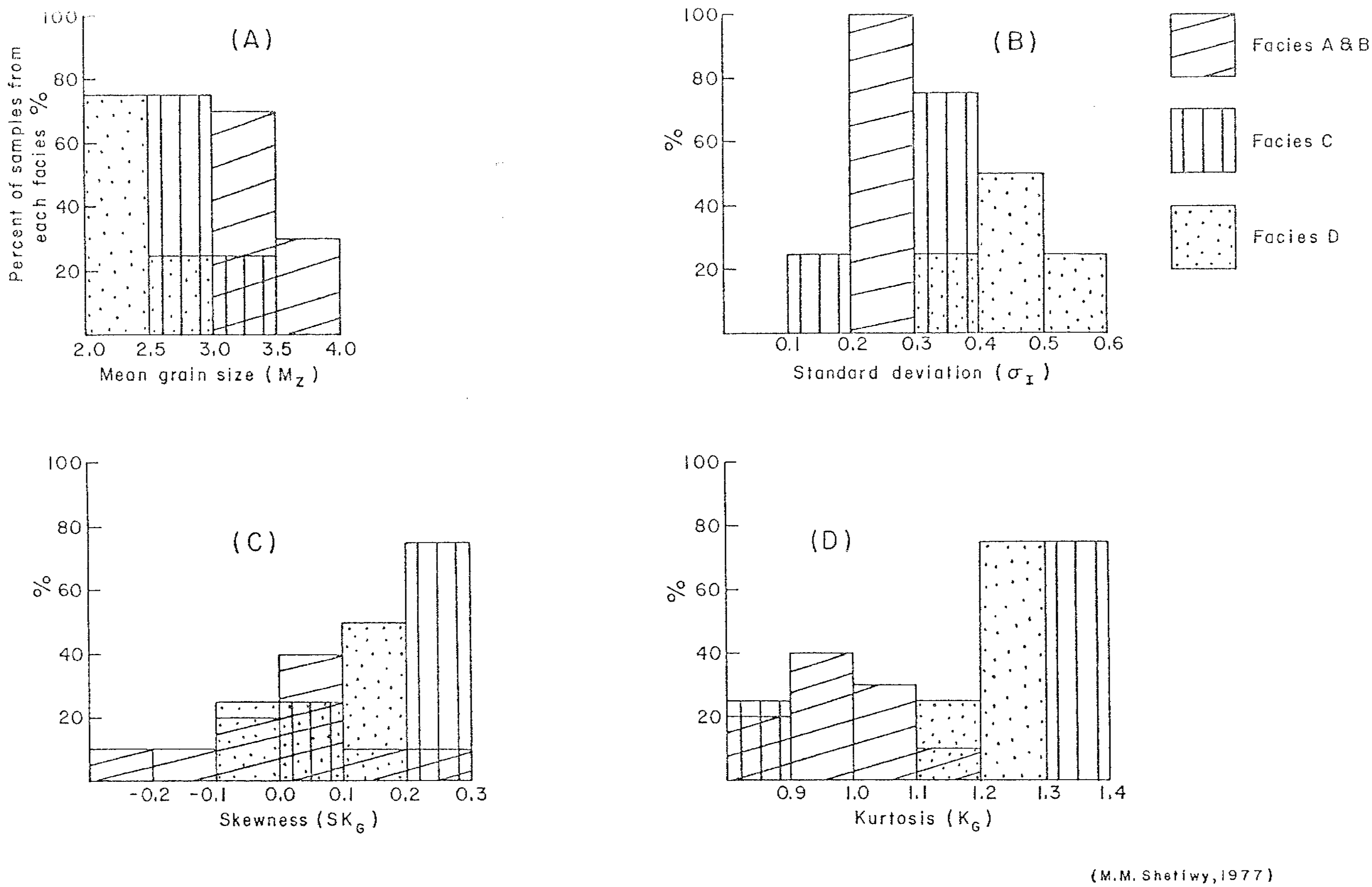


Figure 29. Frequency distribution histograms showing textural differences between the recognized sandstone facies in the Point Lookout Sandstone (data from Table 1).

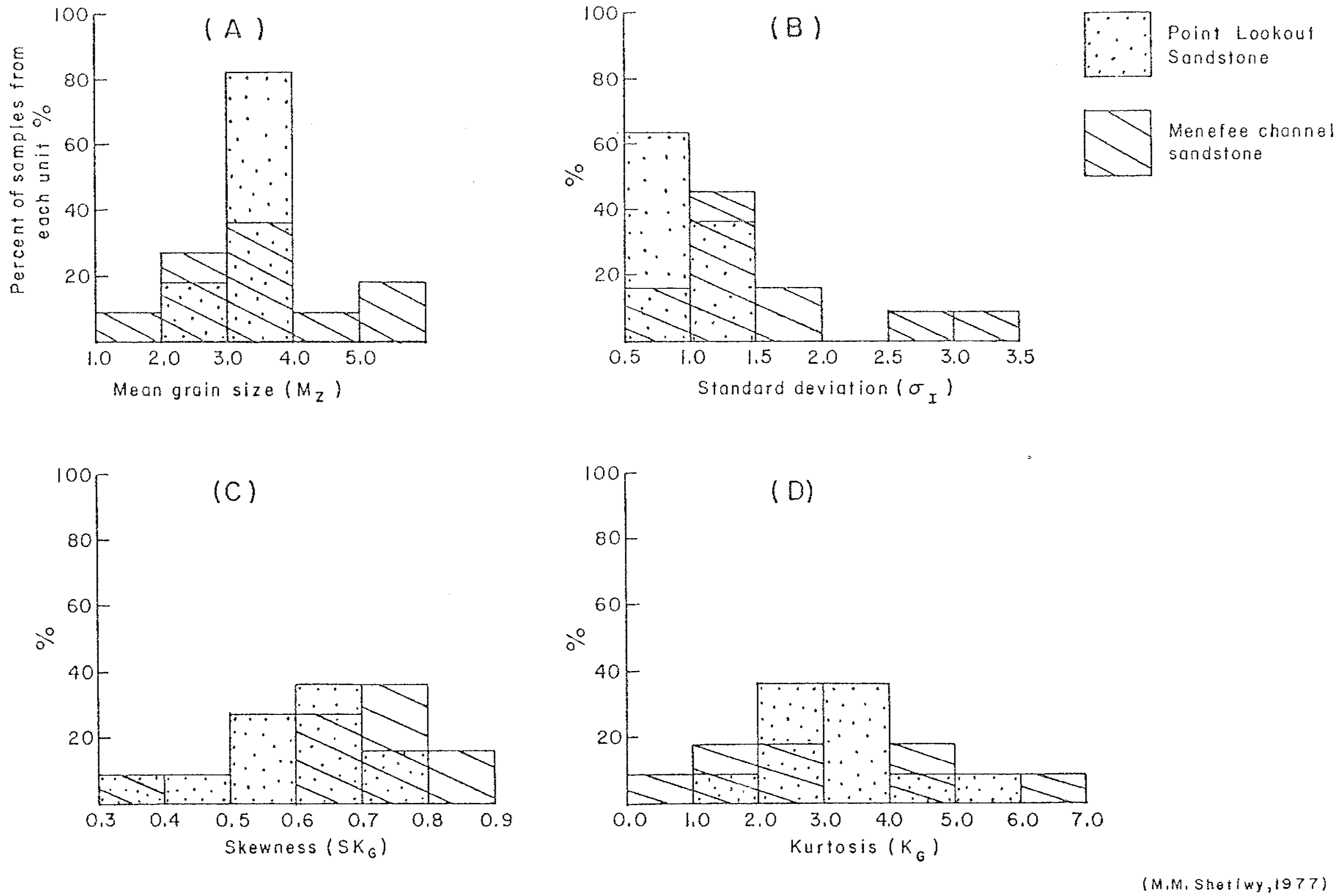


Figure 30. Frequency distribution histograms showing textural differences between Point Lookout Sandstone and Menefee channel sandstones (data from Table 2).

but exhibit a large range of mean grain size, and are poorly sorted (see Table 2); they are positively skewed (arithmetic average SK_I = +0.72) and with highly variable kurtosis (range from 0.53 to 6.42 and arithmetic average 2.92). Although skewness and kurtosis are not significant in this analysis (see discussion later this chapter), general trends are apparent if the average values are used (see Tables 1 and 2).

Bivariate analysis-. Three binary plots were made of the analyzed sandstone samples, following the methods of Friedman (1961 and 1967). The diagrams (Figure 31) represent a combination of mean grain size versus standard deviation (sorting), standard deviation versus skewness, and kurtosis versus skewness. Samples from certain facies fall, more or less, into distinct regions or trends on the diagrams, providing a fairly reasonable distinction between the different sandstone facies.

In Figure 31A, mean grain size versus sorting, the samples plot in a trend with a negative slope. Samples from Facies D plot at the lower right end, samples from Facies A and B cluster at the upper left end of the trend, and samples from Facies C plot in the middle of the trend.

The sorting versus skewness plot (Figure 31B) shows that samples from Facies A and B occupy a long zone in the lower part of the diagram, Facies C samples lie in the middle of the right half of the diagram, and Facies D samples plot near the middle of the upper part of the plot. It is clear in this graphic representation that the separation of the

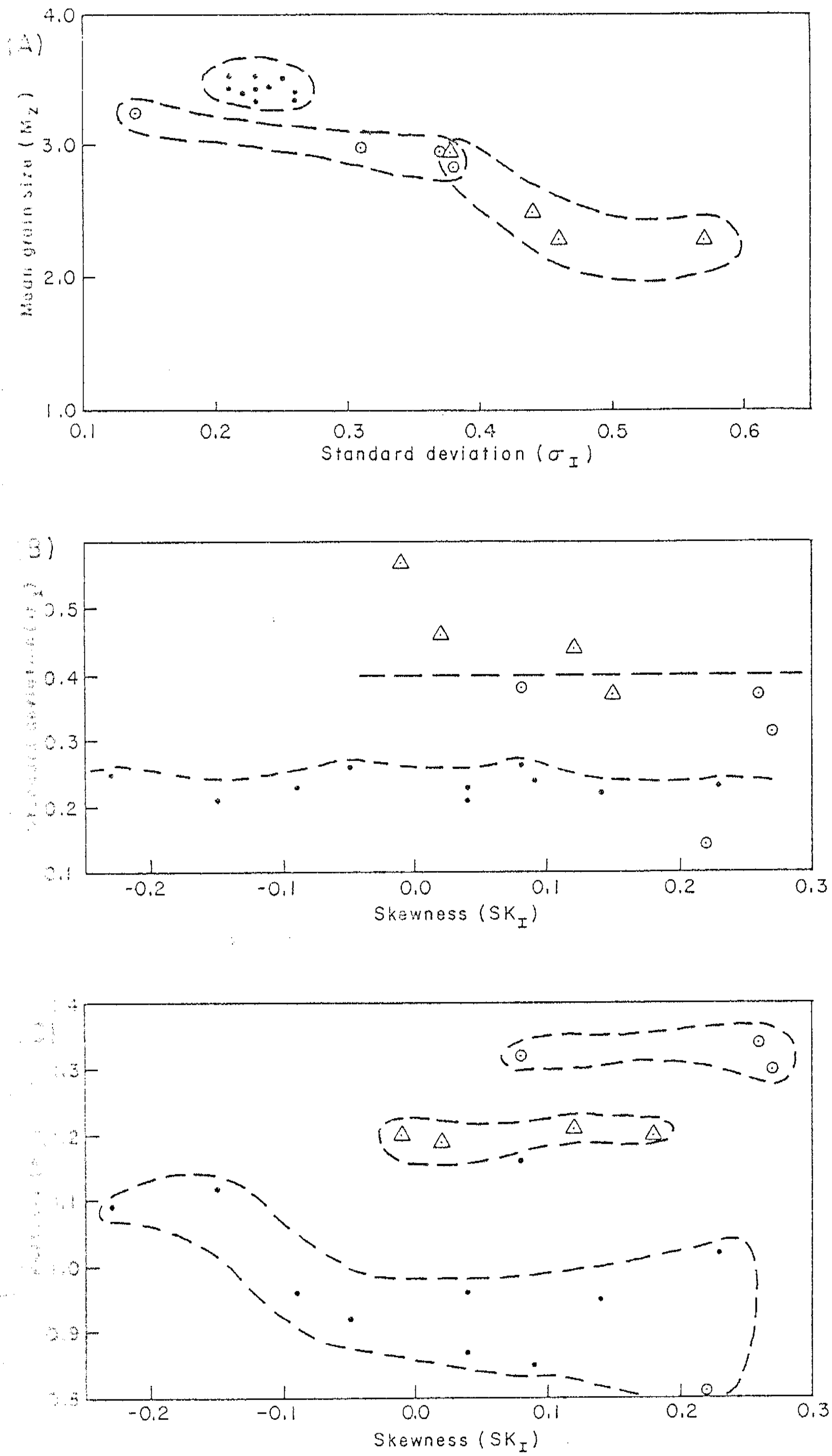


Figure 31. Binary plots of grain-size parameters for the recognized sandstone facies in the Point Lookout Sandstone (data from Table 1). Facies A & B, dots; Facies C, circles; Facies D, triangles.

(M.M. Shetiwy, 1977)

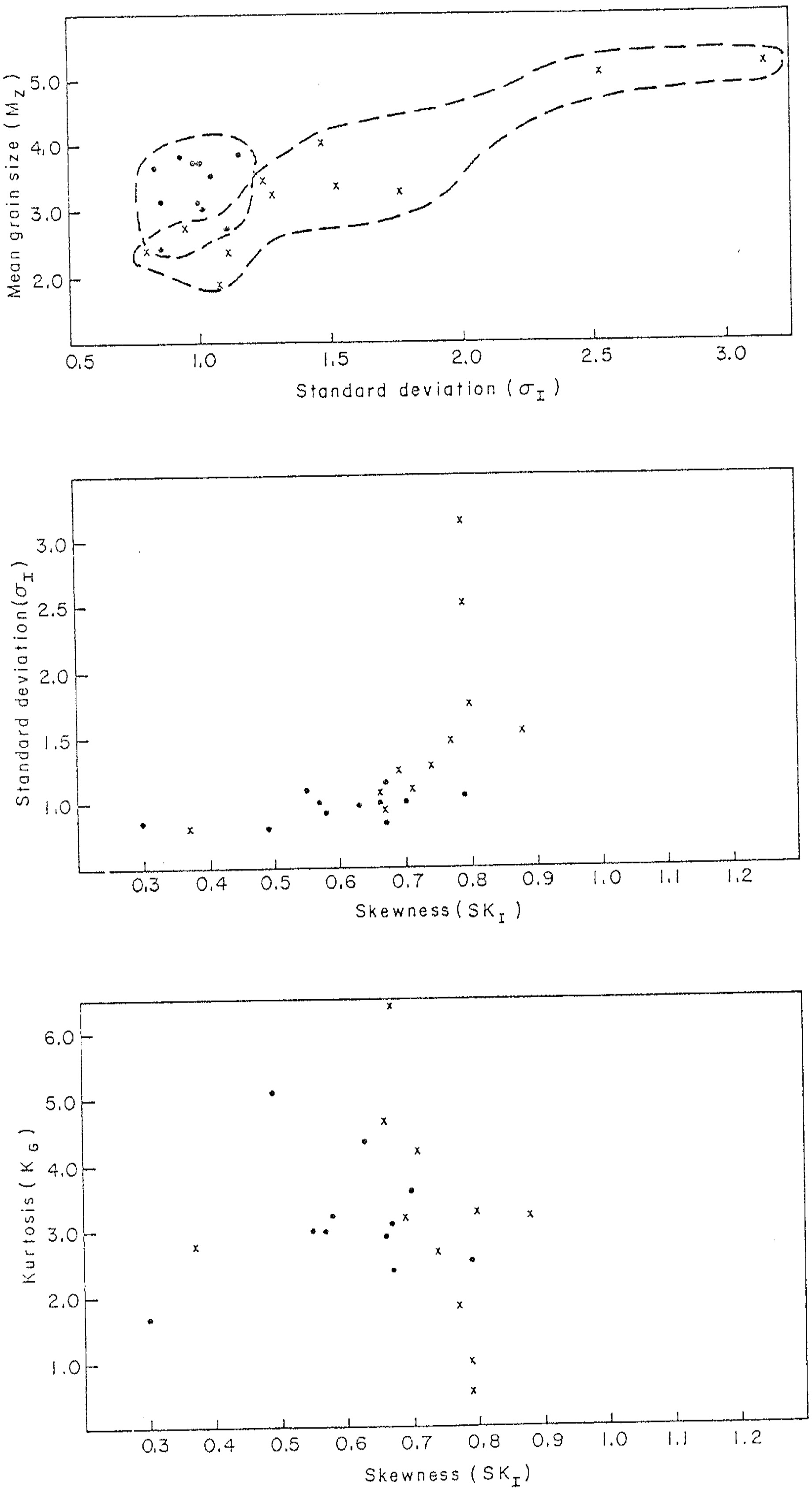
samples from different facies is due to differences in sorting rather than skewness.

The scatter diagram (Figure 31C) based on skewness versus kurtosis shows some trends of separation between the different sandstone facies. However, the separation in this binary diagram is mainly due to variation in kurtosis rather than skewness.

The binary scatter diagrams of Figure 31 show reasonable separation of the different sandstone facies of the Point Lookout Sandstone. The distinction between these sandstones becomes very minimal (almost insignificant with the exception of the mean grain size - standard deviation plot) if the mud fraction of the samples is included in the analyses (see Figure 32). On the other hand, the binary plots provide a fairly clear distinction between the Point Lookout sandstones and the channel sandstones of the Menefee Formation (see Figure 32).

CM diagram-. A CM diagram is a binary plot, devised by Passega (1957 and 1964), in which the coarsest one percentile "C" is plotted against median diameter "M". The coarsest one percentile grain size (C) is such that one percent of the sample is coarser than this size. Median grain size (M) is the size such that 50 percent of the sample is coarser than this size. C is a measure of the competence of the transporting agent, and M is a measure of the average particle size being transported.

A CM diagram was constructed for the Point Lookout sand-



(M.M.Shetiwy,1977)

Figure 32. Binary plots of grain-size parameters for Point Lookout Sandstone (dots) and Menefee channel sandstone (crosses) (data from Table 2).

stones and Menefee sandstones (Figure 33). Samples from the Point Lookout Sandstone facies fall into certain regions on the CM diagram forming a pattern with two segments. Samples from Facies C and D form a trend sloping in the same direction as the C = M line, with Facies D samples occupying the upper part (Figure 33); samples from Facies A and B occupy a small zone starting at the lower end of Facies C and D trend and extend almost parallel to the M-axis (Figure 33). Menefee channel sandstone samples plot in the same pattern as the Point Lookout Sandstone samples; but they generally lie closer to the C = M line in the sloping segment of the pattern, and higher than the Point Lookout samples in the horizontal segment of the pattern (Figure 33).

Facies D samples lie in the upper part of the pattern reflecting their relatively coarse 1st percentile; Facies A and B samples plot near the bottom due to their fine 1st percentile; Facies C samples plot near the middle. The Menefee channel samples are scattered along the pattern reflecting the variation in flow stages that transported the different sediments of the channel sandstones.

The individual segments of the pattern correspond to two modes of sediment transport, uniform suspension and graded suspension. Cu represents the maximum grain diameter transported in uniform suspension. The difference between Cu for the Point Lookout samples and that for the Menefee channel samples indicate that the capacity of the Menefee channel regime was higher than that of the transporting

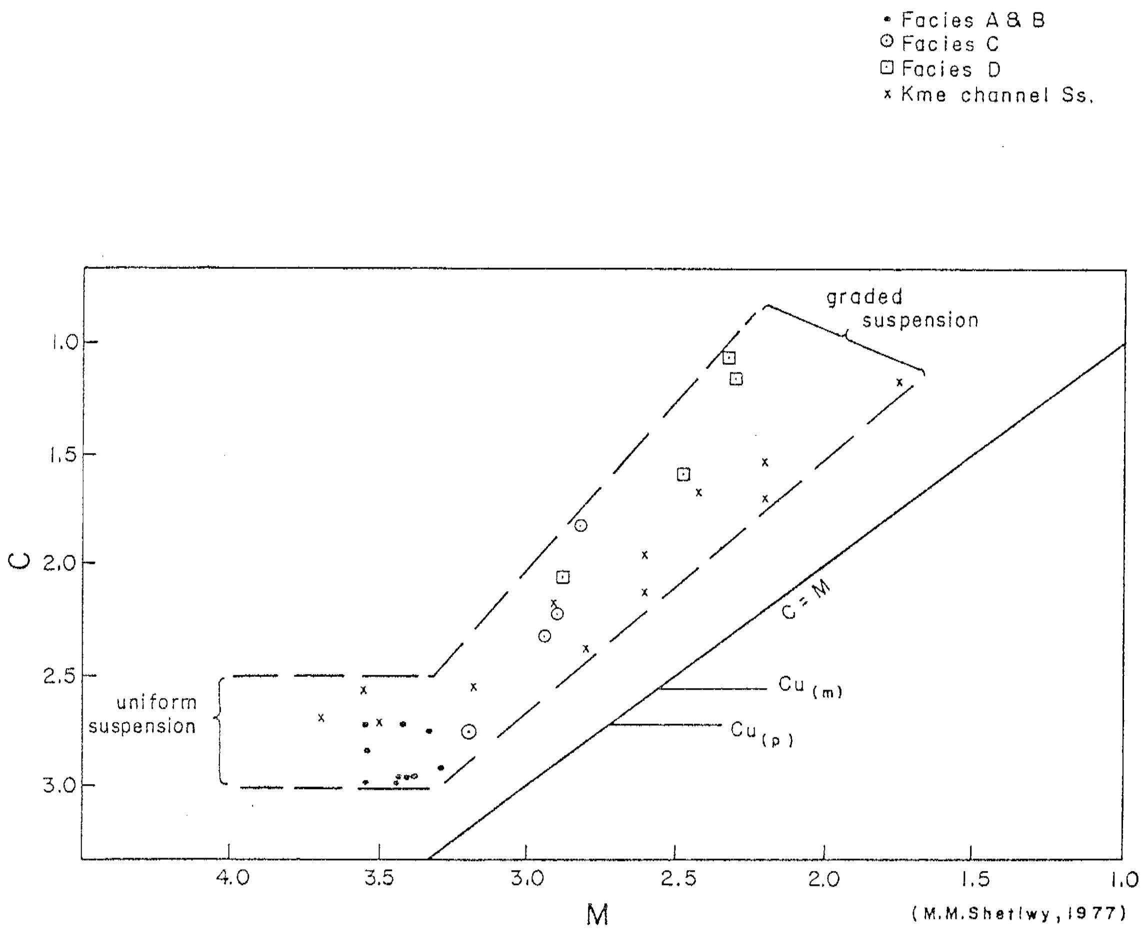


Figure 33. CM diagram for the recognized sandstone facies in the Point Lookout Sandstone, and the Menefee channel sandstones; $Cu_{(p)}$ and $Cu_{(m)}$ represent the maximum grain diameter transported in uniform suspension for the Point Lookout Sandstone and Menefee channel sandstones respectively.

agents of the Point Lookout system.

Discussion

Primary textural characteristics of a sediment reflect the nature and extent of depositional processes which prevailed in the environment of deposition. Hence, grain-size analyses are frequently used to describe clastic sediments; and many workers attempt to use grain-size analyses to characterize depositional environments of clastic sediments (e.g., Folk and Ward, 1957; Passega, 1957 and 1964; Friedman, 1961 and 1967; Visher, 1965 and 1969; and Sagoe and Visher, 1975). However, no environment has been characterized by the texture of its sediments in such a manner as to be readily recognizable in ancient sediments.

The relationship between textural characteristics of a sediment and the depositional processes is moderately applicable to Recent sediments where textural data can be interpreted in terms of depositional processes. But dealing with ancient sediments, such as in this study, textural data do not represent, precisely, the primary texture because of post-deposition changes (such as diagenetic changes, disintegration of less resistant fragments during sample preparation, and introduction or removal of fines by percolating waters). For these reasons, detailed textural analysis of ancient sandstones are used as secondary (or supplementary) means by which environments of deposition of various sandstone facies are defined. In the clastic system under study, Point Lookout Sandstone, environments of deposition of the various sandstone facies are interpreted, mainly, on bases of fossil contents, some diagnostic lithologic contents, sedimentary structures, stratigraphic position, and geometric distribution. Textural parameters are interpreted in reference to the depositional conditions which might have prevailed in the different environments and subenvironments. The specific application of textural analysis to interpretation of the depositional environment of each facies will be considered in a later chapter.

The grain-size distribution shows a gradual increase in mean grain size upward through the whole Point Lookout sequence (Tables 1 and 2), from Facies A with very fine silty sandstones to Facies D with the coarsest sandstones in the sequence.

The results in Table 2 (mud fraction included) show that there is no significant change in sorting between the different sandstone facies. On the other hand, Table 1 (mud fraction not included) shows a regular change in sorting, with Facies A and B being the best sorted, then it declines upward through Facies C and D; but all of them are in the very well to moderately well sorted categories. However, two significant elements must be considered in relation to sorting variations in Tables 1 and 2: 1) the amount of fines (mud content) increases downward from Facies D, having the least, to Facies A, containing the most; 2) the proportion of primary mud fraction among mud content is higher in Facies A and B than in Facies C and D sandstones.

These observations indicate that the sorting of the Point Lookout sandstones is slightly better than that shown in Table 2 but worse than that shown in Table 1, and that the sorting decreases downward from Facies D through Facies C and B to the lowest sorting in Facies A, but within a very small range. Thin section estimates of sorting confirm this conclusion. Sorting depends, mainly, on the size range of the available sediment, its rate of deposition, and the strength and variation in energy of depositing agent. Therefore, it is not an easy measure to interpret. It is generally thought that sorting by environment of a given sediment follows a sequence of, in decreasing order of relative perfection: 1) eolian, 2) beach, 3) river, or nearshore marine, and 4) offshore marine sandstones (Folk, 1965). Again, this approach is mainly based on Recent sediments.

Skewness and kurtosis are not reliable measures in this study. However, positive skewness is dominant in most of the sandstones of the Point Lookout sequence (Tables 1 & 2). Mason and Folk (1958) and Friedman (1961) concluded that beach sands are mostly negatively skewed. The negative skewness of the beach sand is attributed to the winnowing action of fines by waves and tidal currents. In quiet water areas and in deep water, the skewness of the sands is generally positive. Although the sandstones in the Point Lookout sequence are relatively rich in primary fine content, their positive skewness was, most likely, significantly enhanced by diagenesis and postdepositional modifications especially in Facies C and D. As Friedman (1962) pointed out, diagenetic processes primarily affect the tail end of size distribution curves leading to changes in the numerical values for skewness. It can be concluded that skewness of ancient lithic sandstones, such as the Point Lookout Sandstone, is not a significant environmental-sensitive parameter.

Binary scatter diagrams have been proposed to distinguish between beach and dune sands, and beach and river sands (e.g., see Mason and Folk, 1958; Friedman, 1961 and 1967; and Miola and Weiser, 1968). In this study, the distinction between the marine Point Lookout sandstones and the channel sandstones of the Menefee Formation are reasonably maintained in most binary scatter diagrams. But distinction among the different sandstone facies within the Point Lookout Sandstone is generally minimal. From the binary diagrams the mean grain size versus standard deviation (sorting) plot is the most significant discriminator between the sandstone facies in the Point Lookout sequence.

Visher (1969) emphasized the use of grain-size distribution plotted as a cumulative curve on probability axis as a discriminator of environments of deposition; Freeman and Visher (1975) applied this approach to interpret the environments of deposition of the Navajo Sandstone. Such cumulative curves for the different sandstone facies of the Point Lookout Sandstone are shown in Appendix C; they moderately correlate with those for marine sands of Visher (1969).

Steidmann (1977) pointed out it is commonly recognized that both diagenetic effects and disaggregation-produced fines cast serious doubt on the significance of cumulative curves as discriminators of ancient environments.

Microscopic description

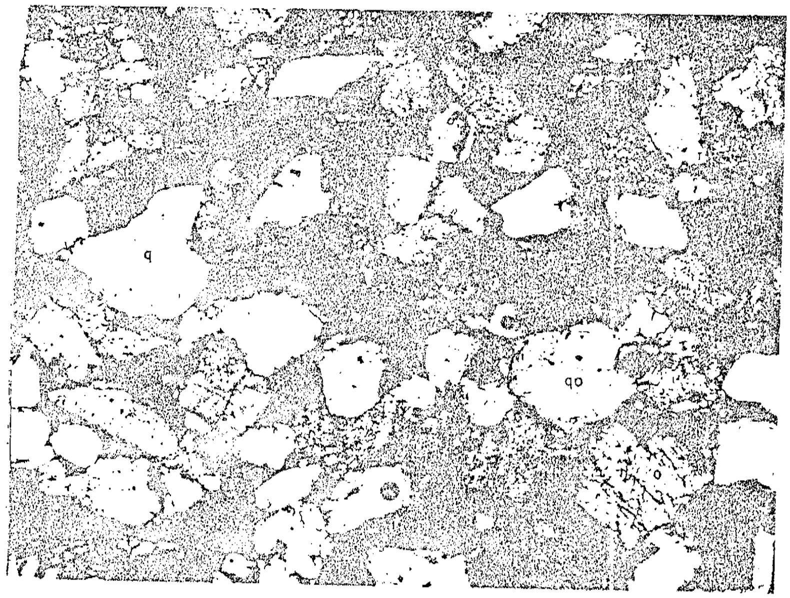
The texture of sandstones in the different facies ranges from fine to very fine and silty sandstone. Figure 34 shows photomicrographs for comparison of sandstones throughout the sequence. They are generally moderately to poorly sorted; grains are subrounded to subangular and slightly to moderately elongate. Detrital framework constituents form 63.5% or more, matrix plus cement ranges from 18.5% to 36.5%, and pore space ranges from 1.0% to 12.0%. These sandstones are generally submature to immature (after Folk, 1974).

Among the striking textural characteristics of the Point Lookout sandstones is quartz grains showing bimodal distribution of roundness and elongation, independent of size. However, quartz grains are dominantly subangular and slightly to highly elongated; some quartz grains (up to about 25% of the quartz) are well to very well rounded and equant (Figure 34). This textural bimodality indicates that some of the quartz has been recycled. Lithic fragments are generally coarser, better rounded and less elongate than quartz grains in the same sample.

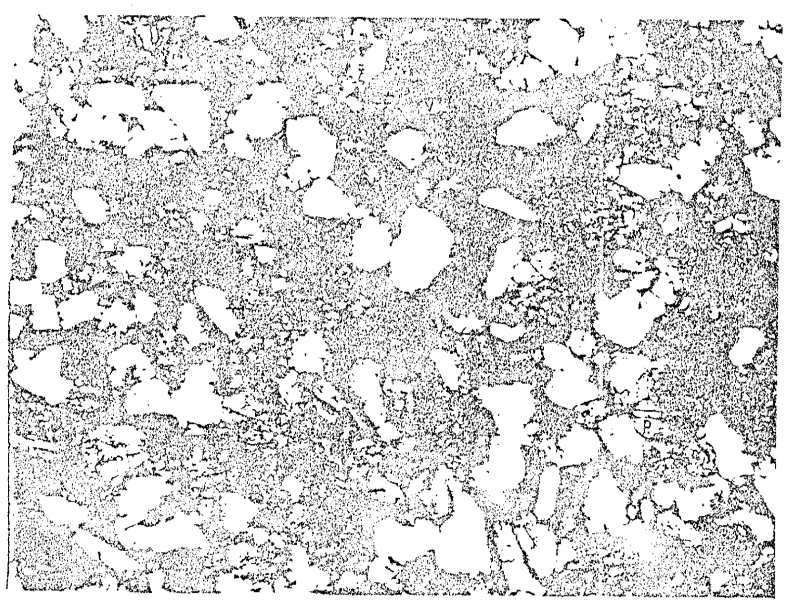
The sandstones are petrographically homogeneous, i.e., the entire thin section can be considered a single rock type. However, layering is evident in some samples of laminated

Figure 34. Photomicrographs for comparison of sandstones from the different facies in the Point Lookout Sandstone. A- From Facies D (unit Kpl-6-14c), rounded quartz grain with overgrowth (qo) and angular quartz (q), moderately altered orthoclase (o), chert(c), low in matrix. B- From Facies C (unit Kpl-6-12A), brownish altered fragment with quartz phenocryst (volcanic fragment?) (v), chert (c), plagioclase (p), more matrix than A. C- From Facies B (unit Kpl-3-7B), quartz with variable roundness (q), dolomite rhomb (d), plagioclase (p), chert (c), abundant matrix. Crossed nicols, 16x.

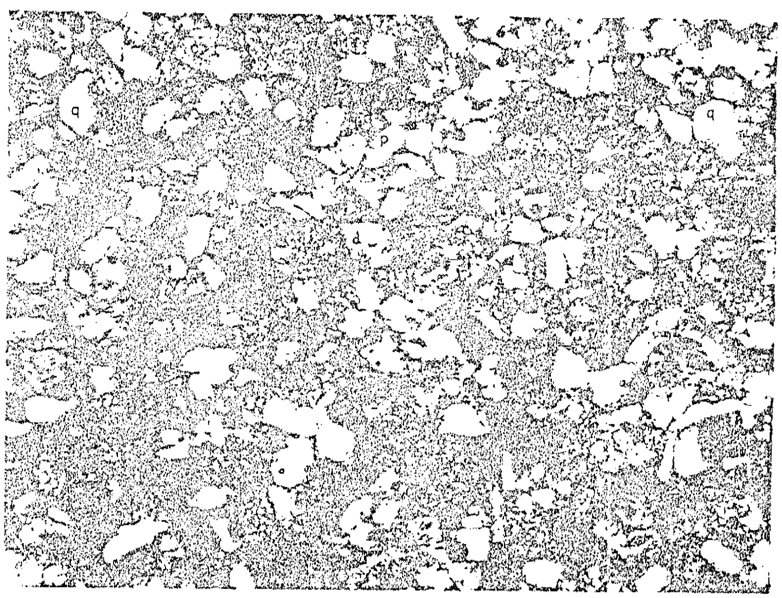
A



B



C



muddy sandstone units from Facies A. Also, matrix material is not uniformly distributed, especially in coarser specimens from Facies C and D.

Grain packing is generally loose; but porosity is relatively low (mostly less than 10%) due to intergranular matrix and cement. Point and long (after Taylor, 1950) contacts between grains are dominant; concavo-convex contacts are rare; sutured contacts are practically absent. Elongate quartz grains in some samples tend to be oriented parallel to bedding; but imbrication of grains in a certain trend was not observed.

Composition

Thin-section analyses

General

Petrographic analysis was conducted on 64 thin sections of sandstone samples from the major facies of the Point Lookout sequence (10 to 12 samples from each measured stratigraphic section, at least one sample from each sandstone unit). The objectives of the petrographic analyses are: 1) description of the mineralogy; 2) description of texture and fabric; 3) determination of any mineralogic differences among the facies; 4) interpretation of dominant depositional processes in the environment of deposition; 5) description and interpretation of diagenetic changes; and 6) interpretation of the provenance of the sandstones.

All thin sections were examined qualitatively, and 18 thin sections, representing the major sandstone facies, were analyzed quantitatively. The various framework (sand grains) and non-framework (matrix, cement, and pore space) constituents of the sandstones as determined from point counts are shown in Table 3. Table 4 shows the relative proportions of the major framework components. The Point Lookout sandstones contain 28.0 to 48.0% quartz, 13.0 to 26.5% rock fragments, and 7.5 to 13.0% feldspar. Chert is common; mica and heavy minerals are very rare. Matrix is relatively abundant in all the sandstone facies, 8.0 to 16.5%; however, a great part, if not most, of it is pseudomatrix (a term used by Dickinson, 1970, for deformed argillaceous rock fragments). Calcite and some clays form the main cementing material; iron oxide cement is generally minor. Small carbonaceous plant fragments occur. These sandstones are rich in diverse rock fragments (see Table 3).

The classical categorization of the framework grains includes three components; 1) quartz, 2) feldspar, and 3) rock fragments. Chert is a disputable subcomponent; some workers group it with the quartz category due to its similar resistance to abrasion, but others group it with rock fragments since it is a sedimentary rock fragment. In this study, chert is grouped with the rock fragment component. Sandstones are classified according to the relative abundance of the major framework components. A triangular plot is shown in Figure 35 to illustrate the sandstone types of

Table 3. Modal analyses (%) of thin sections from the Point Lookout Sandstone.

A - Samples from Facies B sandstones

SAMPLE	1-5e	2-5B	3-3A	3-7B	6-5D	6-9c	Range	Average
FRAMEWORK	73.0	74.5	63.5	77.0	77.0	68.5	63.5-77.0	72.4
QUARTZ	44.0	44.5	35.0	41.0	39.5	36.0	35.0-44.5	40.0
Mono. non-und.	33.0	27.0	27.5	26.0	27.5	30.0		
Mon. und.	10.0	13.5	6.5	10.0	9.0	5.0		
Poly. <3xls	1.0	3.0	1.0	3.0	2.0	1.0		
Poly. >3xls	-	1.0	-	2.0	1.0	-		
FELDSPAR	9.0	9.5	7.5	8.5	9.0	9.0	7.5- 9.5	8.7
Orthoclase	3.5	4.0	3.0	3.5	3.5	4.0		
Microcline	1.0	1.0	0.5	-	1.0	-		
Plagioclase	0.5	2.0	2.0	1.0	1.5	2.0		
Perthite	1.0	0.5	-	1.0	1.0	-		
Altered feld.	3.0	2.0	2.0	3.0	2.0	3.0		
ROCK FRAGMENTS	17.0	14.0	13.0	19.0	18.0	17.5	13.0-19.0	16.4
Volcanic	0.5	1.0	1.0	1.0	1.0	1.0		
Granitic	0.5	-	-	3.0	2.0	1.0		
Metamorphic	1.0	1.5	-	2.0	1.0	1.5		
Sandstone	2.5	5.0	2.0	3.0	2.5	3.0		
Siltstone/shale	9.0	7.0	4.0	7.0	8.5	7.0		
Unidentified	3.5	2.0	6.0	3.0	3.0	4.0		
CHERT	3.0	5.0	4.0	4.5	6.0	5.0	3.0- 6.0	4.6

Table 3, A cont'd

SAMPLE	1-5e	2-5B	3-3A	3-7B	6-5D	6-9c	Range	Average
DOLOMITE	-	-	3.0	3.5	-			
ACCESSORY	1.0	1.5	4.0	1.0	1.0	1.0	1.0-4.0	1.6
Mica	1.0	1.5	1.0	1.0	1.0	1.0		
Heavy min.	trace	trace	3.0	trace	trace	trace		
Glauconite	-	-	-	trace	-	-		
NON-FRAMEWORK	26.0	25.5	36.5	23.0	23.0	31.5	23.0-36.5	27.6
MATRIX	14.5	15.5	11.5	16.5	14.5	11.0	11.0-16.5	13.9
Silt	13.5	13.0	10.5	13.0	10.5	10.0		
Clay	1.0	2.5	1.0	3.5	4.0	1.0		
CEMENT	9.0	9.0	23.0	5.5	7.0	19.0	5.5-23.0	12.1
Calcite	2.0	3.0	19.0	0.5	0.5	12.0		
Silica	-	-	-	-	1.0	-		
Iron oxide	1.5	3.5	-	3.0	3.5	2.0		
Clay	5.5	2.5	4.0	2.0	2.0	5.0		
PORE SPACE	2.5	1.0	2.0	1.0	1.5	1.5	1.0-2.5	1.6

Table 3 cont'd.

B - Samples from Facies C sandstones

SAMPLE	1-7D	2-8B	4-12J	6-12A	6-12C	7-9B	Range	Average
FRAMEWORK	73.0	74.5	75.5	81.5	81.5	74.5	73.0-81.5	76.8
QUARTZ	42.0	33.0	33.0	46.5	48.0	27.0	28.0-48.0	38.4
Mono. non-und.	29.0	23.0	21.0	32.5	33.0	16.5		
Mono. und.	11.0	9.0	9.0	11.0	10.0	8.0		
Poly. <3xls	2.0	1.0	2.0	2.5	4.0	2.0		
Poly. >3xls	-	-	1.0	0.5	1.0	0.5		
FELDSPAR	12.0	9.0	12.0	8.5	9.0	10.5	8.5-12.0	10.2
Orthoclase	5.0	5.0	5.0	4.5	3.0	5.5		
Microcline	1.0	-	1.0	-	1.5	1.0		
Plagioclase	2.0	1.0	3.0	0.5	1.0	1.0		
Perthite	1.0	1.0	1.0	0.5	1.0	1.5		
Altered feld.	3.0	2.0	2.0	3.0	2.5	1.5		
ROCK FRAGMENTS	14.0	26.5	23.0	19.0	17.5	25.5	14.0-26.5	20.9
Volcanic	2.0	1.0	3.0	5.0	3.0	2.5		
Granitic	3.0	3.5	2.0	3.5	3.0	5.5		
Metamorphic	-	-	2.0	1.5	0.5	0.5		
Sandstone	2.0	4.0	4.0	1.5	2.0	5.0		
Siltstone/shale	4.0	12.0	7.0	5.0	6.5	9.0		
Unidentified	3.0	6.0	5.0	2.5	2.5	3.0		
CHERT	4.0	5.0	6.0	6.0	6.5	10.5	4.0-10.5	6.3
DOLOMITE	-	-	-	-	-	-		

Table 3, B cont'd

SAMPLE	1-7D	2-8B	4-12J	6-12A	6-12C	7-9B	Range	Average
ACCESSORY	1.0	1.0	1.5	1.5	0.5	1.0	0.5-1.5	1.1
Mica	1.0	1.0	1.5	1.0	0.5	1.0		
Heavy min.	trace	trace	trace	0.5	trace	trace		
Glauconite	trace	trace	-	-	-	-		
NON-FRAMEWORK	27.0	25.5	24.5	18.5	18.5	25.5	18.5-27.0	23.2
MATRIX	8.0	14.5	12.0	10.0	9.5	13.0	8.0-14.5	11.2
Silt	7.0	13.5	10.0	7.5	8.5	11.5		
Clay	1.0	1.0	2.0	2.5	1.0	1.5		
CEMENT	7.0	6.5	8.5	3.5	4.0	7.5	3.5-8.5	6.2
Calcite	-	-	-	-	-	-		
Silica	-	-	1.5	-	2.5	1.5		
Iron oxide	3.0	1.0	3.0	1.0	0.5	3.5		
Clay	4.0	5.5	4.0	2.5	1.0	2.5		
PORE SPACE	12.0	4.5	4.0	5.0	5.0	5.0	4.0-12.0	5.9

Table 3 cont'd.

C - Samples from Facies D sandstones

SAMPLE	2-9A	2-11C	6-14C	6-17B	7-10B	7-11A	Range	Average
FRAMEWORK	79.5	79.0	77.5	76.0	77.0	78.0	76.0-79.5	77.8
QUARTZ	47.5	39.0	37.0	38.5	33.0	38.5	33.0-47.5	38.9
Mono. non-und.	35.0	27.0	24.0	26.0	27.0	26.5		
Mono. und.	7.0	8.0	7.5	7.5	3.5	6.0		
Poly. <3xls	4.5	3.0	4.5	3.5	2.0	4.0		
Poly. >3xls	1.0	1.0	1.0	1.5	0.5	2.0		
FELDSPAR	12.5	13.0	9.5	13.0	12.0	10.5	9.5-13.0	11.7
Orthoclase	5.0	5.0	4.0	3.0	3.5			
Microcline	1.0	3.0	1.5	0.5	1.5	1.5		
Plagioclase	1.5	1.0	1.0	2.0	2.5	2.0		
Perthite	1.0	1.0	1.0	0.5	1.5	1.0		
Altered feld.	4.0	3.0	2.0	5.5	3.5	2.5		
ROCK FRAGMENTS	14.0	19.5	20.5	15.0	24.5	20.0	14.0-24.5	19.0
Volcanic	2.0	1.0	4.0	2.0	2.0	-		
Granitic	4.0	3.0	4.5	5.0	5.0	5.0		
Metamorphic	1.5	2.0	-	1.0	1.5	1.0		
Sandstone	0.5	3.0	2.0	1.0	4.5	2.0		
Silstone/shale	3.5	7.5	7.0	4.0	8.5	8.0		
Unidentified	2.5	3.0	3.0	2.0	3.0	4.0		
CHERT	5.0	7.0	9.5	8.0	5.5	8.0	5.0-9.5	7.2
DOLOMITE	-	-	-	-	-	-		

Table 3, C cont'd.

SAMPLE	2-9A	2-11C	6-14C	6-17B	7-10B	7-11A	Range	Average
ACCESSORY	0.5	0.5	1.0	1.5	2.0	1.0	0.5-2.0	1.1
Mica	0.5	0.5	1.0	0.5	2.0	1.0		
Heavy min.	trace	trace	trace	1.0	trace	trace		
Glauconite	-	-	-	-	-	-		
NON-FRAMEWORK	20.5	21.0	22.5	24.0	23.0	22.0	20.5-24.0	22.2
MATRIX	8.0	9.0	8.0	9.5	12.0	8.0	8.0-12.0	9.1
Silt	7.0	8.0	7.5	7.5	10.5	8.0		
Clay	1.0	1.0	0.5	2.0	1.5	-		
CEMENT	2.0	3.0	3.0	10.0	3.5	3.0	2.0-10.0	4.1
Calcite	-	-	-	5.0	-	-		
Silica	-	-	1.5	-	1.0	-		
Iron oxide	1.0	1.0	1.0	1.5	1.5	1.0		
Clay	1.0	2.0	0.5	3.5	1.0	2.0		
PORE SPACE	10.5	9.0	11.5	4.5	7.5	11.0	4.5-11.5	9.0

Table 4. Relative distribution (%) of framework constituents of the sandstone in the different facies.

FACIES	SAMPLE	QUARTZ	FELDSPAR	ROCK FRAGMENTS INCLUDING CHERT
	1-5e	60.3	12.3	27.4
	2-5B	61.0	13.0	26.0
	3-3A	58.8	12.6	28.6
FACIES B	3-7B	56.2	11.6	32.2
	6-5D	54.5	12.4	33.1
	6-9c	53.3	13.3	33.3
	Range	53.3-61.0	11.6-13.3	26.0-33.3
	Average	57.4	12.5	29.8
	1-7D	58.3	16.7	25.0
	2-8B	44.9	12.2	42.9
	4-12J	44.6	16.2	39.2
FACIES C	6-12A	58.1	10.6	31.3
	6-12C	59.3	11.1	29.6
	7-9B	36.7	14.3	49.0
	Range	44.6-59.3	10.6-16.7	25.0-49.0
	Average	50.3	13.5	36.2
	2-9A	60.1	15.8	24.1
	2-11C	49.7	16.6	33.7
	6-14C	48.4	12.4	39.2
FACIES D	6-17B	51.7	17.4	30.9
	7-10B	44.0	16.0	40.0
	7-11A	50.0	13.6	36.4
	Range	44.0-60.1	12.4-17.4	24.1-40.0
	Average	50.7	15.3	34.0

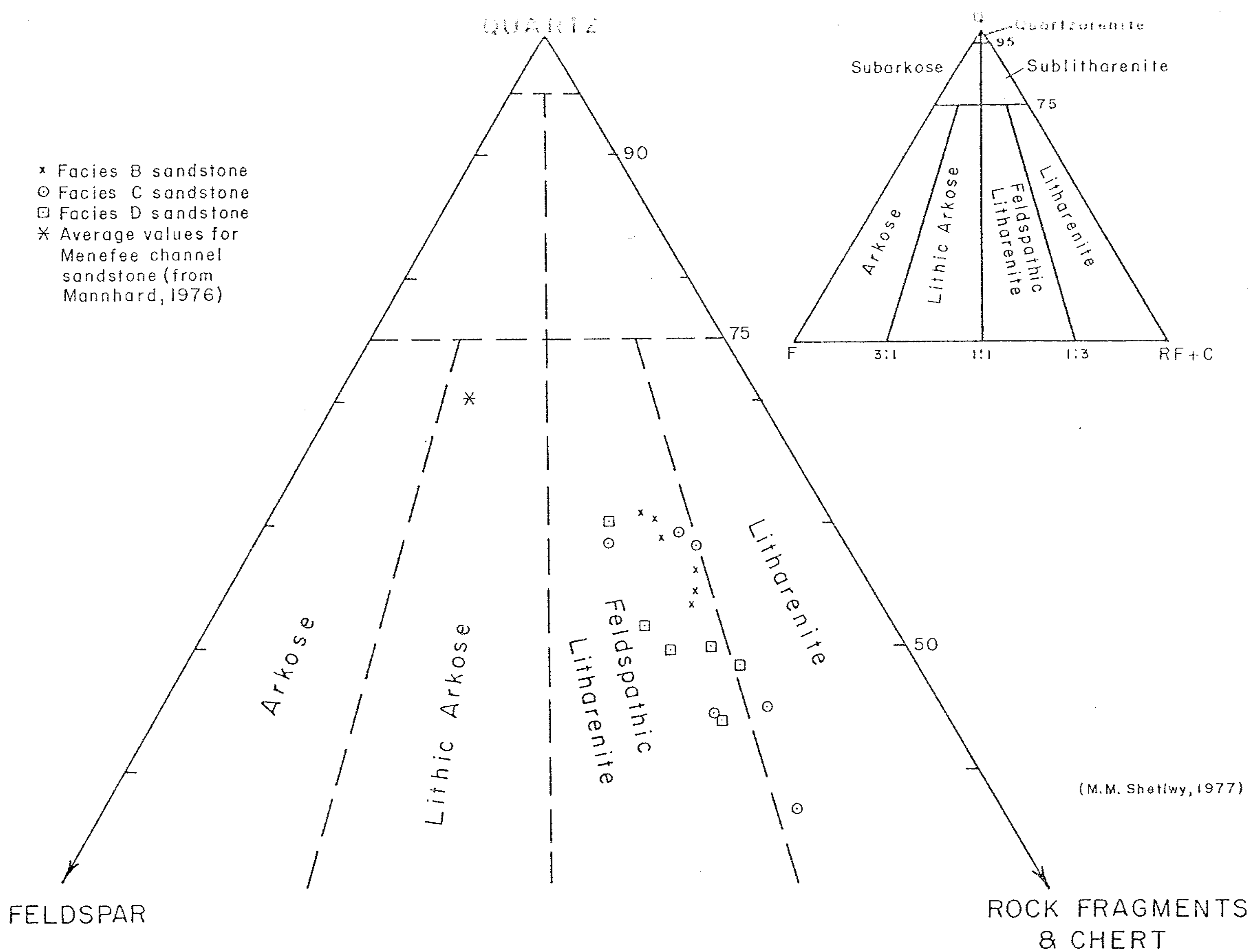


Figure 35. Petrographic classification (after Folk, 1974) of Point Lookout Sandstone samples (granitic fragments groups with rock fragments).

the various sandstone facies. A simple triangular plot is commonly considered as a practical approach for sandstone classification based on composition of detrital components (e.g., McBride, 1963; Pettijohn, Potter, and Siever, 1972; and Folk, 1974). The classification scheme applied here is a combination of classifications applied by Pettijohn, *et al.* (1972), and Folk (1974). It is based only on major constituents of the framework fraction. The three poles (or end members) Q, F, and R represent the sum of quartz grains (including polycrystalline type), feldspar grains, and rock fragments (sum of all polycrystalline particles excluding polycrystalline quartz grains, but including chert) respectively. Terminology in the classification distinguishes between clean sands, indicated as arenites, and dirty sands, indicated as wackes, according to the proportion of matrix; 15 percent matrix is adopted as the separating point by Pettijohn, *et al.* (1972) and is followed in this study.

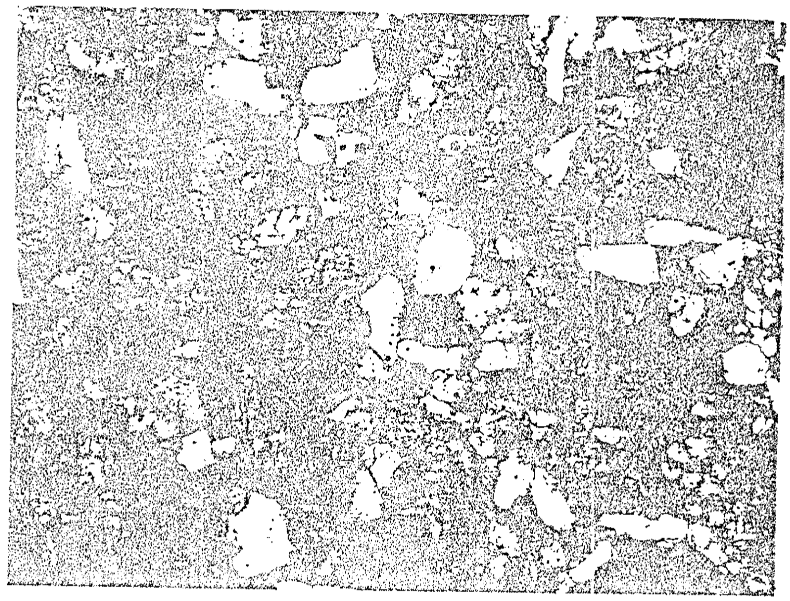
Description of framework grains

Quartz-. Quartz grains are the dominant detrital component (see Table 3). They are dominantly monocrystalline non-undulose type quartz. Some undulose monocrystalline grains occur as do a few polycrystalline grains, mostly with less than three crystals per grain. Quartz grains vary in roundness and elongation; they range from well rounded and equant to subangular and elongate (see Figures 34 and 36).

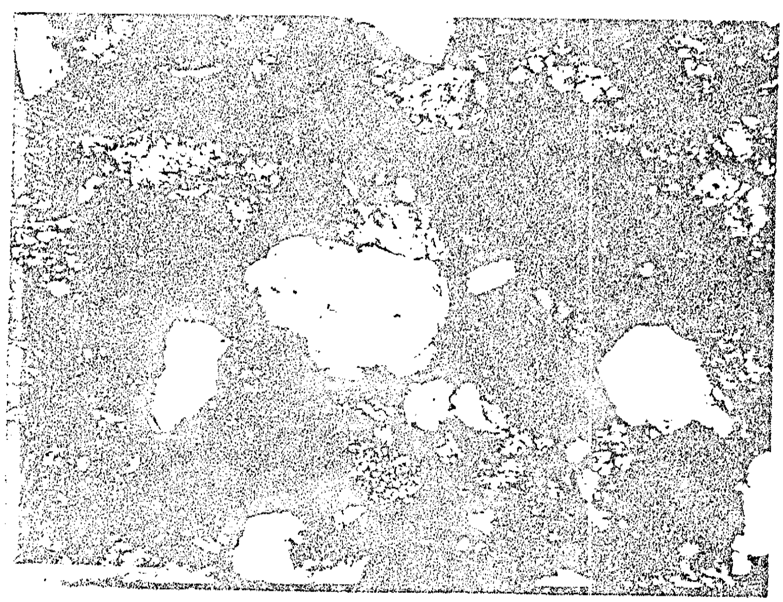
Quartz grains were subdivided into four subgroups according to the number of crystals per grain and extinction: 1)

Figure 36. Photomicrographs showing sandstone composition in the Point Lookout Sandstone. A- Quartz grains are mostly monocrystalline, and range from rounded and equant to subangular and elongate, chert, plagioclase, sandstone fragment (at lower right corner), from unit Kpl-7-9B; crossed nicols, 20x. B- Quartz grain with silica overgrowth, overgrowth is also subjected to abrasion, chert, abundant pore space, from unit Kpl-7-11A; crossed nicols, 20x.

A



B



monocrystalline non-undulatory quartz grains (flat-stage extinction angle less than 5 degrees); 2) monocrystalline undulatory quartz (flat-stage extinction angle more than 5 degrees); 3) polycrystalline quartz grains with three or less than three crystals per grain; and 4) polycrystalline quartz grains with more than three crystals per grain. Undulosity in monocrystalline quartz, the amount of polycrystalline quartz, and the number of crystals per grain of polycrystalline quartz are considered to be useful in provenance interpretation (Basu, *et al.*, 1975). Basu, *et al.*(1975) showed that quartz from plutonic source rocks is dominantly monocrystalline non-undulose type; whereas quartz derived from low-rank metamorphic source rocks is more than 50% polycrystalline with abundant grains possessing more than three crystals, and the monocrystalline fraction contains both undulose and non-undulose; characteristics of quartz from middle and upper-rank metamorphic source rocks lie between those from plutonic and low-rank metamorphic source rocks. However, the significance of this approach seems to be severely limited by extreme compositional maturity, the effects of multiple source rocks and multi-cycle sands. For these reasons, the nature of quartz grains in the Point Lookout sandstones is of limited importance in regard to source rock interpretation but can assist with other criteria toward a reasonable provenance interpretation.

Feldspar. Feldspar is relatively common in these sandstones (Table 3). Sandstones in the upper part of the sequence, Facies C and D, generally contain a higher amount of feldspar than the underlying, finer Facies B and A (see

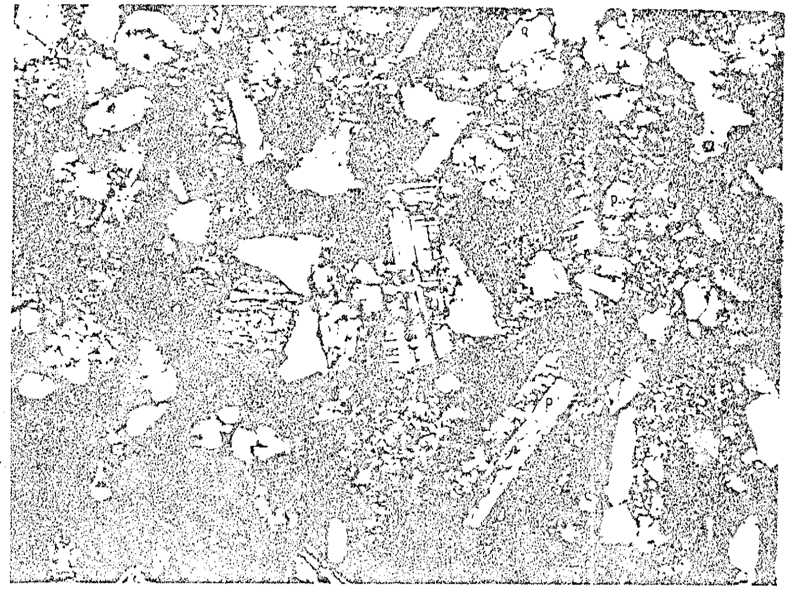
Table 3). Orthoclase is the most abundant species, followed by plagioclase which is mainly sodic type; microcline is not abundant, but occurs in most samples. Very few perthitic grains exist in some samples. There is a significant amount of completely altered feldspar grains. These grains are grouped with feldspar because they resemble the very few extensively altered feldspar grains which show a trace of diagnostic internal structure (cleavage or twinning).

Feldspar grains in these sandstones range from fresh grains (<5% alteration) to completely altered grains (Figure 37). Fresh and extensively altered plagioclase grains, which are the most susceptible to alteration among the feldspars, exist in the same part of some of the thin sections. The variability in alteration rate in the feldspar grains is not only due to the difference in stability of the different species, which is well demonstrated in these sands, but is most likely enhanced by multiple source rocks. Kaolinite is the dominant product of feldspar alteration, with sericite (and illite) forming minor products. A few plagioclase grains in the calcite-cemented sandstones are partially replaced by calcite (Figure 38A).

Rock fragments-. Rock fragments are relatively abundant among sandstones in most facies of the Point Lookout sequence (Table 3). In addition to chert, sedimentary (clastic) rock fragments (and possibly metasedimentary fragments) are the dominant types. Clastic rock fragments are mostly argillaceous types. It is very difficult to differentiate

Figure 37. Photomicrographs showing sandstone composition in the Point Lookout Sandstone. A- Fresh microcline (middle) plagioclase (p), altered feldspar (f), polycrystalline quartz (q), argillaceous fragment with poorly defined boundaries (below microcline), from unit Kpl-7-9B; crossed nicols, 20x. B- Granitic fragment (g) with quartz and plagioclase, sandstone aggregate (s), argillaceous fragment (a), matrix patch (m) derived from an argillaceous fragment, from unit Kpl-6-12A; crossed nicols, 16x.

A



B

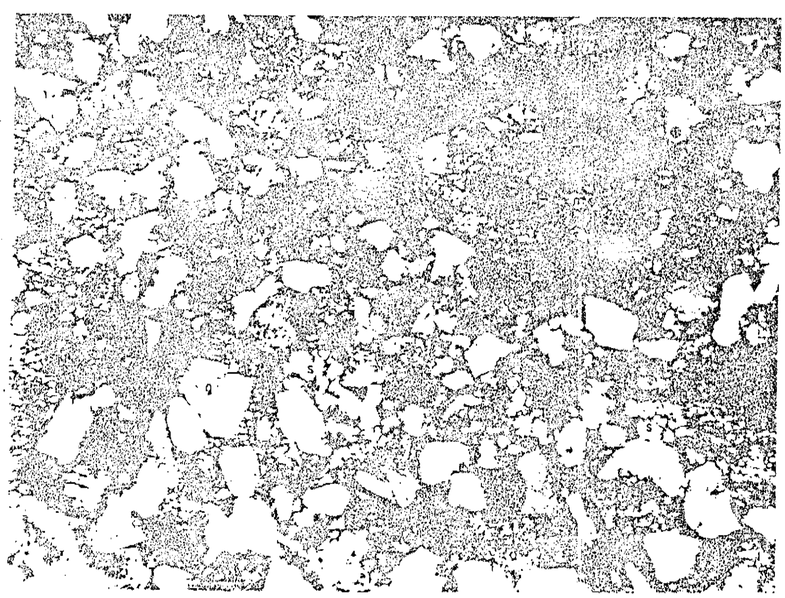
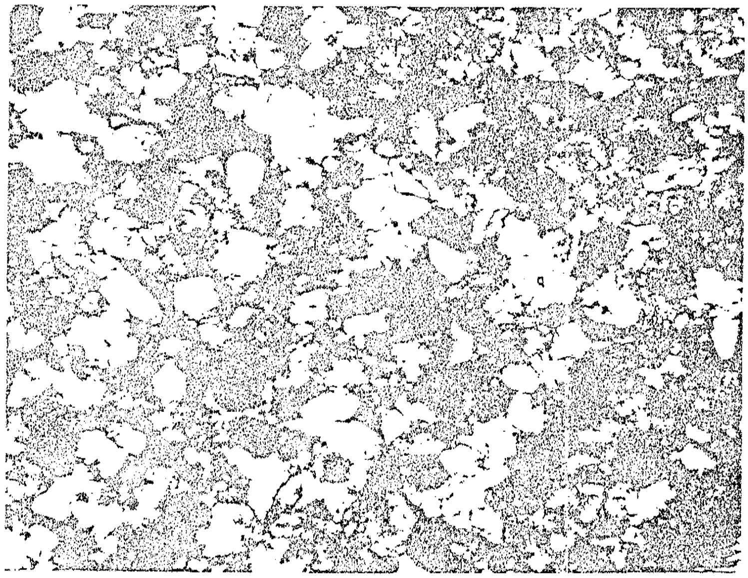
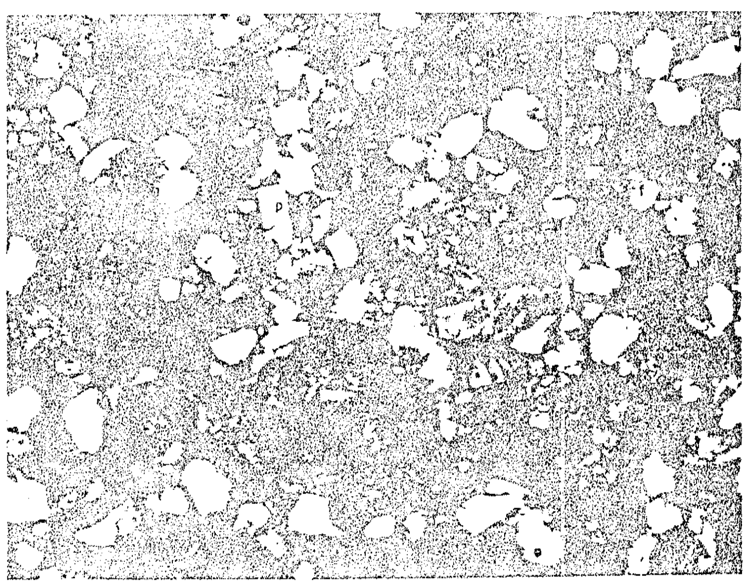


Figure 38. Photomicrographs showing sandstone composition in the Point Lookout Sandstone. A- Plagioclase partly replaced by calcite (near the middle), calcite cement, quartz grains with etched boundaries partially embedded in calcite cement (q), altered feldspar (f), from unit Kpl-3-3A; crossed nicols, 20x. B- Dolomite rhomb (middle) and rounded dolomite grain nearby, plagioclase (p), altered feldspar (f), from unit Kpl-3-7B; crossed nicols, 20x. C- Bent biotite (middle), deformed biotite (middle right), matrix patch near biotite in the middle, from unit Kpl-6-12C; crossed nicols, 20x.

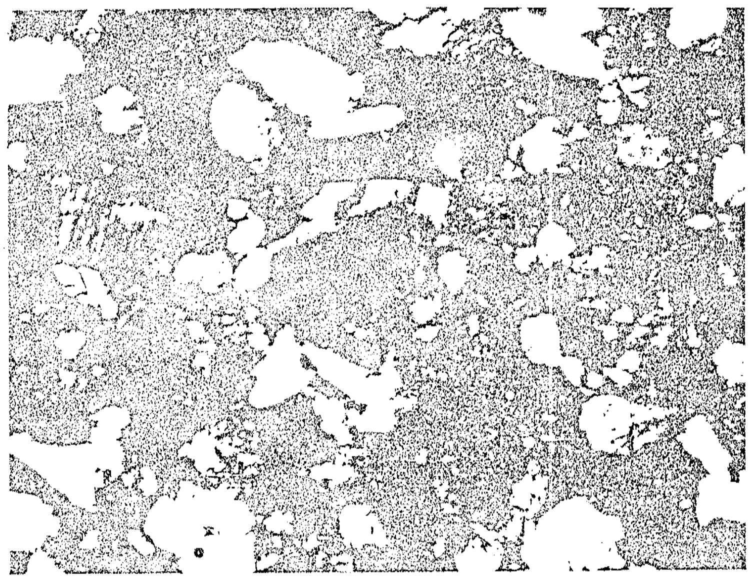
A



B



C



precisely between argillaceous sedimentary rock fragments and metamorphic (phyllitic) fragments. The distinction between them was based on a random orientation of phyllosilicates, perhaps associated with rounded fine silt-sized quartz, for sedimentary argillaceous rock fragments versus an indication of foliation defined by oriented phyllosilicates for metamorphic (phyllite) rock fragments. Silty-sandy fragments exist in very small amounts; they consist of a few grains, mostly quartz, with some of the grains showing detrital outlines (Figure 37B). Granitic rock fragments are less common; they are relatively more abundant in Facies C and D sandstones (see Table 3). They are generally composed of two or three crystals in some combination of orthoclase or microcline, plagioclase, and quartz (Figure 37B). Feldspar in the granitic fragments is generally extensively altered. Rock fragments, which were identified as volcanic, are also altered and consist of minor, very fine phenocrysts in an extensively altered aphanitic groundmass (Figure 34B). The phenocrysts are quartz and/or altered feldspar.

Diversity of the rock fragments and their nature suggest a multiple source for the sediment and that they were not subjected to extensive abrasion; i.e., they were not derived from a very distant source, and were not extensively reworked at the depositional sites. The diversity among the rock fragments in the Point Lookout sandstones is very striking. Rock fragments are generally coarser than quartz grains in the same sample, but more rounded and less elongate than quartz grains. They are less resistant, and most likely formed a great part of the matrix and clay materials by disintegration, chemical alteration, and ductile deformation.

Chert-. Chert is moderately common in all the sandstones of the Point Lookout sequence (Table 3). It consists mainly of microcrystalline quartz; crystal size is generally less than a few microns (Figures 34 and 36). Although most of the particles, categorized as chert in this analysis, were identified with reasonable confidence, there are other particles which closely resemble chert but contain some inclusions of clay crystals and other brownish material. These variegated chert-like particles were categorized with other groups whenever there was some evidence linking them to another group, and with the unidentified category when evidence is completely lacking. Chert is grouped with rock fragments in the classification of the sandstones in this study. Chert particles contain some inclusions of organic matter which seem to be responsible for the dark color of the chert. Chert particles are generally of the same size as the associated quartz but better rounded.

Dolomite-. Dolomite grains occur in few sandstones of the Point Lookout sequence (see Table 3). They are monocrystalline; some of them maintain rhombohedral shapes and cleavage (Figure 38B); however, their corners are mostly rounded; and they exhibit average grain size closer to that of quartz rather than the size of the rock fragments in the sample. Presence and nature of dolomite grains in these sandstones are confirmed by investigating some samples using cathodiluminescence. The nature of dolomite grains and their presence in sandstones, which are interpreted as marine sandstones in this sequence, suggest that this dolomite is most likely of primary type. Most carbonate detrital grains appear as polycrystalline aggregates (Pettijohn, Potter, and Siever, 1972). Sabins (1962) recognized dolomite grains in Upper Cretaceous sandstones in the Unita Basin of Utah, and indicated that they are a primary dolomite. Sabins (1962) claims that dolomite of this kind is common in Cretaceous sandstones of the Western Interior of the United States. Mannhard (1976) reported primary dolomite grains in the La Ventana Sandstone; he also reported dolomite grains in the Menefee channel sandstones, and interpreted them as detrital dolomite.

Accessory minerals-. Accessory minerals are relatively rare in the Point Lookout sandstones. Biotite occurs in very limited amount, generally less than 2 percent; muscovite exists in some samples in very minor amounts. Glauconite is also very minor, less than 1 percent (see Table 3); however, its presence is relatively significant for interpretation of depositional environment.

Heavy minerals exist only in a trace amount, generally less than 1 percent. Zircon, occurring as rounded but moderately elongate prisms, is the most common heavy mineral. Hematite and magnetite occur in several samples. Also, pyrite exists in a few samples together with hematite. Tourmaline, epidote, and rutile exist in only a few samples.

Description of non-framework components

Matrix-. Sandstones from all the sandstone facies in the Point Lookout sequence contain a considerable amount of matrix (see Table 3). Matrix material consists mostly of variegated particles similar to the diverse rock fragments; it also contains quartz, chert, and some feldspar grains of medium to fine silt size. Except for the quartz grains and some of the chert grains, matrix particles are extensively altered. Some clay material is categorized as matrix in Table 3; this again was an approximate approach. Most of the clays in the Point Lookout sandstones are of secondary origin. Detrital clays are distinguished by their extremely fine size and lack of well displayed crystallinity.

Although matrix is abundant among these sandstones, most of it, especially in Facies C and D sandstones, is a secondary (pseudomatrix) type formed by disintegration of some of the weaker argillaceous rock fragments. This conclusion is based on: 1) abundance of argillaceous rock fragments; 2) resemblance between the matrix material and that of the argillaceous rock fragments; 3) irregular distribution of matrix indicating that some of the weaker lithic fragments were squashed between adjacent more durable grains resulting in patches of matrix-like material resembling matrix-filled pores (see Figure 38C); in contrast, true (or primary) matrix would probably be distributed more regularly among all pores; and 4) contrast between composition of matrix material in different patches in the same thin section; primary (or true) matrix constituents should maintain better uniformity.

The proportion of matrix is commonly used to divide sandstones into two major groups; the poorly-sorted, matrix-rich "wackes", and the well-sorted, matrix-poor "arenites" (Pettijohn, *et al.*,1972). In this approach, matrix refers to original, detrital, extremely fine-grained interstitial material. Although the textural factor seems to be undeniable for a meaningful sandstone classification, and most sedimentary petrographers seem to prefer explicit indication of it, major problems arise with determining matrix in ancient sandstones: 1) the critical proportion of matrix to distinguish between the better sorted "arenites" from the poorly sorted "wackes" is not definite (see Dickinson, 1970); 2) the upper size limit of matrix is a disputable matter (Pettijohn, *et al.*, 1972), in addition it is in practice difficult to determine precisely the upper size limit of matrix during point counting; 3) Welsh (1967) has shown an operator error of 3% for estimation of matrix abundance and approximately 10% between operators; 4) as Cummins (1962) reasonably criticized the primary origin of matrix, and as it is clear in some of the sandstones of this study, a great part, if not most, of the matrix is a secondary type due to alteration, deformation, and disintegration of weak framework particles.

Cement-. A variable amount of cement occurs in the sandstones (see Table 3). Cementing materials include, in approximate decreasing order of abundance, calcite, clays, iron oxide and silica. Description of individual types of cements is included in the diagenesis section.

Diagenesis

The term diagenesis is used for many processes (chemical and physical) involved in post-depositional alteration of freshly deposited sediments. Diagenetic effects and their extent depend on the original composition and texture of the sediment, composition of the pore fluid (formation water), depth of burial (i.e., effect of temperature and pressure), and duration (i.e., time span over which diagenetic processes operated).

The Point Lookout sandstones, with their abundant unstable detrital constituents, were certainly susceptible to diagenetic changes. Alteration of some rock fragments, alteration of some feldspar grains, replacement (mostly partially) of some quartz and feldspar grains by calcite, cementation by carbonate, authigenic clay and iron oxide, and secondary matrix (or pseudomatrix) are the main diagenetic features of these sandstones. Authigenic clay is produced by alteration of some of the framework particles and/or pre-existing clay material; crystals are randomly oriented and do not exhibit a well arranged orientation of clay crystals.

Feldspar grains show a wide range of alteration, from fresh grains to partially altered to completely altered (Figure 37). Tiny flakes of kaolinite are the dominant alteration product; sericite and illite are minor products. Some of the completely altered feldspar grains show a ghost of the original grain shape and internal structure, while some other grains appear as a kaolinitic mass; they were categorized as feldspar because of their similarity to those partially altered grains with relict structure, such as twinning, and many show a trace of feldspar illumination under cathodo-luminescence microscopy. The highly altered feldspar grains are probably not a contribution of an arkosic source rock where they were subjected to an earlier stage of alteration because they do not exhibit better rounding and finer size compared to the presumably recycled quartz grains. They are, rather, a less resistant species of feldspar; cathodo-luminoscope observations indicate that most of the grains showing remnants of internal structure are plagioclase. Early stage of alteration during weathering at the source area and during transport may have contributed to this wide range of alteration of feldspar grains. Several feldspar grains show partial replacement by calcite and few are almost completely replaced by calcite in the calcite-cemented units (Figure 38A). It seems that weathering, upon exposure of the Point Lookout Sandstone, is the major factor in feldspar alteration because grains in less porous zones (either cemented with carbonates or relatively compacted with local abundance of matrix and cement material) are generally less altered to clays than those grains in more porous zones.

Many lithic fragments are extensively altered. Feldspar in granitic fragments is generally altered to clays; cathodo-luminoscope observations also confirm the feldspar origin of these altered parts of these rock fragments. Grains categorized as volcanic are completely altered, and they were identified only on the basis of a few surviving quartz phenocrysts and/or presence of contrasting patches within the fragment which probably are altered feldspar phenocrysts. Sedimentary argillaceous fragments were also subjected to a variable degree of alteration; some of them are practically indistinguishable from metasediment fragments. How much of this change was inherited in these fragments is not possible to determine. However, some fragments show moderately developed authigenic clay material, microcrystalline silica, and have very poorly preserved boundaries. Such fragments would not have survived, in this presumably littoral environment, if they inherited those characteristics.

Quartz grains in samples from calcite cemented units show partial replacement by calcite. Some grains show etched boundaries; some are embedded in calcite with etched boundaries (Figure 38A). Also the quartz-replacing calcite contains ghosts of inclusions originally in quartz grains.

Clays are the dominant alteration product of many framework particles; authigenic clay is not a major cementing agent (generally less than 5%, mostly less than 2%, Table 3). Such clay is mainly kaolinitic (i.e., small flakes with optical characteristics of kaolinite); also X-ray analysis indicates the dominance of kaolinite among clays from sandstones. It occurs as a thin film partially coating some of the framework particles, or as small mosaic-like aggregates filling parts of intergranular areas. The abundance of kaolinite among alteration products of altered particles and among intergranular clay reflects the influence of meteoric water which has penetrated the sedimentary rock upon exposure at the outcrop.

Calcite cement is the main cementing agent in zones with large sandstone concretions which are abundant in Facis B and C throughout the study area (see Plate 1). Some calcite cement also occurs in other sandstone samples not associated with concretions. Calcite cement exists either as a thin film coating some of the framework particles or as a mosaic of large crystals filling, partially or completely, some of the intergranular areas (Figure 38A). There are at least two stages of calcite cementation. This conclusion is based not only on contrast in texture, but also, to a limited extent, by cathodo-luminoscope observations. A thin zone of orange illuminating calcite cement occurs either as a base for the larger non-illuminating calcite cement crystals or by itself as a remnant around parts of the grain. The illuminating calcite cement represents an earlier stage of cementation; the non-illuminating calcite cement, which forms the bulk of the calcite cement, represents a more recently formed calcite cement. Some of the early cement could have been removed prior to the final stage of calcite cementation.

Some of the large sandstone concretions are fossiliferous. This may suggest the shells provided nuclei around which calcium carbonate deposition was initiated. Alternatively, because concretions were formed relatively early, the fossils were preserved from dissolution. Calcite cement was precipitated from solutions which could have gained their calcium carbonate both from connate water (expelled by compaction) and from the dissolution of shells.

Silica cement is rare in sandstones of the Point Lookout sequence. However, some quartz grains exhibit rounded silica overgrowths, indicating overgrowths were developed in the source (or parent) rock of these grains and rounded by abrasion during transport (see Figure 36B). This phenomenon confirms the recycling character of some of the quartz grains. The Point Lookout sandstones do not seem to have reached the silica-cement formation stage. Lack of silica cement can be attributed also to the presence of clay matrix, which could have protected the detrital quartz grains preventing silica overgrowth, in addition to causing reduction in permeability.

Iron oxide cement occurs in most of the exposed sandstones mainly as a limonite stain on the surface which decreases inward. Limonite and/or hematite cemented concretions (few millimeters to about 5cm in diameter) exist in several zones (see Plate 1). Also some burrow tubes are highly cemented by limonite and/or hematite. Iron material is relatively more abundant in zones rich in carbonaceous material where some pyritic concretions, partially to completely oxidized, also occur. In these zones jarosite also exists with limonite, resulting in the variegated color of the sediments. Concentration of iron oxide cement at the surface of exposed sandstones and its absence in subsurface samples, which are light gray (Hollenshead and Pritchard, 1960), indicate that it is mainly a product of weathering upon exposure. However, the pyritic concretions, associated with carbonaceous horizons, are most likely a product of an early stage (or stages) of diagenesis.

The absence of chemically unstable accessory heavy minerals can be attributed to dissolution, referred to as "intrastratal solution" by Pettijohn, *et al.*(1972).

Deformation of some of the physically least resistant argillaceous rock fragments is evident in several sandstone samples. This effect of physical diagenesis is due to compaction (Dickinson, 1970). Although mica is not abundant among these sandstones, some biotite flakes are bent and some are highly deformed and wrap partially around detrital grains (Figure 38C).

Porosity, and accordingly permeability, of many of the sandstones has been reduced as a result of all the above-mentioned diagenetic aspects. However, some samples, especially from Facies C and D, possess 4.0 to 12.0% porosity.

Discussion

Classification of the Point Lookout Sandstone

The representation of the petrographic modal analyses in the triangular plot (Figure 35) indicates that the Point Lookout Sandstone consists mostly of feldspathic litharenites; a few samples lie in the litharenite field near the boundary with the feldspathic litharenite field. The average channel sandstone from the Menefee Formation lies in the lithic arkose field (Figure 35); most of the channel sandstone samples lie in the lithic arkose field and a few in the arkose field (Mannhard, 1976, Figure 36).

More specific classification of the sandstones in the Point Lookout Sandstone reveals that they generally belong to the sedarenite field of the first stage subclassification at the RF (rock fragments) pole of Folk's (1974) triangular classification; to be more specific, they are chert-shale-arenites. This approach of detailed terminology on the basis of lithic fragments type was proposed by Folk (1974) for the sublitharenite, litharenite, and feldspathic litharenite clans. But if we seek specific and representative terminology, this approach fails to represent the felspathic character of the feldspathic litharenite clan. It seems illogical to neglect the feldspar content, which may be subequal to the amount of rock fragments in the feldspathic litharenite field, while specifying rock fragment composition in great detail of subdivisions; this problem is well represented in applying Folk's approach of sandstone classification to most of the sandstones in the Point Lookout Sandstone. To apply this classification approach consistently, the choice is to stop at the feldspathic litharenite division level, or to modify Folk's approach by stating the feldspathic character of the sediment in the detailed terminology, for example "feldspathic sedarenite", or for more detail "feldspathic shale-arenite" or "feldspathic chert-arenite". Accordingly, the Point Lookout Sandstone consists mostly of immature feldspathic chert-shale-arenite and some chert-shale-arenite.

The fact that the Point Lookout Sandstone is a lithic, texturally submature to immature sandstone may raise the question: is it a graywacke? To answer this question, it is necessary to consider definitions of graywacke. It was originally defined by Jameson in 1808 as a kind of sandstone composed of grains of sand of various sizes bound together by a clay paste (Dickinson, 1970). In common field usage, graywacke is applied imprecisely for dark gray or green, firmly indurated sandy rocks with obscure grain boundaries but without much calcareous cement (Dickinson, 1970). The ambiguity in its usage led to its application for sandstones bearing similar appearances due to unstable lithic fragments, and to two (or more) definitions of graywacke. The popular usage based on texture refers to any unstable, immature sandstone containing an interstitial matrix (primary), which is mainly microcrystalline phyllosilicates, in excess of certain volumetric proportion; Pettijohn, *et al.* (1972) adopted 15 percent as the critical amount of matrix. The less popular usage, based on composition, is applied to sandstone, texturally immature or not, in which unstable lithic fragments exceed feldspar grains.

Although the textural graywacke usage is the reasonable approach, its characterizing matrix must be well defined and precisely identified in petrographic investigations of the sandstone. The issue of matrix is a major problem for sedimentary petrographers, as previously discussed. Since the amount of matrix in the Point Lookout sandstones is generally less than 15 percent (Table 3) and a great part of it is pseudomatrix, the Point Lookout sandstones can be confidently classified as arenites rather than graywackes. The relatively limited amount of lithic fragments in the Point Lookout sandstones (generally less than 20 percent, Table 3), the nature of the lithic fragments, and the general appearance of these sandstones eliminate grouping them with the graywacke category even by the minor usage of the term graywacke. Therefore, sandstones in the Point Lookout Sandstone at the eastern San Juan Basin are a good example of feldspathic litharenite and litharenite.

Clay mineralogy of sandstones and mudrocks in the Point Lookout sequence

Selected sandstone and mudrock samples from the different facies in the Point Lookout sequence were analyzed for clay mineralogy using X-ray diffraction. The analyzed samples were selected mainly from sandstone and mudrock units in stratigraphic section Kpl-6, which contains a complete sequence of the different facies; a few more samples from the southern part of the study area, at stratigraphic section Kpl-1, were also analyzed to check for possible lateral variations in clay mineralogy within the specific facies. The objectives of the clay mineral analysis are to: 1) determine the type of clay minerals in both the sandstones and mudrocks; 2) detect any differences in clay mineralogy between sandstones from different facies; and 3) define any differences in clay mineralogy between the typical marine shales and the non-marine lagoon and swamp claystones. In other words, in addition to determining the type of clay mineral suites present, the analysis was also aimed at determining any possible relation between clay mineral suites and depositional environments.

The type of clay minerals and their relative abundance in the sandstones and mudrocks from the various facies of the Point Lookout sequence are illustrated in Figure 39; X-ray patterns are included in Appendix C. The clay minerals in sandstones are highly dominated by kaolinite (see Figure 39A); illite, mixed layer illite-montmorillonite, and montmorillonite occur generally in very minor amounts. Among the sandstones, it was observed that the relative abundance of mixed layer illite-montmorillonite and montmorillonite increases slightly from Facies D sandstones (estuarine-beach

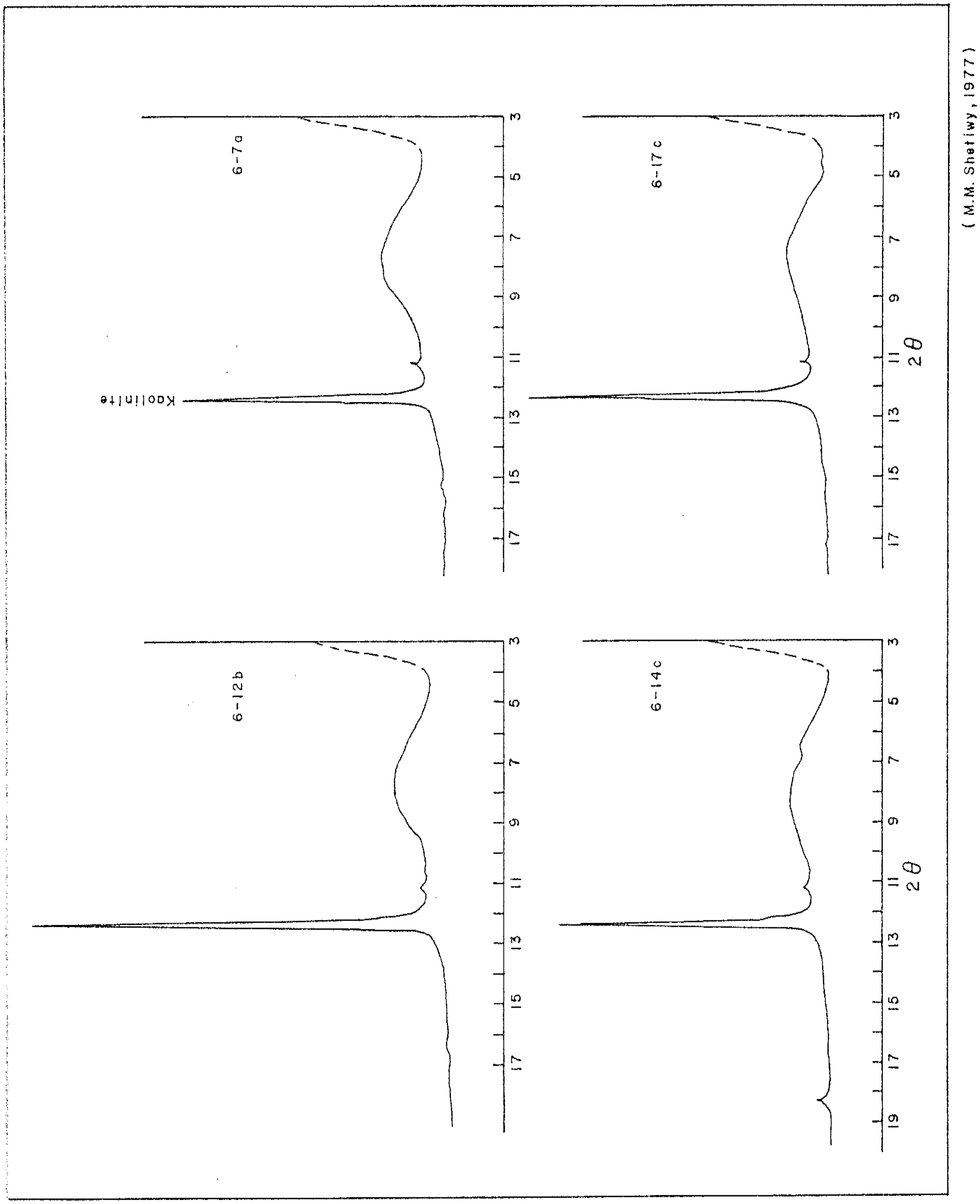
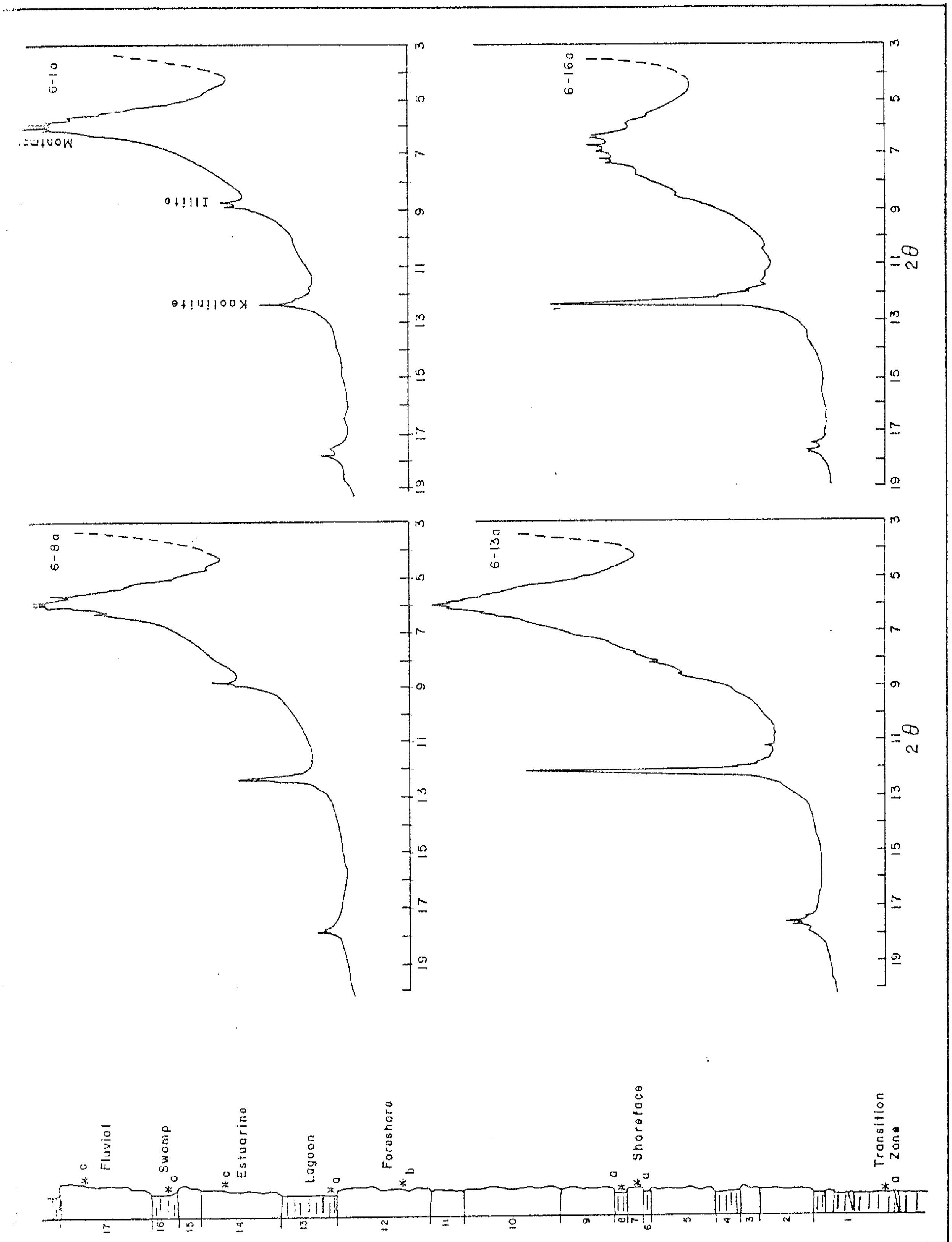


Figure 39A. Examples of the X-ray analysis of clay mineralogy in sandstones from the different facies of the Point Lookout sequence. Kaolinite (peak at 2θ = 12+) is the dominant clay mineral. Location of samples and interpreted depositional environment of the units are shown on the stratigraphic section Kpl-6 at the left side of Figure 39B.

Figure 39B. Examples of clay mineralogy in mudrocks from the different facies of the Point Lookout sequence. Notice the relative abundance of montmorillonite and kaolinite among the different samples which represent different depositional environments. (*indicates sample location).



sandstones) to Facies C sandstones (foreshore sandstones) to Facies B sandstones (shoreface sandstone) where the montmorillonite peak (around $6^{\circ}2\theta$) becomes fairly recognizable, while relative abundance of kaolinite in the same sandstone samples declines slightly in the same trend (see Figure 39A). The clay mineral suite in the non-marine channel sandstone of the Menefee Formation is also dominated by kaolinite (Mannhard, 1976). It contains a very minor amount of montmorillonite and illite.

The clay mineral suite in shales from Facies A (beach-offshore transition zone), and from shale breaks in Facies B (shoreface facies) is highly dominated by montmorillonite (see Figure 39B). Illite and mixed layer illite-montmorillonite occur in all shale samples, but have low relative abundance, and a minor relative abundance of kaolinite also occurs. The kaolinite peak is slightly higher in samples of shale breaks separating sandstone units in Facies B than in the shales of underlying Facies A (see Figure 39B). Lagoon and swamp claystones, Facies E, are also rich in montmorillonite; but they contain a subequal to equal abundance of kaolinite (see Figure 39B). The illite peak is almost indistinguishable in samples of lagoon and swamp claystones, but mixed layer illite-montimorillonite seems to be slightly more abundant. The clay mineral suite of the shales and claystones is generally more varied than that in sandstones.

The major contrast in clay mineralogy between marine sandstones and associated marine shales, and the similarity of clay mineralogy in marine sandstones and non-marine channel sandstones indicate that clay mineralogy in the sandstones is not primarily controlled by environment of deposition. The difference in the clay mineral suite of the sandstones from that in associated shales reflects the effect of post-depositional changes in the sandstones which are relatively permeable and accordingly more infiltrated by large volumes of pore water. Kaolinite, which is the dominant clay mineral in the sandstones of the Point Lookout sequence, is known to be a product of diagenetic processes in sandstones (e.g., Weaver, 1959, 1960; Blatt, *et al.*, 1972; Pettijohn, *et al.*, 1972; Folk, 1974; Weaver, 1975); it forms due to alteration of sand particles, such as feldspar, and/or alteration of pre-existing clays, such as illite and montmorillonite, to kaolinite. Weathering at the outcrop also leads to the formation of kaolinite (Altschuler and Dwornik, 1964). Kaolinite is considered, in general, to be abundant in nonmarine sediments (Weaver, 1959); however, leaching processes by near surface ground water, which is usually acidic, and weathering processes at the outcrop seem to be the major factors leading to abundance of kaolinite in the marine sandstones of the Point Lookout Sandstone as well as in the channel sandstones of the lower Menefee Formation.

Despite the fact that clay minerals are susceptible to chemical and physical changes at any stage, the observed difference in clay mineral suite in the mudrocks of the Point Lookout sequence displays a significant relation to environments of deposition. Marine shales from Facies A (beach-offshore transition zone) and Facies B (shoreface zone) are dominated by montmorillonite, and kaolinite is very minor, while lagoonal and swamp organic-rich claystones contain less montmorillonite and a substantial amount of kaolinite. Kaolinite in the nonmarine claystones may reflect the effect of acidic fresh water in the swampy areas. The dominance of montmorillonite in the marine shales may reflect the absence of acidic conditions as indicated by lack of kaolinite, and that K/Na and K/Mg ratios were low favoring formation of montmorillonite rather than illite (Weaver, 1975).

Clay minerals in sandstones of the Point Lookout sequence can be used neither for interpretation of environment of deposition nor for identification of source rocks, because they are related mainly to post-depositional conditions. But clay mineral suites in the associated shales and claystones, where differences in clay mineralogy fairly well coincides with environment of deposition, can be considered in relation to the type of depositional environment. Although clay minerals are mostly controlled by conditions at the source area and by the chemical and physical conditions at the site of deposition and during post-depositional history, abundance of montmorillonite in the shales and claystones suggests volcanic rocks and/or montmorillonite-rich shales as source rocks.

Provenance

Terrigenous material of a sediment represents the weathering residue of source rocks which has been eroded, transported and deposited. Each type of rock in the source area yields a certain type of fragment and a distinctive suite of mineral grains. Accordingly, mineralogical composition of a sediment is expected to provide a guide to the nature of the parent rocks. But the composition of a sediment is not only controlled by the character of its source rocks, but also is a function of climate and relief within the source area (Pettijohn, 1975). Moreover, parameters such as length and nature of transport and conditions at the depositional site may affect the composition of the sediment. The particles constituting an ancient sediment, such as the Point Lookout Sandstone, have also been subjected to diagenetic alteration during their long post-depositional history. It is obvious that the petrographer ought to be aware of all the factors which might have affected the sediment since his goals are: to determine the mineralogic composition of the sediment, to remove the effects of diagenesis in order to decipher the primary composition, and to make inferences about the nature and character of the source rock or rocks from which the sediment was derived. Detailed discussion of the provenance concept is beyond the topic of this study, and the rest of this section will be devoted to interpreting the possible source rocks of the Point Lookout Sandstone based on petrographic observation.

The abundance of monocrystalline quartz grains with straight to slightly undulose extinction, the occurrence of a significant amount of feldspar, which is dominated by orthoclase with some microcline and sodic plagioclase, and the presence of some granitic fragments indicate that a granitic source was a major contributor to the sediments constituting the Point Lookout Sandstone. Granitic source rock may also contribute at least some of the polycrystalline quartz grains which contain 3 crystals or less (e.g., Blatt, *et al.*, 1972; and Basu, *et al.*, 1975).

The diverse nature of the lithic fragments in the Point Lookout Sandstone suggests a variety of source rocks. The rounded monocrystalline quartz grains, which form up to about 25 percent of the total quartz in some sandstones, are most likely recycled from older sandstones. The argillaceous fragments, which are relatively abundant among the lithic fragments, and the sandstone fragments indicate nearby sedimentary source rocks. Some of the clays, for example some illite and montmorillonite, could have been derived from older shales composed of these mineralogies. Lithic fragments of sedimentary origin are not abundant in the Menefee channel sandstones (Mannhard, 1976). Assuming that the channel system within the Menefee facies was the major sediment supplier to the coastal area, the relative abundance of the sedimentary lithic fragments in the Point Lookout sandstones and their rarity in the channel sandstones also suggest a nearby source for the argillaceous and sandstone fragments.

Chert, which is relatively abundant in the Point Lookout Sandstone, also indicates a sedimentary source rock. It is usually associated with carbonate rocks; absence of carbonate fragments is probably due to their low chemical resistance during weathering and transport. Some of the chert, especially the well rounded grains which are not abundant, could have been recycled from older sandstones which supplied the rounded quartz grains.

Metamorphic source rocks seem to be an insignificant contributor of sediments to the Point Lookout Sandstone. Some of the polycrystalline quartz with 3 crystals or less, might have been derived from a high-rank metamorphic rock (Basu, *et al.*, 1975); however, absence of indicative heavy minerals discredits this possibility.

The few volcanic rock fragments indicate that volcanic rocks existed in the source area, but were not abundant (assuming they were not completely altered to clay minerals during weathering).

The diversity of the lithic fragments and accordingly the interpretation of multiple source rocks for the Point Lookout Sandstone correlates with the geologic setting of the presumed source area to the south and southwest. The Late Cretaceous mountainous areas in southwestern New Mexico and southeastern Arizona probably provided most of the sediments of the Mesaverde Group (Hayes, 1970). At the beginning of the Cretaceous, Precambrian plutonic rocks and Paleozoic strata were exposed in the high region of southwestern New Mexico and southeastern Arizona; the relatively low terrain to the north was occupied by Late Paleozoic and Early Mesozoic sediments. Volcanic rocks also existed in some parts of the region (Hayes, 1970). The presence of fresh feldspar grains suggests that the source areas, at least that of granitic rocks, were characterized by low humidity and/or high relief; the latter factor was probably the most effective.

PALEONTOLOGY

Fossil Assemblages

Body fossils

A fairly extensive search for macroinvertebrate fossils was conducted during field work, and moderately representative taxa were collected from the Point Lookout Sandstone and sandstone units in the underlying transition zone. Macroinvertebrate fossils in the Point Lookout Sandstone are more common in Facies B sandstones than other facies. They are moderately to highly abundant in zones which are relatively predominantly calcite-cemented and contain large highly calcite-cemented sandstone concretions. Two different assemblages can be recognized within the fauna of the Point Lookout Sandstone, based on diversity. A somewhat different assemblage exists in some of the sandstone beds in Facies A (transition zone). Identified fossils and their relative abundances are listed in Table 5; the bivalves and cephalapoda were identified by W. A. Cobban (U.S. Geological Survey, Denver). Although the faunal content of the Point Lookout Sandstone, which is mostly molluscan, is moderately well represented in the combined collection (Table 5), more thorough search will most likely reveal more species.

A nondiverse assemblage consisting mainly of bivalves occurs in units Kpl-3-5 and 8 (Plate 1). The bivalves are dominated by medium-sized *Cymbophora* and *Inoceramus*. Their occurrence is associated with large calcite-cemented

Table 5. Macroinvertebrate taxa and trace fossils in the Point Lookout Sandstone at the southeastern part of the San Juan Basin, New Mexico.

MOLUSCA:

Bivalvia:

Cymbophora formosa (abund.)
Ethmocardium whitei (abund.)
Legumen ellipticum (moderately abund.)
Cucullaea (?) sp. (several)
Cymella montanensis (several)
Nucula (?) sp. (several)
Inoceramus balticus (few)
Ostrea (very few)
Phelopteria cf. *linguaeformis* (two)

Gastropoda:

Gyrodes sp. (moderately abund.)
Turritella sp. (several)
three other miscellaneous snails

Cephalopoda:

Placenticeras planum (several)
Placenticeras syrtale (few)
Scaphites sp. (very few)
Baculites sp. (two)

TRACE FOSSILS:

Burrows and Trails:

Ophiomorpha (abund.)
Thalassinoides (moderately abund.)
Skolithos (several)
Gyrochorte (several)

Borings:

Teredolithus

Plant Structures:

Root molds

sandstone concretions. The original shell material essentially does not exist; but molds are fairly complete, although detailed features are missing. The abundance of these bivalves is low to moderate; they are not confined to a very thin zone or bedding surfaces, but are disseminated throughout the concretionary zone. They do not exhibit a preferred orientation of long dimensions, but essentially all specimens are concave downward.

A relatively diverse assemblage also occurs in some horizons within Facies B sandstones at stratigraphic sections Kpl-4 and Kpl-6 (Plate 1). At section Kpl-4, a mixture of different size fragments mostly of bivalves and gastropods, and some moderately complete small bivalves and gastropods, and shark teeth occur in very thin zones in units Kpl-4-5-7 and 9. The fragments are of different size and shape with variable degree of abrasion, and lack a dominant preferred orientation. The small relatively complete bivalves are dominantly *Ethmocardium whitei, Cymbophora,* and *Cucullaea (?);* gastropods are mainly *Gyrods*, with a very few *Scaphites*. Few moderately complete bivalves also occur through the rest of unit Kpl-4-7. Again, the fossiliferous zones are associated with large calcareous concretions. A similar thin zone of a highly diverse accumulation of shell fragments and of moderately complete small forms exists in unit Kpl-6-5. This unit also contains a fairly diverse assemblage dominated by bivalves and ammonites, with some gastropods. They are present in sandstones with poorly to moderately developed thick laminations. The preservation is moderately good. Bivalves are of variable size and shape, and have both convex and concave side up, but the former is more abundant; they are dominated by *Cymella montanesis*, *Ethmocardium whitei*, and some *Cymbophora* and possibly *Cucullaea (?)*. *Placenticeras syrtale* is moderately abundant; and the few gastropods are mainly *Gyrodes*.

A relatively highly diverse assemblage also occurs in laminated and moderately calcite-cemented thin sandstone intervals in the transition zone (Facies A); the best example is at section Kpl-3. Complete specimens are relatively abundant; but fragments also occur in narrow zones within the fossiliferous interval. The fossils form clusters in a local zone within a sandstone interval, with fossils in contact with each other in a vertical direction but lacking any preferred orientation. The bivalves are principally *Cymbophora*, *Legumen ellipticum*, and some *Ethmocardium whitei*; gastropods are mainly *Turritella*, and some *Gyrodes*; and cephalopods are mainly *Placenticeras planum* and some *Placenticeras syrtale*. The *Placenticeras* in this assemblage are generally larger than those in Facies B sandstones.

Shark teeth occur sporadically in almost all the fossiliferous horizons. Two very small pieces of a vertebrate material (fishbone?) were found in units Kpl-4-5 and Kpl-6-5.

Facies C sandstones are essentially devoid of body fossils with the exception of two molds of bivalves (*Inoceramus?*) in unit Kpl-4-12. They are poorly preserved; a few more unidentified molds, which are most likely after fossils, occur in the same horizon.

With the exception of woody material and carboneous debris, the sandstones of Facies D and E are devoid of body fossils. Wood material and lignitic lenses are abundant in Facies E sequence.

Trace fossils

Trace fossils are among the most important, relatively wide spread features in many sandstone units of the Point Lookout Sandstone. They are dominated by *Ophiomorpha* in Facies C sandstones, *Ophiomorpha* and *Thalassinoides* in Facies B sandstones, and *Skolithos (?)*, *Thalassinoides* and trail type traces *(Gyrochorte(?))* in Facies A sandstones, and *Teredolithus* in Facies D sandstones. Trace fossils occur in more units and are more widely distributed through the individual sandstone units than the body fossils which are generally confined to calcite-cemented zones, with or without concretions; however, the concretionary zones provide the most and best preservation of burrows.

Ophiomorpha are the most abundant (or at least the most preserved). They occur mostly as non-branched long tubes, up to 70 cm long and 2.5 cm in diameter (see Figure 15). Some of them have iron oxide-cemented walls; this provides good preservation, especially for the knobby structure of their walls which generally is not well preserved. *Ophiomorpha* occurs mostly in Facies B sandstones, especially the trough cross-stratified zones, and comprises the only significant faunal characteristics of Facies C sandstones. They show from vertical to oblique to horizontal orientation; the latter apparently was the least preferred. They seem to be very limited in sandstones of subfacies B_2 and are essentially absent in Facies A below.

The second most abundant type of burrows in the Point Lookout Sandstone are *Thalassinoids*. They are similar to, and may exist with, *Ophiomorpha*. They have smooth walls and tend to branch more than the associated *Ophiomorpha*. They occur in Facies B sandstones, and to a certain extent in Facies A; they are apparently more abundant than *Ophiomorpha* in subfacies B_2 sandstones. They show variable orientation, but they seem to be more abundant as horizontally oriented on bedding surfaces, especially near shale breaks within Facies B sequence.

Vertical to oblique, sand-and-silt-filled tubes, up to about 1.5 cm in diameter and several centimenters long, occur in some zones of Facies A. They extend through the shale from the overlying interbedded sandstone zone (see Figure 8).

Facies A is also characterized by thin burrow tubes (few millimeters in diameter) which are concentrated mainly on bedding surfaces in sandstones. Curved or sinuous trail type features are relatively common on bedding surfaces of some of the sandstone intervals in Facies A. They are thought to be *Gyrochorte*.

Age of the Point Lookout Sandstone

At the southeastern part of the San Juan Basin, ammonoid cephalopods are relatively abundant in sandstone intervals in the lower part of the Point Lookout Sandstone and the underlying transition zone. The observed specimens (Table 5) indicate that the Point Lookout Sandstone in the study area is of Lower Campian age (personal communication, Dr. W. A. Cobban, U.S. Geol. Survey, Denver). The identified *Scaphites* species places the Point Lookout Sandstone in the *Scaphites hippocrepis* zone (personal communication, Dr. W. A. Cobban); the collected *Scaphites* specimen was from unit Kpl-4-7 (Plate 1). Accordingly, the estimated age of the Point Lookout Sandstone, based on interrelated biostratigraphic and radiometric age dates (Gill and Cobban, 1966, Table 2), is 81 to 82 million years.

Landis, Dane, and Cobban (1974) reported the presence of *Scaphites hippocrepis,* which is an index for the Lower Campanian, in the lower part of the upper half of the "Upper Shale Unit" of the Mancos Shale in the Tierra Amarilla area in New Mexico. The "Upper Shale Unit" becomes sandier upward in a zone transition into the overlying Point Lookout Sandstone. Accordingly, the Point Lookout Sandstone is most likely related to the upper *Scaphites hippocrepis* zone, or slightly younger, in the Tierra Amarilla area. The fact that the Point Lookout Sandstone rises stratigraphically progressively north-northeastward across the San Juan Basin (see Figure 42) indicates that the Point Lookout Sandstone at the southern part of the basin is certainly older than that at the northern part of the basin. However, the paleontologic collections from the Point Lookout Sandstone do not permit precise determination of such age differences, which would provide a reasonable means for estimating the rate of regression during deposition of the Point Lookout Sandstone. The inadequacy of the paleontologic data for such an approach was confirmed in a discussion with Dr. W. A. Cobban. Thus, the age of the Point Lookout Sandstone is best regarded as 81 to 82 million years.

SUBSURFACE STRATIGRAPHIC ASPECTS OF THE POINT LOOKOUT SANDSTONE

A detailed study of the subsurface aspects of the Point Lookout Sandstone is essentially beyond the scope of this study. However, in order to illustrate the overall regional stratigraphic nature of the Point Lookout Sandstone and accordingly to decipher any stratigraphic features that are significant in relation to its depositional system, this relatively brief subsurface analysis is included.

The Point Lookout Sandstone and other units of the Cretaceous sequence have been the target of oil and gas exploration since the initiation of exploration in the San Juan Basin area. Accordingly, subsurface data about the Point Lookout Sandstone, as well as other units of the Upper Cretaceous sequence, are available from several industrial corporations; subsurface data used for this study were obtained from the New Mexico Bureau of Mines and Mineral Resources. Data from more than 400 scout cards, from wells throughout the San Juan Basin in New Mexico which penetrated to the Mancos Shale, are used to construct an isopach map for the Point Lookout Sandstone and a structure contour map on its top; collected data are tabulated in Table 7 (Appendix D).

The isopach map (Figure 40) shows that the Point Lookout Sandstone is present throughout the basin with thickness varying, somewhat irregularly, from about 75 feet to about 380 feet. Except for the northwestern portion of the

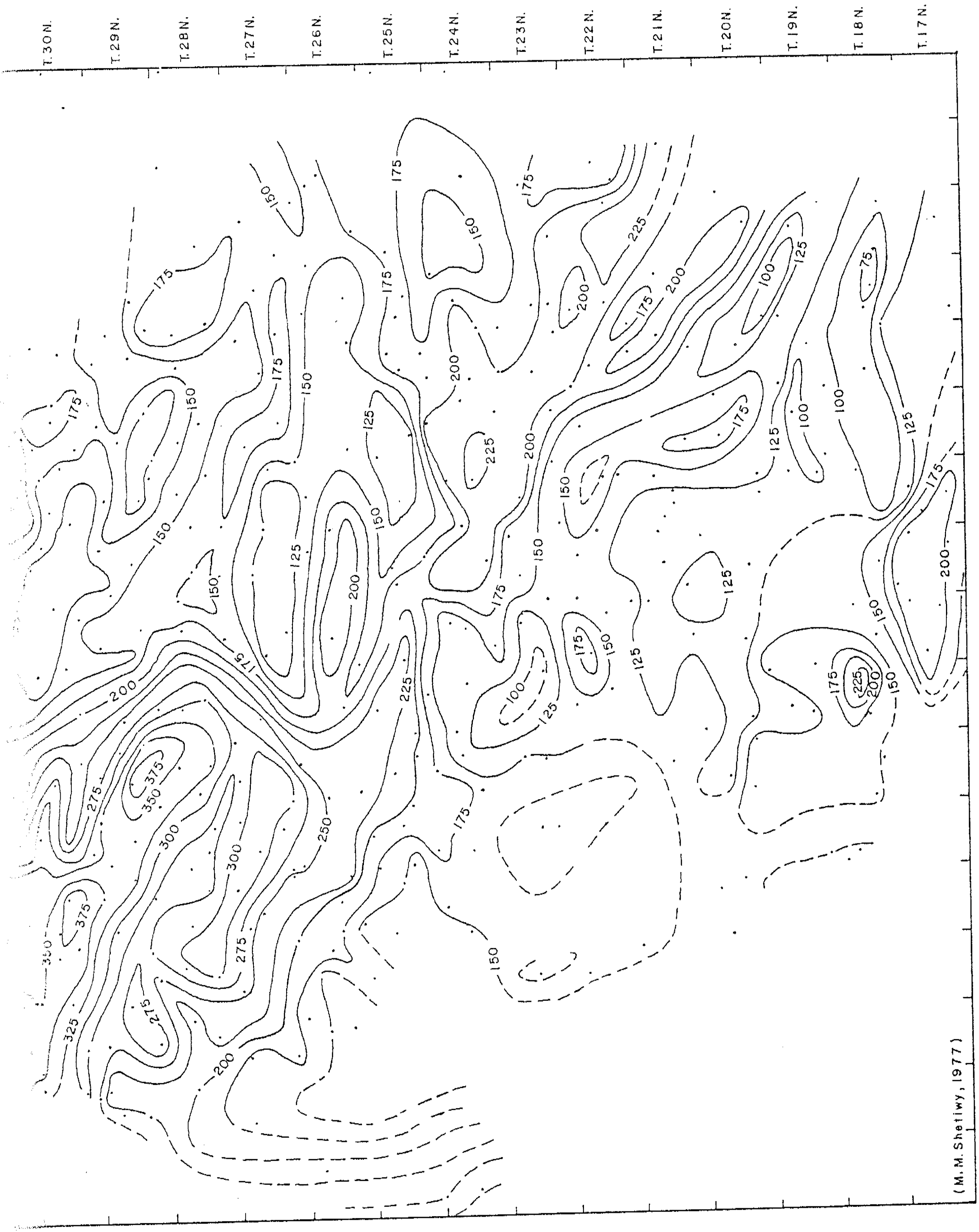
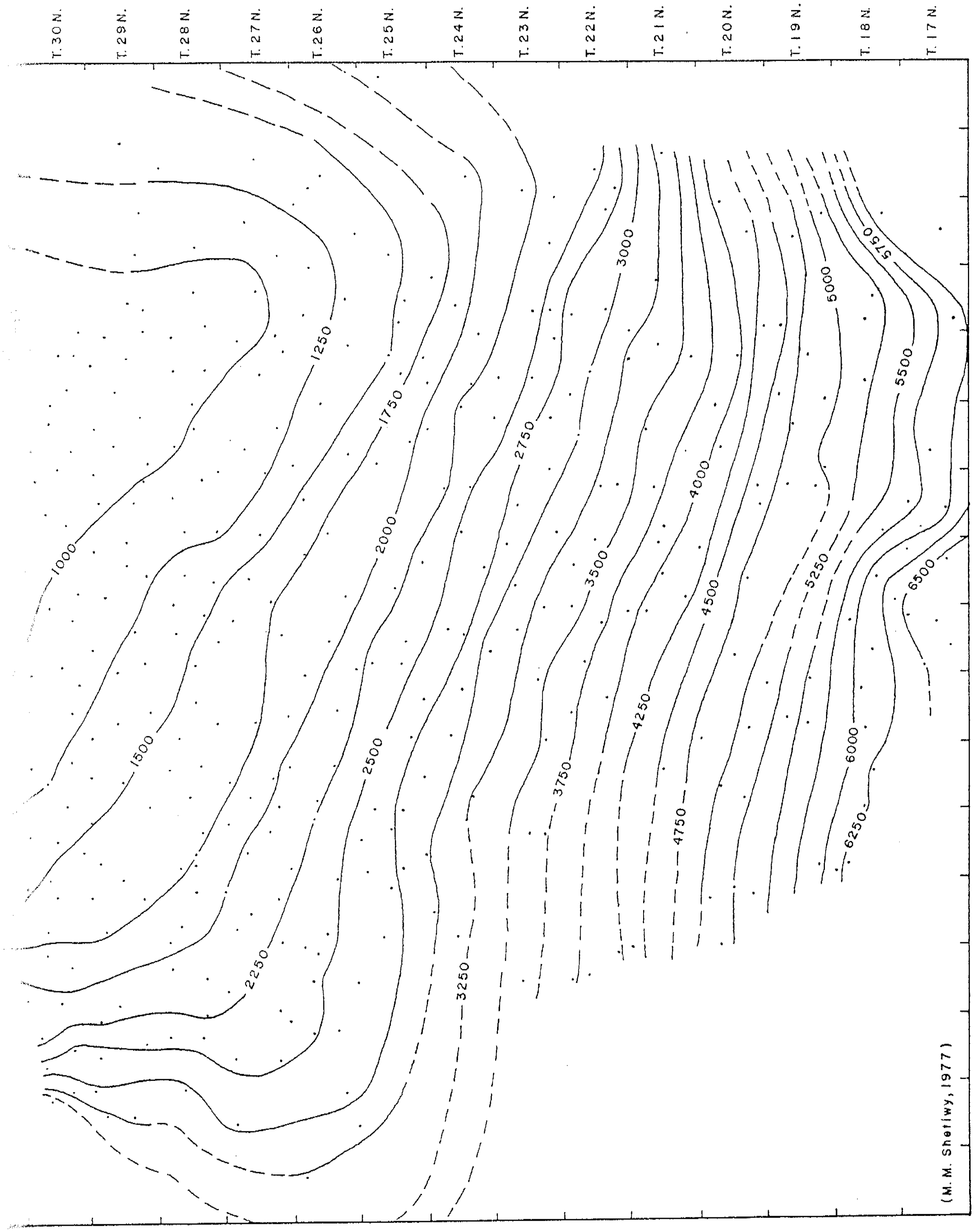


Figure 40. An isopach map of the Point Lookout Sandstone in the San Juan Basin area, northwestern New Mexico. Contour interval is 25 feet.

basin, its thickness ranges mostly between 125 and 200 feet. The thickness varies the most along a southwest-northeast trend. The presence of a relatively thick transition zone below the prominent Point Lookout Sandstone results in some degree of discrepancy in the placement of the lower contact with the underlying Mancos Shale by different workers, but the observed dominant trend of variation in thickness is essentially due to the trend of elongated sandstone bodies. Checking several electric well logs shows that the discrepancy in the placement of lower contact is generally within 20 feet. Hence, the isopach map indicates that there were stages of buildup of sandstone bodies which were several tens of miles long in a southeast-northwest trend and only a few miles in width. It is obvious that as the shoreline retreated gradually, long sandstone bodies were built up along the shoreline at stages of very slow rate of shoreline retreat, or almost stationary shoreline. The dominant trend of sandstone bodies confirms the general southeast-northwest trend of the paleoshoreline, and that the shoreline retreat was northeastward at a generally slow rate, becoming almost stationary at certain stages.

The southeast-northwest trend of the Point Lookout paleoshoreline is also indicated by the trend of the northernmost and southernmost extent of the Point Lookout Sandstone. The Point Lookout Sandstone progressively rises stratigraphically northward until it merges with the Cliff House Sandstone on the northern side of the basin; the total pinchout is probably not much further north. The merging point of the Point Lookout Sandstone and the Cliff House Sandstone at the accompanied pinchout of the nonmarine Menefee Formation at the northwestern corner lies in a northwest direction in relation to the merging point at the northeastern corner of the basin; Beaumont's stratigraphic sections (Figures 6 and 7, in Shomaker and others, 1971) show that the northern pinchout of the Menefee Formation (or the merging of the Point Lookout Sandstone and the Cliff House Sandstone) in the northwestern corner of the basin was several miles north of Durango, Colorado, while in the northeastern corner it was just near the New Mexico-Colorado state line. Regional mapping (e.g., Dane and Bachman, 1965) shows that the line marking the southernmost extent of the Point Lookout Sandstone follows a southeast-northwest trend; Molenaar (1977) indicated that a line connecting the points of the southern pinchout of the Point Lookout Sandstone trends about N60°W. Molenaar also noted that the sandstones mapped as Point Lookout Sandstone in the Acoma embayment on the state geologic map were not related to the Point Lookout unit.

The structure contour map of the top of the Point Lookout Sandstone (Figure 41) shows a generally planar surface with no significant local structures. However, small scale local structure probably would not be pronounced within a unit which is mostly less than 250 feet thick by using a 250 foot contour interval. But the planarity of this sur-



e 41. A structure contour map on top of the Point Lookout Sandstone in the San Juan Basin area, northwestern New Mexico. Contour interval is 250 feet.

face is also generally maintained in a structure contour map on the top of the Point Lookout Sandstone with a 100 foot contour interval by Kilgore and Budd (Budd, 1957) in most of the basin. The contoured top surface of the Point Lookout Sandstone is generally sloping gently northeastward; the slope decreases gradually to the northeast. Assuming that the upper surface of a conformable interval is the depositional surface (Krumbein and Sloss, 1963), the structure contour map (Figure 41) indicates that the Point Lookout Sandstone was deposited on a smooth, very low northeastward sloping surface with no significant local structural features; such characteristics of the depositional surface were displayed also in a structure contour map contoured on the base of the Dakota Sandstone throughout the San Juan Basin by Silver (1950, Figure 6).

The transition zone marking the boundary between the Point Lookout Sandstone and the underlying deeper marine Mancos Shale is usually clearly shown on the electric logs. Cross sections across the San Juan Basin in south to southwest-north to northeast trends show that the Point Lookout Sandstone rises stratigraphically north-northeastward (or seaward; see Figure 42). The rate of northward stratigraphic rise of the Point Lookout Sandstone is relatively high; Figure 42 shows about 800 feet of stratigraphic rise for the top of the Point Lookout Sandstone over a horizontal distance of about 80 miles across the basin. This seaward stratigraphic rise is a diagnostic feature of a major regression characterized by a slow rate of shoreline retreat.

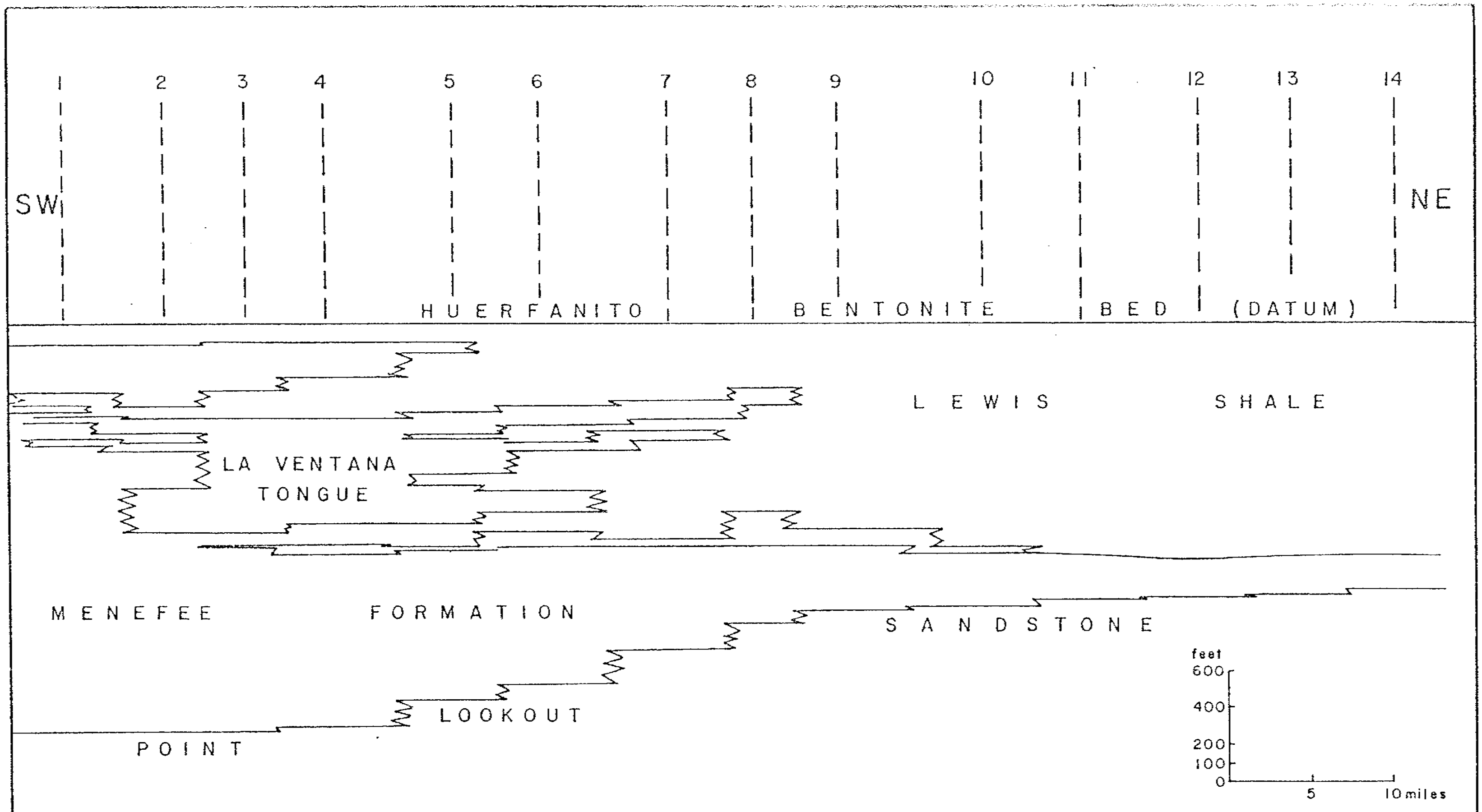


Figure 42. Subsurface stratigraphic cross section across the San Juan Basin showing the stratigraphic position of the Point Lookout Sandstone relative to a bentonite bed in the Lewis Shale; the top of the Point Lookout Sandstone rises about 800 feet within a distance of about 80 miles in a northeast direction (seaward) (modified from Fassett, 1977).

(M.M. Shetiwy, 1977)

DEPOSITIONAL MODEL FOR THE POINT LOOKOUT SEQUENCE

General

The overall depositional system of the Point Lookout sequence in the southeastern and eastern San Juan Basin can be reasonably deduced from the following major criteria; 1) the vertical and horizontal relationships between the Point Lookout Sandstone and the underlying Mancos marine shale are well displayed in many places along the eastern side of the San Juan Basin; 2) fossil content (both body and trace fossils), sedimentary structures, spatial distribution, and lithologic and textural characteristics of the Point Lookout Sandstone indicate that it is dominantly of near-shore marine origin; 3) the Point Lookout Sandstone is over-lain by claystones, carbonaceous shales, humate and coal beds, and lenticular sandstones of lagoonal, bay, swamp and fluvial origin that form the Menefee Formation (Mannhard, 1976). Based upon these lines of evidence, the Point Look-out sequence represents a regressive system in which the Point Lookout Sandstone was developed by a prograding sandy shoreline. To interpret this depositional system in detail, a description of sandy shoreline profiles is outlined in the following section.

Shoreline profiles of sandy mainland coasts

A typical sandy shoreline profile and its significant zones or subenvironments is shown in Figure 43. These zones starting from mainland to offshore zone are described below.

(1) The profile starts with a mainland zone which may consist of lagoon, bay, swamp, alluvial plain, or older rocks, depending on the prevailing conditions and stability of the strandline. Claystones, carbonaceous shales, coal, muddy sand, and lenticular coarse to very fine channel sands are the possible major deposits of this zone; abundance of the different sediment types depends upon the relative prevalence of the subenvironments within this zone.

(2) Dune zone-. Sandy beaches are commonly bordered by a belt of coastal dunes due to abundant supply of loose sand and common onshore winds (Harms, 1975; and Reineck and Singh, 1973). Their size depends upon rate of supply of fine sand material, climatic conditions, and vegetation. Coastal sand dunes are generally characterized by well-sorted, fine-grained sands with large trough (festoon) type cross-bedding (Klein, 1975).

(3) Backshore-. The seaward side of the profile starts with a backshore zone which represents the uppermost part of the beach. This part of the beach is above mean high-water level, and is flooded and subjected to wave action only intermittently under extremely high water. Bedding in the backshore zone is dominated by nearly horizontal stratification and low angle, mostly landward dipping cross lamination (Reineck and Singh, 1973).

(4) Foreshore-. The foreshore is that part of the

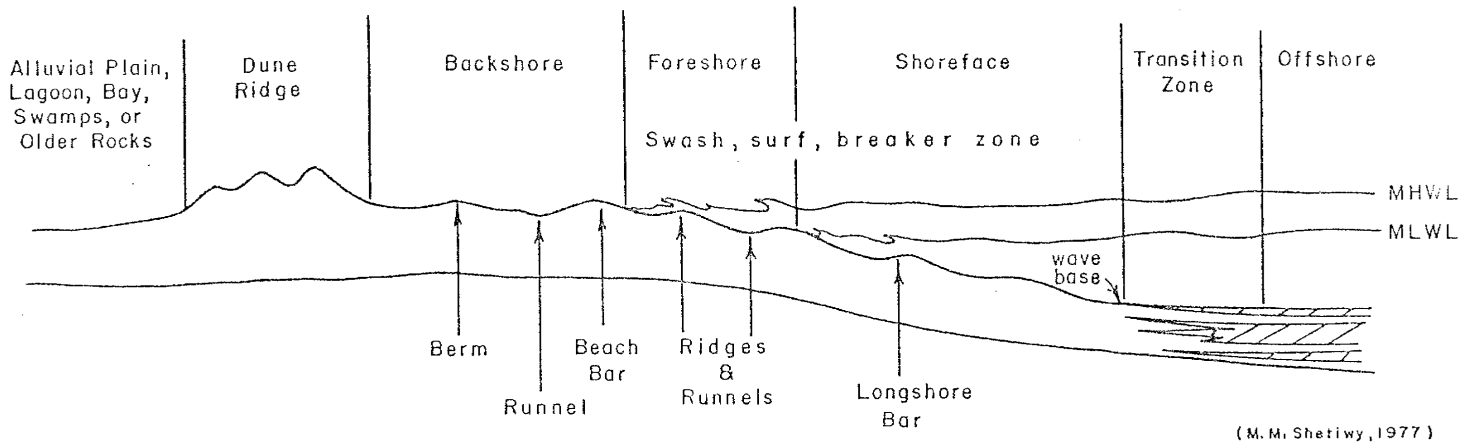


Figure 43. Shoreline profile typical of sandy mainland coasts (modified from Reineck and Singh, 1973; and Harms, 1975). MHWL and MLWL refer to mean high and mean low water level.

beach which is flooded and exposed during normal tidal cycles. Stratification in the foreshore zone is dominantly one to fifteen centimeters thick bedsets of evenly laminated sand with low-angle, seaward dipping cross-stratification (Reineck and Singh, 1973). Foreshore sand also is characterized by good sorting due to the action of swash and backwash processes. It is not uncommon that one or more longshore bars develop in the foreshore zone (e.g., Reineck and Singh, 1973).

(5) Shoreface--. The shoreface is the nearshore zone which lies between the mean low-water level and the wave base (depth where sediments of sand size are not moved by normal waves typical of that beach). Submerged longshore bars, commonly two or more, usually occur in the shoreface zone (Reineck and Singh, 1973). In the area of the uppermost longshore bar of the shoreface, wave ripple marks and undulatory megaripples are produced by strong waves (Reineck and Singh, 1973). Small trough type cross-stratification characterizes the upper shoreface; whereas in the deeper part, cross-stratification is rare and lamination is the dominant stratification type. Bioturbation is generally abundant in the shoreface zone especially in the lower part.

(6) Transition zone--. A transition zone occurs between shoreface sands and offshore muds. The presence and depth of the transition zone depends upon the availability of both sand and mud, and upon the energy of the coast. Sediments in the transition zone are usually clayey silt to

silty sands; and bioturbation is very abundant (Reineck and Singh, 1973).

(7) Offshore-. The offshore zone is the shelf area beyond the transition zone. Mud sediments dominate the offshore sediment; however, a great number of the present continental shelves are covered with sediments of earlier sea level stands (Emery, 1968). Although offshore sediments are mainly silty clay to clayey silt (Reineck and Singh, 1973), layers of coarse silt or very fine sand commonly occur; they are related to heavy storms (Hayes, 1967).

Point Lookout Prograding Sandy Shoreline System

General

In a regressive marine sequence, the deeper water sediments (below wave base) are successively overlain by sediments deposited nearer shore and in shallower and shallower water. Such progradational sequences develop in coastal (or shore) areas where ample sediment supply is maintained. As sediments accumulate along the shoreline of a stable sea level, beach sand builds upward and seaward overlying, transitionally, finer sediments of deeper water, and is overlain by nonmarine coastal sediments, resulting in laterally continuous facies such as illustrated in Figure 44.

The Point Lookout sequence is a regressive sequence in which the fundamental components shown in Figure 44 occur to some extent in all the measured stratigraphic sections (Plate

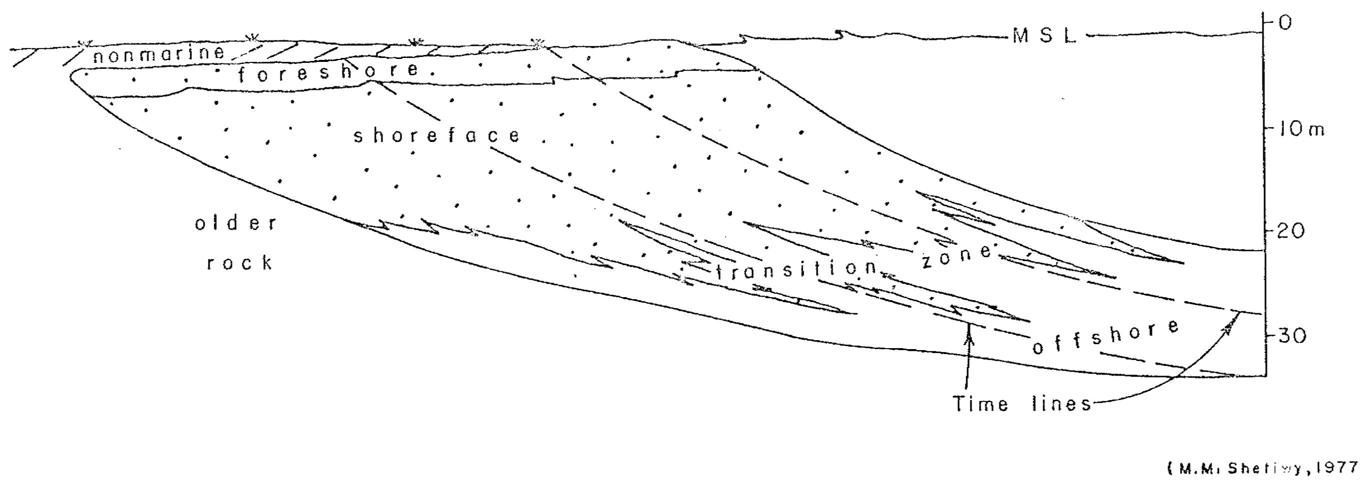


Figure 44. Schematic facies relationships of a prograding shoreline during stable sea level (modified from Busch, 1974, and Harms, 1975).

1). Complete sections of the Point Lookout sequence consist of a zone of interbedded shale and very fine sandstone overlying deep marine shales of the Mancos Shale, an overlying sequence of very fine to fine marine sandstone units, and a sequence of carbonaceous shale, coal seams, and lenticular, "channel type", sandstone units.

Depositional environments of the different facies in the Point Lookout sequence

Detailed field studies of the Point Lookout Sandstone and the adjacent portions of the underlying Mancos Shale and the overlying Menefee Formation showed that this sequence (referred to as the Point Lookout sequence) consists of several sedimentary facies (see Chapter 2). These facies are fairly readily distinguishable in complete sections and are moderately persistent laterally (see Plate 1). The overall system which produced this fairly complete sequence is a regressive system in which the upper Mancos Shale represents an offshore marine, the Point Lookout Sandstone represents near shore or beach environment, and the coal-bearing lower Menefee represents coastal lagoon, swamp and fluvial environments. Figure 45 is a highly schematic diagram illustrating the distribution of various environments and stratigraphic relationships for the Point Lookout sequence. The Point Lookout system consists of the following northward (seaward) succession of facies (see Figure 45): 1) swamp channel, and lagoon facies; 2) beach modified estuarine and fluvial sandstone facies; 3) beach sandstone, including foreshore and

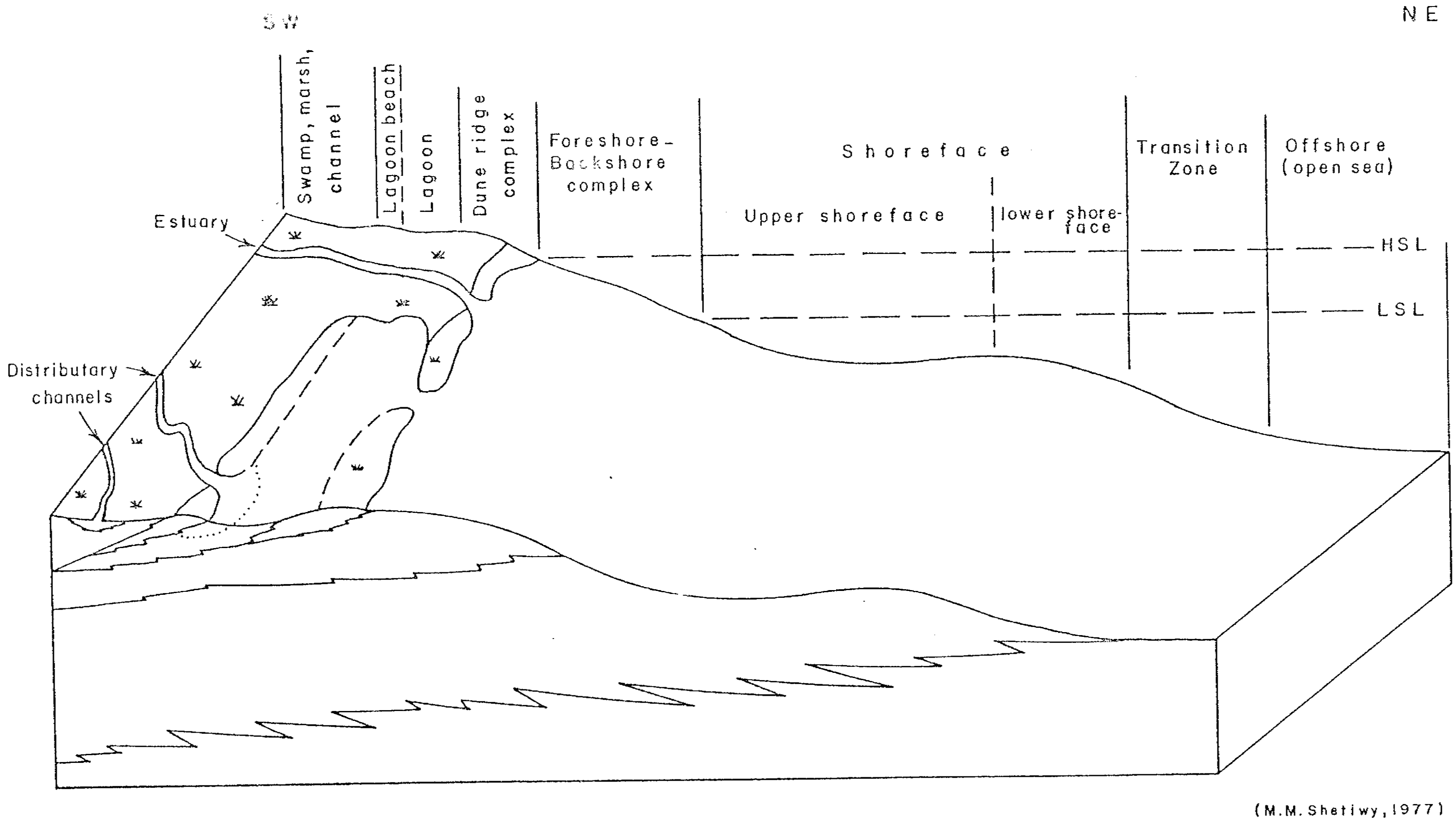
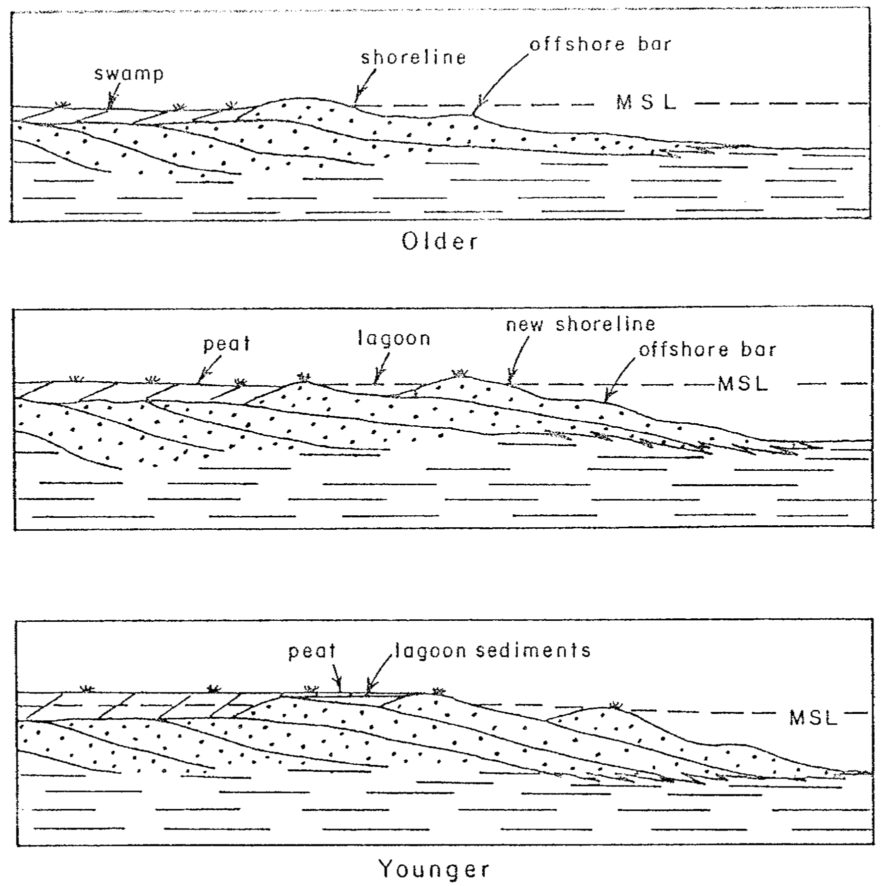


Figure 45. Schematic distribution of environments and stratigraphic relationships for the Point Lookout Sandstone and adjacent units. HSL and LSL refer to high and low sea level.

backshore subfacies; 4) shoreface sandstone facies; and 5) beach-offshore transition facies. The beach-offshore transition zone grades seaward into offshore siltstone and shale facies. Dune sandstone subfacies may overlie beach sandstones, or estuarine sandstones.

As the shoreline shifted gradually north to northeastward during deposition of the Point Lookout sequence, adjacent environments and subenvironments accordingly shifted in the same trend resulting in a vertical stacking of the developed sedimentary units in a manner that the landward unit (or facies) overlies adjacent seaward facies (see Figure 46). The sedimentary facies forming the Point Lookout sequence represent a classical fairly complete regressive system that resulted from a gradual retreat of the shoreline, north to northeastward. The five different facies identified in the Point Lookout sequence (see Chapter 2) correspond to the five environments (and subenvironments) listed above, with Facies A corresponding with the beach-offshore transition zone, Facies B with shoreface, Facies C with foreshore-backshore, Facies D with estuarine and fluvial-beach intermixed zone, and Facies E with the coastal swamp-channel-lagoon complex. In the following section, the environment of deposition of each facies of the Point Lookout sequence is discussed in detail. Also environmental interpretations of specific stratigraphic units in the measured stratigraphic sections are shown to the right of the sections in Plate 1; interpretations were based on stratigraphic relations, lithology and



(M.M. Shetiwy, 1977)

Figure 46. Schematic diagram illustrating the development of the Point Lookout beach sandstones and the associated units (modified from Young, 1955, and Hollenshead and Pritchard, 1960). MSL refers to mean sea level.

texture, paleontology, and sedimentary structures.

Beach-offshore transition (Facies A)

The lowest facies of the Point Lookout sequence, Facies A, composed of interbedded shales, siltstones and lenticular to tabular sandstones, retains considerable thickness throughout the study area indicating that the shelf during the Point Lookout time was characterized by a relatively wide transition zone between the beach environment where sand was deposited and the offshore deeper marine environment where finer mud accumulated. The sandstone beds within Facies A are generally characterized by sharp lower boundaries; a phenomenon which indicates a sudden change of conditions. Sandstone beds and lenses generally lack vertical to oblique burrows, but upper bedding surfaces exhibit horizontal burrows, indicating rapid deposition. Rapid deposition of sandstones in this facies is also indicated by the occurrence of ripple marks on some bedding surfaces and the absence of such structures within the beds, and by the lack of trough cross-stratification which may indicate reworking of the sand by currents and waves. Such rapid deposition of sand units beyond the normal beach zone most likely took place during storms. The presence of undulatory cross-lamination (see Figure 7) with lower gently curved erosional surfaces was also recognized in the Gallup Sandstone, in southwestern San Juan Basin, by Harms (1975). He referred to this type of sedimentary structure as hummocky cross-stratification and related it to storm surges (see Figure 47).

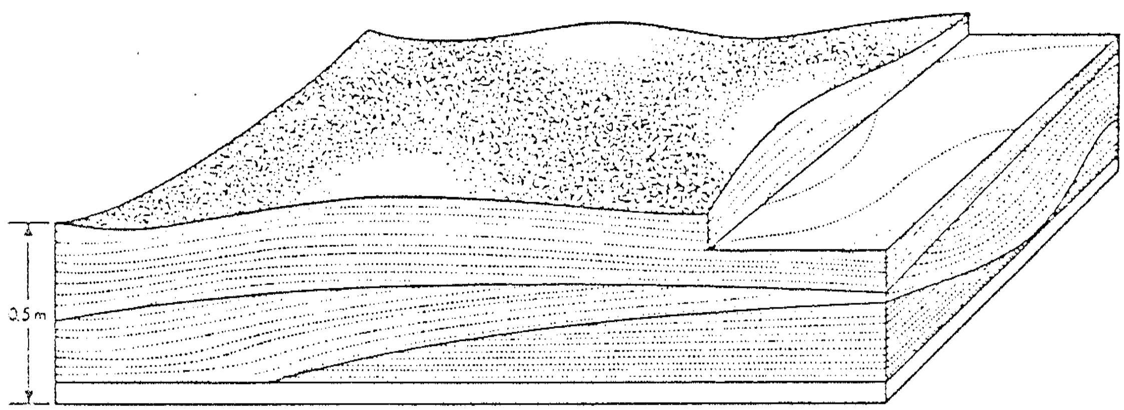


Figure 47. Hummocky cross-stratification. This form is common in coarse siltstone or very fine sandstone within the lower shoreface and transition zone facies. It is thought to form under strong storm-wave surges (from Harms, 1975).

The presence of a significant transition zone, such as Facies A of the Point Lookout sequence, points out that both sand and mud were available and conditions changed repeatedly from those suitable for mud deposition to those suitable for sand deposition. The alternation in depositional conditions was not periodic (at regular intervals); rather it was intermittent, which resulted in a non-systematic alternation of the developed units and a large vertical variation in their thickness (see Figure 4). Dominance of discrete sharp lower contacts at the base of sandstone subunits and less discrete upper boundaries with the shale and siltstone subunits indicate that the change from mud to sand deposition was more sudden than from the sand to mud stage. By definition, the transition zone is below wave base under normal conditions of that beach; therefore, mud subunits accumulated under normal conditions. But as storm conditions strike the area, wave base is lowered and some of the shoreface sand is stirred up and transported offshore. The transported sand is deposited forming the sand subunits with a discrete lower boundary above the previously deposited mud subunits. Sedimentary structures of this rapid deposition would have been dominated by horizontal stratification, which is the case in many sand intervals of Facies A. However as Harms (1975) reasonably explains the origin of hummocky cross-stratification, consequent strong storm surges may scour the previously deposited sand beds throwing the sand into suspension, and resulting in irregular hummock-type depressions. As sand settles out during following stages, undulatory (or hummocky) cross-stratification is developed at these irregular surfaces. As storm conditions diminish, and a normal wave regime prevails again, some bedforms, such as ripple marks, develop on the sand bed, and infauna inhabit the sand bed leaving their print as trails and/or burrows in the upper part of sand beds. Some of the muddy layers, which are deposited under more normal and quieter conditions, are reworked and mixed with sand layers by burrowing organisms, resulting in structureless highly muddy sandstone to sandy mudstone such as in Figure 8. The confinement of burrowing to the upper part of some sandstone beds indicates that deposition was rapid then slowed so that infauna populated the bed; but it was mantled and might have been killed by succeeding rapid erosion and deposition before reworking was complete (Howard, 1972).

This interpretation of the origin of the sandstone intervals in Facies A, which are numerous, may lead to the indication that stormy conditions prevailed during deposition of the Point Lookout sequence. But, as pointed out later in this chapter, the coastal regime during deposition of the Point Lookout sequence was relatively quiet. Accordingly, this transition zone was relatively shallow because its depth depends upon the nature of the energy of the coast; the lower the energy of the coast, the lesser the depth of the transition zone (Reineck and Singh, 1973). With a relatively shallow upper limit of transition zone, i.e., wave base, and availability of sand in the adjacent shoreface, any increase of the coastal energy would lead to the introduction of some sand into the transition zone, and moderate to fairly strong storm conditions produce significant sand beds in the transition zone.

Shoreface (Facies B)

Marine fossils and trace fossils in several zones of this major sandstone facies of the Point Lookout Sandstone indicate its marine origin. The occurrence of some glauconite grains in some of these sandstones also indicates the marine origin of the sandstones.

The transitional relationship of the sandstones in Facies B with the offshore marine shales, through a significant transition zone (Facies A), implies that these sandstones were deposited in shallower waters adjacent (landward) to the transition zone; i.e., beach zone. The type of stratification and cross-stratification of Facies B sandstones, dominated by trough and some tabular forms, distinguishes them from the overlying sandstones with thin to medium bedded and nearly parallel and even low lying laminasets of Facies C. The dominant, moderately well preserved trough cross-stratification in many sandstone units of this facies matches reasonably well with modern shoreface sand cross-stratification; trough cross-stratification is known to occur in the wave breaking zone in modern environments (e.g., Clifton, *et al.*, 1971; Howard and Reineck, 1972; and Reineck and Singh, 1973). Trough cross-stratification with similar characteristics was also described in ancient sandstone units interpreted as shoreface in origin (e.g., Masters, 1967; Molenaar, 1973; and Harms, 1975).

The trough cross-stratification is thought to represent upper shoreface (Molenaar, 1973; Reineck and Singh, 1973; Harms, 1975), and accordingly subfacies B_1 is interpreted as upper shoreface origin. Megaripple structure occurs in Facies B sandstones (see measured stratigraphic sections, Plate 1). Megaripple bedding is also known to occur in the upper shoreface (Howard and Reineck, 1972; Reineck and Singh, 1973). Cross-stratification with interset laminae truncation, similar to that in Facies B sandstone (Figure 13), was also observed in the Gallup Sandstone by Campbell (1971) who referred to it as truncated wave-ripple laminae. Campbell believes that these truncated wave-ripple laminae may commonly form in the surf zone bordering beaches (Campbell, 1971).

The origin of the trough sets is related to migrating dune bed forms in the zone of breaking waves (Clifton, *et al.*, 1971; Harms, 1975). Figure 48A illustrates the typical trough cross-stratification produced by migrating dune bed forms. Similar, but smaller, trough type cross-stratification is known to form by migrating current ripples (e.g., Allen, 1963; Masters, 1967; and Harms, 1975) (also see Figure 48B). Megaripples of similar forms would produce large scale trough cross-stratification; such structure occurs in Facies B sandstones.

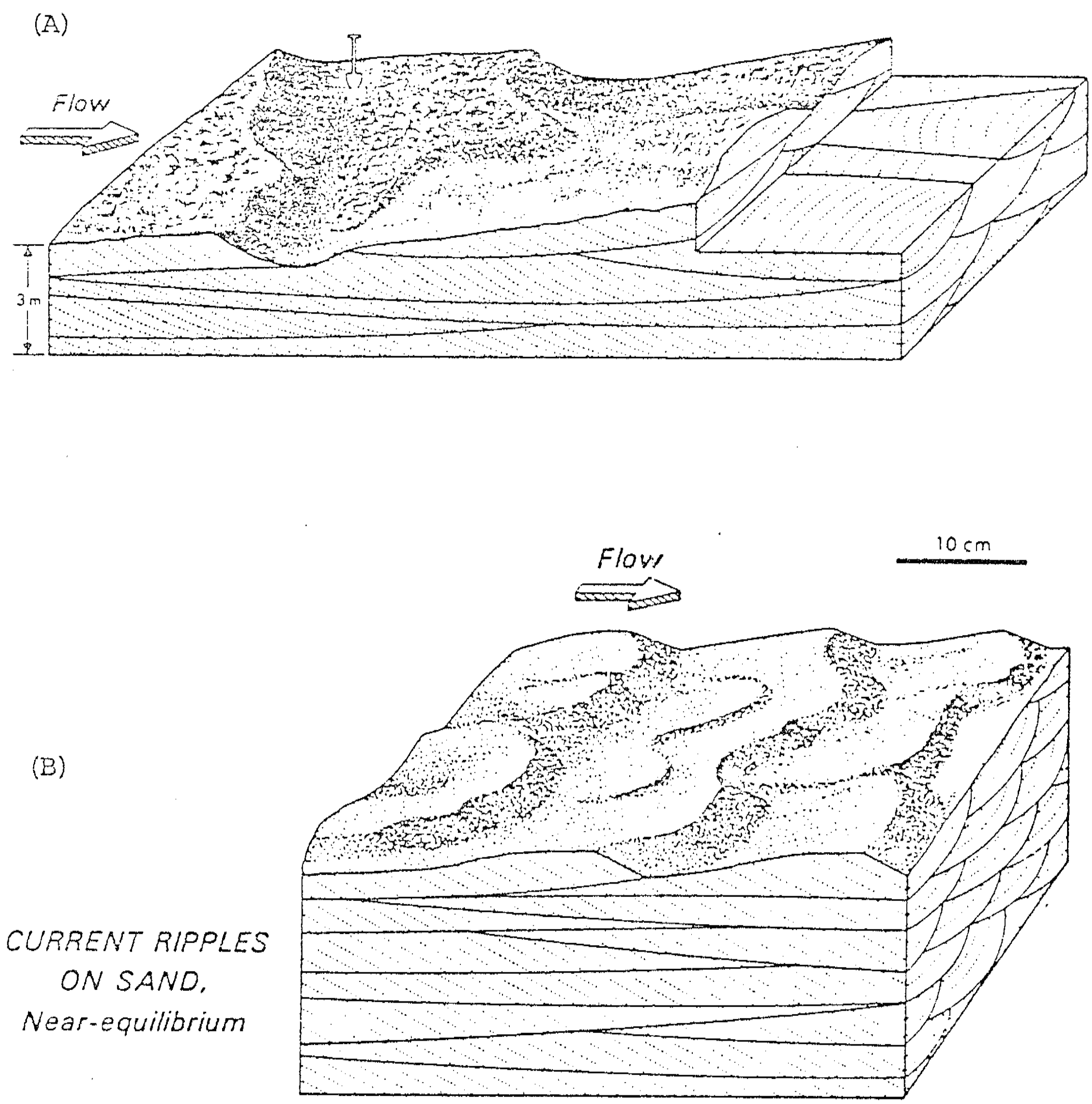


Figure 48. A- Trough cross-stratification formed by migrating dune bed forms; B- current ripples and associated cross-stratification (from Harms, 1975).

The shoreface is usually made up of longshore bars (see Figure 43). Longshore bars form in the breaker zone where sediment is brought in from both offshore and land (Ingle, 1966); and strong longshore and rip currents develop. Longshore currents and waves are the energy forces operative in the formation of longshore bars (Busch, 1974). Reineck and Singh (1973) believe that the number of longshore bars in a coast is in direct proportion with the wave energy of that coast. But McKee and Sterrett (1961) emphasized the effect of factors such as slope of sand floor, intensity of wave action, and supply of sand. They produced, experimentally in a 46-foot wave tank, the form and structure of longshore bars. Busch (1974) provides a brief review of the characteristics and origin of offshore bars. The consecutive sandstone units forming Facies B in the Point Lookout sequence conform with the characteristics expected for development of longshore bars in the shoreface environment.

Complex paleocurrent patterns for Facies B sandstones (Figure 12) suggest that their sedimentary structures were produced by waves and currents with variable direction. The southeast to east components and the opposing northwest to west components are believed to be related to longshore currents. The offshore and onshore components are attributed to rip currents. Dune-like bedforms (or megaripples) are known to form in the breaker zone (upper shoreface environment) and on longshore bars (e.g., Clifton, *et al.*, 1971; Howard and Reineck, 1972; Southard, 1975). Reineck and Singh (1973) documented that megaripples develop on longshore bars and are oriented at an angle to the axis of the bar and the shoreline; while in the trough (or runnel) on the landward side of the bar, megaripples are oriented parallel with the shoreline trend. Davidson-Arnott and Greenwood (1974) also reported the development of megaripples on longshore bars in the upper shoreface subenvironment. Landward migration of these megaripples produces landward dipping trough type cross-stratification similar to that in Facies B sandstones.

The planar cross-stratification in Facies B sandstones resembles planar cross-stratification observed in longshore bars of modern shoreface environments. Planar cross-stratification is interpreted as produced by moving sand waves (Harms, 1975). Components dipping in a longshore trend (NW-W and SE-E) seem to be produced by migration of sand waves generated by longshore currents in the shoreface area. Davidson-Arnott and Greenwood (1974) described landward dipping planar cross-stratification in longshore bars in the upper shoreface zone of Kouchibougauc Bay. Landward dipping components may be attributed to onshore migration of longshore bars; such a migration has been recorded by Davies and Fox (1975) during low energy conditions between storms on Mustang Island. Seaward dipping components may be related to the accretion process on the seaward slopes of longshore bars. McKee and Sterrett (1961) have reported the development of gently seaward dipping planar cross-stratification on the seaward side of longshore bars in North Bimini Island

and in their wave tank experiments.

The nearly horizontal lamination in parts of Facies B, referred to as subfacies B_2 and the associated churned (structureless) sandstones are interpreted as lower shoreface subenvironment. These flat-layered sandstones were most likely deposited beyond the agitating effects of the breaker zone and seaward from the stronger longshore currents, where sediment settled out of suspension or was distributed by weak bottom currents. Very small cross-stratification occurs locally as does some hummocky-like cross-stratification (see Figure 7B) whose origin is most likely related to storm surges similar to that discussed above. Wave ripple marks also occur locally; similar wave ripple marks have been observed in modern lower shoreface subenvironments (Howard and Reineck, 1972; Reineck and Singh, 1973). The crests of these wave ripples are most commonly oriented nearly parallel with the shoreline (Masters, 1967). Average crest orientation of measurements from lower shoreface sandstones in the Point Lookout Sandstone is about N40°W;therefore, the average trend of the Point Lookout paleoshoreline was about N40°W.

Megaripples, or dune-like bedforms, to which trough cross-stratification is related, provide a means to interpret hydrodynamic conditions. Strength of longshore and rip currents that were required to produce these bedforms (in the upper shoreface subenvironments) can be estimated from the sediment grain size-flow velocity diagram (Figure 49). The grain size of the trough cross-stratified and megarippled

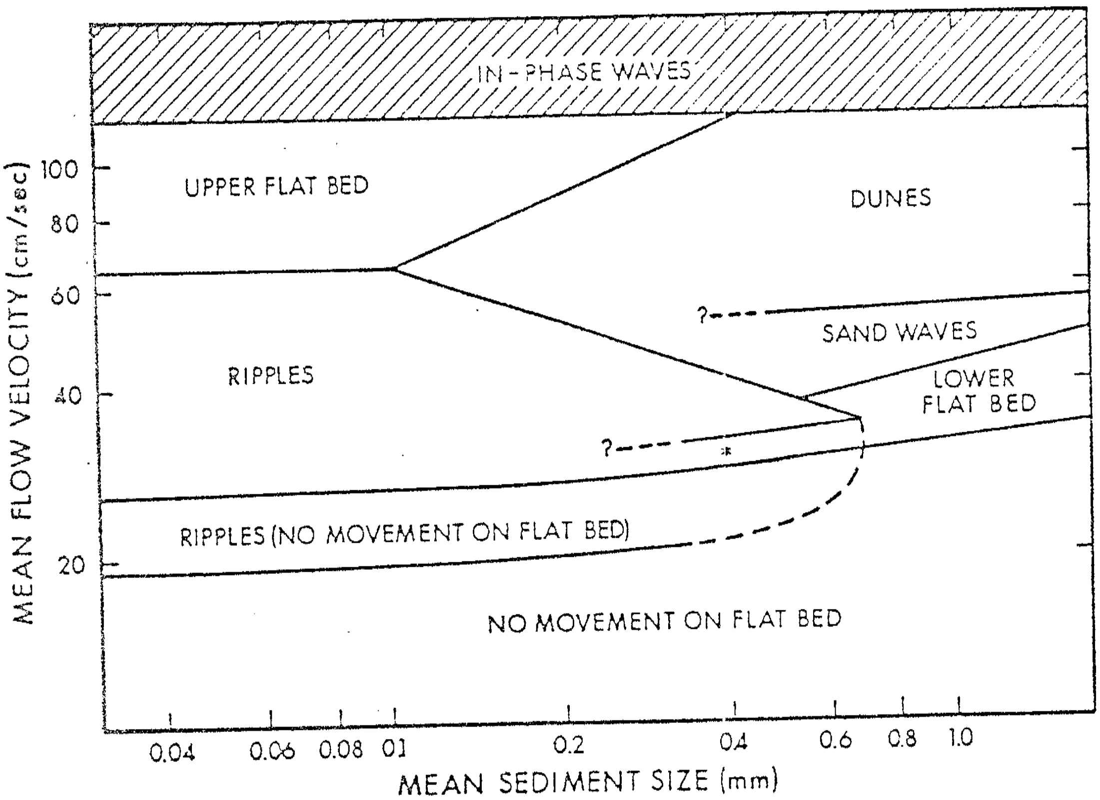


Figure 49. Schematic size-velocity diagram for a flow depth of approximately 20cm, derived from depth-velocity sections drawn using flume data (from Southard, 1975).

sandstones ranges from about 0.10 mm to 0.15 mm. For such a fine grained sand, dune forms would be stable at mean flow velocities of about 60 to 70 cm per second. These values are within the range of longshore and rip current velocities observed in modern upper shoreface zones of low to moderate energy coasts during periods of somewhat higher than normal wave action (e.g., Gorsline, 1966; Davidson-Arnott and Greenwood, 1974; and Davies and Fox, 1975). Sandwaves, to which planar cross-stratification was attributed, form at lower current velocities than dunes, as low as 30-40 cm per second (Southard, 1975).

Sedimentary structures, especially trough-type cross-stratification, suggest moderate to moderately high energy conditions along the Point Lookout paleocoastline. Storm intervals also were interpreted from the nature of sandstone beds and hummocky type cross-stratification in Facies A. The presence of a highly diversified mixture of fragments and whole shells in very thin zones (e.g., units Kpl-4-5, 7 and 9, Plate 1) indicates the accumulation of such mixtures during a storm. However, textural characteristics of Facies B sandstones suggest low energy conditions. Although the observed textural immaturity seems to contradict moderate or higher wave energy conditions, it does not necessarily imply very low energy conditions either because: 1) a significant amount of the fine fraction (matrix) in these lithic sandstones is not of a primary origin; 2) sediment with high mud content was continuously supplied to the beach; and 3) the rate of sediment supply was relatively high and therefore the operating duration of wave action was relatively limited. On the other hand, trough cross-stratification, which is generally confined to limited horizons within the sandstone units (see Plate 1), may reflect short periods of somewhat higher than the normal moderate wave energy conditions which seem to be dominant along the Point Lookout coast.

Burrows, which are mostly oriented vertically or diagonally in trough cross-stratification zones and horizontally to gently inclined in nearly horizontally laminated horizons, reflect the influence of the energy conditions mentioned above. Lithologically, there is no strikingly significant change in composition of framework grains within sandstones of Facies B (Table 3). Lithologic differences among framework grains with respect to sandstones from adjacent facies (Facies A below and Facies C above) are also minor (Table 3). Fairly significant changes in mean grain size occur between sandstones from Facies B and sandstones from adjacent facies (Tables 1 and 2, and Plate 1). However, mean grain size change within Facies B sandstones is very limited; slight coarsening in trough cross-stratified zones of the units and a slight upward increase in the overall grain-size trend of Facies B sandstones occurs.

The shoreface sandstones were deposited under overall prograding shoreline conditions. This interpretation is based on: 1) their stratigraphic position, overlying offshore deeper marine shales through a considerable transition zone; 2) the slight upward coarsening in grain size; and 3) the vertical sequence of sedimentary structures which generally reflects progressively shallower water conditions (local reversals occur due to local minor fluctuations). Dominance of Facies B sandstones throughout the area with a considerable thickness and development of a significant beach-offshore transition zone suggests a gradual, slow progradation of a wide sandy shoreline with a continuous ample supply of sediments.

Land (1972) proposed that the thickness of the coarsening-upward sequences produced by prograding barrier islands is controlled by depth of water. Recognition of foreshore beach sandstone, which coincides with sea level, determines the approximate position of the sea level. Therefore, the thickness of a deposit, representing a complete cycle between the sea-level datum, as defined by foreshore sediment, and the transition zone's interbedded sandstone and mudstone, reflects the depth of water in the shoreface which was prograded by the barrier. Klein (1974) discussed the application of this approach in barrier island and deltaic sedimentary sequences. Accordingly, the depth of water in the shoreface zone during deposition of the Point Lookout sequence was about 5m at measured section Kpl-7 (Plate 1, units 7,8 and lower 2m of unit 9 were used as a cycle), and about 7m at measured section Kpl-5 (Plate 1, interval between 13m and 20m).

Foreshore (Facies C)

The flat bedded, low angle planar cross-stratified and burrowed sandstones of Facies C are thought to represent the upper part of the beach; i.e., foreshore-backshore complex. The low angle planar cross-lamination to subhorizontal lamination in some horizons of Facies C sandstones resembles that observed in foreshores of modern beaches (e.g., Thompson, 1937; McKee, 1957; Bernard, *et al.*, 1962; Milling and Behrens, 1966; Clifton, 1969; and Howard and Reineck, 1972). Low angle, dominantly seaward dipping planar cross-lamination and subhorizontal lamination develops in the swash zone due to the action of swash and backwash; Thompson (1937, Figure 2) and Harms (1975, Figure 5-4) illustrated swash cross-stratification. The average inclination of laminae in the foreshore zone of modern beaches is toward the sea; however, landward dipping laminasets may be interbedded or laterally equivalent to the seaward dipping sets due to the presence of a ridge and runnel system (Harms, 1975). Also, variations in dip directions may occur due to the development of beach cusps (McKee, 1957). The paleocurrent diagram for Facies C sandstones (Figure 18A) shows that northward (seaward) inclined components are dominant, but southward (landward) components, which are either related to ridge and runnel development or to interbedded backshore laminasets, also occur. The average dip of seaward dipping sets is 8 degrees. This is in accordance with the average dip of planar cross-stratification in the upper foreshore of modern beaches, which is on the order of 10 degrees or less (Dickinson, *et al.*, 1972; Klein, 1975). Dips of 2 degrees landward to 7 degrees seaward were reported by Milling and Behrens (1966) in the upper foreshore of Mustang Island, Texas. Striking interbedding between northeast and southwest inclined laminasets, such as that which develops at the berm ridge (e.g., see Reineck and Singh, 1973, Figure 436), which defines the boundary between foreshore and backshore zones, is lacking in the bedded, low angle, planar cross-stratified sandstones of Facies C. Details of lamination and cross-lamination are generally poorly expressed on weathered surfaces, and heavy minerals, which may provide a better expression of lamination, are lacking in Facies C sandstones.

Very thick, poorly cross-stratified sandstones overlying the moderately well, thin to medium bedded sandstones (e.g., upper part of units Kpl-1-7 and Kpl-5-4, Plate 1) are interpreted as backshore subenvironment. They overlie the bedded sandstones either transitionally or with irregular contact, but textural and compositional similarity and occurrence of *Ophiomorpha* are maintained. This sandstone may change upward into finer sandstone with root structure in the upper part (e.g., unit Kpl-1-8, Plate 1). The upper finer part with root structures represents gradation to the dune ridge part of the shoreline complex.

Sandstones characteristically poorly bedded with poorly developed planar wedge shaped cross-stratification in Facies C overlie trough cross-stratified shoreface sandstones, underlie well bedded sandstones, and are believed to have developed in the lower foreshore zone as beach bars. Longshore bars often develop in the foreshore zone (e.g., McKee and Sterrett, 1961; and Reineck and Singh, 1973). Paleocurrent data (see Figure 18B) show abundance of landward as well as along-paleoshoreline components. Longshore bars in the lower foreshore zone of modern sediments are characterized by landward dipping planar stratification with angles ranging between 10° to 30° (Thompson, 1937; McKee, 1957; McKee and Sterrett, 1961; Hoyt, 1962; Reineck and Singh, 1973). Hoyt (1962) indicated that sand bars develop on either lower or upper foreshore, but commonly originate on the lower foreshore. The average dip of landward dipping readings from sandstones, interpreted to be of foreshore bar origin in Facies C (units Kpl-1-7 and Kpl-2-8, Plate 1), is about 15 degrees; this is within the range reported from bars in modern beaches (Hoyt, 1962).

Considering that laminae, when deposited, conform approximately with the dip and strike of the beach surface (Thompson, 1937), the slopes of the Point Lookout foreshore zones can be approximately deciphered from the attitudes of the laminasets. Accordingly, the paleoslope of the Point Lookout foreshore zone was in the range of 2 to 14 degrees seaward, and the landward slope of longshore bars in the foreshore zone was about 15 degrees. Such gentle seaward slopes are typical of beaches dominated by fine-grained sand. Such a low lying foreshore slope also suggests that low energy wave regime dominated the beach zone, because action of larger, storm waves results in steepening of the foreshore and upper shoreface profile.

The limited development of well-defined foreshore deposits, in the form of well-developed stratification with regular, nearly parallel lamination, which is subhorizontal to seaward dipping at very low angle, indicates that beach sediments had not been subjected to wave action for a suficient length of time. This observation conforms with the low sorting of the sediments in the foreshore facies (Facies C) due to the presence of a significant amount of silt and clay size components; sediment was not winnowed enough. Also, the limited action of waves on the sediment is reflected by the occurrence of a considerable number of lithic fragments, many of which are not resistant to any significant mechanical action.

Body fossils are lacking in Facies C sandstones, but trace fossils (*Ophiomorpha*) occur locally throughout the study area (see stratigraphic sections, Plate 1) confirming their beach origin.

Estuarine-Beach (Facies D)

The very thick, prominent sandstones of Facies D represent the uppermost major sandstone facies in the Point Lookout sequence. It has been recognized in subsurface studies and referred to as the upper massive sandstone unit of the Point Lookout Sandstone. Stratigraphically, Facies D sandstones represent a transition facies between the underlying burrowed (*Ophiomorpha*), fine grained beach sandstones and the overlying nonmarine carbonaceous to humic mudstone and coal-bearing units of Facies E; hence, it is a coastal sandstone body. In order to interpret the environment of deposition of these somewhat enigmatic sandstones, their overall characteristics will be summarized in the following section.

This coastal sandstone facies is characterized by: 1) lack of marine body or trace fossils; 2) lithologic similarity to the beach sandstones of Facies C below; 3) the coarsest sandstones in the sequence, and grain size decreases upward in some units, but increases upward in others; 4) grains range from very well rounded and equant to angular and very elongate; 5) some *Teredolithus*, fairly large clay clasts, and carbonaceous fragments and small coal (lignitic) lenses; 6) medium to large scale cross-stratification which ranges from poorly-developed wedge to well-developed trough (festoon) type, dip direction is generally variable, but seaward direction is dominant; several horizons are structureless. Facies D has either a gradational contact with the underlying beach sandstones of Facies C or the contact is a sharp erosional scour surface with moderate relief; at measured section Kpl-3 a small channel cut-and-fill structure truncates the underlying marine fossil-bearing and burrowed sandstone.

These characteristics of the sandstones indicate several different origins or processes: fluvial, marine, and eolian. Estuarine and distributary channel subenvironments of the coastal complex seem to be the most reasonable zone for such fluvial sediment to be modified by marine and/or wind action. *Teredolithus* indicates brackish water conditions (Siemers and King, 1974). Sharp scoured basal contacts, mud clasts, and fining upward grain size are indications of fluvial processes. Small lignitic and carbonaceous lenses or pockets are usually common in the estuarine zone (Molenaar, 1973). Relatively small channel sandstones cutting into finer marine sandstone reflect a distributary channel system.

Where marine and/or wind influence is relatively limited, distributary channel and estuarine channel sandstones are preserved with their characteristic channel geometry; the best example is at measured stratigraphic section Kpl-3 (Plate 1). But the majority of the sandstone in Facies D was modified by coastal conditions giving a sheet type sediment. Partial reworking led to better sorting due to removal of a considerable amount of the fine fraction and concentration of coarser particles. The influence of wind action is also significant and is best represented by moderately well-developed large trough (or festoon) type cross-stratification in some stratigraphically highest units (e.g., Kpl-7-11 and Kpl-2-11, Plate 1) in Facies D. The influence of marine and eolian processes accounts for the variation in the cross-stratification dip directions.

The widespread distribution of Facies D sandstones with a considerable thickness, and their diverse characteristics suggest the occurrence of a coastal system in which ample supply of sediment was maintained through rivers and their distributary channels to the coast and in which the wave regime was strong enough to rework the sediments preventing the establishment of a well defined delta system. However, reworking by wave action did not totally obliterate the fluvial deposits, producing clean and possibly quartzose beach sandstones. The apparent limited effectiveness of coastal wave energy may be due to its low profile or to rapid sediment supply, or a combination of both. Considering the depositional processes for Facies D sandstones and underlying beach sandstone facies, the Point Lookout coast seems to have been characterized by the balance between moderate wave condition and ample, continuous sediment supply. Sediments were most likely supplied by several relatively small rivers distributed along the coast, rather than a single major river which most likely would have led to development of a delta system.

Coastal sand dunes are common to most modern barrier islands (Dickinson, *et al.*, 1972), and their recognition in ancient sediments depicts the nature of the paleoclimate. Recognition of coastal dunes is difficult, even if they are preserved, because of destruction of their characteristic structure by erosion and vegetation; however, they were not dominant in the Point Lookout coast zone. The occurrence of Facies D sandstones, rather than major coastal dune fields, suggests the climate was not dominantly dry during deposition of the Point Lookout sequence.

Nonmarine Coastal Complex (Facies E)

Highly diversified sediments are categorized together as Facies E. They are interpreted to be developed on the land side of the paleocoast. Thus, they are all nonmarine and their diversity is the result of the many different subenvironments that usually occur in such a coastal plain. Subenvironments proposed for specific units in Facies E are: 1) lagoon and bay; 2) coastal swamp and marsh; 3) channel; 4) levee and possibly crevasse splay. Facies E units will also be described and analyzed in more detail by S. Wallace who is working with C. T. Siemers on the Menefee Formation in the La Ventana-Cuba area. In this study, Facies E units are considered to define and illustrate the complete picture of the Point Lookout regressive system.

Lagoons and bays--. Coastal lagoons are common on many coasts of the world, and in many areas they constitute the dominant coastal features, e.g., the Gulf of Mexico coast. They form behind barriers (see Figure 45) usually with the long axis parallel to the coastline (Phleger, 1969). Marshes are not uncommon in coastal lagoons. Assemblages of plants develop in marsh zones, and trap fine grained sediments (mud). The finest sediment available in the system is deposited in the innermost part of the lagoon where currents are lowest (Phleger, 1969); rivers are the main source of mud deposited in lagoons.

Fissile, gray to brownish gray shales and silty shales with low to abundant fine carbonaceous detritus and local lenticular laminated siltstones in Facies E are considered to be of lagoon or bay origin. Thick units of gray fissile shale to silty shale, which are not interbedded with swampy deposits, and are overlain by backbarrier sandstones, are most likely of bay origin (e.g., unit Kpl-6-13, Plate 1). Lagoonal type deposits locally interbedded with humate and/or coal material suggests that the lagoon which was originally brackish had become more of a swamp environment through time perhaps due to complete detachment from the sea and invasion of fresh water (e.g., units Kpl-2-12 and 13, Plate 1). No marine fossils occur in these bay or lagoon deposits. Mudstone and muddy sandstone with root structure associated with lagoon sediments represent vegetated marsh flats. Stratigraphic units in Facies E, interpreted as lagoon and marsh deposits, are indicated on Plate 1. Lack of marine fauna and discontinuity of typical open lagoons behind the coastal barriers suggest the tidal range was low; in a high tidal range tidal channels would have developed permitting passage of some sediments and marine fauna into the lagoon. Association of lagoon deposits with vegetated marshes and swamp deposits indicate a humid climate; Dickinson, *et al.*, (1972) reported association of lagoon and bay deposits with marsh deposits and peat and humate material in humid areas in the Texas Gulf coast, whereas organic deposits (peat and humate) were not reported in adjacent subhumid areas. With adequate river flow into the lagoon and with low tide range, a continuous current out of the lagoon is developed, and accordingly, a significant amount of mud is transported to the coastline. As the shoreline progrades seaward, lagoons also shift in that direction, resulting in the development of lagoon deposits over the previously deposited barrier and beach deposits.

Swamps-. Intervals of interbedded gray mudstone, brown humic shale, humate, and coal material in Facies E are interpreted as swamp deposits. The swamps were dominated by fresh water, and mud influx into the swampy area was provided by rivers during floods. Light gray claystones with low carbonaceous content represent the well drained parts of the swamp, such as on the flanks of levees. Dark gray claystone and brown humic shales represent poorly drained swamp deposits; ground water table coincided with the surface, and reducing conditions prevailed in the swamp. Ample accumulation of organic material resulted in humate material, and the interbedded coal seams and lenses developed during intervals of very low mud influx.

Humate and coal-bearing zones increase south to southwestward (landward), reflecting better establishment of coal-swamps landward. Abundance of plant debris, humates, and coal material in Facies E units indicate both the dominance of fresh water swamps and a humid climate in the coastal plains during deposition of the Point Lookout sequence. Stratigraphic units interpreted as swamp deposits are indicated on Plate 1.

Levees and crevasse splays-. Wedge shaped to moderately tabular nonmarine sandstone units in Facies E are regarded as levee or crevasse splay deposits (Plate 1). Levee deposits are muddy and interbedded with gray claystone (e.g., unit Kpl-6-16); they developed from material carried by the rivers in suspension, and spilled over the banks during flooding. Development of levees affects the adjacent interdistributary swamps, adds mud resulting in carbonaceous mudstone or humates rather than coal. Root structure exists in the upper part of levee or splay sediment (e.g., units Kpl-1-18 & 20). Crevasse splays develop locally where levees are breached. Splay deposits are very fine to fine grained sandstone with less mud than levee deposits. The lower contact is generally sharp and locally erosional above levee and/or swamp deposits.

Channels-. Fluvial channel sandstones occur in Facies E and are abundant and well developed in the rest of the Menefee Formation above (e.g., see Siemers and others, 1975; and Mannhard, 1976). Channel sandstone bodies either occur within sequences of lagoon and swamp deposits (e.g., units Kpl-2-15, and Kpl-6-17) or overlie estuarine sandstones with sharp, irregular and scour shaped contacts and underlie swamp deposits (e.g., units Kpl-3-17-19).

Tan to light gray, fine to medium grained, thick to very thick sandstones are characteristic of channel sandstones in Facies E. They have erosional scour basal contacts, contain lignite lenses (developed from wood logs) and clay clasts, and have sharp to transitional upper contacts with swamp type deposits. Channel sandstones change in stratification and grain size laterally, and are of lenticular shape so that they are laterally discontinuous. Cross-stratification is medium to large scale, high angle wedge to trough type; it generally has unidirectional dip direction within a cross-bed set, but overall the paleocurrents have variable directions suggesting a meandering stream system. Channel systems in the Menefee Formation were interpreted by Mannhard (1976) to represent relatively small rivers with deep channels (width/depth ratios of 9:1 to 11:1) and low gradient, generally less than 1 meter/Km.

Relationship between sandstone composition and depositional processes

Petrographic analyses show significant differences in composition among the various sandstone facies of the Point Lookout Sandstone, and also in comparison to Menefee channel sandstones. Sandstone modal analysis data (Table 3A) show that Facies B sandstones, which are interpreted as shoreface sandstones, contain the lowest average percent of framework grains (72.4%), the highest average percent of matrix (13.9%), and cement (12.1%), and the lowest average percent of pore space (1.6%). Among the framework grains, Facies B sandstones contain the highest average percent quartz (40.0%), and the lowest average percent of feldspar (8.7%), rock fragments (16.4%) and chert (4.6%).

The data in Table 3C indicate that Facies D sandstones, which are interpreted as estuarine-beach sandstones, are characterized by the highest average percent of framework grains (77.8%), the lowest average percent of matrix (9.1%) and cement (4.1%), and the highest average percent of pore space (9.0%). Their framework grains include the highest average percent of feldspar (11.7%) and chert (7.2%), but contain less rock fragments (19.0%) than Facies C sandstones; their average quartz content is 38.9%.

Facies C sandstones, which are interpreted as foreshore sandstones (see Chapter 7), contain intermediate values between Facies B and Facies D sandstones, with the exception of higher average content of rock fragments (20.9%). They are generally closer in their composition to Facies D sandstones (see Table 3B).

The average composition of channel sandstones in the Menefee Formation, as shown by Mannhard (1976), is markedly different from that of the Point Lookout Sandstone. The average composition of channel sandstones is lower than the Point Lookout Sandstone in framework grains (63.9%), higher in cement (17.6%), and approximately similar in matrix (10.9%) and pore space (7.6%). They contain almost the same amount of quartz (36.5%) as Facies C and D sandstones, but higher in feldspar (12.8%) and chert (8.1%), and lower in rock fragments (5.9%). The rock fragments in the channel sandstones are mainly granitic and volcanic; their abundance is generally similar to that in Facies C and D sandstones of the Point Lookout Sandstone, and the major difference is the variation in relative abundance of argillaceous and sandstone fragments.

Comparison of sandstones from the different facies shows that there is a gradual reduction in feldspar and chert downward from the channel sandstones through the estuarine-beach and foreshore sandstones to the shoreface sandstones. Quartz grains generally increase downward over the same interval. Such changes reflect the effect of abrasion on the less resistant grains in the wave zone where sand grains are expected to be moved continuously. Particle selectivity in the wave zone also is reflected in the depletion in rock fragments from the beach complex, Facies C and D, to the shoreface zone, and enrichment in matrix. The proposed nearby sedimentary source rock for the argillaceous and sandstone fragments, which are relatively abundant in the Point Lookout Sandstone and rare in the Menefee channel sandstones, also accounts for the influx of fine material to the beach zone. If it were not for that local (or nearby) contributor of fine material, the beach sandstone (Facies D and C) would have been significantly lower in matrix than the channel sandstones; shoreface sandstones (Facies B) also might have been in channel sandstone range, if not lower, in matrix. Again, a significant amount of the matrix, especially in the beach sandstones (Facies D and C), where the best sorting is expected, is due to disintegration of some of the less resistant argillaceous fragments.

General significance of paleontologic aspects

Fossil contents of a sedimentary unit are one of the most important means of identifying its depositional environments, and one of the few methods of determining age. The macroinvertebrate assemblages and trace fossils in the Point Lookout Sandstone revealed and/or confirmed the marine origin of most sandstones in the Point Lookout sequence and is the basis for determination of its age. Also, observations on the faunal content of the Point Lookout Sandstone indicate that significant assemblages do occur and certainly can be a major contributor to a detailed paleontologic analysis of the Upper Cretaceous sequence in the area.

The relative abundance and diversity of molluscan taxa (see Table 5) and the biogenic structures, together with sediment types, sedimentary structures and stratigraphic relationship, suggest shallow, nearshore conditions for Facies B and C sandstones. The diverse assemblage, dominated by bivalves in the trough cross-stratified and concretionary zones of Facies B, resembles, to a certain extent, the diverse, nearshore, shallow water marine mollusc assemblage described by Kauffman (1967) (assemblage H) for some Cretaceous units in the central Western Interior region. The diversity in shell morphology and life habitats of the fauna associated with relatively uniform lithology suggests that this diverse assemblage is composed of multiple communities that seem to have been mixed and concentrated by wave action; the observed high degree of fragmentation also indicates strong wave energy. The very thin fossiliferous zones at section Kpl-4, with their extensively fragmented shells as well as lack of sorting and wide range of abrasion of the fragments, suggests accumulation during short intervals, perhaps moderately strong storms. The relatively less diverse assemblage in unit Kpl-6-5, with abundant ammonites and flat shelled bivalves, and large porportion of complete forms suggests relatively deeper and quieter parts of the nearshore environment.

Ophiomorpha, which is relatively abundant throughout most of the Point Lookout Sandstone, is interpreted as indicative of littoral or shallow neritic sandy environments and is considered ecologically similar to *Callianassa major* (Weimer and Hoyt, 1964). *Thalassinoides*, which resemble *Ophiomorpha* except for the knobby walls, are related to the same kind of organism (Siemers and King, 1974). The curved or sinuous trails (gyrochorte) on the bedding surfaces were probably developed by browsing gastropods (Siemers and King, 1974). *Teredolithus* structures were produced as logs bored by an organism identified as *Teredo* (Harms, et *al.*, 1965). Presence of *Teredolithus* structure strongly suggests brackish to marine conditions (Siemers and King, 1974).

Modern Analogues of the Point Lookout System

Aspects of sedimentary environments are basically defined in modern environments, and features and observations from ancient sediments are accordingly interpreted. Although this study deals with an ancient sedimentary unit, a comparison of its proposed depositional model with modern depositional models provides a better understanding of the aspects of the proposed mode. However, one should bear in mind that some problems arise with making such a comparison due to the fact that: 1) large scale features observed in ancient sediments, such as stratification and large scale sedimentary structures cannot be seen in small trenches and cores; 2) features observed in old sediments may represent only a few of the many non-represented sedimentary features; 3) not all of what we see in modern environments will be preserved; and 4) post-depositional changes may modify the deposit significantly.

The proposed depositional model for the Point Lookout sequence is a north-northeast prograding, non-deltaic shoreline; low to moderate wave energy dominated the coastal regime and ample supplies of sand and finer sediment are maintained by relatively small rivers across low lying coastal plains. The plains were characterized by humid climate and occupied by bays, lagoons and swamps.

Certainly, it is not expected to find a modern system which would match precisely the Point Lookout system. But the overall stratigraphic framework and morphology of the Point Lookout Sandstone resembles, to a certain extent, the modern coastal complex of the Texas coast of the Gulf of Mexico, where linear beaches, barriers and beach ridges are well developed bounded by bays, lagoons and low lying coastal plains.

The recent history of the northwestern Gulf of Mexico began more than 25,000 years ago with the last rising sea level substage, that ended between 3,000 and 5,000 years ago, with the present high standing sea level substage (Late Recent) (Barnard, *et al.*, 1962). The present standing sea level substage resulted in the modern depositional model with a great volume of sediment deposited in the coastal region of Texas and Louisiana (Bernard, *et al.*, 1962). As the standing base level was established, sediments prograded seaward resulting in a net regression of the shore and developed a regressive sequence of sediments; processes, such as lateral shifting of sites of maximum deltaic sedimentation, local changes in sediment supply, wave and current action, have caused local and temporary transgression and produced transgressive intervals (Bernard, *et al.*, 1962). The Point Lookout sequence was most likely produced by a similar framework. But the Point Lookout regressive system was characterized by a steadier (or longer term at a slower rate) interrelationship between sea level and sediment supply, rather than the relatively short term sea level fluctuations in the Gulf Coast due to glacial stages.

Although the influence of factors controlling the development of the two prograding systems differ, the two depositional models exhibit remarkable similarity among the developed facies and their characterizing aspects, such as stratigraphic relationship, spatial distribution, some petrographic characteristics, and sedimentary structures. The Galveston Island, which began as a small bar on the southwestern side of the mouth of Galveston Bay about four miles offshore in five to eight feet of water during the initial standing sea level substage (Barnard, *et al.*, 1962), is an excellent example of a prograding barrier island. A profile across Galveston Island and its sediment distribution are illustrated in Figure 50. The vertical sequence is characterized by an upward coarsening, and consists of a zone of interbedded muds and sands overlying offshore muds, followed by shoreface zone, beach sands with coastal dune sand at the top, and finally to be overlain by lagoon or bay facies with continued progradation (Klein, 1975). Bernard, *et al.* (1962) outlined that the depositional features consist principally of numerous narrow, parallel beach ridges which trend almost parallel to the present shoreline, and of intervening swales. They also pointed out that four breaker bars (longshore bars) can be observed in the shallow water immediately off the beach; their position, height, and number vary with the wave height and direction, tides, and possibly with the longshore currents. The Galveston Island profile provides an ideal counterpart for intervals in the Point

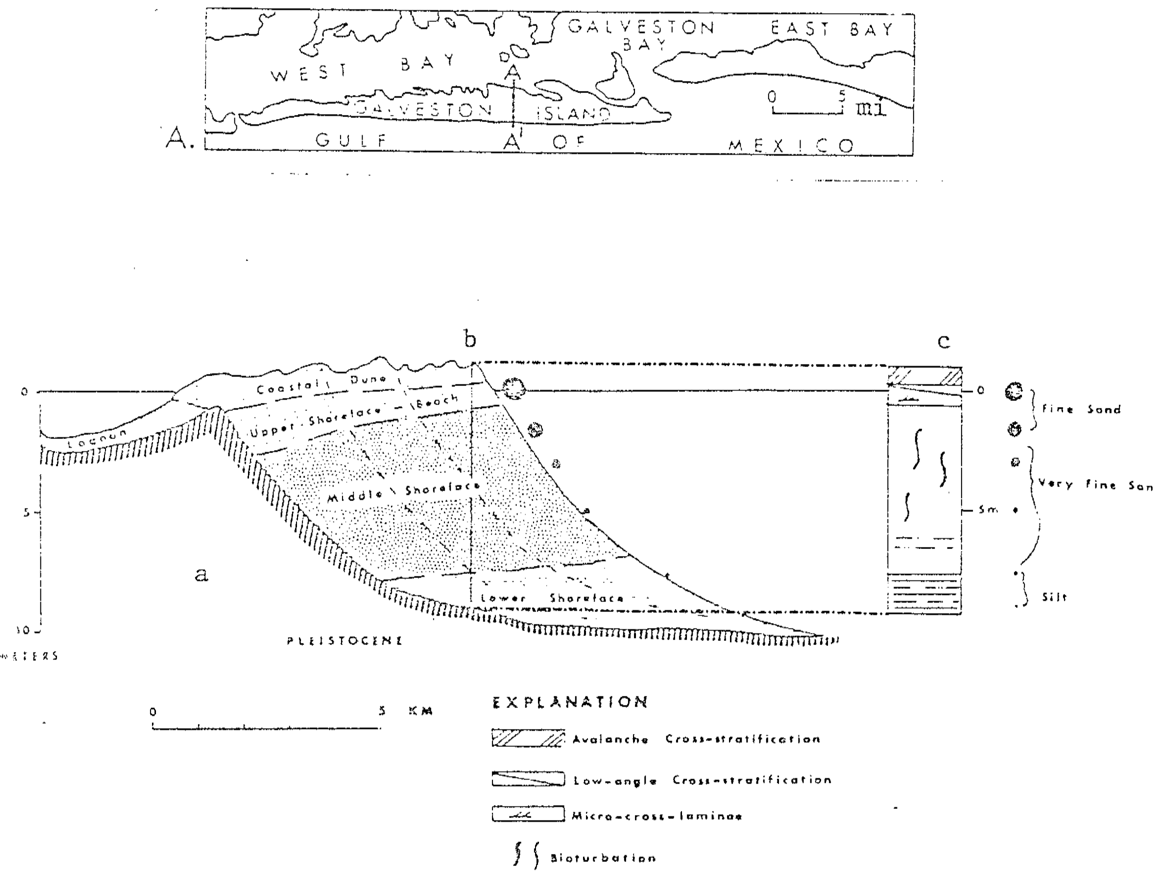


Figure 50. A- Galveston Island, Texas Gulf Coast; B-(a) profile showing vertical and lateral sediment distribution and subenvironments (lower shoreface corresponds to transition zone in this study), (b) vertical section through this prograding barrier island shown in column c, (c) vertical sequence of textures and sedimentary structures at b (from Busch, 1974, and Klein, 1975).

Lookout sequence along the southeastern part of the San Juan Basin.

Other modern to Recent examples include Sapelo Island, described by Howard and Reineck (1972), and the Gulf of Gaeta, described by Reineck and Singh (1973), where complete prograding sequences are developed. The significance of the resemblance between the ancient Point Lookout sequence and the modern prograding shoreline models is in the existence of the different facies starting with a transition zone overlying offshore muds, followed by shoreface zone, beach complex, and finally lagoon or bay and other nonmarine coastal zones, and in the major characteristics of each facies. However, thicknesses and dominance of a certain feature (or features) may vary due to the influence by wave energy regime, tidal range, and relative rates of progradation, subsidence, eustatic sea level change and sediment supply.

ECONOMIC POTENTIAL OF THE POINT LOOKOUT SANDSTONE

The nature of the Point Lookout Sandstone and its stratigraphic relationship with the thick sequence of the marine Mancos Shale provides the prerequisites for significant hydrocarbon accumulation. The thick areally extensive sandstone bodies, especially in Facies C and D with relatively high porosity and adequate permeability, are excellent potential reservoirs. Reneau and Harris (1957) reported that the range of porosity of the Point Lookout Sandstone is 2.7 - 18.4%, average 10%, and that permeability ranges from 0.0 to 158 millidarcys, average 2.1 millidarcys.

Oil and gas (the latter is more abundant) have been produced from the Point Lookout Sandstone at several fields in the San Juan Basin, for example, Blanco Mesaverde Pool in Rio Arriba and San Juan Counties (Prichard, 1973). Arnold (1974) reported the cumulative production from the Mesaverde Group as of January 1974 and indicated that Mesaverde sandstones have contributed more gas than any other unit in Rio Arriba County.

The Point Lookout Sandstone also provides a reservoir rock (aquifer) for ground water in some parts of the basin. It has been used in McKinley County (Dr. W. J. Stone, New Mexico Bureau of Mines and Mineral Resources, and Dr. W. M. Turner, Consultant, Albuquerque, N.M., personal communication).

Its stratigraphic association with the humate and coal-bearing units of the Menefee Formation makes the understanding of its nature and distribution of great importance.

SUMMARY AND CONCLUSIONS

The Point Lookout Sandstone and adjacent portions of the underlying marine Mancos Shale and overlying continental Menefee Formation were investigated at the outcrops along the southeastern part of the San Juan Basin; detailed descriptions of stratigraphic relationships, spatial distribution, lithology, fossil content, and sedimentary structures were conducted at seven measured stratigraphic sections (see Plate 1). In addition to synthesizing field data, laboratory analyses included mechanical textural analysis, thin-section analysis, clay mineralogy analysis, and subsurface analysis of the Point Lookout Sandstone through the San Juan Basin in New Mexico. The stratigraphy and depositional environments, and subenvironments, of the studied sequence were interpreted mainly on basis of collected data in conjunction with previous work on the Cretaceous sequence of the San Juan Basin, and by comparison with other ancient and modern similar systems.

Field descriptions revealed that the Point Lookout Sandstone, which crops out almost continuously along the southeastern and eastern parts of the San Juan Basin, exhibits a considerable thickness ranging from 23.5m at San Luis to 65.5m at measured section Kpl-3. Three major facies dominated by very fine to medium sandstone are recognized, separated from the underlying Mancos Shale by a relatively thick transition zone of interbedded sandstones and shales and intertonguing with the overlying nonmarine coastal complex of the lower Menefee Formation. The transition zone between the typical Mancos Shale and Point Lookout Sandstone is indicated as Facies A and forms the lowest facies of the studied sequence. The three facies constituting the Point Lookout Sandstone are indicated as, in ascending order, Facies B, Facies C, and Facies D; the lower portion of the Menefee Formation is included in the studied sequence as Facies E. The characteristics of each facies of the studied Point Lookout sequence are summarized in Table 6; interpreted environment of deposition of each facies is also indicated.

The Point Lookout sequence is a regressive sequence in which the fundamental components of a prograding shoreline are present in some degree throughout the study area. In complete exposure, the Point Lookout sequence consists of, in ascending order, transition zone (Facies A), shoreface facies (Facies B), foreshore-backshore complex (Facies C), estuarine-beach complex (or fluvial-beach intermixed zone, Facies D), and nonmarine coastal (or bay, lagoon, swamp and channel) complex (Facies E). An overall upward increase in grain size among the Point Lookout sandstones is also a typical characteristic of a regressive sequence.

The vertical and horizontal relationships of the Point Lookout Sandstone facies with the underlying marine upper Mancos Shale, and with the overlying lower Menefee nonmarine units, indicate that the Point Lookout shoreline migrated north to northeastward. The sea retreat during the Point

Table 6. Summary of diagnostic characteristics and interpreted environment of deposition of the recognized facies in the Point Lookout sequence.

a- Facies A

Stratigraphy	A few meters to about 20m of a gradational zone between typical Mancos Shale below and Point Lookout Sandstone above. Laterally extensive throughout the area. Arbitrary lower and upper contacts. Units grade into Mancos Shale northward and into Facies B sandstones south-southwestward. Individual sandstone units are less than 1m thick, lenticular, pinch out within a few 10's of meters, lower contacts usually sharp, upper contacts moderately sharp to gradational, some have large scour-shaped basal surface.
Lithology	Interbedded and interlaminated sandy to silty shales and silty sandstones. Sandstones are typically yellowish-gray, very fine grained, poorly to moderately sorted, subrounded, friable, laminated and cross-laminated to bioturbated, fossiliferous, silty sandstone. Shales are brownish black to gray, fissile, and generally silty. Fine carbonaceous material occurs between sandstone laminae and in some shale zones.
Sedimentary structure	Subhorizontal lamination and small scale cross-lamination. Wavy (or undulatory) cross-stratification (similar to hummocky cross-stratification of Harms, 1975). Poorly preserved, apparently symmetrical, small ripple marks. Sedimentary structure is generally poorly preserved, most likely due to bioturbation.
Fossils	Moderately abundant marine fauna. Macroinvertebrates in sandy zones are dominantly, in descending order, ammonites (relatively large), bivalves (mainly pelecypods, small whole valves or fragments), gastropods (small snails), and a few shark teeth. Trace fossils typically exist on bedding surfaces of sandstone beds as curved or sinuous trails, and very thin, generally branched tubes (*Thalassinoides?*).
Environmental interpretation	Transition zone.

b- Summary of diagnostic characteristics and interpreted environment of deposition of Facies B.

Stratigraphy	A very prominent portion of the Point Lookout sequence with thickness ranging from 13 to 34m. Units grade laterally north-northeastward into Facies A and south-southwestward into Facies C. Individual sandstones range from 1m to about 8m in thickness, laterally continuous, and with sharp, commonly irregular lower contacts, and regular, sharp, rarely erosional upper contacts. Shale breaks generally thin, increase in thickness northward, and pinch out into thick sandstones southward.
Lithology	A sequence of thick, tabular sandstones with thin shale breaks. Sandstones are generally tan weathering to orangish gray, very fine to fine grained, moderately sorted, subrounded to subangular, friable to moderately indurated, laminated and cross-laminated to structureless, locally bioturbated, medium to very thick bedded, moderately fossiliferous, feldspathic letharenites. Abundant large, carbonate-cemented sandstone concretions. Carbonaceous material in some laminated zones. Shales are generally of similar lithology as in Facies A.
Sedimentary structures	Dominantly shallow trough cross-stratification displaying variable transport directions, and some tabular cross-stratification. Cross-lamination consisting of sets with laminae truncating each other (similar to what Campbell, 1971, calls truncated wave-ripple laminae) locally exist. Megaripple type structure also occurs.
Fossils	Contains the densest and most diverse fauna within the Point Lookout Sandstone. They occur either as a diverse and fragmented assemblage in thin zones dominated by bivalves, gastropods, and shark teeth, or a low diversity assemblage (mostly bivalves) disseminated in thick zones, and typically concave downward. Trace fossils are also moderately abundant, dominantly *Ophiomorpha* and/or *Thalassinoides;* they range from horizontal on bedding planes to vertically oriented.
Environmental interpretation	Shoreface

c. Summary of diagnostic characteristics and interpreted environment of deposition of Facies C.

Stratigraphy	Facies C consists of well developed, steep slope to cliff forming, tabular sandstones with thickness of 3.2m to about 13m. It consists of laterally extensive massive and/or thin to medium bedded sandstone intervals. Lower contacts with Facies B are sharp and locally irregular; upper contacts are either sharp, locally irregular, or gradational, with either Facies D or Facies E units.
Lithology	Generally tan weathering to orangish gray, fine grained, moderately well sorted, subrounded to subangular, moderately indurated, very thin to thick bedded to massive, moderately laminated and cross-laminated, feldspathic litharenite to litharenite. Massive units are muddier and locally contain lignitic fragments.
Sedimentary structures	Subhorizontal stratification and/or low angle planar cross-stratification. Cross-laminae within sets are relatively uniform, dipping gently, and subparallel with set boundaries. Wave ripple marks occur locally.
Fossils	Except for some local poorly preserved bivalves, body fossils are very sparse in Facies C. Trace fossils are low but ubiquitous, mainly inclined to vertically oriented *Ophiomorpha*. Some root structure exists locally at the top.
Environmental Interpretation	Foreshore-backshore complex.

d- Summary of diagnostic characteristics and interpreted environment of deposition of Facies D.

Stratigraphy	Cliff-forming, laterally extensive sandstones, persist in most of the area with thickness of 6 to 25m. Individual units are moderately tabular with sharp, locally irregular lower contacts; laterally variable units with basal erosional, shallow scour contacts occur locally; few display lenticular (channel type) shape. Units intertongue with Facies E units to the south-southwest and grade into Facies C sandstones north-northeastward.
Lithology	Tan to orangish gray, fine to medium grained, moderately well sorted, subangular to subrounded, moderately indurated, very thick to massive, poorly cross-stratified, fossil-barren, feldspathic litharenite to litharenite. Small to fairly large clay clasts, carbonaceous debris in local muddy zones, and lignitic fragments and thin coal pockets occur locally.
Sedimentary structures	Poorly developed, large scale, very shallow trough to wedge cross-stratification. Moderately developed large scale trough cross-stratification exists locally in top units. Paleocurrent measurements show dominant northward transport. Some slightly asymmetrical ripple marks occur locally.
Fossils	Neither macroinvertebrate fossils nor beach trace fossils exist in Facies D. *Teredo* borings are locally common. A log cast occurs in one locality.
Environmental Interpretation	Estuarine-beach complex.

e- Summary of diagnostic characteristics and interpreted environment of deposition of Facies E.

Stratigraphy	Variegated units of mudstones, carbonaceous shales, humates and thin coal lenses and beds, carbonaceous muddy sandstones, and lenticular to tabular sandstones interbedded and laterally intermingled with each other. Individual units vary in thickness laterally within a short distance. They maintain an intertonguing relationship with Facies D or Facies C units. It forms the basal part of Menefee Formation.
Lithology	Interbedded gray to brownish gray, moderately indurated to friable, carbonaceous silty shales to mudstones, locally contain ironstone (siderite) concretions; light to dark brown, fissile to friable, silty humic shales to humates, with abundant plant debris and carbonized wood material; black, moderately dirty coal seams; light gray, very fine grained, poorly sorted, friable, muddy sandstones, with vertical root casts; yellowish gray to tan, fine to medium grained, moderately sorted, subangular, moderately indurated, medium to thick bedded to massive, moderately cross-stratified, lenticular with scour basal contacts, litharenite.
Sedimentary structures	Very small scale cross-lamination and poorly developed, nearly symmetrical ripple marks in muddy sandstones. Large scale, high angle trough and some planar to wedge cross-stratification in thick lenticular sandstones; transport direction generally due northeast.
Fossils	Carbonized wood and plant fragments are common. *Teredo* structures occur locally, and root structure is locally moderately abundant.
Environmental interpretation	Nonmarine coastal complex.

Lookout time, as it was recorded by deposition of the Point Lookout Sandstone, represents the most extensive retreat of the Late Cretaceous sea in the San Juan Basin region.

The average overall trend of the Point Lookout shoreline was northwest-southeast. Several lines of evidence confirm this conclusion: 1) the northern most limit of the Point Lookout Sandstone shows a northwest-southeast trend between the western and eastern sides of the San Juan Basin; 2) elongate, thick sandstone bodies within the Point Lookout Sandstone, that are interpreted to be developed parallel to the shoreline, are generally oriented in a northwest-southeast trend; 3) average orientation value of wave ripples crests, which are presumed to be parallel to shoreline, is about N34^{o}W; 4) northwest and southeast trending components, which are evident in many paleocurrent analyses, indicate longshore currents.

The Point Lookout sequence, which represents a classical fairly complete regressive system, resulted from a gradual retreat of the shoreline, north to northeastward, due to a moderately balanced interrelationship between the coastal conditions to the northeast and a steady supply of sediment from the southwest through, most likely, small rivers across low lying coastal plains characterized by humid conditions. The coastal regime during deposition of the Point Lookout was generally characterized by low to moderate wave energy, which was strong enough to develop a linear shoreline complex rather than a deltaic complex, but its influence was not sufficient to produce texturally nor mineralogically mature beach sandstones.

The Point Lookout Sandstone and adjacent units provide a classical example of an ancient regressive system. The vertical and lateral relationships between the constituting units provide an excellent example for understanding the relationship between sedimentary facies, their environments of deposition, and provide a valid argument against the use of pin-point contacts of formations for a sequence such as the Cretaceous sequence of the San Juan Basin. Composition of the Point Lookout Sandstone is a good example of lithic sandstones.

The Point Lookout Sandstone, especially Facies C and D, provides an adequate reservoir rock for hydrocarbons. The underlying marine Mancos Shale and abundance of organic matter in the sequence provide a likely source rock. Production of petroleum, mainly gas, from the Point Lookout Sandstone has been established in several areas in the San Juan Basin. It also provides an adequate aquifer. Understanding of its distribution and relationship with the overlying Menefee Formation can be of great importance to coal and/or humate exploration.

APPENDICES

Appendix A

I. Classification of cross-stratification (from McKee and Weir, 1953)

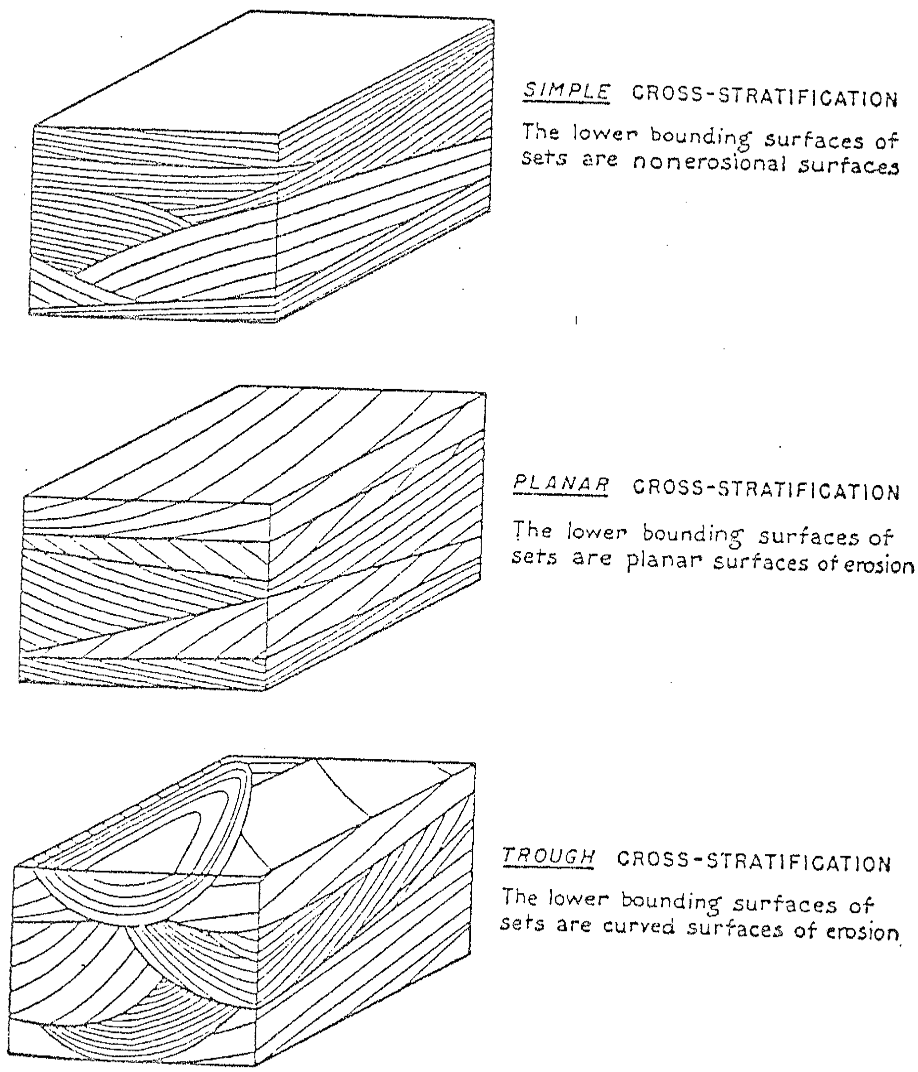


Figure 51. Classification of cross-stratification according to McKee and Weir (1953, Fig. 2)

Length of cross-strata:

Small scale <1 foot
Medium scale 1 to 20 feet
Large scale >20 feet

Dip of cross-strata:

High angle >20 degrees
Low angle <20 degrees

II. Calculation of paleocurrent parameters (following Potter and Pettijohn, 1963)

Azimuth of the mean vector "$\overline{X}$"

$$\overline{X} = W/V$$

$$\text{where: } V = \sum_{i-1}^{n} n_i \cos X_i$$

$$W = \sum_{i=1}^{n} n_i \sin X_i$$

Standard deviation "S_x"

$$S_x = \sqrt{S_x^2}$$

$$\text{where: } S_x^2 = \sum_{k=1}^{n} (x_k - \overline{X})^2 \Big/ (n - 1)$$

for grouped data (for each of the recognized facies, Figures 12, 18 and 23), standard deviation was calculated from:

$$S_x^2 = \sum_{i=1}^{n} n_i (X_i - \overline{X})^2 \Big/ (n - 1)$$

X_i = midpoint azimuth of the i^{th} class interval.

n_i = number of readings in each class interval.

n = total number of readings.

x_k = individual azimuth measurements.

S_x^2 = sample variance.

III. Calculation of grain-size parameters (following Folk and Ward, 1957)

Mean grain size "M_z" $= \Phi16 + \Phi50 + \Phi84/3$

Standard deviation "σ_I" $= \dfrac{\Phi84 - \Phi16}{4} + \dfrac{\Phi95 - \Phi5}{6.6}$

Skewness "SK_I" $= \dfrac{\Phi16 + \Phi84 - 2\Phi50}{2(\Phi84 - \Phi16)} + \dfrac{\Phi5 + \Phi95 - 2\Phi50}{2(\Phi95 - \Phi5)}$

Kurtosis "K_G" $= \dfrac{\Phi95 - \Phi5}{2.44(\Phi75 - \Phi25)}$

M_z:

-1.0 to 0.0Φ	very coarse sand
0.0 to 1.0Φ	coarse sand
1.0 to 2.0Φ	medium sand
2.0 to 3.0Φ	fine sand
3.0 to 4.0Φ	very fine sand
4.0 to 5.0Φ	coarse silt
5.0 to 8.0Φ	medium to very fine silt
>8.0Φ	clay

σ_I:

<0.35Φ	very well sorted
0.35 - 0.50Φ	well sorted
0.50 - 0.71Φ	moderately well sorted
0.71 - 1.0Φ	moderately sorted
1.0 - 2.0Φ	poorly sorted
2.0 - 4.0Φ	very poorly sorted
>4.0Φ	extremely poorly sorted

IV. Scale of stratification thickness (after Ingram, 1954)

Very thickly bedded	>100cm
Thickly bedded	30 - 100cm
Medium bedded	10 - 30cm
Thinly bedded	3 - 10cm
Very thinly bedded	1 - 3cm
Thickly laminated	0.3 - 1cm
Thinly laminated	<0.3cm

Appendix B

Description of measured stratigraphic sections shown on Plate 1.

Abbreviations used in the description of units

Color:

bl	black
br	brown
gr	green
gy	gray
or	orange
pr	purple
rd	red
tn	tan
yl	yellow

(combination of colors is written as: e.g., br-gy means brownish gray)

Grain size:

v.f	very fine
f	fine
m	medium
c	coarse
v.c	very coarse

Sorting:

v.w.sr	very well sorted
w.sr	well sorted
m.sr	moderately sorted
p.sr	poorly sorted
v.p.sr	very poorly sorted

Roundness:

w.R	well rounded
s.R	subrounded
s.A	subangular
A	angular

Consolidation:

fi	fissile
fr	friable
m.In	moderately indurated
w.In	well indurated
e.w.In	extremely well indurated

Section Kp1-1 (about 5 miles north of San Luis)

T.18N., R.2W., Sec. 36 (NW)

Unit No.	Thickness	Major Lithology	Description
1	6.70m	Sh-Ss	Br-bl, fi silty to sandy Sh interbedded with yl-gy, v.f, fr, laminated and with some very small scale x-lamination, lenticular silty Ss. Fine to coarse carbonaceous fragments are abundant especially between Ss laminae. Few small burrows present throughout the unit.
2	1.86	Ss-Sh	Relatively prominent Ss lenses interbedded with shales. Ss is v.f, mo. sr, fr, with some carbonate cement in lower part, laminated and x-laminated (small scale trough to planar); carbonaceous debris is common on laminae surfaces, and some mica flakes; occasional burrows in Ss lenses and few in shale breaks.
3	1.95	Sh-Ss	Interlaminated silty Sh and sandy siltstone to silty Ss, with some laminated, v.f., silty Ss lenses.
4	4.52	Ss-Sh	Lenticular, laminated, friable, silty Ss interbedded with silty Sh breaks in the lower part; prominent, slightly coarser, better sorted, better indurated, less laminated Ss interval in the middle part; and silty to sandy Sh in the upper part. Carbonaceous debris in lower part; well developed burrows (skolithos?) abundant also in lower part, they are vertical to slightly inclined and some of them extend through shaley intervals as sand filled tubes.
5	12.82	Ss	Well developed cliff-forming Ss. Tn weathers to or-gy, v.f, w.sr, s.R to s.A,fr to mo.In, highly porous; medium to very thick bedded, laminated and cross-laminated (very low angle, planar type) in lower and middle parts. Small Fe-claystone pebbles are abundant in zones in lower part and near top. A zone with shaley breaks and laminated carbonaceous, silty Ss exists near the middle.

Appendix B, Section Kpl-1 cont'd

Unit No.	Thickness	Major Lithology	Description
6	2.20m	Ss-Sh	Friable, laminated silty Ss interbedded with irregular Sh laminae. Some carbonaceous debris exist between laminae.
7	11.55	Ss	Well developed, cross-bedded, cliff forming Ss. Basal part interbedded with carbonaceous shale and contains abundant small lignitic fragments. Tn weathers to or-gy, f, w.sr, s.R, mo.In, thick to thin bedded, laminated, cross-bedded and cross-laminated, highly porous Ss. X-lamination is generally planar with very low angle and nearly parallel laminae.
8	1.15	Ss	Tn to br-gy, v.f, mo.-p.sr Ss with some mud and carbonaceous debris which becomes more abundant upward; some poorly defined root tubes in the top carbonaceous zone.
9	1.15	Coal	Well developed coal seam with thin zones of humate at basal and upper parts.
10	1.60	Ss	Very fine grained, poorly sorted, muddy Ss with abundant lignitic plant fragments along laminae; few vertical root tubes near the top.
11	0.58	Coal	Black coal bed with brownish humate type (or clayey lignite) zones at base and top.
12	1.50	Ss	Lower 25-30cm is v.f, laminated, slightly muddy Ss with abundant lignitic debris between laminae. Followed by highly bioturbated Ss interval (~20cm) with abundant ophiomorpha-type burrows (some extend down into laminated interval below). Upper interval (about 1.0m) is ripple bedded Ss with well developed bedding surface and biogenic structures; ripple bedding is highly irregular, with somewhat interference type, poorly defined troughs and crests, somewhat symmetrical, but many are current ripples; horizontal branched ophiomorpha tubes are common; some small scale cross-bedding present. Upper Ss interval has

Appendix B, Section Kpl-1 cont'd.

Unit No.	Thickness	Major Lithology	Description
			much less clay matrix and abundant calcite cement.
13	0.78	Sh	Br to br-gy, fi, carbonaceous, sandy at base, silty shale.
14	1.16	Ss-Sh	Laminated, fr, v.f muddy Ss interbedded with silty to sandy shale. Carbonaceous debris exists between laminae; very small cross-lamination in Ss; iron oxide siltstone nodule zone at the base.
15	1.14	Clys-Hum	Humate-rich claystone grading upward to clayey humate and to coaly humate at top.
16	0.53	Coal	Well developed, black coal seam.
17	0.51	Sh	Br-gy, fi, slightly silty Sh with some carbonaceous matter.
18	1.83	Ss-clys	Well developed lenticular v.f, fr Ss with very thin claystone zones. Some poorly developed ripple bedding, well developed mudcracks in muddy zones, abundant plant debris, and well developed vertical root tubes at top are present.
19	0.22	Hum	Well defined humate seam with thin black coal stringers.
20	0.75	Ss	Tn weathers to or-gy, v.f, mo.In, silty Ss broad lense with some poorly developed ripple marks, abundant teredo structure in lower part, and vertical root tubes in upper part.
21	0.40	Hum	Well developed humate bed.
22	0.60	Coal	Well developed black coal bed.
23	0.79	Sh	Br-gy, silty shale grading upward into l.gy, mudstone.
24	1.48	Mud	L.br to br-gy, humate-rich, thinly laminated, mudstone.

Appendix B, Section Kpl-1 cont'd.

Unit No.	Thickness	Major Lithology	Description
25	0.13	Coal	Thin coal seam thickens laterally; it contains some flaser-type sand ripples, and sand filled burrows (thalassinoides) extend into it from the Ss unit above.
26	1.40	Ss	Basal unit of a prominent, cliff-forming Ss interval (units 26-29). Lower part is v.f, fr, silty Ss with abundant lignitic fragments; grading upward into burrow mottled cleaner and coarser Ss. Well developed thalassinoides? structure is abundant in certain zones and burrow mottling throughout the unit.
27	2.42	Ss	Well developed, cross-bedded, relatively clean Ss with few ophiomorpha? burrow structure. L.gy to tn weathers to gy-or, f, w.sr, s.R, mo.In, thick to thin bedded Ss. Cross-bedding is mainly tabular type and some shallow troughs.
28	0.65	Ss	Bioturbated, muddy Ss with some carbonaceous debris. It is finer and less resistant than Ss above and below, relatively highly bioturbated, with some thallassinoides? type burrows, and makes an irregular contact (scour) with underlying unit.
29	0.65	Ss	High calcite-cemented Ss with sparse marine fossils and burrows. L.gy weathers to br-gy, v.f to f, w.sr, s.R, w. to extremely w.In, thick to medium bedded, laminated, highly calcite cemented Ss with some small bivalve fragments and very few snails, and sparse burrow structure (ophiomorpha?).

Above this Ss ledge is a covered, very low-lying slope (almost flat), but in adjacent area it is overlain by humate and humate-rich claystone followed by the typical Menefee sequence (coal, channel type Ss, mudstone, humate, etc.).

Kpl 32.25m (unit 4 through unit 7)
Total thickness of measured section is 63.00m.

Section Kpl-2 (La Ventana Rest Area)

T.18N., R.1W., Sec. 5 (NW-NW)

Unit No.	Thickness in Meters	Major Lithology	Description
1	1.70	Sh-Ss	Thin to very thin bedded to laminated sandstone interbedded with numerous shale breaks. Ss is yl-gy weathers to or-gy, v.f, mo.sr, s.R, fr, and silty. Sh is olive gy weathers to light olive gy, fi, and silty; small sand-filled burrows present in Sh.
2	6.90	Ss	Well developed Ss with local carbonate cemented and concretioned zones. Yl-gy weathers to l.gy and yl-or (in concretion zones), v.f, mo.sr, s.R, mo.In, massive in lower 2.5 meters, laminated in middle and upper parts (with wedge and small trough x-lamination) Ss, with very few horizontal tubes of thalassinoids. Two zones with highly calcite-cemented large Ss concretions exist in upper half; some carbonaceous material exists on bedding surfaces, and small Fe-rich claystone pebbles in upper part.
3	1.75	Ss-Sh	Silty shale in lower part followed by silty Ss, then sandy Sh in upper part. Ss interval is gy-or weathers to generally same color, v.f, mo.sr, s.R, fr, and thinly bedded to laminated; with carbonaceous debris between laminae. Sh is olive gy, fi, silty and sandy in upper part, and some carbonaceous material exists between some of the laminae.
4	8.00	Ss	Well developed Ss with carbonate-cemented Ss concretion zones. Tn weathers to pale yl-and or-gy, v.f, w.sr, s.R, mo.In, laminated Ss, with small wedge and trough cross-lamination in lower and upper parts, arge wave ripples in upper part, one small bivalve and very few shark teeth in lower part and very sparse small ophiomorpha tubes near top. Upper part is with abundant cemented large concretions (up to 1.5m long and 70.5cm thick) forming a prominent ledge.

Appendix B, Section Kpl-2 cont'd.

Unit No.	Thickness in Meters	Major Lithology	Description
5	4.90	Ss	Well developed Ss with Sh break at base and prominent carbonate cemented Ss concretion zone at top. Ss is generally similar to unit 4 in texture and composition; medium bedded, laminated, with small trough sets in upper half, variably oriented burrows are abundant at top where long ophiomorpha tubes are preserved as iron-oxide cemented casts. Concretion zone at top makes a prominent ledge through the area. Well developed truncated wave ripples exist in upper part.
6	1.85	Sh	Well defined Sh break; slightly silty, becomes more silty to sandy at top. It is olive gy weathers to br-gy, fi, with some fine plant debris and few very small burrow structures.
7	5.25	Ss	Slope forming Ss with notable upward increase of brown carbonaceous debris. L. gy to l.br-gy weathers to l.gy, f to v.f, mo.sr, s.R, fr, poorly laminated Ss. Brown plant debris concentrated mainly between laminae surfaces and increases upward.
8	5.30	Ss	Similar to Ss below with continual increase in carbonaceous debris and abundance of iron oxides staining. Pyrite nodules zone in lower part, some are oxidized to limonite; well developed teredo borings in upper part, and detrital coal in local zones at top; shallow troughs with cross-lamination in upper part.
9	3.82	Ss	Well developed Ss forms vertical cliff. Tn weathers to or-gy, f, w.sr, s.R to s.A, mo. to w.In, thick to thin bedded, laminated Ss, with large scale poorly developed trough to wedge x-stratification, and some claystone clasts.
10	0.50	Ss	Thinly bedded Ss with iron oxides staining. It is finer, less sorted, and less

Appendix B, Section Kpl-2 cont'd.

Unit No.	Thickness in Meters	Major Lithology	Description
			resistant than the Ss below. It contains some clay galls and few shallow trough x-laminations.
11	5.20	Ss	Prominent Ss unit with irregular, very thin shale breaks in lower 1.5m. Lower part (2.0m) consists of v.f to f, mo.sr, s.R, fr Ss, interbedded with irregular very thin shaley zones where some carbonaceous debris exists. A few nearly symmetrical ripple marks also occur in lower part; wave length 15-25cm, amplitude about 1.0cm, crest orientation 92^{o}-272^{o}, and paleocurrent direction about 2^{o}. It grades upward into tn, better sorted, more indurated Ss with large scale troughs; root-like structures locally exist in upper surface. This unit is regarded as the top of the Point Lookout Ss.
12	3.05	Sh	Brownish, slightly silty shale forms a low slope above the sliff-forming Ss. It contains weathered plant debris and humate-rich zone at top.
13	0.97	Coal	Well developed coal seam with thin humate zones in middle and at top.
14	3.18	Mud	Brownish silty claystone grading upward into clayey siltstone, with abundant fine carbonaceous and lignitic debris.
15	12.00	Ss	Well developed Ss unit, with moderately abundant burrows (thalassinoides?) at base, and prominent large scale trough cross-bedding throughout most of it. Basal contact is erosional.
16	1.25	Ss	Muddy Ss with abundant carbonaceous debris, and zones of carbonate cemented, laminated Ss. It is finer and less indurated than unit 15 below, but the contact is gradational.

Kpl 43.47m (unit 2 through unit 11)
Total thickness of measured section is 58.97m.

Section Kpl-3 (near Clod Buster Mine)

T.19N., R.1W., Sec. 10 (NW-SW)

Unit No.	Thickness in Meters	Major Lithology	Description
1	1.25	Sh-Ss	Interbedded gy, fi shale and yl-or, v.f, fr, very thinly laminated, thin sandstone lenses.
2	3.45	Ss-Sh	Interbedded laminated and cross-laminated thin beds and lenses of sandstone and gy to d.gy fi shale. Ss is l.gy weathers to yl-gy, v.f, fr, silty with tabular type cross-lamination and few small burrow tubes (skolithos?) and trails on bedding surfaces. Some carbonaceous debris exists between Ss laminae and in upper Sh. Ss lenses mostly have irregular basal contact.
3	1.43	Ss	The first more than a meter thick Ss interval. L.gy weathers to yl-or, v.f, mo.sr, s.R, generally fr, laminated, tabular cross-laminated moderately carbonate-cemented Ss. Wavy or undulatory cross-stratification exists in lower part and megaripples in upper part; very few burrow tubes (skolithus?) on bedding surfaces. Unit changes northeastward into dominantly laminated Ss interbedded with Sh zones and becomes inseparable from unit 2; cluster of fossils exist locally in Ss units (bivalves, gastropods, ammonites).
4	1.52	Ss-Sh	Br-gy, fi, silty Sh in lower 40cm overlain by yl-gy, v.f, fr, partly laminated Ss interval, and silty zone in upper 5cm Fine carbonaceous debris is relatively abundant in laminated Ss.
5	6.70	Ss	Well developed, steep slope to small cliff-forming Ss. L.gy weathers to pale yl-gy, v.f to f, mo.sr, s.R, fr to mo.In, low to fairly porous, thin bedded to laminated Ss. Large, highly carbonate-cemented Ss concretions are abundant forming prominent ledges. Small trough cross-lamination exists in lower and upper middle parts; planar cross-lamination in upper part, and megaripples at

Appendix B, Section Kpl-3 cont'd.

Unit No.	Thickness in Meters	Major Lithology	Description
			the bottom. Pyrite concretions (up to ~3.5cm) are present in upper part, mostly partly or completely oxidized. Some bivalves and shark teeth exist in lower concretioned zone, and burrow tubes (ophiomorpha? and/or thalassinoides) relatively abundant in concretioned zones with vertical to oblique orientation.
6	1.15	Sh-Ss	Br-gy to gy, fi Sh interbedded with very thin lenses of v.f, fr, silty Ss. Few small burrow(?) structures are present.
7	4.55	Ss	Well developed Ss with shaley zone at the top. Similar to unit 5 except no fossils observed.
8	5.75	Ss	Well developed Ss with rounded cliff-forming ledges. Lithologically it is essentially similar to unit 5 and 7 below except slightly coarser. Lower half is generally bioturbated and contains claystone galls in lower 2 meters. Upper part contains prominent zone of large, carbonate-cemented Ss concretions where fossils (bivalves) and burrows (ophiomorpha) are better preserved; trough cross-stratification is abundant and megaripples near top; it also contains iron oxide-rich claystone pebbles (up to 8cm in diameter) and pyritic nodules.
9	1.30	Ss-Sh	Thin Ss intervals interbedded with Sh breaks.
10	5.80	Ss	Steep slope-forming Ss yl-gy to l.gy, f, mo.sr, s.R to s.A, mostly fr to mo.In Ss with bioturbated zones, and disturbed cross-lamination in upper part. Large Ss concretions exist in middle part, very few molds which are possibly after bivalves in lower part, and few Fe oxide nodules in upper part.
11	1.05	Sh-Ss	Gy, fi, silty Sh interbedded with very thin, lenticular, friable Ss zones.

Appendix B, Section Kp1-3 cont'd

Unit No.	Thickness in Meters	Major Lithology	Description
12	3.00	Ss	Relatively steep slope-forming Ss. Lithologically similar to unit 10 below. Lower part is generally massive (no structure), middle part contains a zone of large, carbonate-cemented Ss concretions and poorly developed trough cross-stratification, and upper part is also massive (apparently bioturbated).
13	6.35	Ss	Massive yl-gy to or-gy, fr Ss in lower part topped by highly carbonate-cemented, concretioned zone forming the down-dip slope. Upper part consists of variegated colored (Fe oxides), poorly thin to very thinly bedded, friable Ss. Lower part is similar to unit 12 below except for color due to Fe oxides and slightly coarser. Upper part is more variegated in lithology, coarser, and less sorted. Very few ophiomorpha burrows exist in middle part, and carbonaceous debris is disseminate in upper part.
14	1.65	Ss	Continuation of the section down the dip slope. Ss is better sorted than unit 13 below, rippled, contains abundant ophiomorpha burrows and very few shark teeth. Ripple marks are small, wave-current type. This is the highest unit in the section with marine evidence.
15	1.55	Ss	Three adjacent channel Ss bodies exist within a distance of about 50 meters, cutting through underlying burrowed finer Ss. The channels are well developed, contain medium grained and highly porous Ss, and have shallow trough shaped, relatively smooth basal boundary (see Figure 21B). Ss is l.gy weathers to yl-gy, m, mo. sr, s.A, mo. to w.In, poorly cross-stratified (wedge type), and relatively rich in chert. Upper 50cm is thinly moderately bedded, and forms a tabular sheet above the lenticular intervals.
16	9.80	Ss	Unit is generally covered. Lower part consists of variegated colored (Fe oxides

Appendix B, Section Kp1-3 cont'd

Unit No.	Thickness in Meters	Major Lithology	Description
			staining) f,p.sr, fr, carbonaceous Ss. Then a sequence of coarser (medium grained decreases gradually upward to fine grained), slightly better sorted, thinly poorly bedded to laminated Ss with variegated colors due to Fe oxide staining, and a zone with disseminated carbonaceous matter (some fragments up to 2cm or more).
17	3.00	Ss	Well developed Ss interval with erosional shallow trough shaped (scour) basal boundary. It consists of l.gy weathers to yl-gy, m, mo.sr, mo. to s.In, fair to highly porous Ss. Large scale cross-stratification of wedge to trough type with erosional basal boundaries and angular to slightly tangential internal laminae characterize the lower part. Upper part is thinly poorly bedded to laminated.
18	0.93	Ss-Clys	Thin interval of relatively finer, muddier Ss with very thin, weathered plant material-rich, muddy zones.
19	10.07	Ss	A thick sequence of well indurated Ss similar in lithology to unit 17 below and together they form a low ridge along the valley. Large scale wedge to trough shaped cross-stratification is moderately developed in several parts; several of them show erosional, irregular to trough shaped basal boundary (see Figure 22), and internal laminae range from highly tangential to angular with the basal surfaces. Middle part is generally massive with no significant structure. Poorly developed mudcrack type structure was observed nearly at the base of the unit. As in unit 17, disseminated carbonaceous debris is sparse, but a local very thin carbonaceous zone exists in lower part.
20	1.00+	Hum-Coal	Ss unit 19 is overlain, down the slope, with a sequence of carbonaceous clay-

Appendix B, Section Kpl-3 cont'd

Unit No.	Thickness in Meters	Major Lithology	Description
			stone, humate material and very thin coal lenses. It grades into the typical Menefee sequence of humates, coal, claystones, and channel sandstones forming the eastern slope of the adjacent ridges.

Kpl 65.60m (bottom of unit 3 through unit 19)
Total thickness of measured section is 71.30m.

Section Kp1-4 (near San Pablo)

T.20N., R.1W., sec. 14 (SW-SE)

Unit No.	Thickness in Meters	Major Lithology	Description
1	7.75	Sh-Ss	Br-gy to gy, fi, silty shale interbedded with tn to gy, v.f, silty sandstone lenses. Some Ss lenses show irregular lower boundary; some are laminated. Few small burrow tubes and trails exist near or on upper surface of some Ss intervals.
2	1.50	Ss	Yl-gy, v.f, mo.In, highly carbonate-cemented, fossiliferous sandstone. This interval forms a small ridge, but decreases in thickness laterally within few tens of meters. Some bivalves, other mixed fragments, shark teeth and fish bone fragments are present; also few burrow tubes exist.
3	8.25	Ss-Sh	Interbedded lenticular sandstone intervals and silty shale. Similar to unit 1 below except Ss lenses are relatively thicker; Ss is more dominant, and shale is siltier. Prominent Ss lenses range from massive (structureless) to thinly well laminated; some poorly preserved fossils exist, and burrow tubes (skolithos and thalassinoides) mostly restricted to upper part or bedding surfaces.
4	5.35	Ss-Sh	Generally a continuation of unit 3 below but relatively thick (>1m) and laterally extensive Ss intervals form a considerable part of it. Ss is generally laminated and slightly coarser than below.
5	2.45	Ss	Well developed, ridge-forming sandstone. Tn weathers to yl-gy, v.f, mo.sr, s.R, mo. w.In, thinly bedded to laminated planar cross-stratified sandstone with calcite cement in lower half and fossiliferous zone in upper lower half. Fossils are well preserved and numerous in a thin zone; they are highly diverse, with small forms being relatively complete and abundant fragments of larger forms.

Appendix B - Section Kpl-4 cont'd.

Unit No.	Thickness in Meters	Major Lithology	Description
6	0.47	Sh	Gy, fi, silty shale break. It decreases in thickness southward.
7	4.68	Ss	Well developed sandstone, generally similar to unit 5 below in lithology except slightly coarser and better sorted in its upper part. Lower part is laminated, less indurated and muddier than middle and upper parts which contain abundant fossils of mixed types. Highly fossiliferous thin zones exist in the upper part where carbonate-cemented large Ss concretions and small shallow trough cross-stratification exist. Carbonaceous debris occurs in lower part and small iron oxide-rich claystone pebbles below the concretioned zone.
8	2.45	Ss-Sh	An alternation of v.f, fr, silty sandstone, and fi to fr silty shale and siltstone. It forms a break between the ridge-forming, vertical sandstones of units 7 and 9.
9	2.95	Ss	Prominent ridge-forming, fossiliferous sandstone. Sandstone is v.f to f, mo. to w.sr, s.R, w.In, and carbonate cemented especially in the middle concretioned zone. Thin zones of abundant, highly diverse, highly fragmented fossils exist at the basal part and near the top. Thalassinoides and some ophiomorpha are also abundant in the fossiliferous zones, especially near the top where branched thalassinoides are abundant.
10	1.95	Sh-Ss	Silty shale to shaly siltstone interbedded with laminated friable sandstone zones. The whole unit decreases in thickness southward within a few tens of meters.
11	6.45	Ss	Well developed thick interval with highly carbonate-cemented concretioned zones forming prominent ridges. L.gy to tn, v.f to f, mo. to w.sr, s.R, mo. to w.In, massive to poorly bedded and

Appendix B - Section Kpl-4 cont'd.

Unit No.	Thickness in Meters	Major Lithology	Description
			laminated sandstone. Small shallow, poorly developed trough cross-stratification exists in concretioned zones, poorly developed planar type in middle part. A very thin (few centimeters) shaley zone exists at the top to the south and pinches out northward.
12	18.20	Ss	Generally a continuation of unit 11 below with similar lithology except slightly coarser and less cemented by carbonates. Claystone clasts are relatively abundant in the lower-most part; few ophiomorpha burrows also exist in this part. Two carbonate-cemented concretioned zones exist in lower few meters forming ridges; thin zone with some fossils, mostly broken, is present above lower concretioned zone and few ophiomorpha burrows in upper concretioned zone. Poorly developed lamination and cross-lamination in lower part. Middle and upper parts are generally massive, most likely due to bioturbation which is recognizable in some horizons; poorly developed lamination exists in lower part. Muddy zone is present in middle part; some ophiomorpha tubes also present in middle part, few more exist near top where two poorly preserved molds of bivalves were observed. Very few greenish rounded grains (glauconite) occur in upper part.
13	1.25	Ss-Sh	Yl-gy to yl-or, f, p.sr, fr, carbonaceous sandstone topped with a zone of gy to br-gy, fr, carbonaceous clayey siltstone.
14	7.00	Ss	Prominent sandstone interval which together with unit 15 above form a wall-like ridge next to the low-lying less resistant variegated units of lower Menefee Formation to the west. Tn weathers to yl-or, m, mo.sr, s.A to s.R, mo.In, massive to thick poorly bedded sandstone with zones rich in carbona-

Appendix B - Section Kpl-4 cont'd.

Unit No.	Thickness in Meters	Major Lithology	Description
			ceous debris and plant fragments. Poorly developed large scale wedge cross-stratification exists throughout the unit. Muddy zone is present at about 1.5m from bottom; scour marks are on the base of the overlying Ss. Grain size declines slightly toward the top.
15	10.50	Ss	Lithologically generally the same as unit 14 below except slightly finer and contains few very thin carbonaceous muddy zones. Lower few meters are thin to medium moderately bedded; middle and upper parts are generally massive.
16	1.00+	Cly-Hum	Low lying slope above interbedded and intertongued carbonaceous muddy Ss, carbonaceous mudstone, humate and very thin coal lenses. It grades upward into the typical variegated humate and coal-bearing sequence of Menefee Formation with lenticular channel sandstone bodies.

Kpl 61.20m (middle of unit 4 through unit 15)
Total thickness of measured section is 82.25m.

Section Kpl-5 (about 1 mile north of

T.23N., R.1W., Sec. 1 (NE-SE)

Unit No.	Thickness in Meters	Major Lithology	Description
1	6.80	Sh-Ss	Gy to br-gy, fi, silty shale interbedded with tn, v.f, fr, laminated to structureless, lenticular, silty sandstones. Some fine carbonaceous material exists between laminae.
2	9.90	Ss-Sh	Moderately tabular sandstone intervals and interbedded shales. Sandstone is yl-gy to tn, v.f, p.- mo.sr, s.R, fr, silty, well laminated to structureless (bioturbated). Thick sandstones exhibit irregular lower contacts; thin sandstones are lenticular. Shales are l.gy to br-gy, fi to fr, silty to sandy.
3	3.30	Ss	L.gy to tn weathers into yl-gy, v.f to f, mo.sr, s.R, mo.In, laminated and cross-laminated, burrowed, fossil-bearing, locally bioturbated, laterally extensive sandstone forming small ledges above the underlying gentle slope. Lower contact is sharp and irregular; cross-stratification dominated by well developed, small scale, shallow troughs; ophiomorpha is abundant, mostly vertically oriented and with iron oxide-cemented walls (some show knobby surfaces); fossils are not abundant, mainly bivalves; grain size increases gradually upward.
4	13.00	Ss	Steep slope to cliff-forming, laterally extensive sandstone. Tn weathers into or-tn-gy, f, mo. to w. sr, s.R, mo. to w. In fairly porous sandstone. Lower part (2m) is very thin to medium moderately bedded, with very gently dipping, poorly developed planar cross-laminae, and moderately abundant diagonally oriented ophiomorpha tubes (1.5 to about 3.0cm in diameter, and some > 50 cm long). It has moderately regular basal contact and irregular (erosional) upper contact with the overlying massive sandstone. The rest of the unit consists of thick to very thick poorly bedded, burrow-barren sandstones with poorly developed planar cross-stratification in lower part; followed by massive sandstones with moderately abundant ophiomorpha (thin

Appendix B, Section Kpl-5 cont'd.

Unit No.	Thickness in Meters	Major Lithology	Description
			tubes, some are long, mostly with iron oxide-cemented surfaces, some exhibit knobby surface, and mostly oriented obliquely); the upper part is slightly finer, less indurated, and contains no burrows. Grain size increases slightly upward, except for the upper part.
5	5.50	Ss	L.gy to tn weathers into yl-tn, v.f to f, mo.Sr, s.R, mo.In, cross-laminated (lower part), bioturbated (middle part), and moderately laminated (upper part), non-fossiliferous sandstone. Cross-lamination in lower part is well developed, small scale shallow troughs (similar to that in unit 3 below). Grain size decreases upward.
6	2.80	Sh-Ss	Gy,fi, silty shale in lower part; followed by gy, v.f, p.sr, fr, poorly laminated, slightly carbonaceous, silty sandstone; upper part consists of br-gy, fi to fr, highly silty, carbonaceous shale. Lower contact of Ss interval is irregular sharp but upper contact is gradational.
7	2.05	Ss	Tn weathers into yl-gy, f, mo.sr, s.R, mo. In, medium to thick poorly bedded, with poorly developed wedge to planar cross-laminated sandstone. Basal boundary is irregular, and grain size decreases slightly upward.
8	1.50	Ss	Generally similar to unit 7 below except finer, massive, and less indurated.
9	4.00	Ss	Lithologically similar to unit 7 below, except slightly coarser (lower half) and contains clay galls in lower part (few are up to about 30 cm long and 4 cm thick). It ranges from poorly bedded to massive to laminated and cross-laminated (small scale troughs in upper part). Uppermost part (30 cm) is highly carbonaceous silty zone.
10	4.20	Ss	Tn-gy weathers into or-gy, f to m, mo. to w.sr, s.R to s.A, mo. to w.In, massive

Appendix B, Section Kpl-5 cont'd

Unit No.	Thickness in Meters	Major Lithology	Description
			sandstone with poorly developed planar to wedge cross-stratification. Lower contact is irregular (erosional), clay galls in lower part, and log cast in upper part. Grain size increases slightly upward but declines in upper part.
11	1.70	Ss-Mud	Gy to br to bl, moderately to highly carbonaceous mudstone interbedded with fine, iron oxide cemented, lenticular sandstones. Lignitic debris is abundant.
12	7.50	Ss	Lithologically similar to unit 10 below. Poorly bedded to massive Ss with poorly developed large scale wedge cross-stratification with tangential interlaminae, clay galls in upper part (some are carbonaceous), grain size decreases gradually upward, irregular lower contact.
13	1.40+	Mud-Hum-Coal	Interbedded br-gy to br, highly carbonaceous mudstone, humate, and coal lenses, forming the dip slope above the cliff-forming Ss of unit 12 below. It grades upward into typical variegated Menefee sequence.

Kpl 46.20 m (unit 2 through unit 10)
Total thickness of measured section is 63.40 m.

Section Kpl-6 (about 2 miles SE of Llaves)

T.25N, R.1W., Sec. 32 (E-SE)

Unit No.	Thickness in Meters	Major Lithology	Description
1	8.25	Sh-Ss	Gy to br-gy, fi to fr, silty shale interbedded with very thinly laminated lenses of very fine silty sandstone. Fine carbonaceous debris exists between laminae; some burrow tubes are present horizontally oriented on upper surfaces of Ss intervals. Some Ss lenses show irregular basal contact; some lenses (at about 7.0m) have wavy basal contact and laminae lying more or less concordantly with it (similar to the hummocky structure described by Harms, 1975).
2	4.05	Ss	Tn weathers to gy-tn, v.f, mo.sr, s.R., m. In, silty sandstone. Laminated in lowermost part, then a zone with megaripples and hummocky type structure (with shallow undulatory basal contact which seems erosional and laminae are generally concordant with it); rest of the unit is either structureless or poorly stratified due to some degree of bioturbation. Few small burrow tubes exist in middle part.
3	1.40	Ss-Sh	Silty shale zone at bottom followed by moderately bioturbated Ss which grades upward to cross-laminated (planar type) and calcite-cemented Ss where mixed, moderately fragmented fossils zone exists. Small wave ripples with average crest orientation of 281^{o} are present near top.
4	1.85	Sh-Ss	Gy to pr-gy, fissile, silty shale interbedded with friable, thin lenses of silty Ss.
5	4.70	Ss	Well developed sandstone interval. Ss is l.gy weathers to tan, v.f., mo.-w.sr, w. to s.R, mo.In, and laminated and cross-laminated; fine carbonaceous material in lower and upper parts, calcite-cemented zones with large concretions, highly fossiliferous zone in lower part with mixed and moderately fragmented fossils, and few burrows (thallasinoides). Cross-stratification is shallow small trough type in lower and middle parts and planar in upper part. Few Fe oxide-rich claystone pebbles exist in middle part.

Appendix B, Section Kpl-6 cont'd

Unit No.	Thickness in Meters	Major Lithology	Description
6	0.60	Sh-Ss	v.f, silty sandstone interbedded with silty shale. Lower part contains fine carbonaceous debris.
7	1.15	Ss	Moderately laminated v.f sandstone with moderately developed megaripples type structure in lower part; upper part is stained by Fe oxide.
8	0.90	Sh	Gy to pr-gy, fr to fi, silty shale. It seems to thin very gradually southward.
9	4.05	Ss	L.gy to tn, v.f to f, mo. to w.sr, w. to s.R, mo.In; poorly laminated in lower part grades into poorly developed small trough x-lamination, bioturbated in middle part, followed by a zone of small trough cross-lamination and calcite-cemented large concretions, and laminated uppermost part with carbonaceous debris. Few burrows (thallasinoides) in concretioned zone.
10	7.20	Ss	Lithologically is similar to unit 9. Lower part is poorly laminated and contains few Fe oxide-rich claystone pebbles, middle part dominated by shallow small trough. Cross-lamination and calcite-cemented large concretions followed by a bioturbated zone, and upper part is laminated to very thinly bedded. Basal contact is irregular.
11	2.45	Ss	Lithologically is generally similar to unit 10 below, except slightly coarser, and contains Fe oxide-cemented concretions (few mm to about 4cm in diameter) and some surface Fe oxide stain. It is characterized by poorly developed very thin to thin, parallel regular bedding.
12	6.90	Ss	Lgy weathers to tn with orangish zones, f, w. to mo.sr, s.R, mo. to w.In fairly porous, moderately very thin to medium bedded with very low angle planar cross-lamin tion (laminae nearly parallel) in upper half. Small Fe oxide-cemented concretions fairly abundant on the surface especially in lower half; a few ophiomorpha tubes in upper part, and poorly preserved

Appendix B, Section Kp1-6 cont'd

Unit No.	Thickness in Meters	Major Lithology	Description
			small ripples at top. Lower contact is irregular. Grain size increases very gradually upward.
13	4.10	Sh	Lower part consists of br mottled with gr-yl, fr, highly carbonaceous, sandy shale interbedded with v.f, fr, muddy very thin Ss lenses. Middle and upper parts are gy-br to gy, generally fi, less carbonaceous silty shale; few siderite nodules in upper part. Carbonaceous material in lower part is irregularly concentrated in thin, non-continuous zones. Unit 13 becomes significantly thinner northward.
14	6.00	Ss	Tn weathers to gy-tn, f, w. to mo.sr, s.R to s.A, fr to mo.In, fair to highly porous cliff-forming sandstone. It has an irregular lower contact, very poorly developed very thick bedding to massive, and very poorly developed large scale wedge to trough type cross-stratification. Carbonaceous debris and plant material exist in thin muddy zone in middle part where teredo structure exists, and some burrow structure (worm tubes?) on basal surface of overlying sandstone. Unit in general is fairly continuous laterally but changes in thickness. No marine evidence.
15	1.65	Ss	The prominent Ss of unit 14 below changes gradually into highly carbonaceous, relatively muddy, poorly thinly bedded to laminated Ss with few teredo structures and claystone galls. Carbonaceous matter is present as irregular lenticular zones (humatic) and/or disseminated through this Ss. Very poorly developed small ripple marks exist in middle laminated zone.
16	2.00	Sh-Ss	Lower half is gy-br, fi, highly carbonaceous, silty shale. It grades into v.f, fr, muddy sandstone with abundant disseminated carbonaceous debris and lignitic and humatic lenses, and root structure. Its thickness varies laterally

Appendix B, Section Kpl-6 cont'd

Unit No.	Thickness in Meters	Major Lithology	Description
			within a few tens of meters.
17	6.85	Ss	Lithologically is similar to unit [illegible] below but lacking carbonaceous debris except in uppermost part. Its basal contact is a shallow, slightly irregular trough shaped; poorly developed large scale wedge type cross-stratification in lower part, and moderately developed large trough type cross-stratification in upper part. It grades laterally (within [illegible] meters) into laminated and very thinly bedded, silty Ss with some small, nearly symmetrical ripple marks with average crest orientation of about [illegible]° and current direction seems to be approximately N20°E.
18	1.00+	Hum-Clys-Coal	The prominent Ss of unit 17 is overlain by a low surface-forming sequence of carbonaceous claystone, humate, and lenticular coal zones intermingling with each other. The sequence continues upward in a repetitive manner to the typical Menefee sequence with lenticular channel Ss bodies intertonguing with the claystone, humate and coal intervals.

Kpl 47.00m (unit 2 through unit 15)

Total thickness of measured section is 65.00 m.

Section Kpl-7 (near San Luis)

T.17N., R.2W., Sec. 21 (E-NW)

it No.	Thickness in Meters	Major Lithology	Description
1	10.30	Sh-SS	Gy to br-gy to pr-gy, fi, silty Sh interbedded and intermixed with l.gy, v.f, p. sr, s.R, fr, muddy Ss. Ss intervals are generally lenticular with irregular (sometimes scour shaped) and sharp basal contacts, and regular and sharp to slightly gradational upper contact. Small burrow tubes and few trails are usually present on bedding surfaces. Intermixing of lithology by organisms is well displayed in several sandy zones.
2	3.85	Ss-Sh	A few centimeters to about 85cm thick Ss lenses interbedded with l.gy to br-gy, fi, silty Sh. The relatively thick Ss lenses show good irregular and scour type basal contacts with load casts in some of them (e.g., see Fig. 5); upper contact is either gradational (lower lens) or sharp (middle and upper lenses). Burrows are relatively abundant in some sandy zones, but thick Ss lenses are generally devoid of burrows except near top; some sand-filled burrows may extend down through a shale zone from overlying sandy interval. Some fine carbonaceous material exists above lower thick Ss lens.
3	1.15	Ss	Well developed, laterally extensive, small ledge-forming Ss interval. Ss is tn to gy weathers to tn, v.f to f, mo.sr, s.R, mo.In Ss. Wavy bedding, most likely due to poorly developed megaripples, is abundant, upper part is thinly laminated, and some burrow tubes (thalassinoides?).
4	3.70	Sh-Ss	Gy to br-gy, fi to fr, silty Sh interbedded with tn, v.f, fr, v.thin to thin laminated, carbonaceous, silty, lenticular Ss zones.
5	1.35	Ss-Sh	L.gy, v.f, p. to mo. sr, fr, bioturbated Ss grades into laminated, with poorly developed small trough cross-laminated Ss with some carbonaceous debris between laminae. Ss interval grades upward into mudstone zone.

Appendix B, Section Kp1-7 cont'd

Unit No.	Thickness in Meters	Major Lithology	Description
6	1.40	Ss	L.gy weathers to tn, f, mo.sr, s.R, mo. In, laterally extensive Ss. Lower part is laminated and contains some horizontally to slightly inclined branched burrow tubes (thalassinoides), middle part is massive and contains some small Fe-rich claystone pebbles, and upper part is laminated and contains moderately developed megaripples.
7	1.80	Ss-Sh	Lower and middle parts consist of v.f, p. sr, fr Ss interbedded and intermixed with mudstone. Upper part consists of f, mo. sr, mo.In, laminated and cross-laminated (planar type) Ss; it has an irregular (erosional?) contact with underlying muddy Ss.
8	0.95	Ss-Sh	Variegated in color (tn, br to yl-gy, l.gy), v.f, p.sr, fr, very thinly bedded to laminated Ss interbedded with very thin mudstone zones. Some carbonaceous debris exists, and some poorly developed, small wave ripple marks are present.
	3.20	Ss	Basal part is very thin to thinly bedded sandstone, followed by structureless Ss, then muddy Ss zone with few small scale ripple marks. Middle part consists of well developed very thin to thin beds of Ss with some ophiomorpha burrows in its lower part (mostly horizontally to slightly inclined oriented, some are branched). Upper part is poorly developed medium to thick bedded Ss with some vertically oriented ophiomorpha burrows in lower part and small iron-rich claystone pebbles in middle part. Planar, low angle, cross-stratification exists in middle and upper parts. Some symmetrical ripple marks in lower middle part have flat topped crests oriented from 296^{o} to 307^{o}, wave length of about 15cm, and amplitude of 1 to 2cm. Ss is, except for the muddy zone, tn weathers to or-gy, f, mo. to w.sr, s.R., and mo. to w. In.
	4.30	Ss	Tn weathers to or-gy, f to m, mo. to w.sr, s.R to S.A, mo. to w. In, generally massive Ss with moderately to poorly developed

pendix B, Section Kpl-7 cont'd.

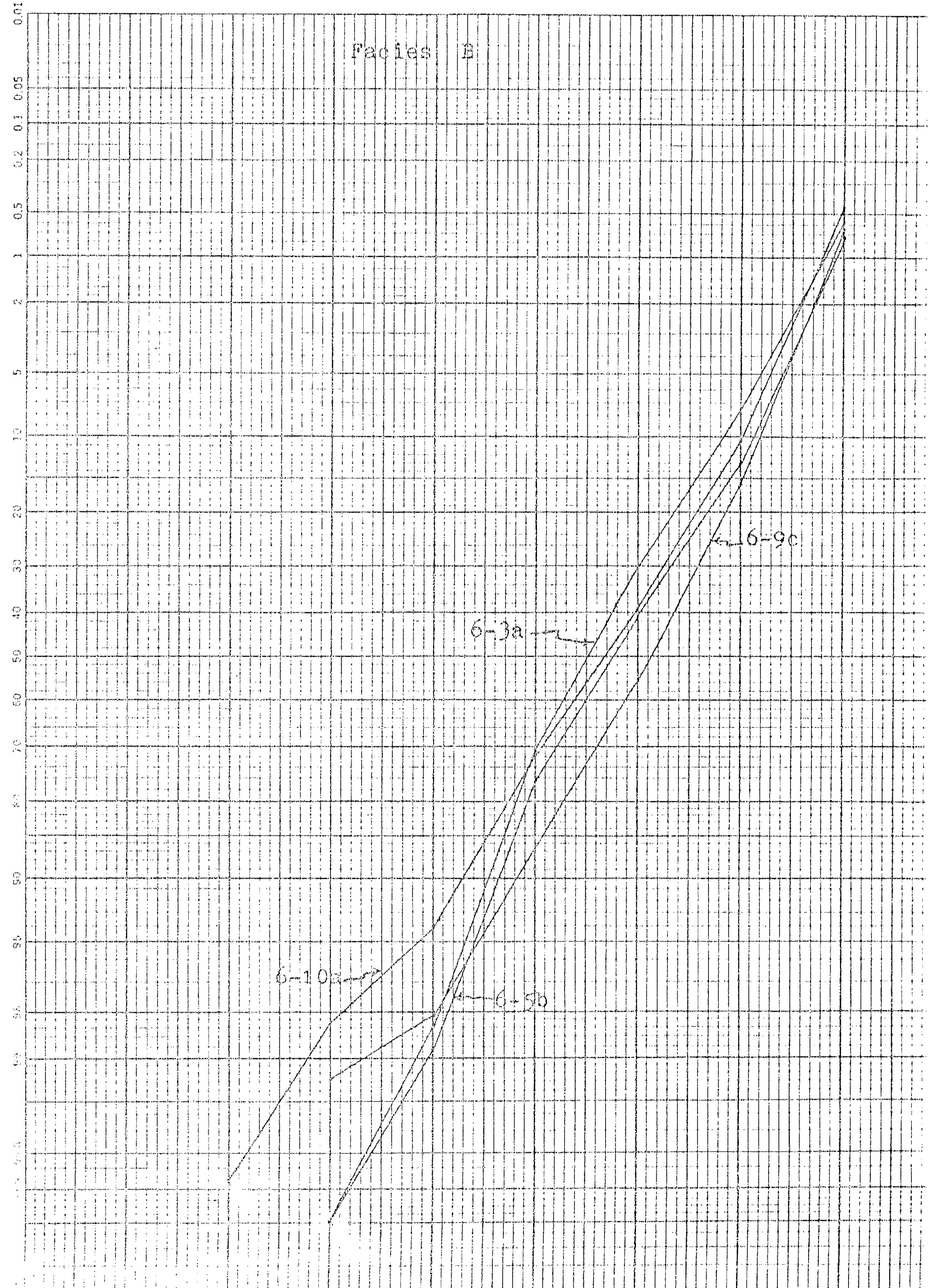
No.	Thickness in Meters	Major Lithology	Description
			large scale wedge cross-stratification. It has an irregular lower contact and a few small claystone galls in basal part. It shows a gradual upward increase in grain size, and contains no fossils or burrows.
	1.80	Ss	Lithologically similar to unit 10 below, except slightly coarser. It has moderately developed large scale trough cross-stratification with inter-laminae being highly tangential to almost concordant with basal set boundary. It is topped by a flat surface but few tens of meters to the SW is overlain by humate, coal lenses, and carbonaceous claystone.

23.50 m (unit 2 through unit 11).

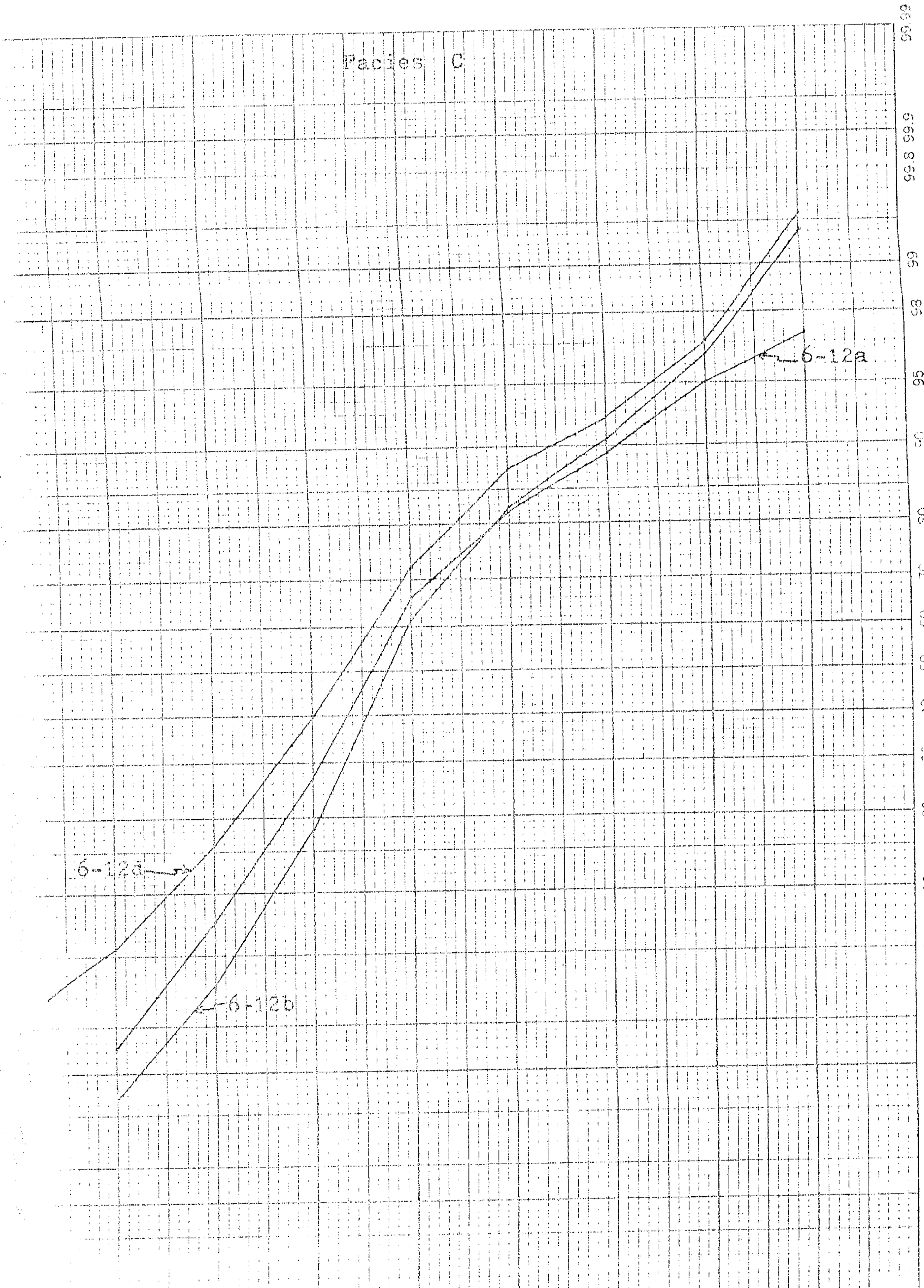
l thickness of measured section is 33.80m.

APPENDIX C

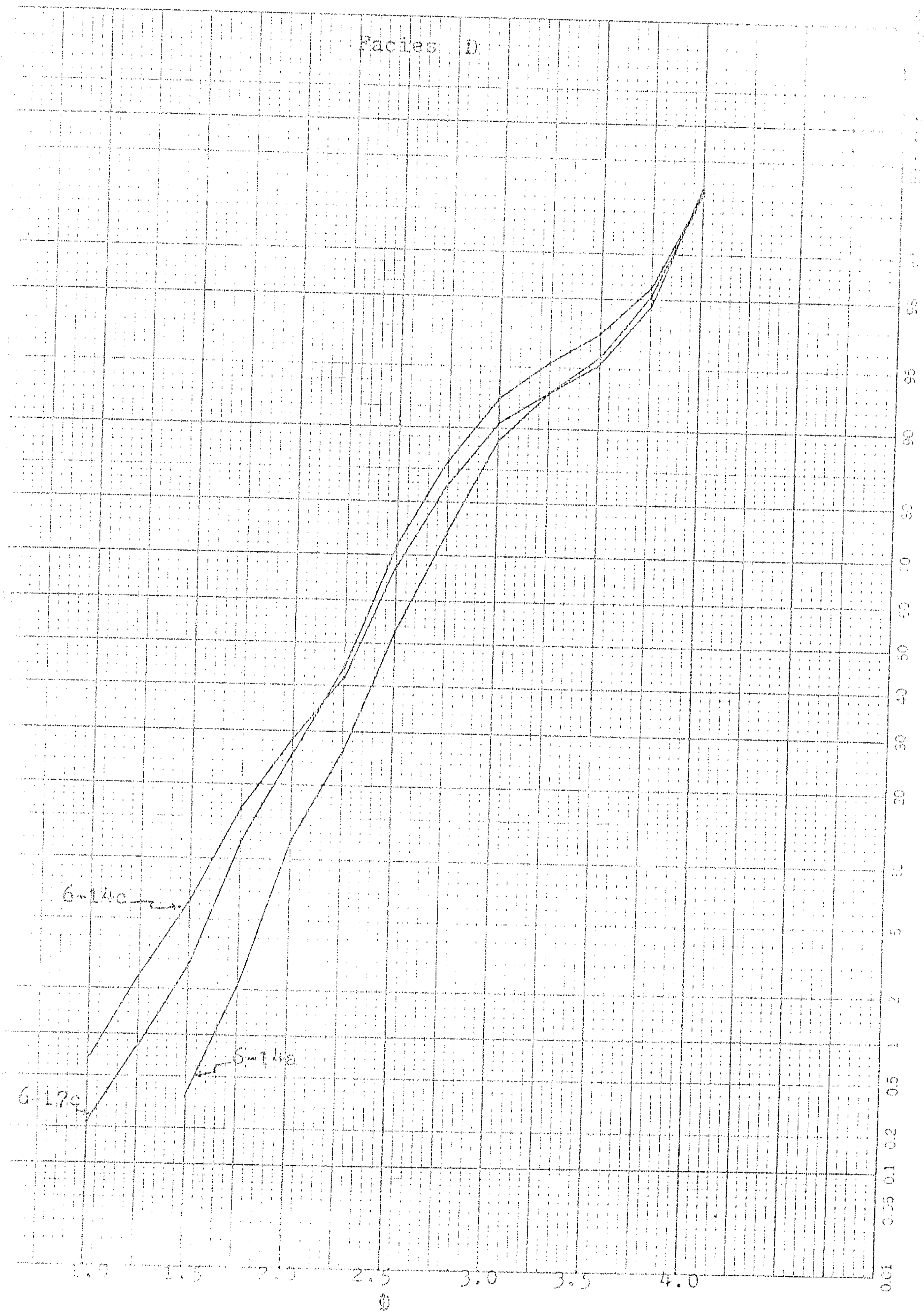
I. Examples of cumulative curves of grain-size distributions



Facies B
6-3a
6-9c
6-10a
6-5b
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
2.5
2.75
3.0
3.25
3.5
3.75
4.0
Φ

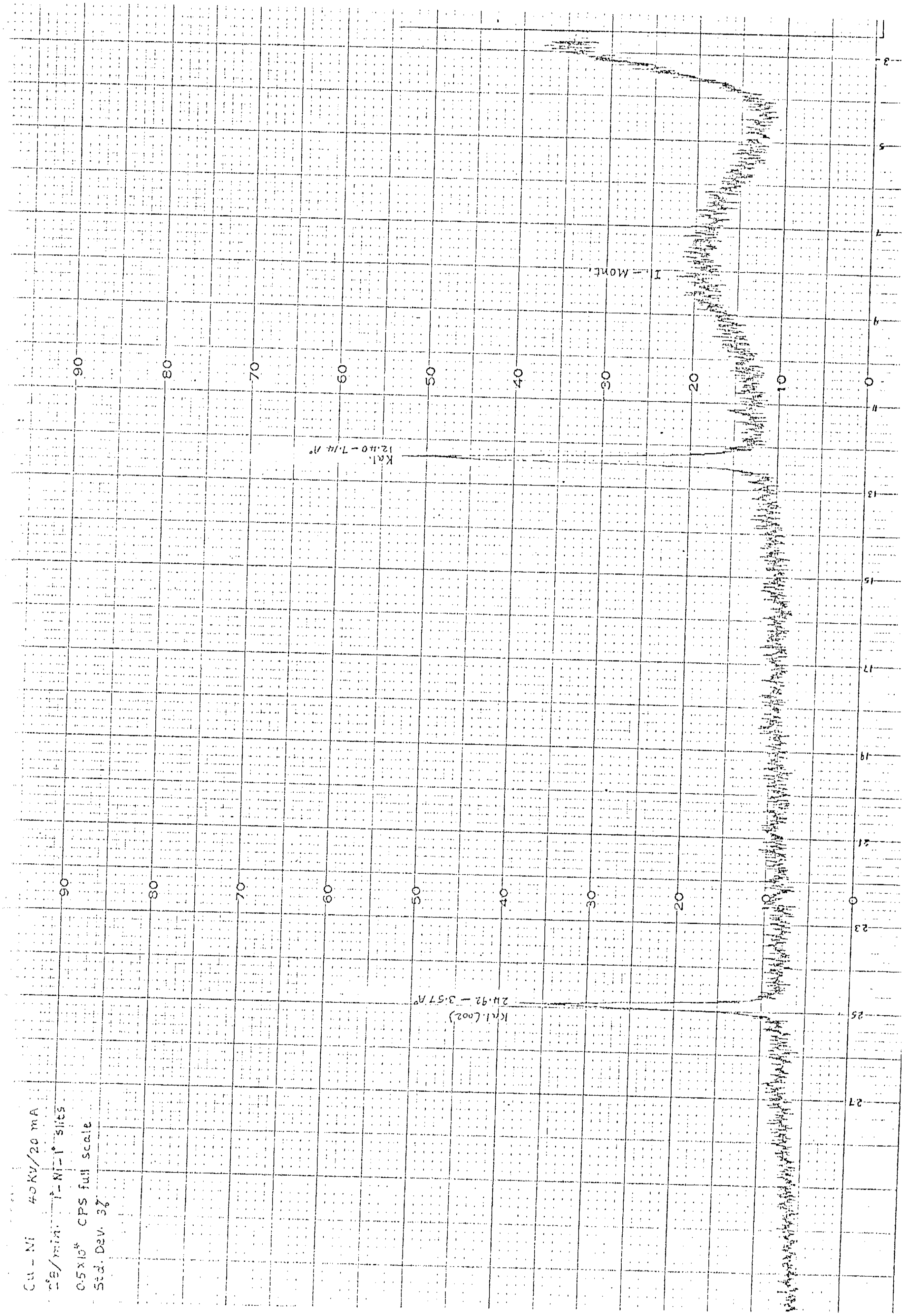


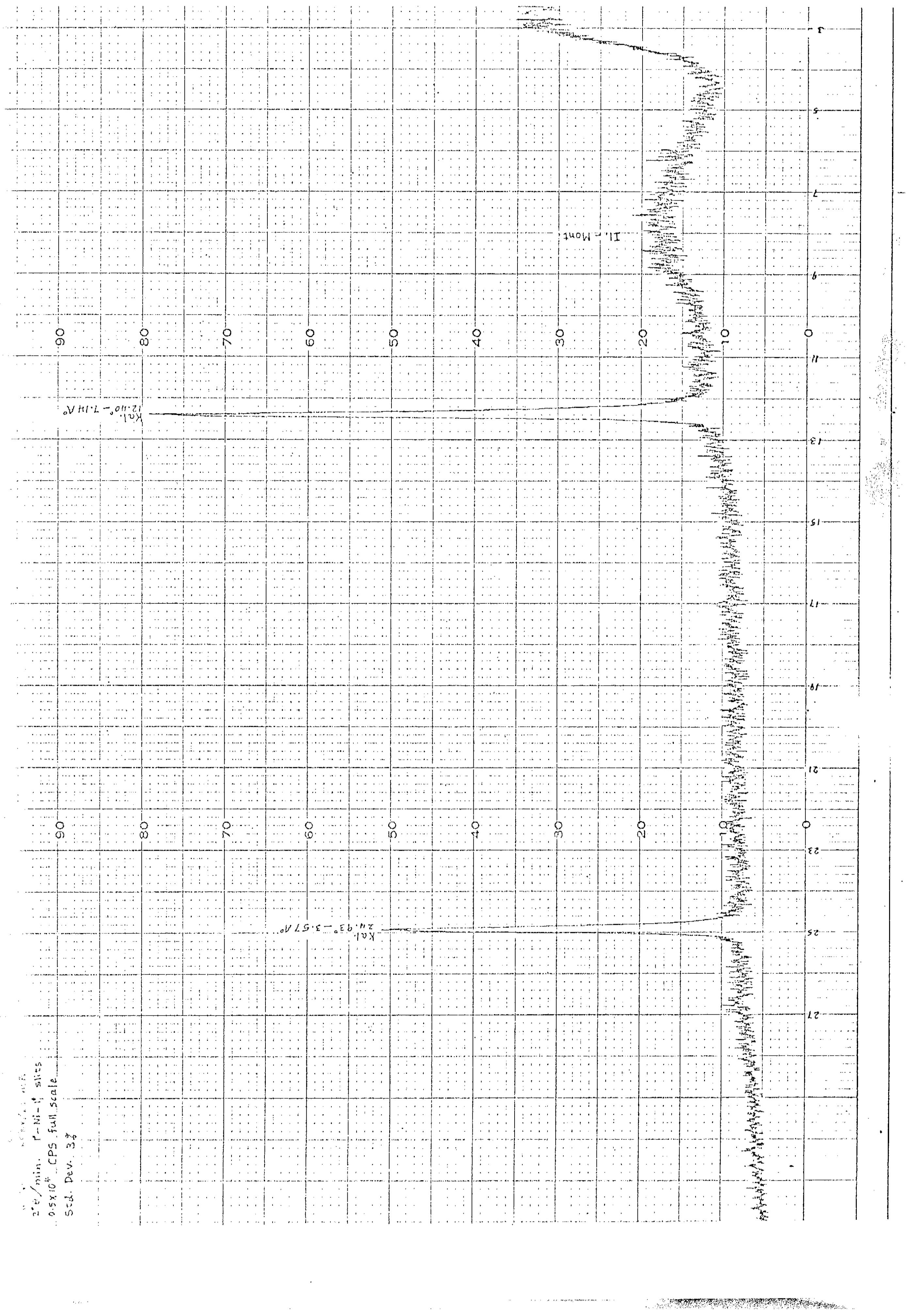
Facies C
6-12a
6-12d
6-12b
2.25
2.5
2.75
3.0
3.25
3.5
3.75
4.0
φ
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05

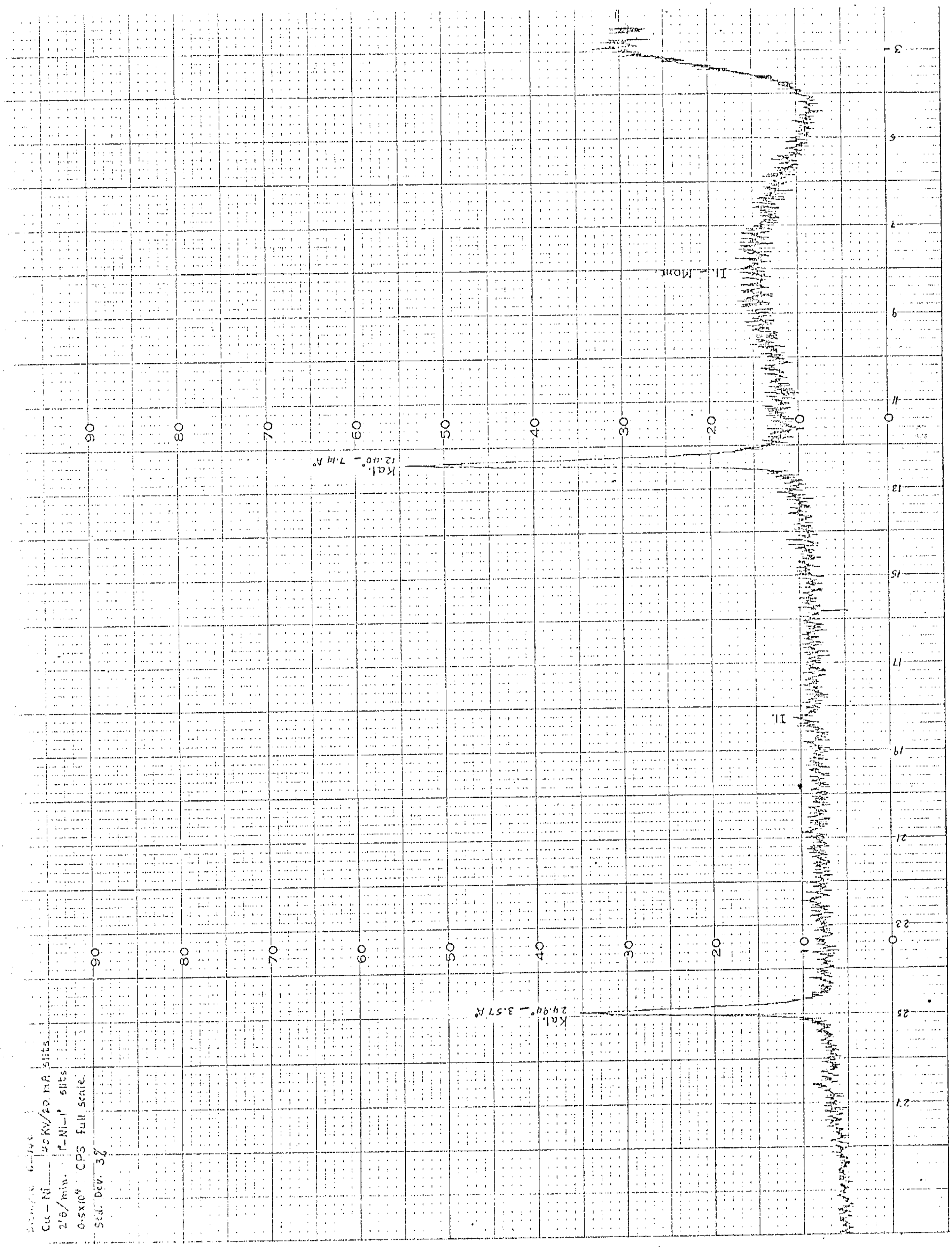

Facies D
6-14c
6-17c
6-14a
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Ø
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99

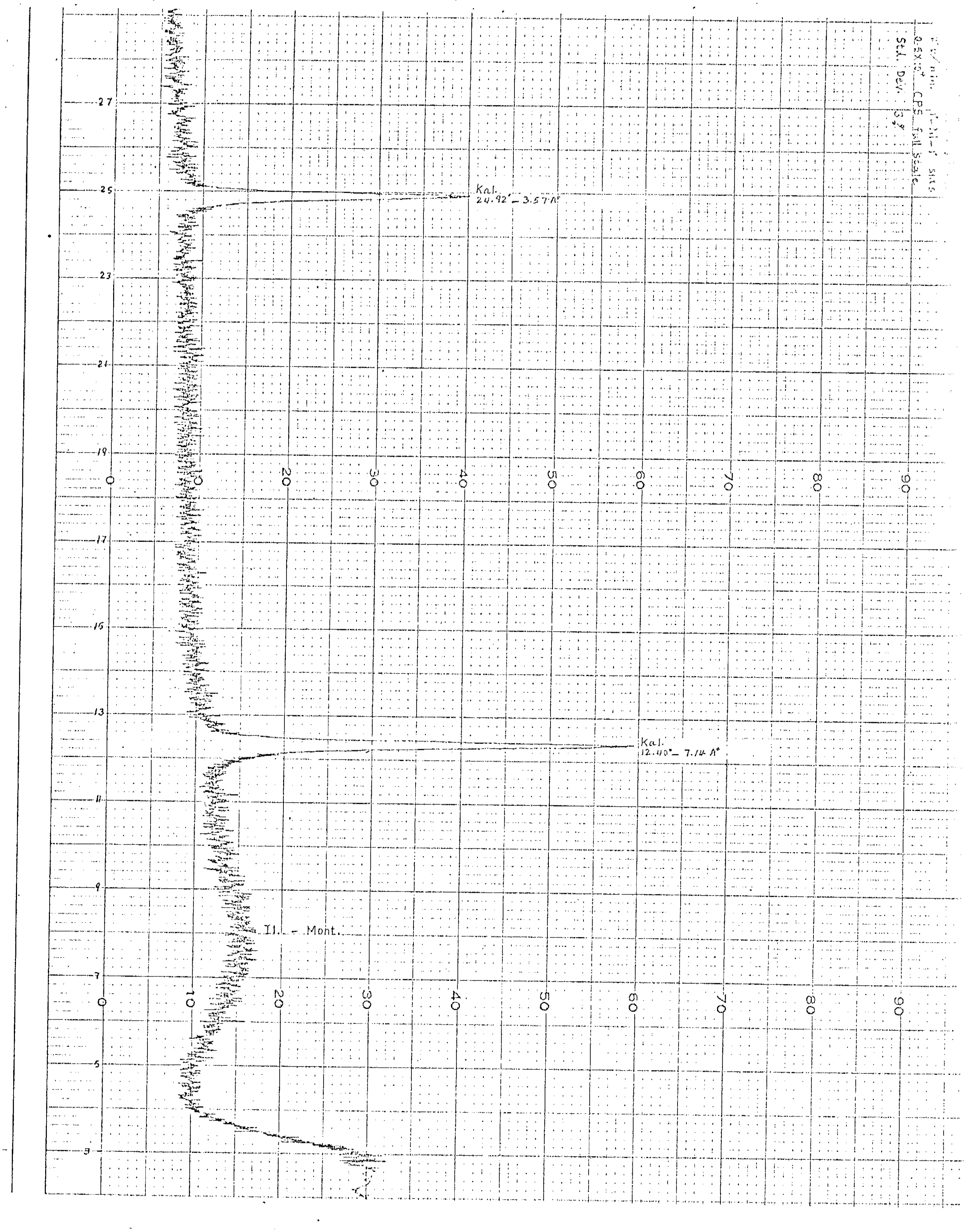
Appendix C cont'd.

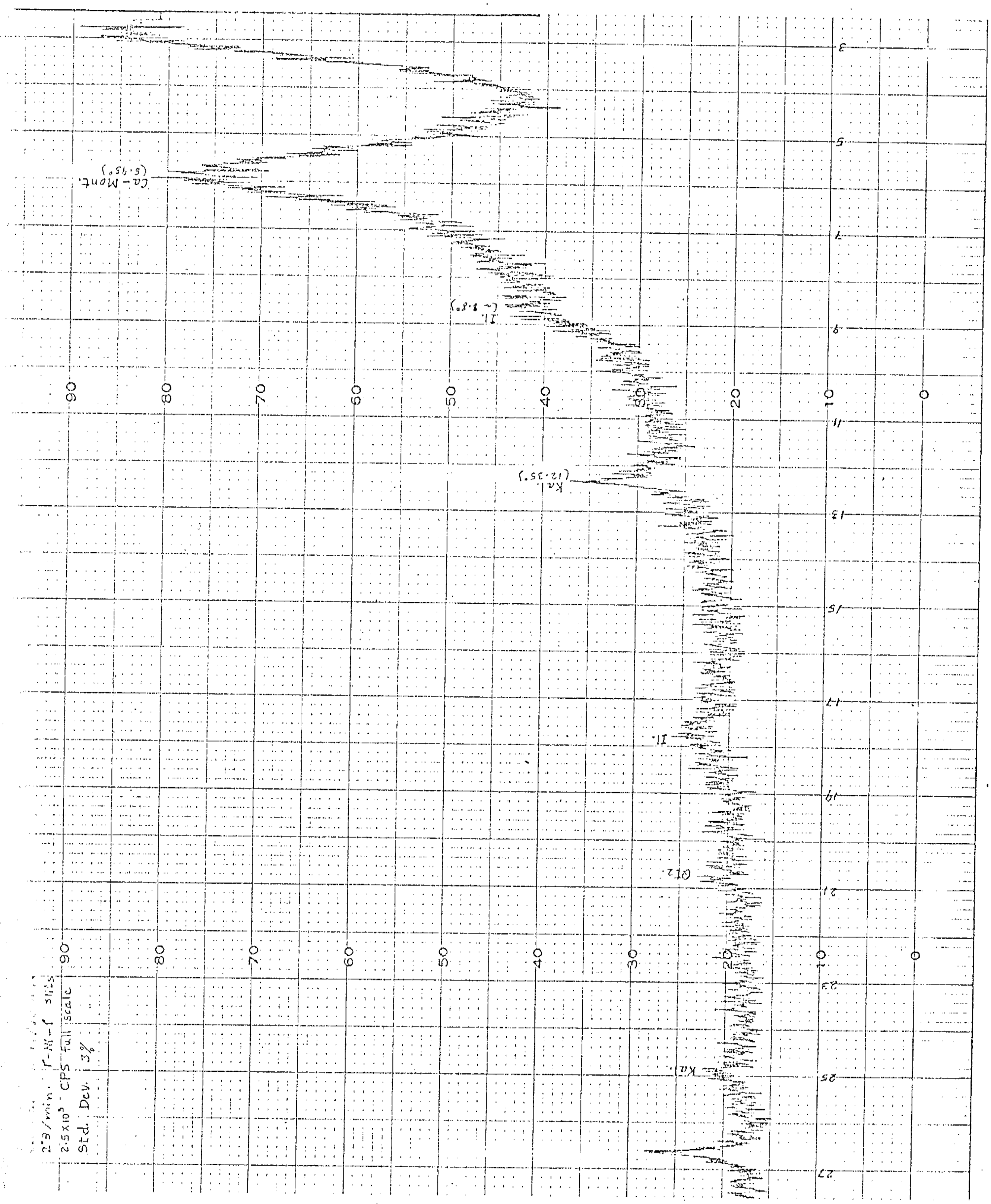
II. Examples of X-ray patterns of clay mineralogy analysis. These patterns were used for Figure 39.

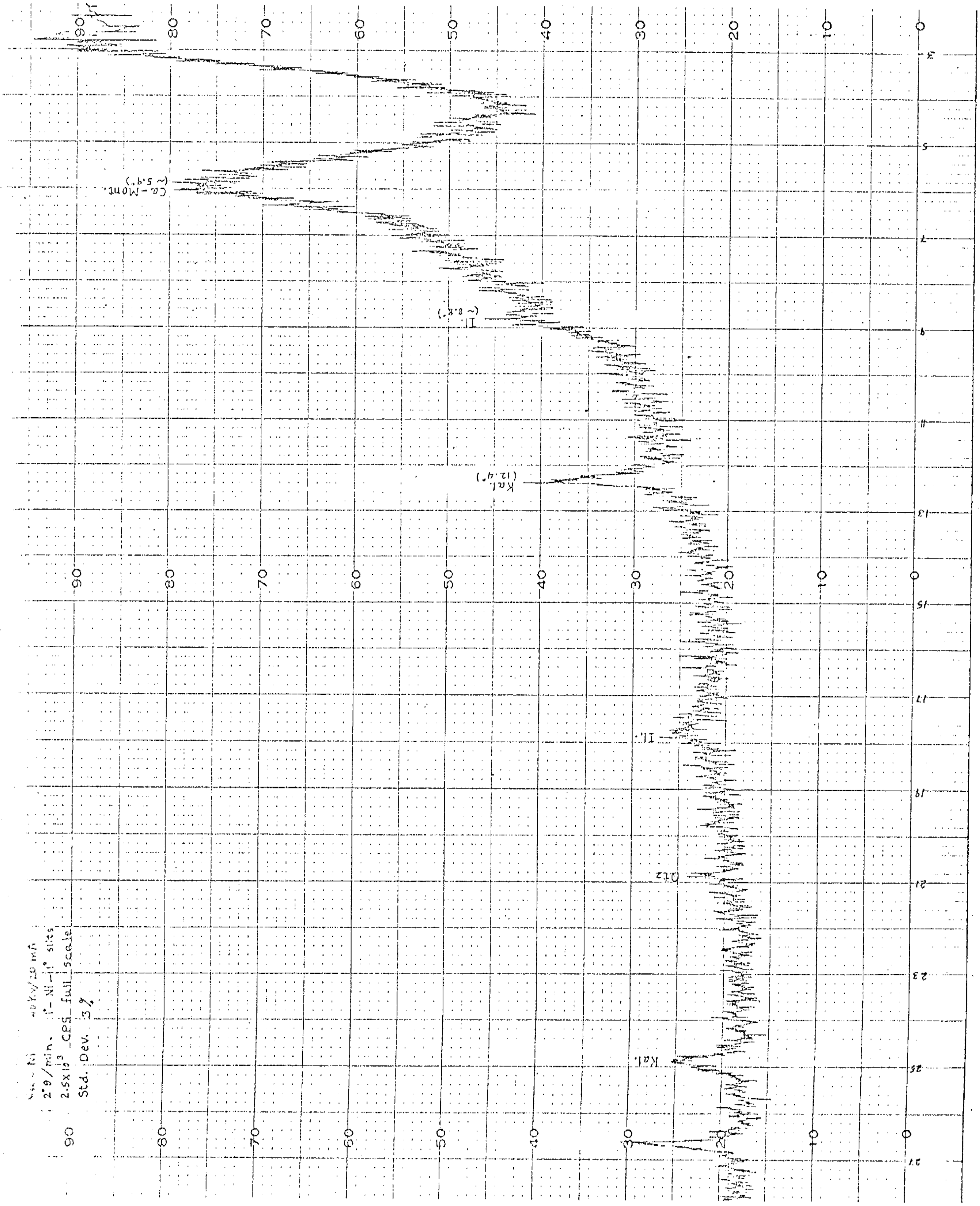

Cu - Ni 40Kv/20 mA
2°θ/min 1°-Ni-1° slits
0.5x10^4 CPS full scale
Std. Dev. 3%
I - Mont.
Kal.
12.40 - 7.14 Å
Kal. (002)
24.92 - 3.57 Å

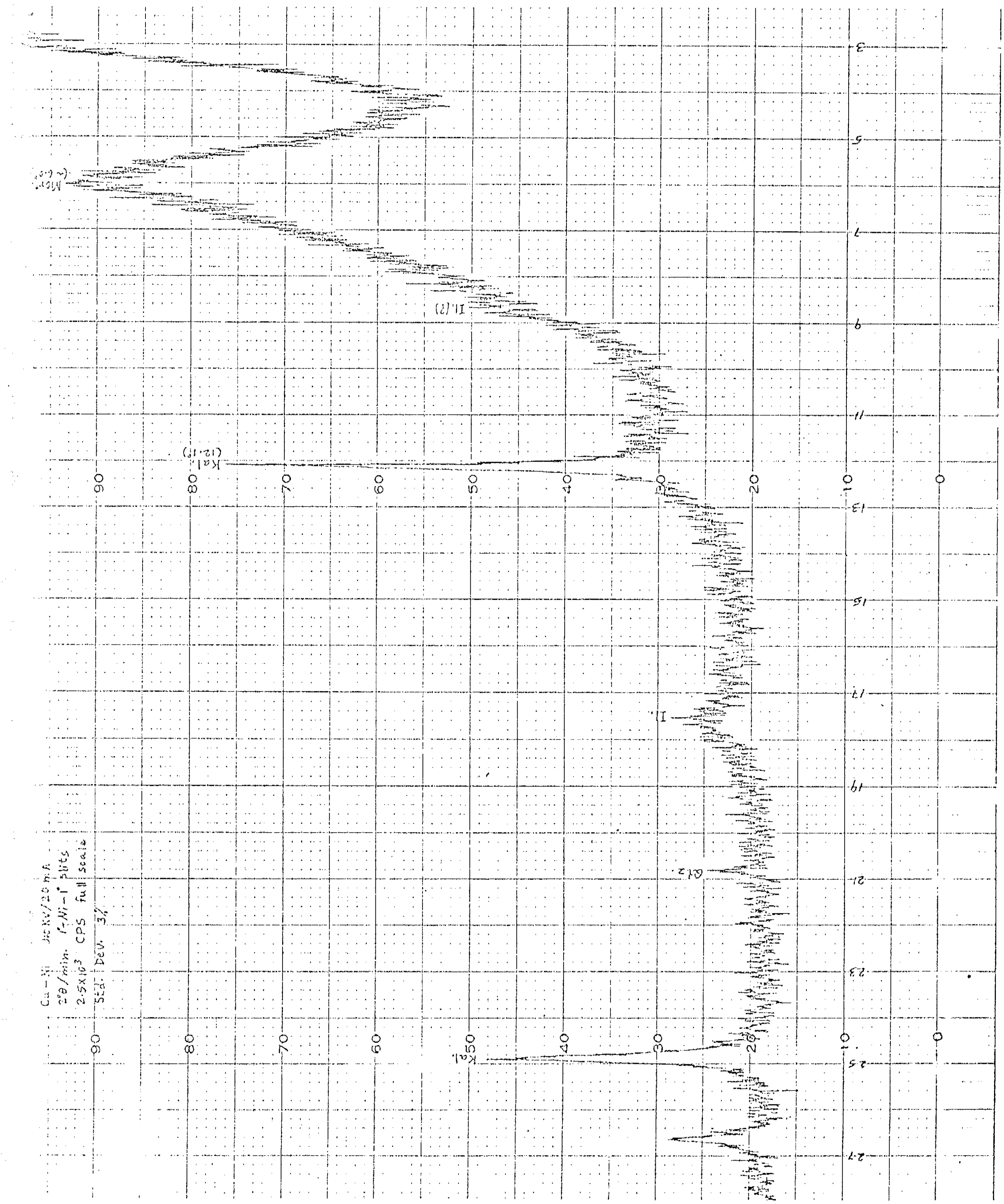

Il.-Mont
Kal.
12.40° - 7.14 A°
Kal.
24.93° - 3.57 A°
CPS full scale
Std. Dev.

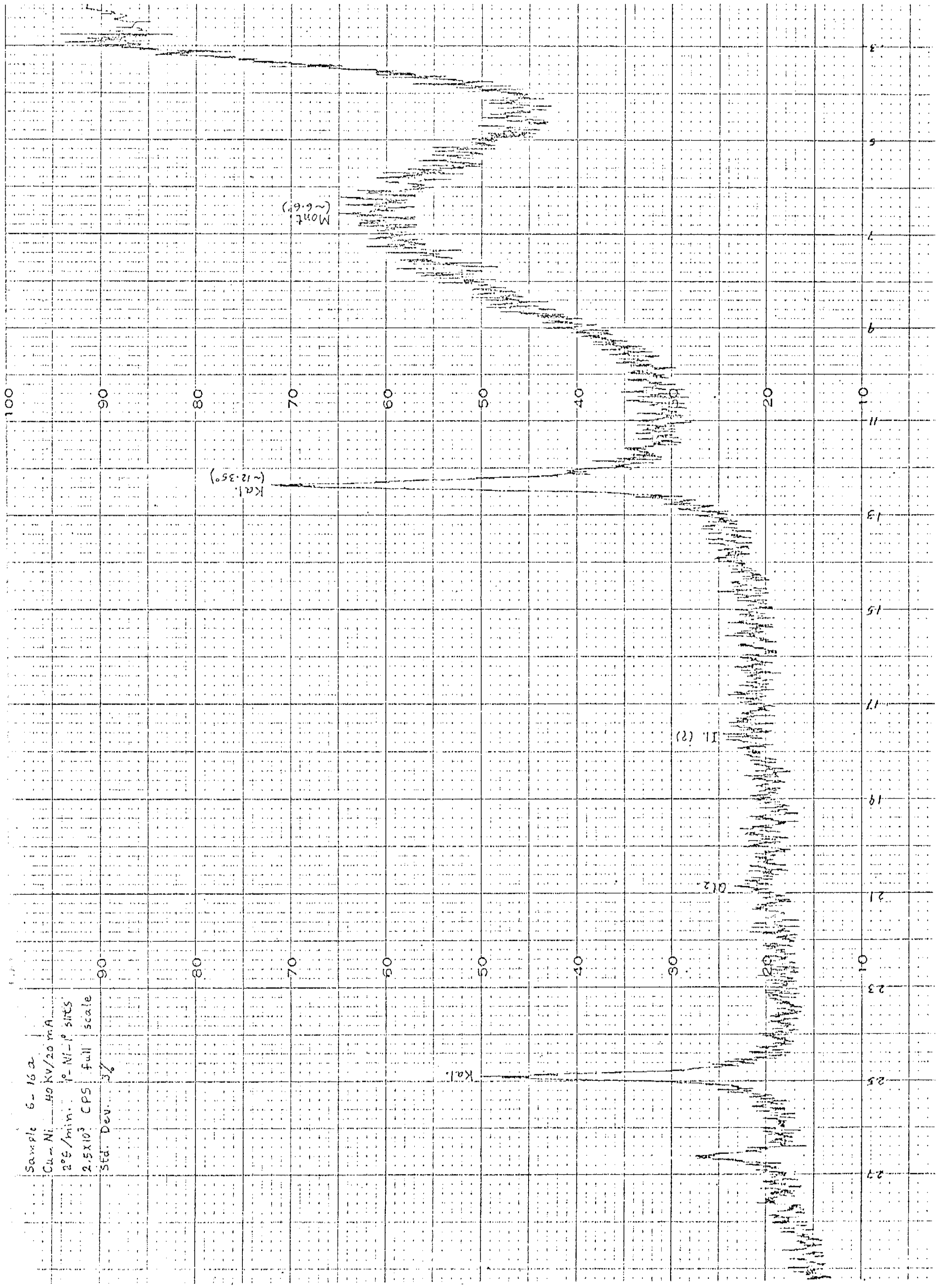

Cu – Ni
40 KV/20 mA slits
2°θ/min. 1°–Ni–1° slits
0.5x10⁴ CPS full scale
Std. Dev. 3σ
Kal. 12.40° – 7.14 Å
Kal. 24.94° – 3.57 Å
Il.-Mont.
Il.


Kal.
24.92° – 3.57 Å
Kal.
12.40° – 7.14 Å
Il. - Mont.
0 10 20 30 40 50 60 70 80 90
3 5 7 9 11 13 15 17 19 21 23 25 27


Ca-Mont. (5.95°)
Il. (~8.8°)
Kal. (12.35°)
Il.
Qtz.
Ka.
2.5x10³ CPS full scale
Std. Dev. 3%


Ca.-Mont. (~ 5.4°)
Il. (~ 8.8°)
Kal. (12.4°)
Il.
Qtz
Kal.
Std. Dev. 3%


Cu-Ni 30 KV/20 mA
2°θ/min. 1°-Ni-1° slits
2.5x10³ CPS full scale
Std. Dev. 3%
Kα1
Kα1
Qtz
I


Sample 6-16a
Cu-Ni 40 kv/20 mA
2°θ/min. 1°-Ni-1° slits
2.5x10³ CPS full scale
Std. Dev.
Mont (~6.6°)
Kal. (~12.35°)
Il. (?)
Qtz
Kal.

APPENDIX D

Table 7. Subsurface data from well data cards, at New Mexico Bureau of Mines, used for isopach map (Figure 40) and structure contour map (Figure 41).

No.*	Location Sec.	T.N.	R.W.	Thickness of Kpl ft	Elevation on top of Kpl	No.	Location Sec.	T.N.	R.W.	Thickness of Kpl ft	Elevation on top of Kpl
1	22	17	3	130	6237	25	20	18	10	169	6039
2	29	17	4	145	5838	26	16	19	3	119	4651
3	17	17	6	150	5996	27	22	19	3	145	5114
4	34	17	6	154	6012	28	6	19	4	85	4440
5	3	17	7	110	5686	29	7	19	4	145	4441
6	8	17	7	196	5823	30	7	19	5	135	4552
7	28	17	7	208	5995	31	26	19	5	111	4913
8	1	17	8	242	6129	32	31	19	5	116	4904
9	26	17	8	194	6572	33	14	19	6	84	4757
10	1	17	9	220	6591	34	31	19	6	116	5069
11	18	17	9	216	6502	35	14	19	7	113	4877
12	23	17	9	207	6530	36	26	19	7	92	4706
13	32	17	9	160	6761	37	1	19	10	163	5120
14	26	18	3	108	5623	38	16	19	10	130	5347
15	20	18	4	76	5010	39	25	19	10	154	5518
16	22	18	4	72	5118	40	29	19	10	145	5617
17	20	18	5	100	5180	41	13	20	3	180	4381
18	25	18	5	125	4665	42	27	20	3	207	4169
19	30	18	7	100	5690	43	23	20	5	120	3960
20	28	18	8	165	6145	44	12	20	6	153	3735
21	31	18	8	214	6442	45	16	20	6	178	4074
22	11	18	9	140	5980	46	34	20	7	115	4706
23	21	18	9	126	6088	47	35	20	7	132	4624
24	14	18	10	228	6051	48	1	20	8	108	4155

*Numbers do not refer to well numbers on data cards.

Appendix D, Table 7 cont'd.

No.	Location			Thick-ness of Kpl ft	Eleva-tion on top of Kpl	No.	Location			Thick-ness of Kpl ft	Eleva-tion on top of Kpl
	Sec.	T.N.	R.W.				Sec.	T.N.	R.W.		
49	28	20	8	120	4844	79	19	22	7	140	3330
50	20	20	9	115	4886	80	23	22	7	174	3263
51	28	20	9	105	4878	81	35	22	7	140	3331
52	6	20	10	144		82	6	22	8	139	3372
53	29	20	10	110	5097	83	10	22	8	140	3330
54	23	21	2	240	3335	84	17	22	9	179	3723
55	6	21	4	164	3148	85	23	22	9	133	3734
56	14	21	4	186	3244	86	9	22	10	143	3702
57	3	21	5	220	3293	87	26	22	10	144	3932
58	13	21	5	213	3388	88	18	23	2	184	2149
59	35	21	5	136	3548	89	31	23	2	176	2366
60	10	21	6	150	3513	90	33	23	3	228	2349
61	32	21	6	176	3789	91	6	23	4	185	-
62	14	21	7	130	3656	92	21	23	4	182	2412
63	20	21	7	123	3889	93	33	23	4	210	2567
64	13	21	8	121	3917	94	4	23	5	200	2344
65	22	21	8	111	4019	95	21	23	5	205	2547
66	32	21	8	131	4216	96	36	23	5	207	2653
67	1	21	9	145	3946	97	2	23	6	209	2361
68	12	21	9	109	4051	98	31	23	6	145	2867
69	33	21	9	120	4482	99	35	23	6	186	2791
70	22	21	11	136	4509	100	15	23	7	213	2804
71	21	22	2	147	2453	101	31	23	7	145	3179
72	32	22	2	165	2660	102	12	23	8	154	2821
73	25	22	3	220	2633	103	16	23	8	183	3017
74	8	22	4	188	2931	104	30	23	8	131	3322
75	28	22	4	215	2978	105	14	23	9	118	3189
76	7	22	5	200	2859	106	25	23	10	99	3434
77	16	22	5	184	2998	107	14	23	11	150	3395
78	10	22	6	131	2999	108	26	23	11	153	3535

Appendix D, Table 7 cont'd.

No.	Location Sec.	T.N.	R.W.	Thickness of Kpl ft	Elevation on top of Kpl	No.	Location Sec.	T.N.	R.W.	Thickness of Kpl ft	Elevation on top of Kpl
109	14	24	1	184	2161	139	35	25	8	174	2342
110	24	24	1	181	2387	140	2	25	10	147	2216
111	21	24	2	170	1949	141	9	25	10	241	2133
112	1	24	4	147	1638	142	30	25	10	205	2720
113	16	24	4	198	1819	143	35	25	10	157	2675
114	30	24	4	200	2148	144	8	26	2	158	1344
115	5	24	5	184	1925	145	16	26	2	170	1346
116	29	24	5	210	2230	146	1	26	3	140	1275
117	3	24	6	205	2095	147	7	26	3	160	1163
118	24	24	6	204	2268	148	34	26	3	177	1305
119	11	24	7	205	2232	149	8	26	4	157	1138
120	19	24	7	179	2515	150	27	26	4	128	1290
121	26	24	7	231	2496	151	36	26	5	147	1378
122	34	24	8	222	2668	152	32	26	6	139	1616
123	11	24	9	132	2559	153	6	26	6	150	1360
124	22	24	9	140	2683	154	10	26	7	129	1551
125	33	24	9	160	3103	155	19	26	7	185	1813
126	23	14	10	130	2882	156	29	26	8	–	1896
127	18	24	10	128	2924	157	11	26	8	140	1741
128	11	25	1	199	2422	158	22	26	9	217	1966
129	17	25	3	176	1373	159	31	26	9	170	2212
130	20	25	4	181	1588	160	27	26	10	178	2133
131	27	25	4	184	1530	161	16	27	2	150	1399
132	14	25	5	188	1501	162	11	27	3	166	1091
133	21	25	5	179	1675	163	27	27	3	164	1078
134	35	25	5	180	1774	164	14	27	4	159	940
135	7	25	6	113	1794	165	30	27	4	183	1028
136	28	25	6	122	1967	166	12	27	5	135	959
137	15	25	8	156	1598	167	21	27	5	136	1068
138	20	25	8	180	2195	168	35	27	5	140	1052

Appendix D, Table 7 cont'd

No.	Location Sec.	T.N.	R.W.	Thickness of Kpl ft	Elevation on top of Kpl
169	9	27	6	185	1139
170	19	27	6	139	1232
171	26	27	6	186	1199
172	19	27	7	125	1388
173	16	27	8	125	1576
174	30	27	8	183	1727
175	1	27	9	175	1621
176	20	27	9	118	1807
177	34	27	9	117	1864
178	6	27	10	135	1710
179	16	27	10	255	1731
180	33	27	10	126	1901
181	19	18	11	165	6188
182	27	18	11	142	6354
183	6	18	12	103	6163
184	8	18	12	115	6321
185	32	19	12	125	5958
186	16	20	11	117	5014
187	25	20	11	162	4987
188	29	20	11	190	5222
189	9	20	13	245	5055
190	18	20	13	229	5123
191	24	20	13	133	5251
192	35	20	13	123	5329
193	7	21	13	83	4389
194	1	21	14	130	4237
195	10	22	14	158	3973
196	23	23	12	186	3614
197	35	23	12	190	3743
198	22	23	14	196	3615
199	3	24	11	174	2892
200	14	24	11	120	2990
201	29	24	11	171	3258
202	4	24	12	185	2991
203	21	24	12	155	2831
204	10	24	13	159	2995
205	20	24	13	146	3197
206	5	24	17	251	3288
207	21	24	17	272	3515
208	7	25	11	215	2658
209	15	25	11	215	2704
210	26	25	11	197	2790
211	3	25	12	188	2616
212	7	25	12	172	2616
213	23	25	12	193	2744
214	29	25	12	140	2806
215	17	25	13	130	2687
216	24	25	13	150	2703
217	3	25	14	166	2627
218	4	25	16	150	2946
219	28	25	16	175	3072
220	2	26	11	233	2106
221	17	26	11	245	2241
222	24	26	11	265	2226
223	32	26	11	245	2523
224	5	26	12	263	2239
225	7	26	13	-	2346
226	20	26	13	174	2422
227	21	26	13	180	2415
228	33	26	13	140	2495

Appendix D, Table 7 cont'd

No.	Location Sec.	T.N.	R.W.	Thick-ness of Kpl ft	Eleva-tion on top of Kpl	No.	Location Sec.	T.N.	R.W.	Thick-ness of Kpl ft	Eleva-tion on top of Kpl
229	10	26	14	150	2384	260	9	28	6	168	943
230	13	26	14	178	2420	261	23	28	6	140	1031
231	15	26	14	-	2450	262	31	28	6	151	1165
232	1	26	15	159	2375	263	11	28	7	135	1070
233	14	26	15	150	2483	264	17	28	7	166	1187
234	24	26	15	137	2596	265	25	28	7	157	1112
235	36	26	16	90	2696	266	32	28	7	172	1275
236	11	26	17	218	3015	267	7	28	8	150	1338
237	17	27	11	-	1953	268	15	28	8	153	1338
238	23	27	11	322	1946	269	33	28	8	136	1442
239	1	27	12	295	1822	270	11	28	9	184	1370
240	16	27	12	324	2017	271	20	28	9	-	1572
241	26	27	12	284	2023	272	34	28	9	165	1610
242	31	27	12	230	2159	273	10	28	10	305	1486
243	1	27	13	308	2000	274	18	28	10	-	1580
244	8	27	13	252	2058	275	23	28	10	300	1578
245	15	27	13	247	2084	276	11	28	11	340	1559
246	31	27	13	201	2286	277	20	28	11	320	1668
247	35	27	13	-	2208	278	26	28	11	330	1712
248	4	27	14	262	2209	279	17	28	12	251	1693
249	31	27	14	171	2370	280	21	28	12	261	1747
250	9	27	15	171	2360	281	26	28	12	271	1712
251	33	27	15	180	2446	282	16	28	13	285	1880
252	9	27	16	181	2718	283	24	28	13	268	1841
253	1	28	1	172	4997	284	11	28	14	295	2057
254	3	28	2	184	1336	285	30	28	14	239	2241
255	21	28	3	154	1023	286	27	28	14	299	2091
256	7	28	4	182	862	287	11	28	15	200	2389
257	29	28	4	179	903	288	13	28	15	218	2330
258	10	28	5	144	858	289	26	28	15	241	2429
259	27	28	5	128	968	290	13	28	16	198	2883

Appendix D, Table 7 cont'd

No.	Location Sec.	T.N.	R.W.	Thick-ness of Kpl ft	Eleva-tion on top of Kpl	No.	Location Sec.	R.N.	R.W.	Thick-ness of Kpl ft	Eleva-tion on top of Kpl
291	25	29	3	153	1156	322	31	29	11	330	1563
292	29	29	3	-	1070	323	1	29	12	325	1496
293	7	29	4	130	904	324	19	29	12	328	1675
294	22	29	4	197	876	325	22	29	12	332	1604
295	31	29	4	197	876	326	2	29	13	350	1643
296	3	29	5	130	860	327	8	29	13	290	1715
297	23	29	5	136	906	328	35	29	13	273	1696
298	2	29	6	158	912	329	17	29	14	283	2139
299	6	29	6	-	838	330	25	29	14	274	2195
300	16	29	6	156	962	331	34	29	14	250	1981
301	25	29	6	175	924	332	3	29	15	258	2466
302	32	29	6	175	992	333	9	29	15	-	2620
303	10	29	7	131	978	334	12	29	15	283	2230
304	19	29	7	-	1126	335	34	29	15	281	2383
305	27	29	7	180	1052	336	1	29	16	211	2764
306	36	29	7	162	1006	337	10	29	16	238	3037
307	1	29	8	144	1060	338	23	29	16	226	2824
308	8	29	8	123	1151	339	28	30	1	113	5808
309	23	29	8	134	1142	340	1	30	5	162	792
310	34	29	8	-	1225	341	18	30	5	174	823
311	4	29	9	153	1160	342	23	30	5	160	848
312	18	29	9	-	1286	343	4	30	6	172	814
313	21	29	9	148	1351	344	14	30	6	190	831
314	24	29	9	165	1259	345	19	30	6	140	863
315	32	29	9	-	1373	346	28	30	6	160	892
316	16	29	10	225	1414	347	5	30	7	190	898
317	30	29	10	350	1456	348	12	30	7	151	836
318	34	29	10	298	1475	349	16	30	7	128	881
319	3	29	11	257	1381	350	29	30	7	124	924
320	13	29	11	289	1431	351	3	30	8	120	872
321	21	29	11	377	1490	352	12	30	8	130	1046

Appendix D, Table 7 cont'd.

No.	Location			Thick-ness of Kpl ft	Elevation on top of Kpl	No.	Location			Thick-ness of Kpl ft	Elevation on top of Kpl
	Sec.	T.N.	R.W.				Sec.	T.N.	R.W.		
353	18	30	8	100	1059	383	5	31	6	235	760
354	6	30	9	110	1036	384	19	31	6	230	775
355	20	30	9	129	1105	385	25	31	6	170	799
356	25	30	9	142	1109	386	8	31	7	-	826
357	3	30	10	-	1075	387	15	31	7	185	821
358	27	30	10	196	1191	388	29	31	7	194	849
359	36	30	10	-	1175	389	9	31	8	147	801
360	2	30	11	270	1209	390	22	31	8	226	836
361	16	30	11	285	1250	391	30	31	8	121	875
362	26	30	11	249	1295	392	2	31	9	167	803
363	30	30	11	235	1356	393	27	31	9	-	952
364	2	30	12	319	1327	394	3	31	10	163	-
365	22	30	12	248	1386	395	8	31	10	170	-
366	33	30	12	315	1511	396	6	31	10	135	990
367	1	30	13	-	1437	397	25	31	10	127	1030
368	17	30	13	368	1692	398	4	31	11	120	1165
369	23	30	13	382	1586	399	17	31	11	133	1162
370	30	30	13	364	1853	400	24	31	11	176	1104
371	5	30	14	350	2142	401	32	31	11	174	1231
372	13	30	14	368	1821	402	18	31	12	346	1296
373	20	30	14	337	2019	403	33	31	12	282	1305
374	26	30	14	352	1930	404	5	31	13	341	1730
375	5	30	15	354	4604	405	15	31	13	-	1387
376	11	30	15	-	2109	406	20	31	13	335	1562
377	27	30	15	274	2511	407	33	31	13	334	1569
378	1	30	16	323	5105	408	13	31	14	387	3164
379	14	30	16	345	3417	409	22	31	14	341	4210
380	25	30	16	290	2939	410	29	31	14	378	2417
381	19	31	4	-	692	411	24	31	15	367	4295
382	8	31	5	223	754						

Table 8. Wells used for stratigraphic cross-section of Figure 42

Well No.	Location		
	Sec.	T.N.	R.W.
1	23	23	12
2	29	24	11
3	3	24	11
4	19	25	10
5	25	26	10
6	4	26	9
7	8	27	8
8	18	28	7
9	22	29	7
10	21	30	6
11	32	31	5
12	35	32	5
13	16	32	4
14	22	32	3

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