Geology, Depositional Environments, and Coal Resources of the Mt. Pennell 2 NW Quadrangle, Garfield County, Utah*

CURTIS SMITH
Marathon Oil, Houston, Texas 77036

ABSTRACT.–Late Cretaceous strata, preserved in the center of the Henry Mountain structural basin, are well exposed in the Mt. Pennell 2 NW 7½-minute Quadrangle. They include the Bluegate Shale, the Muley Canyon Sandstone (new), and the Masuk Shale Members of the Mancos Shale, and the overlying Tarantula Mesa Sandstone (new). Quaternary deposits include pediment gravels, windblown sand and loess, and alluvium.

Lower Muley Canyon Sandstone beds were deposited as a wave-dominated delta front that prograded over the shallow marine and pro-delta Bluegate Shale. Delta-front facies include the transition zone, the lower and upper shoreface, and the shore zone. Upper Muley Canyon beds consist of sandstone with subordinate coal and carbonaceous mudstone. They were deposited in delta-plain distributary channels, levees, backswamps, and lagoons. Overlying Masuk beds are interdeltaic, fluvial, and estuarine deposits, and Tarantula Mesa beds are braided stream deposits.

Subbituminous coal, deposited in delta-plain backswamps and lagoons, occurs in several seams. Some seams exceed 2.0 m, and they could be economically strip-mined because overburden is thin in large areas of the quadrangle.

INTRODUCTION

Developable coal resources have drawn renewed attention to the Henry Mountains. One area of particular interest includes the Mt. Pennell 2 NW 7½-minute Quadrangle, where coal deposits are widespread beneath a relatively thin overburden. Cretaceous formations exposed in the quadrangle include alternating coarse and fine clastic units that represent interfingering marine, deltaic, interdeltaic, and continental deposits. Paludal environments, characteristic of deltaic systems, provided ideal sites for the accumulation of peat which was eventually converted into coal.

This study involved mapping and measurement of formations and key units of the exposed Cretaceous strata (appendix). The Muley Canyon Sandstone Member of the Mancos Shale and the Tarantula Mesa Sandstone are new units that are formally named here.

Surface traces of coal seams were mapped, and detailed stratigraphic sections through the coal intervals were also measured. These data, along with previously measured sections and drill-hole information, have been used to document resources and the economic potential of the coal.

Cretaceous rocks exposed in the quadrangle have been gently folded in the central part of the Henry Mountain structural basin (figs. 1, 2). Although structural patterns are quite simple in the quadrangle, stratigraphic relationships in the deltaic and fluvial deposits are complex. Measured sections have been helpful in determining depositional environments. Mapping of individual depositional units proved to be a useful tool in determining depositional models for the Muley Canyon Sandstone.

Acknowledgments

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Location

The Mt. Pennell 2 NW 7½-minute Quadrangle includes part of the west flank of the Henry Mountains, directly west of Mt. Pennell in Garfield County, Utah (fig. 1). The quadrangle

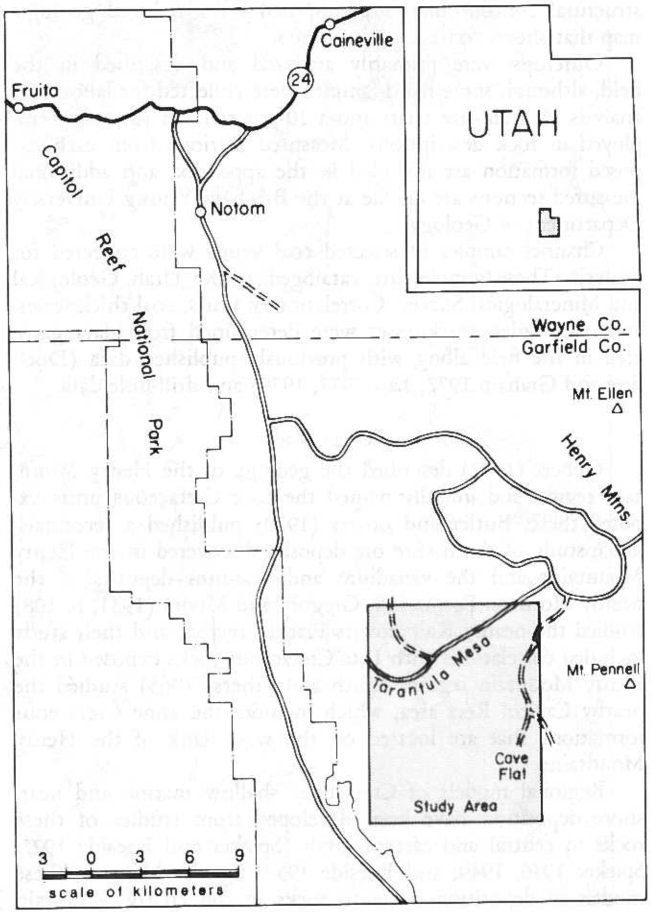

FIGURE 1.–Index map of the Mt. Pennell 2 NW 7.5-minute Quadrangle.

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is also located in the center of the Henry Mountain structural basin, approximately 35 km south of Caineville.

The best route into the area is via Utah 24, through Fruita and Capitol Reef National Park. An improved dirt road leaves the highway east of Capitol Reef National Park and provides access to the area through Notom. Figure 1 shows additional improved dirt roads and jeep trails that provide access into the area. Late summer flash floods often wash out the roads, so the area is most accessible during May and June after the spring road repairs and before the late summer thunderstorms.

Methods

Contacts and structures were mapped on aerial photographs (scale 1:31,000) and enlarged topographic base maps (approximate scale 1:15,000). A Jacob staff was used to measure sections. Attitudes of beds, sedimentary structures, and evidences of current direction were measured with a Brunton compass. Low dips and the lenticular nature of the strata limited numbers of reliable attitudes.

Geophysical logs, from a drill hole located in section 24, T. 33 S, R. 9 E, and previously measured stratigraphic sections (Hunt and others 1953, Smith and others 1963) provided data in determining thicknesses of units shown in the structural cross sections. The geologic map and cross sections, not present in this publication, are published in the Utah Geological and Mineralogical Survey Quadrangle Map Series. Figure 3 is a structural contour map superimposed on a reduced geologic map that shows contacts of key units.

Outcrops were primarily analyzed and described in the field, although some hand-samples were collected for laboratory analysis. A grain-size chart and a 10-power hand lens were employed in rock descriptions. Measured sections from each exposed formation are included in the appendix, and additional measured sections are on file at the Brigham Young University Department of Geology.

Channel samples of selected coal seams were collected for analysis. These samples are cataloged at the Utah Geological and Mineralogical Survey. Correlation of units, coal thicknesses, and overburden thicknesses were determined from data gathered in the field along with previously published data (Doelling and Graham 1972; Law 1977, 1979) and drill-hole data.

Previous Work

Gilbert (1877) described the geology of the Henry Mountain region and initially named the Late Cretaceous units exposed there. Butler and others (1920) published a reconnaissance study of the fissure ore deposits discovered in the Henry Mountains and the vanadium and uranium deposits of the nearby Morrison Formation. Gregory and Moore (1931, p. 108) studied the nearby Kaiparowits Plateau region, and their study included correlations with Late Cretaceous rocks exposed in the Henry Mountain region. Smith and others (1963) studied the nearby Capitol Reef area, which includes the same Cretaceous formations that are located on the west flank of the Henry Mountains.

Regional models of Cretaceous shallow marine and nearshore deposition have been developed from studies of these rocks in central and eastern Utah (Spieker and Reeside 1925, Spieker 1946, 1949; and Reeside 1957; fig. 4). Many of these models of deposition apply to rocks in the Henry Mountain region.

The most detailed regional study of the Henry Mountains to date was by Hunt (1946, Hunt and others 1953). In addition to stratigraphic information, this study included the publication of a moderately detailed regional geologic map and briefly mentioned the coal deposits found there. These coal beds were further investigated by Doelling and Graham (1972, 1975), whose earlier study (1972, p. 92–190) included a chapter concerning the Henry Mountain coalfield. Doelling published several quadrangle maps, including the Mt. Pennell 2 NW 7½-minute Quadrangle. These 1:42200-scale maps are based primarily on Hunt's regional map (1953), with some additional coal data supplied by Doelling. Law (1979a,b) published a regional isopach map of coal in the Muley Canyon Member (new). This map is based on surface and some subsurface sections, which are also included in the publication.

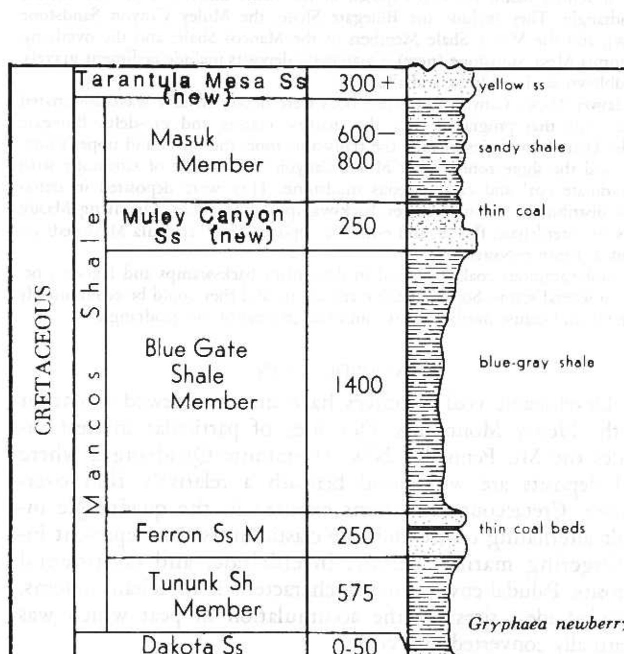


FIGURE 2.–Regional stratigraphic section showing strata exposed in the Henry Mountains region.

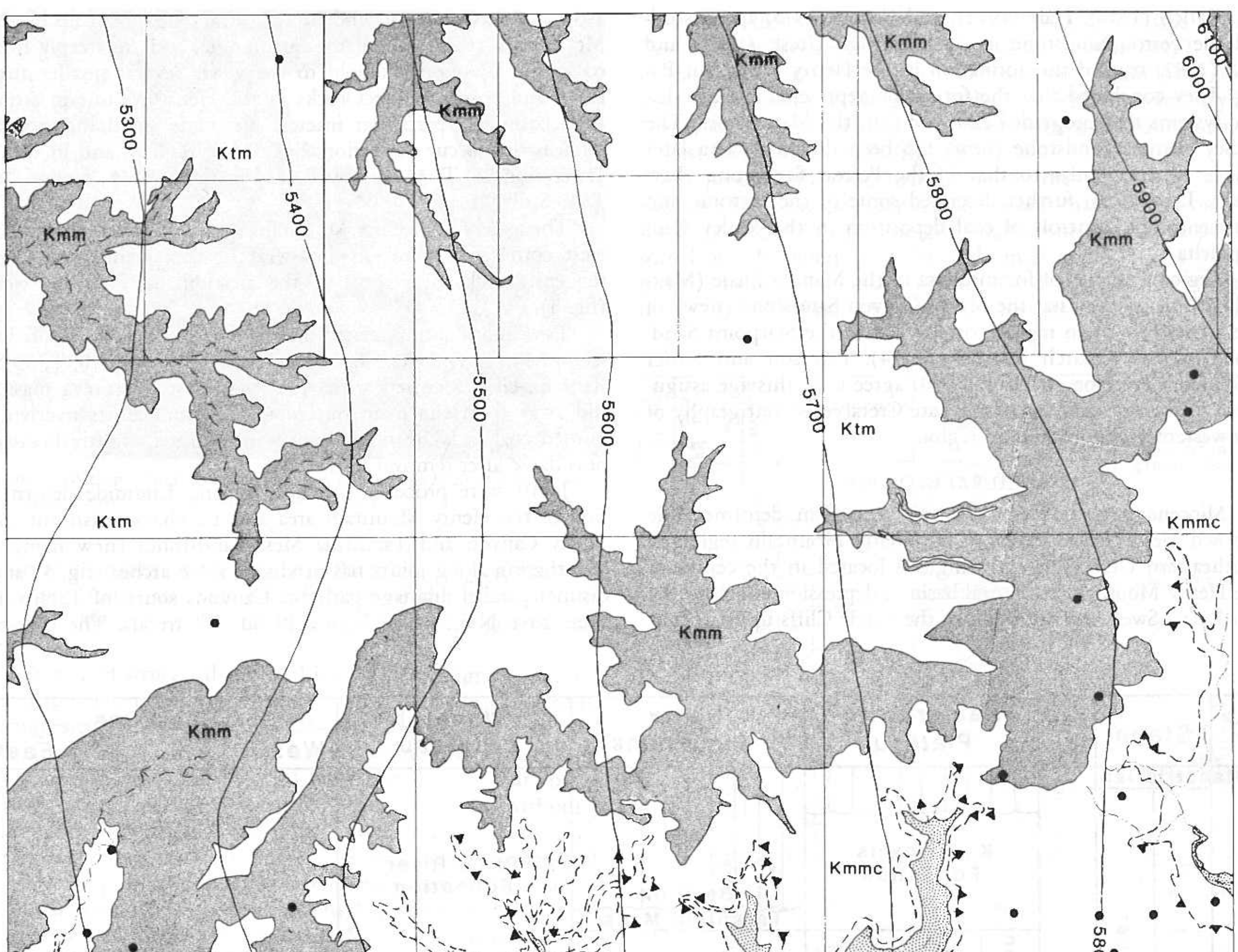


FIGURE 3.–Structural contour map superimposed on simplified geologic map of the quadrangle. Light gray lines = geologic contacts. Exposed strata are as follows: Kmbg (light gray) = Bluegate Shale; Kmmc = Muley Canyon Sandstone; Kmm (dark gray) = Masuk Shale; Ktm = Tarantula Mesa Sandstone. Dashed light lines = coal outcrops, and dark lines = structural contours. Datum for structural contours is at base of lower coal interval. Contour interval is 100 feet.

Katich (1954), Hale (1972), and Cotter (1975, 1976) studied the Ferron Sandstone in central Utah. Uresk (1979) and Hill (1982) studied this formation in the Henry Mountain Basin. They concluded that the formation represents ancient deltaic systems that prograded eastward into the Mancos Sea. The Muley Canyon Sandstone (new) has been described as a later deltaic system similar to that of the Ferron Sandstone (Law 1980). Law (1980) further described some of the tectonic and sedimentologic controls of coal deposition in the Muley Canyon delta.

Regional studies of foraminifera in the Mancos Shale (Maxfield 1976) indicate that the Muley Canyon Sandstone (new) of the Henry Mountain region correlates with the Starpoint Sandstone of the Wasatch Plateau (fig. 4). Peterson and Ryder (1976) and Peterson and Law (1980) agree with this age assignment in their discussions of the Late Cretaceous stratigraphy of the western Henry Mountain region.

STRUCTURAL GEOLOGY

Miocene igneous intrusions and tectonism deformed the exposed Mesozoic sediments in the Henry Mountain region of southeastern Utah. The quadrangle is located in the center of the Henry Mountain structural basin, a depression south of the San Rafael Swell and northeast of the Circle Cliffs uplift (Hunt 1953, p. 88). Cretaceous and Jurassic strata were bent up by the Mt. Pennell stock, east of the quadrangle, and are steeply folded in the Waterpocket Fold to the west. Several smaller anticlines and synclines affect rocks in the Henry Mountain structural basin. Of particular interest are some small monoclinal terraces that occur in section 2, T. 34 S, R. 8 E, and in the E ½, section 28, T. 33 S, R. 9 E, and in the SW ¼, section 16, T. 33 S, R. 9 E.

The axis of the Henry Mountain syncline crosses the southwest corner and generally lies west of the quadrangle. Consequently rocks over most of the area dip 1-2° to the west (fig. 3).

Two minor slump-related faults were mapped in the SE ¼, section 10, T. 33 S, R. 9 E, and in the S ½, section 20, T. 33 S, R. 9 E. They occurred when rotated sandstone toreva masses slid away from the main outcrops. Sandstone units overlying burned coal beds are often folded and faulted slightly because of collapse after removal of the coal.

Joints were probably produced during Laramide deformation of the Henry Mountain area and are characteristic of the Muley Canyon and Tarantula Mesa Sandstones (new names). Weathering along joints has produced some arches (fig. 5) and distinct parallel drainage patterns. Canyons south of Tarantula Mesa have N-S, N 45° E, and N 60° W trends. The lack of

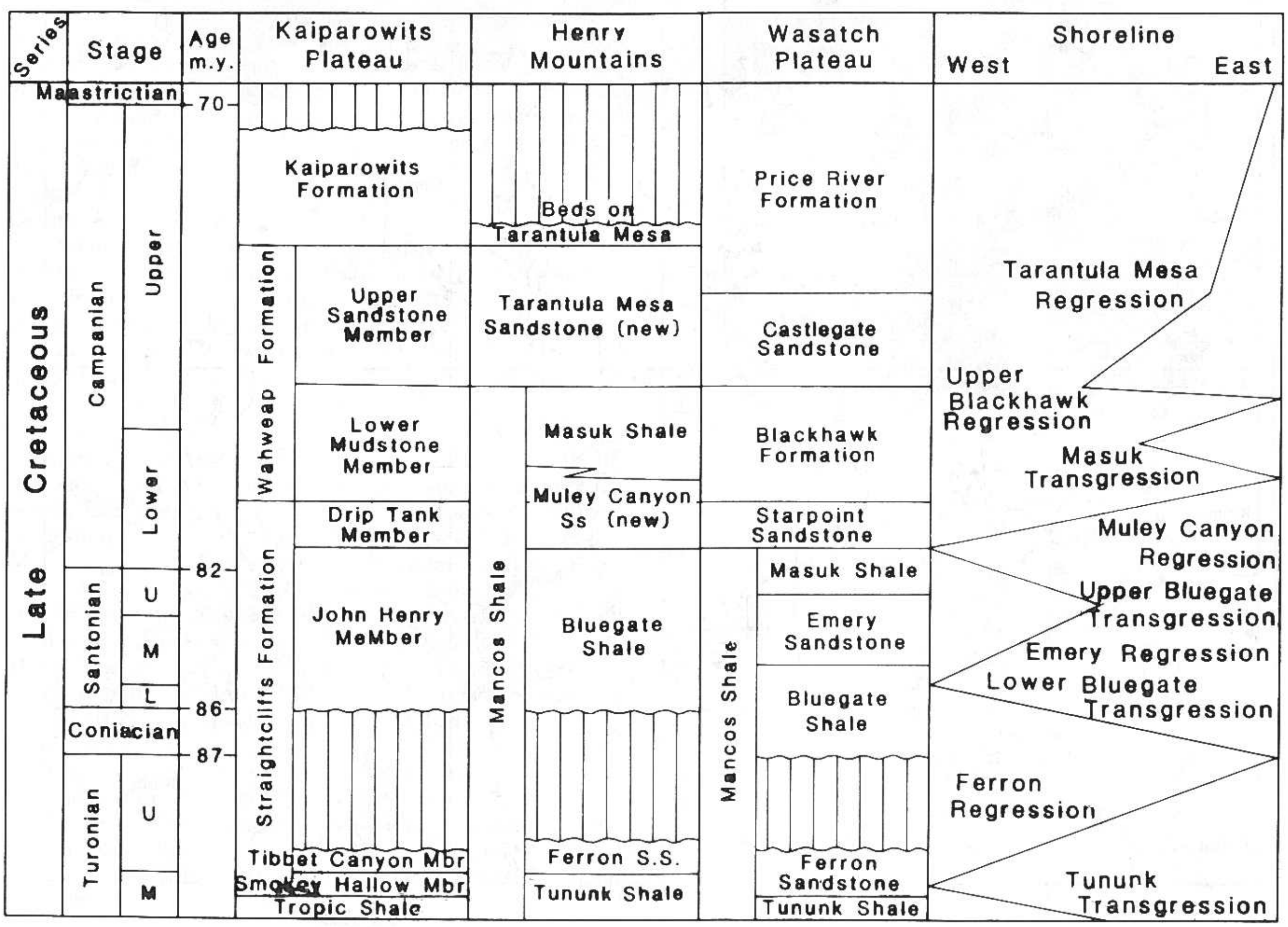


FIGURE 4.–Correlation chart showing relationships and ages of Henry Mountains, Kaiparowits Plateau, and Wasatch Plateau units (modified after Peterson and Ryder 1975, Peterson and Law 1980, Maxfield 1976, Vaninetti 1978, and Obradovich and Cobban 1975).

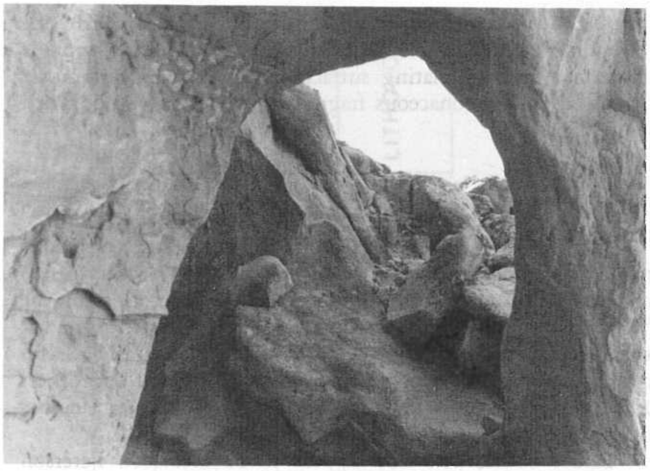


FIGURE 5.—Arch produced by erosion along a joint in the Muley Canyon-1 unit, Swap Canyon, E ½, section 2, T. 34 S, R. 8 E.

dendritic drainages on the relatively flat strata suggest that the drainage patterns are joint related. Many of the canyons from Tarantula Mesa, however, show elongation in the general dip direction.

Combined structural and coal isopach data suggest that minor deformation may have begun during the Late Cretaceous, as suggested by Law (1980, p. 326–29). Contemporaneous coal deposition and faulting have been documented east of the study area by Law (1980, p. 329), who also showed that coal is thinner over anticlines and thicker over synclines. Although coal thicknesses are influenced by a variety of factors, structurally and topographically lower areas may have provided better sites for peat accumulation and preservation. In this quadrangle, individual coal beds are up to 3 m thick in lower Swap Canyon, where the axis of the Henry Mountain syncline crosses through the quadrangle. Law (1980, p. 326) has also shown thin coal seams over structurally high areas to the north.

STRATIGRAPHY

Rocks exposed in the quadrangle (fig. 6), in ascending order, include the Bluegate Shale, Muley Canyon Sandstone (new) and Masuk Shale Members of the Mancos Shale, and the overlying Tarantula Mesa Sandstone (new). These are all of Late Cretaceous Santonian to late Campanian age (fig. 4). Informal units that have been mapped separately include Late Cretaceous beds on Tarantula Mesa (Peterson and Ryder 1975, Peterson and Law 1980), Quaternary pediment gravels, windblown loess and sand deposits, and stream deposits.

Bluegate Shale

The Bluegate Shale was named by Gilbert (1877) as a separate formation, but the unit was later included as a member of the Mancos Shale (Hunt 1946). Bluegate beds in the Henry Mountain Basin correlate to the Bluegate Shale, Emery Sandstone, and Masuk Shale Members of the Wasatch Plateau (fig. 4).

East of Stevens Narrows, 1.6 km northeast of the study area, the Bluegate Shale is 465 m thick (appendix). At Bitter Creek Divide, 3.2 km west of the study area, the member is 366 m thick (Longwell and others 1923). No complete section is exposed in the study area.

Fossils of the *Scaphites depressus* zone of Obradovich and Cobban (1975) were found in the lower 290 m of the Bluegate Shale by Peterson and Ryder (1975, p. 177), and fossils of the *Desmoscaphites bassleri* zone were found by Reeside (1927, p. 5) in the lower part of the unit. No diagnostic fossils have been found in the upper Bluegate rocks, but Peterson and Ryder (1975) show this part of the member to be latest Santonian to earliest Campanian in age (fig. 4).

A pebbly sandstone that occurs as the basal unit of the Bluegate Shale indicates a possible disconformity (Peterson and Ryder 1975, p. 177–78). The gritty sandstone consists of poorly sorted angular chert granules and small pebbles in a poorly sorted, medium- to coarse-grained sand matrix. Chert fragments make up about 15 percent of the deposit. The unit is lat-

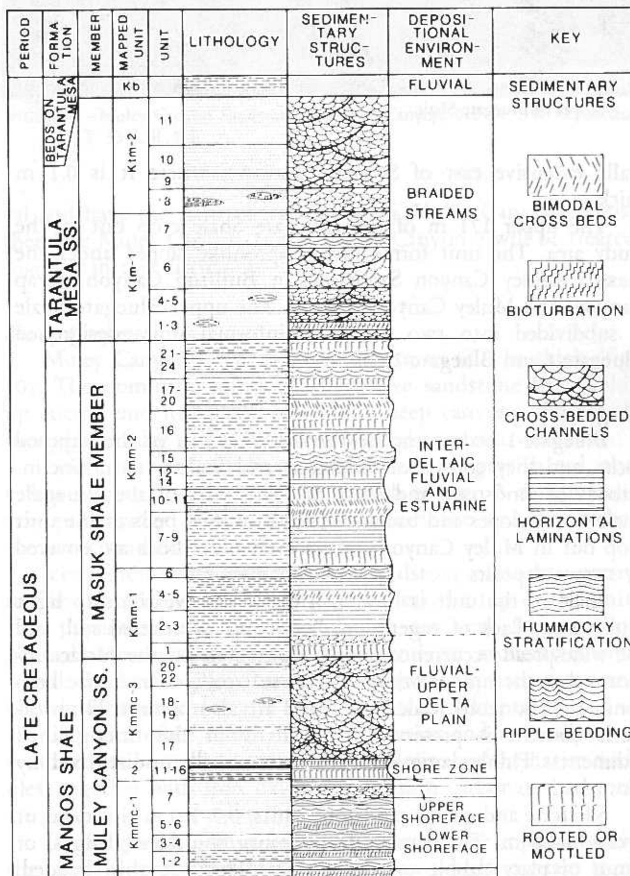


FIGURE 6.—Stratigraphic section of exposed Cretaceous strata within the Mt. Pennell 2 NW Quadrangle. Sedimentary structures and depositional environments are included as well.

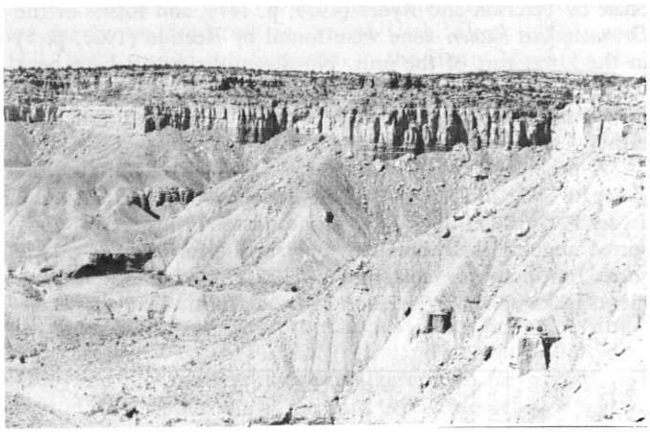


FIGURE 7.–Outcrops of Muley Canyon Sandstone in Muley Canyon overlie slopes of Bluegate Shale.

erally extensive east of Stevens Narrows, where it is 0.1 m thick.

The upper 171 m of the Bluegate Shale crop out in the study area. The unit forms broad, apronlike slopes under the massive Muley Canyon Sandstone in Bullfrog Canyon, Swap Canyon, and Muley Canyon (fig. 7). The upper Bluegate Shale is subdivided into two mappable informal units designated Bluegate-1 and Bluegate-2 (fig. 6).

Bluegate-1

Bluegate-1 beds comprise the lower 121 m of the exposed rocks, and they consist of mudstone and shale with minor interbeds of sandstone and siltstone. This part of the Bluegate Shale forms slopes and badlands (fig. 7). Older beds of the unit crop out in Muley Canyon, where even older beds are covered by stream deposits.

Shale of the unit is brownish black and weathers to light bluish gray. Lack of vegetation, "popcorn" weathered soil, and the widespread occurrence of selenite crystals on the surface indicate that the unit is saline. Thick, soft soils characterize bentonite-rich horizons. Calcareous beds are also present. High organic content is preserved, particularly in the finer-grained sediments. Thinly laminated beds are usually undisturbed by bioturbation.

Siltstone and minor sandstone units, 0.5–2.0 m thick, occur every 15–20 m. These rocks form minor shoulders, ledges, or bands of platy rubble on the surface. They are thin bedded, moderately indurated, and calcium-carbonate cemented.

Bluegate-2

A distinctive change in topographic expression from lower beds occurs where thicker and more common sandstone and siltstone units form ledges and slopes in the upper Bluegate Shale. Coarser sandstone and siltstone occupy less than 10 percent of the total volume in the lower part of the Bluegate-2 unit, but sandstone and siltstone beds make up nearly 40–50 percent of the total volume in the upper 9–12 m. The upper contact with the Muley Canyon Sandstone was drawn at the base of the first persistent massive sandstone (fig. 7).

Shale in the upper Bluegate unit is essentially the same as that of lower beds, although there are local areas of minor soft, sediment deformation. Contacts between shale and sandstone units are generally sharp and undulating.

The sandstone is yellowish gray; weathers to pale yellowish orange; is composed of well-sorted, fine, subangular quartz grains; and is cemented by calcium carbonate and iron oxide. Structures include horizontal laminations with minor ripple laminations and undulating surfaces interpreted as hummocky stratification. Carbonaceous fragments are common along bedding planes.

Muley Canyon Sandstone (New)

The Muley Canyon Sandstone Member was originally named the Bluegate Sandstone by Gilbert (1877). Lee (1915) correlated this unit with the Mesa Verde Formation of the Wasatch Plateau, and Spieker and Reeside (1926) correlated it with the Emery Sandstone of the Wasatch Plateau. The latter correlation was later adopted by Hunt (1946, Hunt and others 1953), when he named this unit the Emery Sandstone Member of the Mancos Shale.

Earlier correlations now appear to be incorrect. Peterson and Ryder (1975) and Peterson and Law (1980) and Maxfield (1976) have shown that Hunt's "Emery Sandstone" of the Henry Mountain region correlates with the Starpoint Sandstone and lower Black Hawk Formation of the Wasatch Plateau (fig. 4). Peterson and Ryder (1975) and Peterson and Law (1980) have suggested that the "Emery Sandstone" be renamed in order to avoid further confusion.

It is here proposed that the "Emery Sandstone Member of the Mancos Shale," as mapped in the Henry Mountain area by Hunt and others (1953), be renamed the Muley Canyon Sandstone Member of the Mancos Shale. The type section for this member (fig. 8) is here designated as outcrops at the head of Muley Canyon in the SE ¼, SW ¼, section 16, T. 33 S, R. 9 E.

The member here consists of a lower massive sandstone; a middle slope-forming unit that contains coal, carbonaceous mudstone, and sandstone; and an upper sandstone (fig. 9). The lower contact is placed at the first persistent sandstone bed, and the upper contact is placed at the top of the uppermost massive sandstone (fig. 6). Interbedded mudstone and sandstone above the massive sandstone beds are included in the Masuk Member of the Mancos Shale.

The Muley Canyon Sandstone Member applies to all rocks in the Henry Mountain Basin that were previously called the Emery Sandstone Member of the Mancos Shale. The age of the member is early Campanian, on the basis of relationships with overlying and underlying units (Peterson and Ryder 1975, Peterson and Law 1980; fig. 4).

Measured sections of Muley Canyon Sandstone range from 57.0 to 109.2 m thick (see appendix). The member is 91 m thick on the east side of Bullfrog Canyon less than 1.6 km east of the study area (Doelling and Graham 1972, p. 110).

The Muley Canyon Sandstone has been subdivided into five informal units in this quadrangle. These subunits represent changes in lithology produced by different depositional environments and are designated as Muley Canyon-1, Muley Canyon-2a, Muley Canyon-2b, Muley Canyon-2c, and Muley Canyon-3 (fig. 6). Relationships and thicknesses of these units are shown in figure 10.

The interval between the Muley Canyon-1 and Muley Canyon-3 was undifferentiated and is designated as unit 2 in the eastern half of the quadrangle. A sandstone wedge separates the single Muley Canyon-2 coal interval into two coal intervals in the western part of the area. Where this separation occurs, the two coal intervals are designated as Muley Canyon-2a and Muley Canyon-2c, and the separating sandstone wedge is designated as Muley Canyon-2b (fig. 10). Within the quadrangle, the Muley Canyon-2a beds continue to be the major coal inter-

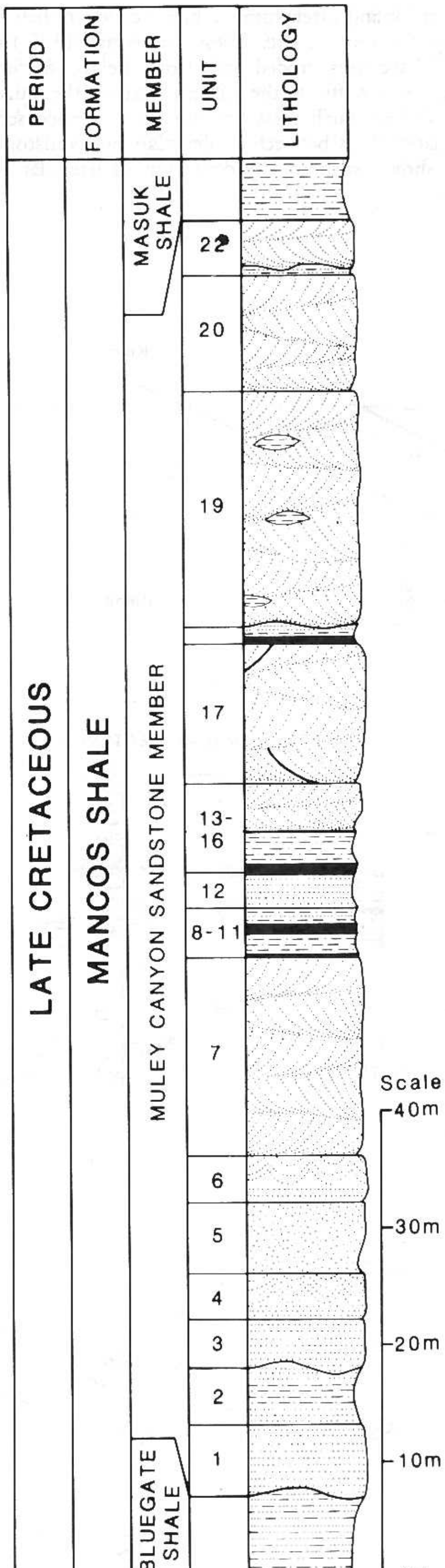


FIGURE 8.–Type section for newly named Muley Canyon Sandstone Member of the Mancos Shale, head of Muley Canyon, SE ¼, SW ¼, section 16, T. 33 S, R. 9 E. Lower massive cliff is Muley Canyon-1; slope-forming interval is Muley Canyon-2; and upper cliff is Muley Canyon-3.

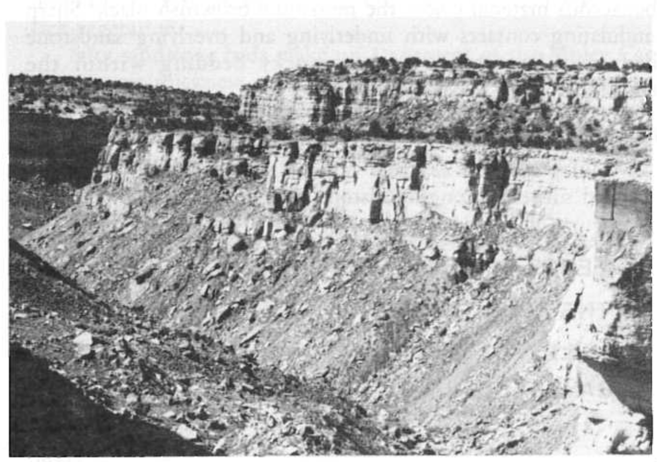


FIGURE 9.–Muley Canyon Sandstone in Muley Canyon, NE ¼, SW ¼, section 15, T. 33 S, R. 9 E.

val and have the same characteristics as Muley Canyon-2 beds; therefore Muley Canyon-2a and Muley Canyon-2 will be treated together in this discussion.

Muley Canyon-1

Muley Canyon-1 ranges from 27.5 m to 66.7 m thick (fig. 10). The dominant lithology is massive sandstone that holds up cuestas and forms the caprock of deep canyons (fig. 7) although there are minor interbeds of mudstone near the base.

Lower sandstone beds are grayish orange, grayish red, and yellowish gray, and they weather grayish orange. A conspicuous very pale orange to very light gray sandstone usually overlies the lower sandstone beds in the unit.

Very fine to fine-grained lower sandstone coarsens upward to fine- to medium-grained sandstone near the top of the unit. The uppermost 1–2 m of sandstone are very fine to fine grained. Most grains are subangular and are moderately well sorted. Sandstone grains consist of 95 percent quartz, 4 percent black and brown chert, and 1 percent altered feldspar.

Limonite often stains the quartz grains and is locally concentrated into small orange patches. Siderite and hematite nodules, together with iron oxide and calcium carbonate cements, are present.

Lower grayish orange units, which comprise approximately the lower three-fourths of Muley Canyon-1 beds, contain horizontal and ripple laminations. Hummocky stratification is locally evident, particularly in the upper part of these grayish orange beds. Bioturbation has obscured some bedding, particularly in the lower part of the unit (fig. 11).

The upper very pale orange or bleached rocks, which comprise the upper one-fourth of the Muley Canyon-1 unit, contain horizontal laminations and low-angle trough cross-beds (fig. 12). Bioturbation was not noted in this unit. These beds lack abundant cement, and, as a consequence, they are poorly indurated to friable.

A moderately continuous massive cliff characterizes Muley Canyon-1 outcrops. Cementation differences, however, cause some beds to form ledges and slopes. The upper bleached unit is often eroded back several tens of meters from the massive cliff of the lower sandstone.

Thin interbeds of mudstone are common in the lower part of the unit (fig. 6). They range from 0.1 m to 1.0 m thick and are commonly lenticular and thinly laminated. Abundant carbonaceous material colors the mudstone brownish black. Sharp undulating contacts with underlying and overlying sandstone beds may be a result of hummocky bedding within the sandstone.

Muley Canyon-2a

Muley Canyon-2a beds consist predominantly of interbedded silty sandstone, mudstone, and coal (fig. 13). The unit is 0–11 m thick and often forms a broad exposure belt because of its slope-forming nature. Loess covers most of the unit where beds have been eroded back from the top of the lower Muley Canyon-1 cliffs in the eastern part of the quadrangle around Cave Flat. Such loess has not been mapped separately because relationships between Muley Canyon Sandstone units are better shown without the confusion of irregular patterns on the map.

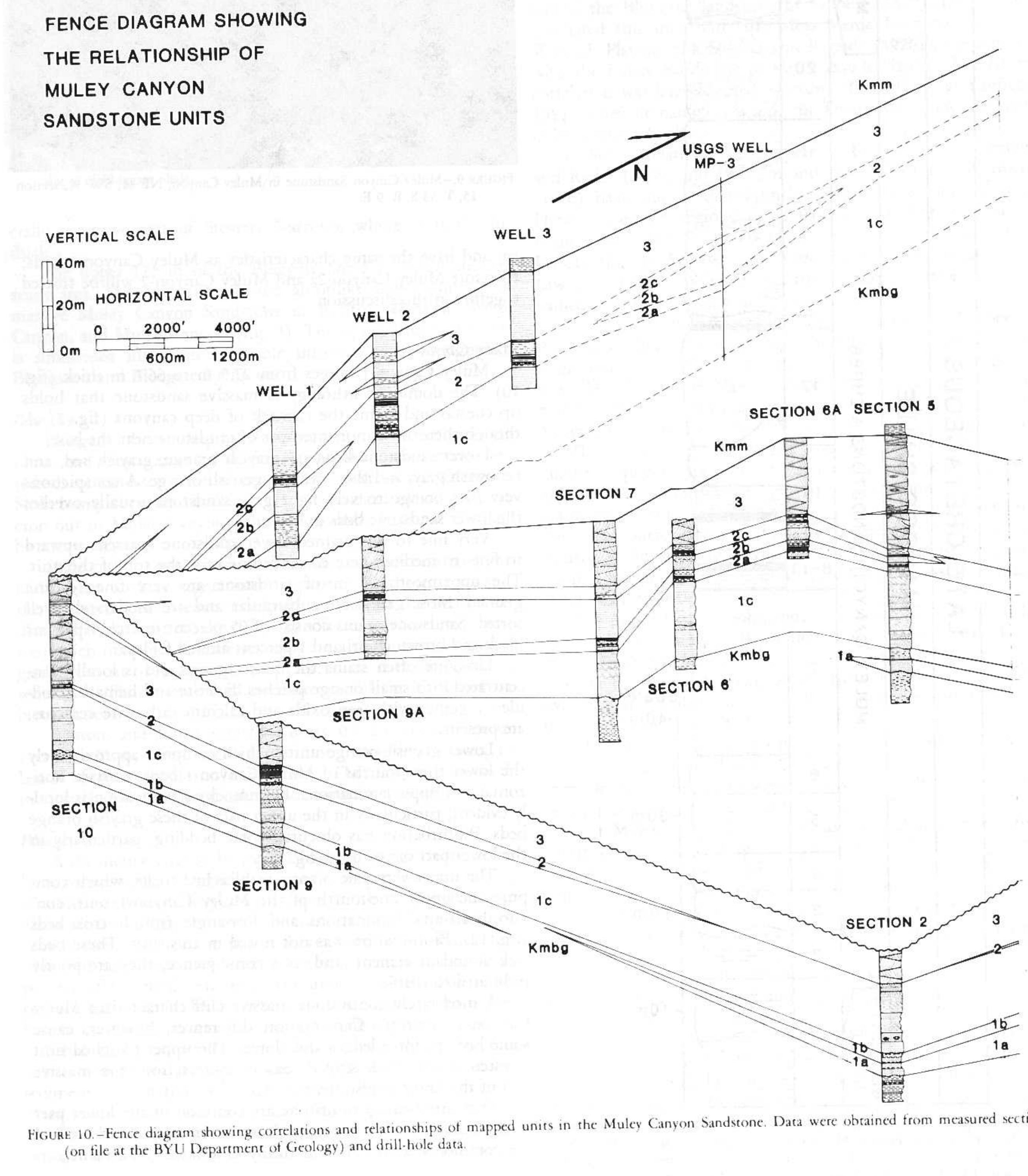
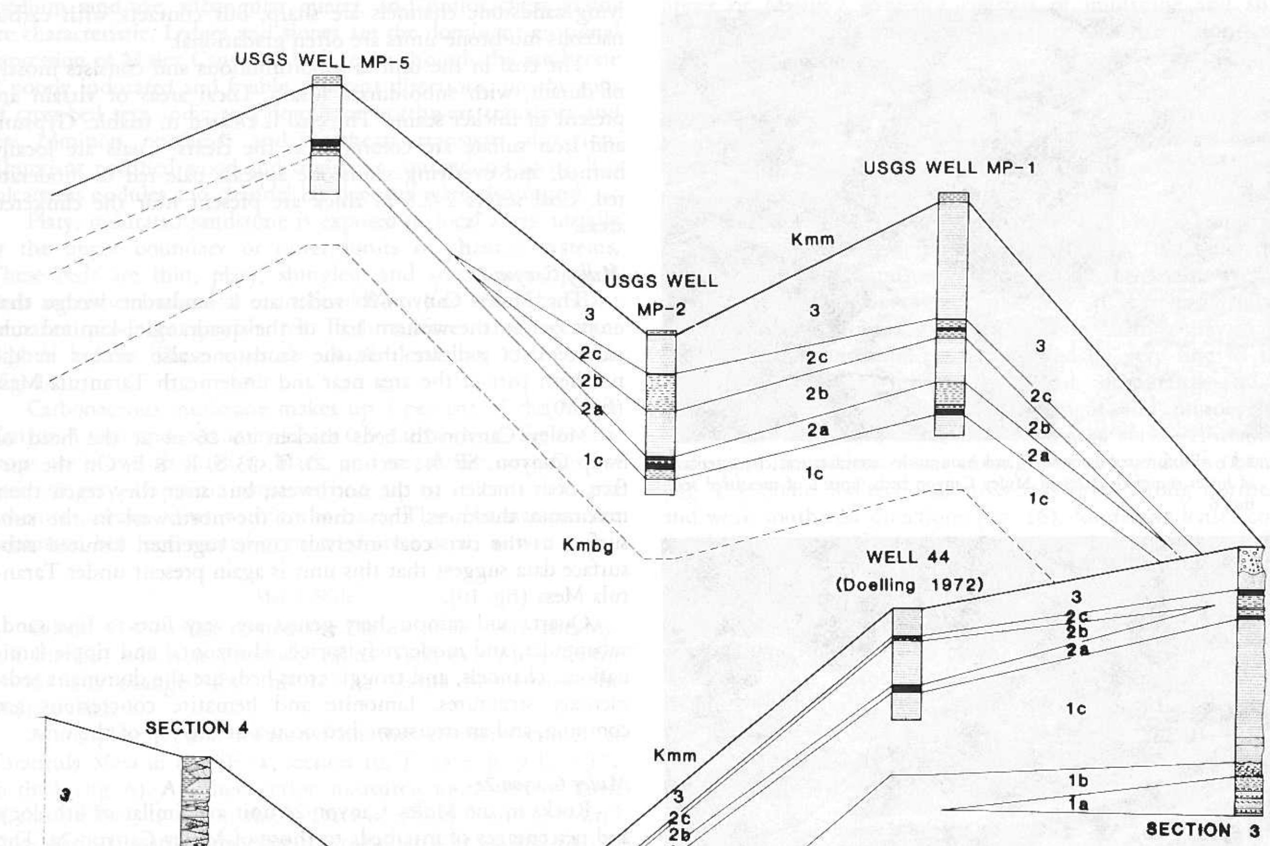


FIGURE 10.–Fence diagram showing correlations and relationships of mapped units in the Muley Canyon Sandstone. Data were obtained from measured sections (on file at the BYU Department of Geology) and drill-hole data.

Carbonaceous mudstone comprises 45 percent of Muley Canyon-2a beds and is a brownish black that weathers to brownish gray. The mudstone is usually silty and sometimes sandy. Increased sand content causes the mudstone to form steeper slopes or shoulders. Abundant macerated plant material is common. Some mudstone beds are thinly laminated, but most of them are rooted or mottled. Selenite crystals are common within the mudstone, and these gypsiferous beds largely lack vegetation.

Silty sandstone beds make up 31 percent of the Muley Canyon-2a unit thickness and include a variety of colors and types that generally are not laterally continuous. Sedimentary structures are rare, but horizontal laminations and rooting are present in some outcrops.



Coal comprises approximately 24 percent of the Muley Canyon unit, with local sections generally containing one to four seams (fig. 13). The lowest coal seam generally occurs directly above the lower bleached sandstone. Exceptions occur where there is no coal or where a thin carbonaceous mudstone directly underlies the coal in local areas. The lowest coal seam ranges from 0.3–2.7 m thick and is the most continuous coal in the quadrangle. Loess often covers the outcrop belt of this lower seam, and the only evidences of its existence are occasional patches of black coal dust.

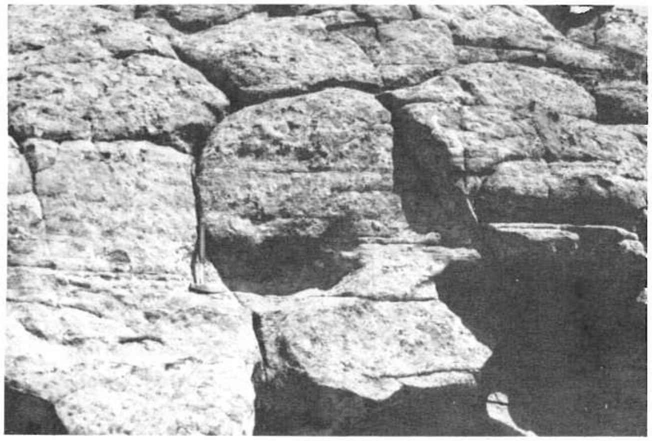


FIGURE 11.–Bioturbated horizontal and hummocky stratification characteristic of lower shoreface facies in Muley Canyon beds, unit 1 of measured section 6.

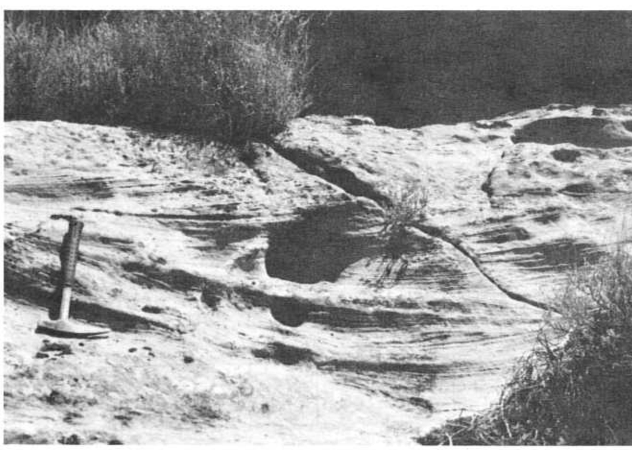


FIGURE 12.–Trough cross-beds characteristic of the upper shoreface facies in Muley Canyon beds, unit 7 of the type section.

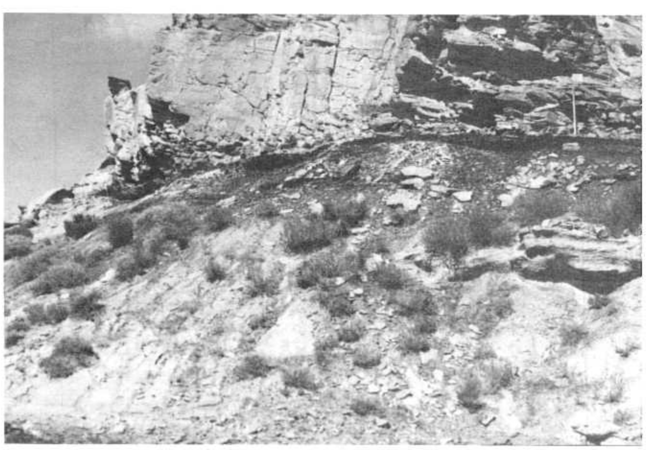


FIGURE 13.–Major coal interval within the Muley Canyon Member, NE ¼, NW ¼, section 20, T. 33 S, R. 9 E.

Upper coal seams are usually thicker than lower seams, but they often grade laterally into carbonaceous mudstone or are cut out by overlying sandstone channels. Contacts with overlying sandstone channels are sharp, but contacts with carbonaceous mudstone units are often gradational.

The coal in the unit is subbituminous and consists mostly of durain, with subordinate fusain. Local areas of vitrain are present in thicker seams. The coal is cleated to friable. Gypsum and iron sulfate are common on the cleats. Coals are locally burned, and overlying sandstone appears pale red to moderate red. Coal seams 2–2.5 m thick are present near the clinkered areas.

Muley Canyon-2b

The Muley Canyon-2b rocks are a sandstone wedge that crops out in the western half of the quadrangle. Limited subsurface data indicate that the sandstone also occurs in the northern part of the area near and underneath Tarantula Mesa (fig. 10).

Muley Canyon-2b beds thicken to 26 m at the head of Swap Canyon, SE ¼, section 25, T. 33 S, R. 8 E. On the surface, beds thicken to the northwest, but after they reach their maximum thickness, they thin to the northwest in the subsurface as the two coal intervals come together. Limited subsurface data suggest that this unit is again present under Tarantula Mesa (fig. 10).

Quartz and minor chert grains are very fine to fine sand, subangular, and moderately sorted. Horizontal and ripple laminations, channels, and trough cross-beds are the dominant sedimentary structures. Limonite and hematite concretions are common, and an ironstone bed occurs at the top of the unit.

Muley Canyon-2c

Rocks in the Muley Canyon-2c unit are similar in lithology and percentages of interbeds to those of Muley Canyon-2a. The Muley Canyon-2c coal-bearing interval either grades laterally into the Muley Canyon-3 sandstone or merges into the Muley Canyon-2a interval where the underlying Muley Canyon-2b unit pinches out (fig. 10). Generally the Muley Canyon-2c coal-bearing interval is not as thick as the Muley Canyon-2a coal interval.

Muley Canyon-3

Uppermost beds in the Muley Canyon Member are included in map unit Muley Canyon-3. Upper contacts of the Muley Canyon Sandstone with the Masuk Shale have been placed at different horizons. Hunt (1953) placed the upper contact at the top of the massive sandstone that overlies the upper coal interval. Peterson and Ryder (1975) and Peterson and Law (1980) placed the Muley Canyon-Masuk contact higher, at the top of a series of interbedded mudstone and sandstone units, at the base of a dominantly mudstone section. The massive sandstone above the coal, but below the interbedded mudstone and sandstone units, is the contact mapped in this study (fig. 6).

The Muley Canyon-3 unit ranges from 9 m in the NE ¼, section 14, T. 33 S, R. 9 E, to 52.3 m thick at the type section (fig. 9), but has an average thickness of 30–31 m over much of the outcrop belt. Sections measured in the southernmost part of the area are probably incomplete because the uppermost beds may have been eroded off (fig. 10).

Sandstone characterizes the Muley Canyon-3 unit, but some minor discontinuous interbeds of carbonaceous mudstone are also present. Sandstone types include a dominant (95%) trough cross-bedded, friable channel-fill type and a subordinate (5%) platy, well-indurated levee type (fig. 14).

Fresh surfaces of channel-fill sandstone are grayish orange, pale red, yellowish gray, or very pale orange; they weather slightly lighter and grayer. Moderately well sorted, very fine to medium sand-size, subangular quartz, and minor chert grains are characteristic. Ledges and slopes are the dominant erosional expression of Muley Canyon-3 beds, even though the sandstone is poorly indurated and friable. Current directions, on the tops of cross-bed sets, indicate a dominant northwest transport and less common northeast and southeast transport direction. Abundant petrified wood and ironstone concretions occur, but calcareous nodules and channel lag deposits were also found.

Platy, indurated sandstone is exposed in local areas, usually at the upper boundary or outer limits of channel systems. These beds are thin, platy, shingled, and sometimes rippled. Beds are either horizontal or inclined from 1 to 20°. Abundant hematite produces grayish red fresh surfaces that weather slightly lighter. These units are usually less than 1.0 m thick (fig. 14).

Carbonaceous mudstone makes up 5 percent of the Muley Canyon-3 unit and occurs in lenses 0.3–1.0 m thick. Fresh outcrops are brownish black to black, and weathered outcrops are greenish gray. Gypsum, ironstone beds up to 10 cm thick, and limonite streaks occur within the unit. Thin laminations are dominant, but local rooted or mottled areas occur as well.

Masuk Shale

Gilbert (1877) first named the Masuk Shale from the Masuk Plateau, which is presently called Tarantula Mesa. Hunt (1946) later changed the unit to the Masuk Member of the Mancos Shale.

A complete section measured on the southeast corner of Tarantula Mesa in the SE ¼, section 10, T. 33 S, R. 9 E, is 171 m thick (fig. 6). Another section measured southwest of Turn of the Bullfrog is 138 m thick. Data obtained from three drill holes (fig. 10 map) show that the member is from 186 to 199 m thick under Tarantula Mesa. The Masuk Shale thins toward the east.

Palynomorphs reported from basal units by Peterson and Ryder (1975, p. 179) indicate that the Masuk Shale is Campanian. Regional correlations further suggest that the Masuk Shale is of early to early late Campanian age (Peterson and Ryder 1975, p. 179; fig. 4).

Two subdivisions of this member were mapped (fig. 6). The lower or Masuk-1 sequence consists of slope- and ledge-forming mudstone, shale, and sandstone beds that sometimes interfinger with uppermost Muley Canyon Sandstone beds. The upper or Masuk-2 sequence consists of mudstone and shale with subordinate sandstone lenses. These form steep slopes under Tarantula Mesa (fig. 15).

Masuk-1

The Masuk-1 beds attain a thickness of 30–50 m in the eastern part of the quadrangle and are thinner and even pinch out in other parts of the quadrangle.

Sandstone makes up 30–50 percent of the Masuk-1 unit and occurs as wide lenticular bodies, 3–8 m thick, that pinch out laterally (fig. 15). Sandstone lenses are yellowish brown and weather to yellowish gray and light gray. Higher iron concentrations near the top of some lenses color them a grayish red (fig. 16). The sandstone is characterized by very fine to fine grained, subangular, moderately sorted, dominantly quartz sand. Extensive calcium carbonate cement and minor iron-oxide cement produce moderately indurated rocks. Horizontal and ripple laminations occur throughout the sandstone bodies (fig. 17). Some bi-directional cross-beds show strong northeast and weak southwest directions (fig. 16). Sandstone lenses commonly have scoured bases that cut into underlying softer units.

Alternating bands of yellowish gray silty mudstone and brownish black carbonaceous shale make up 50–70 percent of Masuk-1 outcrops. The mudstone is siltier, more limonitic, and less carbonaceous than is the shale. Mottling is characteristic of more silty beds. Thinly laminated carbonaceous shale beds are locally rooted and sometimes contain minor coal. "Popcorn" soil indicates that bentonite and gypsum are present in both the mudstone and shale. Selenite crystals are also scattered on the surface.

Masuk-2

The Masuk-2 unit includes most of the member (fig. 6). Thicknesses in the western part of the quadrangle approach 183 m, but thicknesses in the eastern part are between 107 and 122 m.

Mudstone and shale (80–85%) are dominant over sandstone

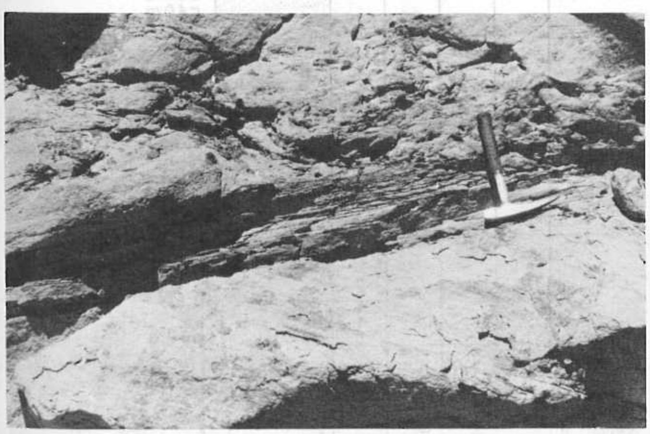


FIGURE 14.–Two types of sandstone within the Muley Canyon-3 unit: Platy levee sandstone behind hammer, and massive channel-fill sandstone exposed above and below platy sandstone bed. These beds were deposited in an upper delta-plain fluvial environment.

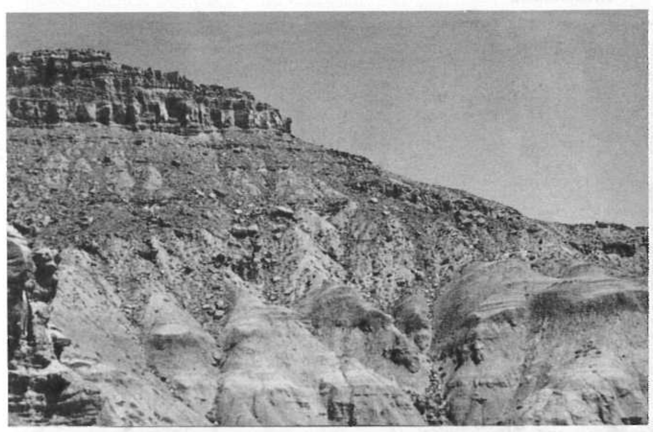


FIGURE 15.–Masuk Shale Member forming slopes in foreground below overlying Tarantula Mesa Sandstone that forms cliff on the skyline, southeast corner of Tarantula Mesa in the SE ¼, section 10, T. 33 S, R. 9 E. The Masuk Shale consists of interbedded sandstone, mudstone, and shale.

(15–20%), except near the top of the unit where sandstone channel fills become more abundant. Mudstone and shale are similar to that in the Masuk-1 unit. Bands of siderite float 15–30 cm thick occur at 5–10-m intervals in the lower part of the unit. Occasional discontinuous thin coal also occurs there.

Sandstone lenses are less than 3 m thick and are less frequent than in Masuk-1 beds. Some local bioturbation or rooting occurs in the uppermost sandstone units. Limestone is rare, but thin lenses of calcarenite also occur.

Tarantula Mesa Sandstone

The Tarantula Mesa Sandstone was originally called the Masuk Sandstone by Gilbert (1877). Hunt (1946) later changed the name to the Mesa Verde Formation. The "Mesa Verde Formation" does not resemble the Mesa Verde Formation of other areas, and Peterson and Ryder (1975, p. 185) have recommended that the formation be renamed in the Henry Mountain area.

It is here proposed that Hunt's "Mesa Verde Formation" of the Henry Mountain area be formally named the Tarantula Mesa Sandstone. The type section (fig. 18) is designated as outcrops located 1.6 km southwest of Turn of the Bullfrog below the Frog in the NE ¼, SE ¼, section 35, T. 32 S, R. 9 E.

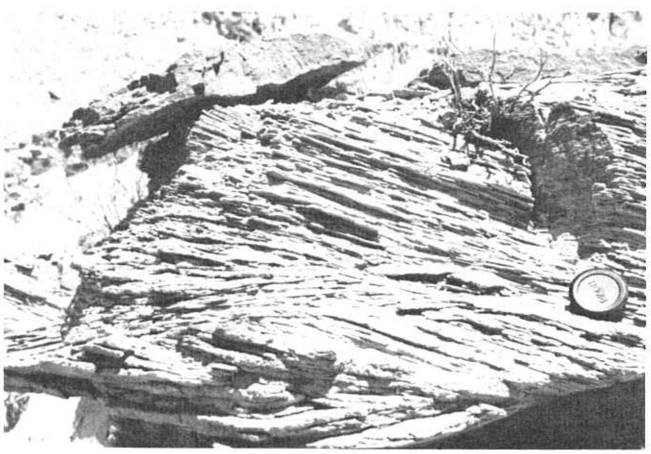


FIGURE 16.—Bidirectional cross-beds within sandstone channel fill; hematite-stained sandstone near top of channel fill, Masuk Shale, SE ¼, section 14, T. 33 S, R. 9 E. Tidal or fluvial channel in an interdeltaic estuarine environment.

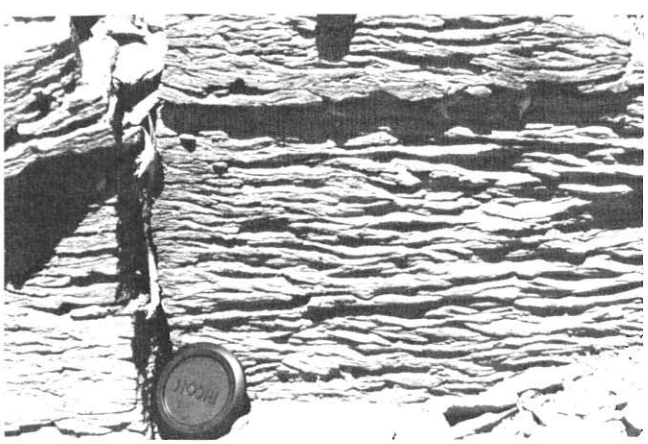


FIGURE 17. Ripple laminae of sandstone channel fill in Masuk Shale Member, SE ¼, section 10, T. 33 S, R. 9 E, probably deposited in a fluvial or tidal channel of an interdeltaic estuarine environment.

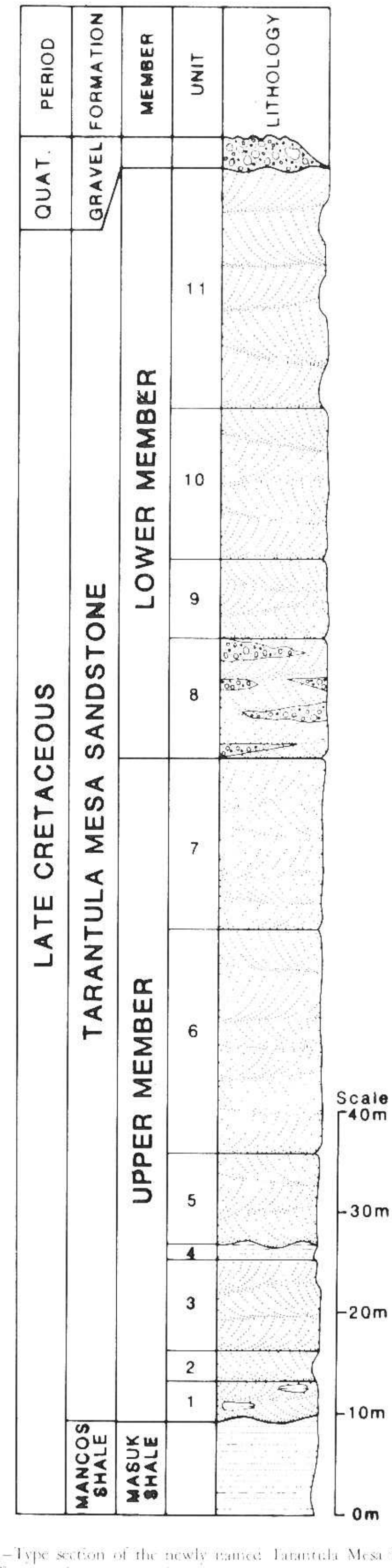


FIGURE 18.—Type section of the newly named Tarantula Mesa Sandstone, NE ¼, SE ¼, section 35, T. 33 S, R. 9 E.

The Tarantula Mesa Sandstone is a distinctive sandstone and forms cliffs that cap mesas and buttes in the center of the Henry Mountain Basin (fig. 19). The lower contact is at the base of the massive sandstone cliff, and the upper contact is at the base of a series of gravel-covered interbedded carbonaceous mudstone and sandstone beds that form low hills on Tarantula Mesa (fig. 18). This formation is present only in the Henry Mountain Basin; however, it correlates to similar early late Campanian rocks of other areas (fig. 4).

The type section is 124.5 m thick and another section measured at the head of Spring Canyon is 71.5 m thick, but the top is probably eroded and the section is probably incomplete. Drill-hole data indicate that the Tarantula Mesa Sandstone is about 100 m thick under Tarantula Mesa.

Separation of upper and lower members was proposed by Peterson and Ryder (1975) and Peterson and Law (1980; fig. 6), and an attempt was made to map these two units. The boundary is mappable in some areas, but in much of the outcrop belt the contact is arbitrary.

Lower Tarantula Mesa Member

The base of the massive sandstone cliff was mapped as the lower contact of the lower Tarantula Mesa Member, and the base of a conglomeratic sandstone, where traceable, was mapped as the upper contact. The unit thins to the west with thicknesses ranging from 44.5 m in Spring Canyon to 65.5 m at the type locality.

Sandstone is grayish orange and very pale orange on fresh surfaces and weathers to pale red to yellowish gray. Sand grains are very fine to fine, subangular to angular, and moderately well sorted. Quartz and minor chert are the major constituents. Local lenses of chert-granule conglomerate are present near the top of the unit. The most characteristic features of the member are thick to massive channel fills (fig. 19) that contain low- to high-angle trough and wedge cross-beds, horizontal and climbing ripples, and local bioturbated or rooted areas.

Local carbonaceous mudstone lenses, less than 0.6 m thick, occur near the base of the unit. The mudstone is brownish gray, laminated, and gypsiferous, and it contains minor ironstone beds. Contacts between mudstone and sandstone units are undulating.

Upper Tarantula Mesa Member

A conglomeratic sandstone (fig. 20), which is often less resistant than the overlying sandstone, forms the base of the upper Tarantula Mesa Member. It is often possible to map this lower contact even from a distance because the conglomeratic sandstone forms a series of steplike ledges above the massive cliffs of the lower Tarantula Mesa Member. In other areas, where the conglomeratic sandstone forms the upper part of the massive cliff, contacts could not be mapped precisely. Conglomeratic sandstone occurs in the lower 6–12 m of the member and is overlain by a series of sandstone units that also form steplike ledges.

Total preserved thicknesses of this member range from 30 m in Spring Canyon to 47 m at the type section (fig. 18). The member thins to the west, but it may be due to erosion of uppermost beds.

Conglomerate makes up 30–50 percent of the lower conglomeratic sandstone beds and occurs as interbedded lenses or as pebbles concentrated along bedding planes (fig. 20). Well-rounded, poorly sorted chert granules and small pebbles characterize the deposit. Clasts are medium gray, very pale orange, and grayish orange. Interbedded sandstone is composed of fine- to coarse-sand-sized, moderately sorted quartz and chert grains and is characterized by trough cross-beds and hematite concretions.

Overlying sandstone units are grayish orange and weather very pale orange. The major constituents are fine- to medium-sand-sized subangular, moderately sorted quartz grains. The beds are also characterized by massive trough cross-beds in channel fills that are separated by limonite-rich horizons. Limonitic and hematitic concretions also occur throughout the unit.

Beds on Tarantula Mesa

The "beds on Tarantula Mesa," although not formally named, were first described by Peterson and Ryder (1975, p. 180) and represent the youngest Cretaceous strata of the Henry Mountain region (fig. 4). They consist of interbedded mudstone and sandstone beds that form low hills or mounds on the plateaulike upland of Tarantula Mesa. Gravel, consisting of diorite porphyry clasts, covers mounds in the eastern part of Tarantula Mesa, and chert gravels cover mounds in the center of Tarantula Mesa. Beds in the center of Tarantula Mesa are about 18 m thick. No diagnostic guide fossils have been found in them.

Sandstone occurs in medium to thick beds and forms ledges and slopes that protrude through the overlying gravels.

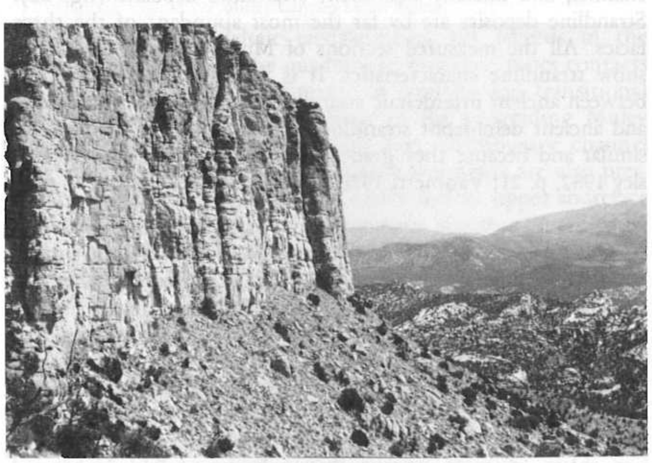


FIGURE 19.–Lower Tarantula Mesa Sandstone forms massive cliff just north of type section. Lenticular channel fills are dominant. In background, Muley Canyon beds hold up a cuesta.

FIGURE 20.–Conglomeratic sandstone of upper Tarantula Mesa Member at type section.

Very fine to fine, yellowish gray sand grains characterize the deposit. Mudstone units are carbonaceous, slightly silty, and bentonitic, and they form slopes.

Quaternary Deposits

Three types of Quaternary deposits have been differentiated in the quadrangle. They include pediment gravels in the eastern part, windblown sand and loess deposits on extensive flat areas, and stream deposits in the bottom of Muley Canyon.

Pediment Gravels

Pediment gravels form mounds (fig. 21) on the eastern edge of Tarantula Mesa, on the northeast part of Cave Flat, and on the cuesta east of Bullfrog Canyon. At least two pediment surfaces are recognized. The lower one cuts on top of the Muley Canyon Sandstone which caps Cave Flat and forms the cuesta east of Bullfrog Canyon. Only a small remnant of the upper pediment surface remains on top of Tarantula Mesa. Gravel was deposited over uparched Tarantula Mesa and Masuk beds east of Tarantula Mesa, but most of them were subsequently eroded.

Bullfrog Canyon has cut through the lower pediment surface and gravel veneer. Additional gravel terraces occur inside the canyon, and they were probably derived from mass wasting of higher pediment gravels.

The pediment gravels were derived from erosion of the Mt. Pennell and Mt. Ellen stocks because more than 90 percent of the clasts are diorite porphyry, and the remaining 10 percent consist of other igneous rocks. Cobbles and boulders are subrounded to very angular and are poorly sorted. The matrix is silty to clayey. No cobbles or boulders of sedimentary rocks were found; however, much of the matrix may have been derived from sedimentary rocks because they are present at elevations higher than the pediment gravels.

Windblown Sand and Loess

Windblown sand and loess are present as extensive pale red and pale reddish brown sheets or mounds on Cave Flat, Swap Mesa, and Tarantula Mesa. A windblown origin is suggested for sand in the mounds, and loess represents dust accumulated more or less as a blanket deposit. Many of the loess deposits are vegetated only with sage brush and lack juniper trees characteristic of other areas.

Very fine to medium, subangular, moderately sorted, limonite-stained grains characterize the sand deposits. Minor ironstone and chert fragments are locally present. Loess deposits are similar to sand deposits although they are finer grained. Grain characteristics of the Tarantula Mesa Sandstone and Muley Canyon Member are similar to those of the sand, and the similarity suggests that these formations may have been a source for the sand and loess.

Stream Deposits

Stream deposits are vegetated terraces and valley fills along the bottom of Muley Canyon. They are mappable on aerial photographs and from above, but no description is given because they are largely inaccessible.

WAVE-DOMINATED DELTA SYSTEM OF THE UPPER BLUEGATE SHALE AND LOWER MULEY CANYON SANDSTONE

Delta Classification

Deltas are classified according to the dominant physical processes that act to shape and modify them. Fisher (1969) proposed a classification scheme based on high constructive and high destructive processes. Construction of a delta front occurs as distributaries deposit sediment there. Destruction occurs as waves and tides modify existing deposits by eroding them and transporting them away from the delta front. Destructive processes can be subdivided into wave-dominated or tide-dominated processes. Galloway (1975) proposed three end members that show either fluvial, tidal, or wave dominance. A combination of these processes shapes and modifies most deltas.

FIGURE 21.—Pediment gravels forming low hills in eastern part of quadrangle, SE ¼, section 14, T. 33 S., R. 9 E.

Ancient fluvial-dominated deltas are lobate or digitate bodies that consist of large-scale, cross-bedded, lenticular sandstone channel fills and coarsening upward interdistributary deposits. Ancient tide-dominated deltas are digitate sand bodies formed from current ridges and channel fills oriented perpendicular to the shore. Neither of these descriptions fits the Muley Canyon-1 unit.

The Muley Canyon Sandstone has the broad areal extent characteristic of ancient wave-dominated deltas. Although sediment was first deposited at a single distributary point source, waves and longshore currents redistributed the bulk of that sediment laterally as part of the delta front or as part of an interdeltaic beach or barrier bar. The result was a sand body of broad extent that contains distributary mouth bar, distributary channel, and laterally equivalent strandline deposits (fig. 22). Strandline deposits are by far the most abundant of the three facies. All the measured sections of Muley Canyon Sandstone show strandline characteristics. It is impossible to distinguish between ancient interdeltaic strandline or barrier island deposits and ancient delta-front strandline deposits because the two are similar and because they grade laterally into one another (Balsley 1982, p. 21; Vaninetti 1978, p. 195).

Depositional System of the Prograding Muley Canyon Delta

As rivers debouch sediment into the ocean, one of three relationships occurs: (1) the rate of subsidence is greater than the rate of deposition; (2) the rate of subsidence is equal to that of deposition; or (3) the rate of subsidence is less than the rate of deposition (Curtis 1970).

Within the Muley Canyon delta progradation was rapid because deposition was greater than subsidence. Rivers changed course where their distributary systems were overlengthened, resulting in the formation of lateral delta lobes. As the delta system prograded seaward, imbricate delta wedges were formed. They are clearly visible in the cuesta just west of the study area. Although the massive sandstone appears to be continuous there, imbrication of two delta lobes can be seen in the cuesta between Swap Canyon and Spring Canyon in at least three places. This imbrication shows a northerly component of transport. Previous studies indicate a regional northeast direction of transport with a northwest-southeast-trending shoreline (Law 1980, p. 326). Further work is still needed to clearly document local shoreline trends.

No growth faults were seen in the prodelta and marine Bluegate Shale. Possible reasons for absence of such faults are twofold. Upper Bluegate sediments may have been silty enough to allow water to escape from them, thus reducing compactional overpressuring as seen in the Book Cliffs by Balsley (1982, p. 49). The maximum thickness of the Bluegate Shale is 457 m, and the overlying Muley Canyon Sandstone, which may contain one or two delta lobes, is only 91.5 m thick. This thickness was probably not enough to initiate growth faulting.

Slump structures and large, extensive ball-and-pillow structures form on steeper substrate slopes. Hubert and others (1971, p. 1656) demonstrated that pillow structures, formed on one-degree slopes in the late Cretaceous Cody-Parkman delta. Sand slid down this gentle, water-saturated slope and piled up as a series of structures. Ball-and-pillow structures are locally developed at the base of the Muley Canyon Sandstone in section 2 (NW ¼, section 35, T. 33 S, R. 9 E) but were not seen elsewhere. This lack of slump structures suggests that the slope of the Bluegate surface of accumulation substrate was probably less than 1°.

The ecology of Late Cretaceous foraminifera was similar to that of modern-day foraminifera on the family level (Maxfield 1976, p. 81). Modern analogs, using foraminifera recovered from the Mancos Shale, are helpful in reconstructing the depth of the Mancos Sea. Calcareous forms recovered from the lower Bluegate Shale indicate a water depth of 23–61 m, and agglutinate forms recovered from the middle Bluegate Shale suggest a water depth of 0–6 m. No specimens have been recovered from the upper Bluegate Shale. It is incorrect to assume that the water depth was the same as the thickness of 46-m-thick Muley Canyon delta lobes. Contemporaneous subsidence and compaction could allow a 46-m sandstone body to be deposited in a 6-m-deep body of water.

Muley Canyon Delta Facies

Most common deltaic environments left records in the Muley Canyon beds of the quadrangle; however, facies contacts are usually gradational. Sediments of prodelta and transitional environments accumulated in front of the prograding Muley Canyon delta. Distributary mouth bars, distributary channel fills, and laterally equivalent strandline sediments are also present. Strandline sediments show a lower and an upper shoreface and an overlying shore zone environment like that described by Harms and others (1975) (fig. 22). Delta-plain deposits accumulated behind and on top of the prograding delta front (fig. 6).

Prodelta Facies

The upper Bluegate Shale is of prodelta facies. Fine-grained, carbonaceous shale was deposited from the suspended load of rivers entering the Mancos Sea. The minor layers of siltstone were probably deposited during storms. Prodelta muds and shelf muds are indistinguishable in the high destructive deltas (Fisher and others 1969, p. 49), such as the Muley Canyon delta. Therefore, it is impossible to tell the boundary between the marine and prodelta parts of the Bluegate Shale.

Laminations in the shale are caused by fluctuations in sediment input and different sediment rates. Bioturbation is rare because most upper Bluegate beds are smoothly laminate. Fossils, including foraminifera, have not been seen in the upper Bluegate Shale (Maxfield 1976). Such a lack of fossils may have been due to either inhospitable environmental conditions or poor preservation. Carbonaceous material was preserved in a reducing environment, and bentonite beds were derived from the fallout of volcanic ash.

Transition Facies

Transition zone deposits consist of interbedded mudstone, siltstone, and sandstone. Mud and silt were also deposited from the suspended load like the prodelta clay and mud. Frequent storms carried sand from near the prograding delta front and deposited it as interbedded units between the mudstone and siltstone.

Rocks in this facies coarsen upward, as can be seen in the uppermost 6–9 m of the Bluegate Shale and the lowermost 0–9 m of the Muley Canyon Sandstone. Rocks of this facies are 8–18 m thick as compared to a 7-m thickness for a similar transition facies on a modern-day California coast (Howard and Reinick 1981, p. 828).

Undulating contacts are probably an indication of hummocky bedding or irregular loading and soft-sediment deformation. Horizontal and ripple laminations and limited bioturbation also occur. Comparison of these features with those of the modern-day California example (Howard and Reinick 1981, p. 828), shows that the lower Muley Canyon delta was probably deposited in a high-energy storm regime.

Distributary Mouth Bar Facies

Distributary mouth bar deposits (fig. 22) do not occur often in wave-dominated delta systems, and none were documented in this study. The distributary mouth bar was the point source for the sediment that was eventually redistributed by waves along the delta front. If found, these deposits should consist of cross-bedded, current ripple-laminated sandstone that contains abundant plant fragments.

Distributary Channel Facies

Distributary channel fills, as described by Balsley (1982, p. 186) (fig. 22), are also rare in wave-dominated deltas, and none were documented in this study. If found, these deposits should be cross-bedded, parallel-laminated, lenticular sandstone channel fills. This facies also lacks an upper bleached unit and overlying coal deposits.

Lower Shoreface Facies

The lower shoreface is that zone below effective wave-base (fig. 22). Sediment of this facies is characteristically very fine to fine-grained sandstone, which coarsens upward to fine- to medium-grained sandstone. Sedimentary structures include abundant horizontal laminations, hummocky stratification, minor bioturbation, and minor ripple laminations (figs. 6, 11). Bioturbation decreases and hummocky stratification increases upward.

The term ***hummocky stratification*** was proposed by Harms and others (1975, p. 87) for a structure often referred to in the past as truncated wave-ripple lamination (Campbell 1971, p. 826–27). Although this type of stratification is inclined, it differs from trough cross-bedding in the following ways: (1)

Dips are usually less than 10°; (2) beds are as commonly arched up as they are arched down; (3) laminations are parallel to erosional boundaries; and (4) dip directions are scattered, and a hummocky unit shows a three-dimensional pattern (Harms and others 1975, p. 87; Balsley 1982, p. 80; Dott and Burgeois 1982, p. 664).

During storms, rip currents and bottom currents carried sand in suspension and deposited it on the lower Muley Canyon-delta shoreface. Dott and Burgeois (1982, p. 666) have observed in other places that a single hummocky bed may have been produced by a single storm event or tsunami that lasted several days or weeks.

Basal lag deposits are often associated with hummocky stratification. Although they were not noted in the present study, Peterson and Ryder (1975, p. 178) observed quartzite granules up to 4 mm in diameter in the lower Muley Canyon beds.

There is a lack of fossils in the lower and upper shoreface outcrops. Heward (1981, p. 258) noted this same lack in similar outcrops and suggested that it was probably due to leaching, which is common in the shoreface environment.

Ripples, which were created by waves, and bioturbation are fair-weather products. They have been preserved locally, but hummocky and horizontal beds are much more common. Storms modified or obliterated fair-weather deposits, leaving predominantly the storm-produced horizontal and hummocky stratification.

Most of the lower Muley Canyon-1 unit is of the lower shoreface facies. Approximate thicknesses of 13–42 m for the lower shoreface facies compares with the 12–30-m thicknesses of rocks in the Late Cretaceous Blackhawk Formation (Balsley 1982, p. 79) and with the 5-meter thickness of a high-energy modern lower shoreface located on the California coast (Howard 1981, p. 828).

Upper Shoreface Facies

The upper shoreface or surf zone is the area affected by shoaling and breaking waves, surf, and longshore and rip currents (Balsley 1982, p. 97) (fig. 22). Fine- to medium-grained sandstone characterizes this facies in the Muley Canyon Sandstone. Sedimentary structures include horizontal laminations and low-angle trough cross-beds (figs. 6, 12). Bioturbation is rare. These characteristics were produced as a result of high energy (Heward 1981, p. 227).

This facies and the overlying shore zone facies are easily recognized because they form a conspicuous very pale orange to light gray unit that crops out over much of the quadrangle. It contrasts with the underlying light grayish orange lower shoreface facies. Balsley (1972, p. 74–75) proposed a reason for this color change. Dolomite grains which were winnowed by waves into the lower shoreface were subsequently colored by limonite pigment, thus producing the color contrast.

Upper shoreface deposits comprise the lower 3–8 m of the upper bleached sandstone (fig. 6). They compare to a 4-m

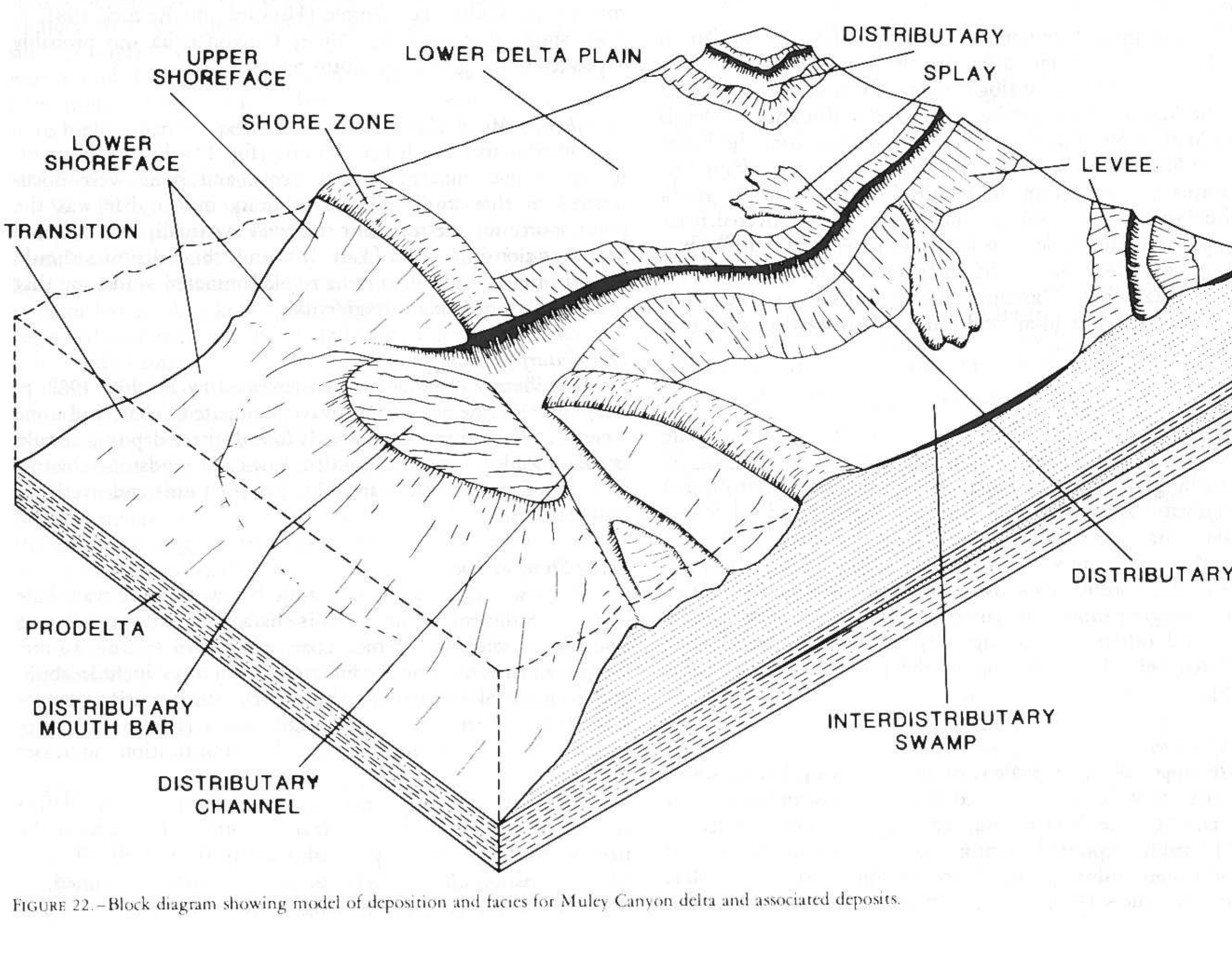


FIGURE 22.–Block diagram showing model of deposition and facies for Muley Canyon delta and associated deposits.

thickness of a modern-day upper shoreface on the California coast (Howard and Reinick 1981, p. 828).

Shore Zone Facies

The shore zone is the area exposed during normal tidal cycles and consists of the foreshore, the beach, and possibly the backshore (Harms and others 1975, p. 83; fig. 22). Fair-weather processes produced finer-grained sandstone with nearly horizontal low-angle cross-beds in Muley Canyon units. These rocks are overlain by nonbedded, sometimes rooted deposits that are overlain by coal or carbonaceous mudstone.

The upper 2–6 m of the Muley Canyon-1 sandstone characterize this facies (fig. 6). It compares with a 4-m thickness for the shore-zone sediments of the California coast (Howard and Reinick 1981, p. 828).

No extensive ridge and runnel deposits and sand dune deposits were noted within the shore-zone facies. They may have once been present but are not now preserved. A tropical climate probably existed during the deposition of the Muley Canyon delta, and Heward (1981, p. 229) suggests that dunes are not common in tropical climates because of abundant vegetation, damp sand, and low wind velocities. Extensive dunes, therefore, may never have developed on the shore of the Muley Canyon delta front.

Delta Plain Facies

The delta plain environment is characterized by lowland emergent or near-emergent topography, between distributary channels behind the prograding delta front beach (fig. 22). A variety of climate-sensitive environments occur and include distributaries, floodplains, tidal channels, and swamps and marshes in which sandstone, carbonaceous mudstone, and coal were deposited.

Sandstone was deposited in distributary channels, levees, or tidal channels. No tidal channels were recognized in the study area; however, Law (1980, p. 329–32) described several in the quadrangle to the north. Sandstone and carbonaceous mudstone were probably deposited in the interdistributary bays during floods when the distributaries either overflowed the levees or broke through as splays.

Late Cretaceous plants grew in poorly drained swamps and shallow lagoons and were quickly buried under reducing conditions. They were eventually converted to peat. Enough peat was accumulated under reducing conditions to produce minable seams of coal.

Rate of subsidence is an important factor controlling peat accumulation. If subsidence is too fast, swamps will be inundated and peat will not accumulate. If subsidence is too slow, peat above the water table will be oxidized (Balsley 1982, p. 183). A prograding delta system, such as the Muley Canyon delta, often provides this balanced rate of subsidence, as suggested by the presence of minable coal resources in the Muley Canyon Sandstone. Areas that lack coal may record occurrence of distributaries, contemporaneous structural deformation (Law 1980, p. 326, 329), or peat elimination by channel diversion into a backswamp area (Balsley 1982, p. 185).

Throughout most of the quadrangle, the lower coal seam lies directly on top of the shore-zone facies and is more widespread and thinner than upper seams. Upper coal seams within the Muley Canyon-2a interval are thicker but less extensive. From studies of Allegheny coal seams, Ferm and others (1979, p. 618–19) suggested that thin, widespread seams like the lower coal seams were formed behind a barrier beach, and thicker, less widespread coals like the upper seams were formed in lower delta plain backswamps.

Distributary channel fills of the Muley Canyon-2b unit separate the two coal intervals, and, since the upper coal interval is found higher up in the section, coals of that interval were probably deposited in backswamps of the upper delta plain. Generally these coal seams are thinner than those in the lower coal intervals, and their thinness may be due to peat elimination by channel diversion into backswamp areas. Upper channels cutting into coal seams were noted in measured section 9a (NE ¼, SE ¼, section 25, T. 33 S, R. 9 E) and in measured section 6a (SE ¼, section 17, T. 33 S, R. 9 E).

DEPOSITIONAL ENVIRONMENTS OF UPPER UNITS

Upper Muley Canyon-Lower Masuk Fluvial System

Rocks of the upper Muley Canyon Sandstone and lower Masuk Shale characterize an upper delta plain fluvial system that advanced behind the prograding Muley Canyon delta (fig. 6). Sandstone was deposited in river channels and on levees, and fine-grained sediments and coal were deposited in associated backswamp and lacustrine or estuarine environments.

The upper Muley Canyon beds show a high proportion of sandstone. Often during the course of deposition, finer material is eroded away as rivers and distributaries sweep over the floodplains. Several stacked channel systems separated by either coal beds, levee sandstone, or carbonaceous mudstone have been documented in measured sections 1, 4, 5, 6a, 7, 9a, 10, and 11 (fig. 10, map) of the upper Muley Creek beds. The more extensive fine-grained deposits of the Masuk-1 beds may have been preserved because rivers became more established in their courses.

Facies

Several facies, characteristic of meander belt systems, have been recognized in upper Muley Canyon and lower Masuk rocks. They include point bars and channel bars, swale fills, levee and overbank deposits, backswamp deposits, and minor crevasse splay deposits.

Thin lenses of lag gravel sometimes characterize the lower surfaces of point-bar and channel-bar deposits. One such lag gravel occurs in unit 12 of measured section 4, near the center of section 15, T. 33 S, R. 9 E. In modern settings, lag gravels are preserved when sand covers coarser bed load, thus allowing it to escape further transport (Allen 1965, p. 129).

Cross-bedded channel fills (fig. 14), which comprise most of Muley Canyon-3 rocks, are point-bar and channel-bar deposits. Sand was deposited on the inside of meanders until dune-like scroll deposits, with slip facies oriented toward the inside of the meanders, were formed. Bed load moved along as sand waves and produced linguoid or transverse bars with slip faces oriented downstream.

Current directions are highly variable in upper Muley Canyon beds because both point-bar and channel-bar deposits are probably present. The dominant current trend is to the northwest, although minor trends to the northeast and southeast are also present. Many additional observations will be needed to adequately determine the major direction of transport because of the high dispersion of current directions.

Channel fills average 1–2 m thick and are generally several tens of meters wide, an indication of the width and depth of streams that produced these deposits. Channel systems are divided stratigraphically at horizons that contain platy levee sandstone or abundant backswamp carbonaceous mudstone or coal.

Minor carbonaceous mudstone lenses found within the channel deposits are probably swale fills. During waning phases of high water, finer-grained suspended material was deposited in the arcuate hollows or swales on the point bars. When regular flow resumed, the bars protected the fine-grained deposits from erosion following observations noted elsewhere by Allen (1965, p. 145).

The fining-outward sequence from channel to levee to floodplain deposits in modern analogs is recorded as a fining upward sequence in ideal fluvial stratigraphic sections. In the Muley Canyon-3 beds, very fine grained platy sandstone and carbonaceous mudstone deposits overlie channel sandstone deposits. Examples can be seen in unit 12 of measured section 1 (NE ¼, section 22, T. 33 S, R. 9 E), units 10 and 11 of measured section 10 (section 2, T. 34 S, R. 8 E), and units 9–11 of measured section 11 (NE ¼, section 26, T. 33 S, R. 9 E).

The platy, hematite-rich sandstone of unit 12, section 1, which overlies channel systems, is a levee sandstone (fig. 14). Generally levee deposits are less than 1 m thick and are sometimes overlain by and grade laterally into carbonaceous mudstone. Levee deposits of the more estuarine Masuk-1 unit are less clearly differentiated although uppermost parts of the sandstone channel fills often contain abundant hematite.

Mudstone and shale characterize the floodplain or backswamp deposits and represent suspended material deposited during floods. Abundant plants in the backswamps and associated reducing conditions in poorly drained areas helped produce carbonaceous, rooted mudstone and minor coal beds in the upper Muley Canyon and lower Masuk beds. Laminated shales of the lower Masuk beds may have been formed in lacustrine or estuarine environments.

Ironstone deposits are abundant throughout the Muley Canyon and Masuk Members as layers interbedded with carbonaceous mudstone and as concretions. Much of the bedded ironstone is siderite, but hematite and limonite are also present as beds and as nodules where iron-bearing minerals have been oxidized. Bands of siderite float indicate that bog-iron is abundant in the Masuk Shale floodplain deposits as well. Bedded bog-iron deposits are characteristic of humid-climate backswamps (Krauskopf 1967, p. 263).

Several ideas have been proposed to explain the presence of ironstone in units like the Masuk and Muley Canyon beds. Bacteria act as catalysts, cause iron to precipitate, and use the energy derived from the chemical reaction (Krauskopf 1967, p. 260). Ammonia and carbon dioxide, which are given off by decaying organisms, may also cause the formation of iron concretions and bedded deposits (Degens 1965, p. 125). Hematite forms under more acidic conditions, and limonite forms under more alkaline conditions (Krauskopf 1967, p. 260).

Some coarser lenses contained in a larger mudstone unit near the top of measured section 4 (NE ¼, section 15, T. 33 S, R. 9 E) may be splay deposits. These coarsening-upward lenses consist of interlaminated sandstone and carbonaceous siltstone and are flat bottomed. Splay deposits form where levees are breached and coarser material is deposited in the floodplain.

Upper Masuk Shale Interdeltaic Environments

During deposition of Masuk-1 beds, the main delta system shifted to another location so the Masuk-2 beds were probably deposited in interdeltaic fluvial and estuarine environments. Channel courses were more fixed, causing a higher proportion of fine-grained floodplain deposits.

Horizontal laminations and ripple laminations (fig. 17) were produced in river and estuarine channels with a low flow regime like those cited by Reading (1978, p. 26). Small-scale cross-laminations that show a strong direction and a weak opposed direction (fig. 16) suggest that tides influenced sedimentation. The strong direction was probably a result of river current and ebbing tides, and the weak direction was a result of flooding tides. Cross-laminated sets, parallel beds, and ripple laminae are similar to those in the estuarine Fall River Formation in northeastern Wyoming described by Campbell (1973).

Peterson and Ryder (1975) and Peterson and Law (1980) reported *Corbula*, a brackish-water pelecypod, and freshwater gastropods, pelecypods, and garpike scales from Masuk beds. Shark teeth have been reported by Hunt (1953, p. 85), but sharks may have extended far up into channels in estuarine environments.

Tarantula Mesa Braided Stream Deposits

Floodplain, meandering stream, and estuarine beds gradually change upward to braided stream deposits in the Tarantula Mesa Sandstone as sandstone channel fills become more abundant. Extensive sandstone sheets, such as the Tarantula Mesa Sandstone are produced by braided streams because finer-grained sediment is more likely to be removed by higher river velocities and laterally shifting streams (Reading 1978, p. 753). The Tarantula Mesa sand sheet is similar to the Westwater Canyon Member of the Morrison Formation, which forms a sand sheet 100 km wide and 160 km long and has been interpreted as a braided stream deposit (Campbell 1976, p. 1009–10). The cross-bedded lenticular units are a result of sand wave deposition that occurs in rivers of moderate flow regime.

In the past the Tarantula Mesa Sandstone has been interpreted as a beach deposit (Hunt 1953, p. 86; Doelling and Graham 1972, p. 172), possibly because of the well-sorted, mature nature of the sandstone and bioturbation in lower beds. The lenticular nonbedded conglomerate (fig. 20) in the lower part of the upper member is more characteristic of braided stream deposits because a persistent, regular depositing agent—such as waves—produces less lenticular, more bedded conglomerates than those of the Tarantula Mesa Sandstone (Clifton 1973).

REGIONAL CORRELATIONS

The Sevier orogenic belt in eastern Nevada and western Utah was the source of the Late Cretaceous sediments deposited in eastern Utah (Spieker 1949, Reeside 1957, Armstrong 1968, Kauffmann 1977). A foredeep basin developed east of the orogenic belt and was periodically inundated by the sea. The thickest accumulation of sediment occurred near the western margin of the basin where subsidence rates were greatest (Kauffmann 1977, p. 78). During times of maximum transgression, a seaway extended from the Gulf of Mexico to Alaska (Spieker 1949). Local regression occurred when deltas prograded into the shallow seas during times of accelerated erosion in the orogenic belt (Kauffmann 1977, p. 81). Transgression occurred during periods of tectonic quiescence.

Five Late Cretaceous transgressive-regressive cycles have been documented in eastern Utah (Peterson and Ryder 1975, Peterson and Law 1980). Evidence of some of these cycles is present in the Late Cretaceous strata exposed in the Henry Mountains. Figure 4 is a compilation of work done by Peterson and Ryder (1975), Peterson and Law (1980), Maxfield (1976), Obradovich and Cobban (1975), and Vaninetti (1978) and shows the cycles and formations that were deposited as a result of Late Cretaceous transgression and regression in eastern Utah.

The Turonian Tununk Shale was deposited over the Dakota Formation during the first transgression. Several deltaic lobes of the Ferron Sandstone Member later prograded into the shallow seas causing the first regressive cycle (Cotter 1976).

The Bluegate Shale was deposited during the late Coniacian, early Santonian transgression. A later regression resulted in the deposition of the John Henry Member of the Straight Cliffs Formation in the Kaiparowits region and the Emery Sandstone Member of the Mancos Shale in the Wasatch Plateau; however, shoreline clastic deposition did not extend into the Henry Mountain region during this regression. The Masuk Shale of the Wasatch Plateau was deposited during a third transgression.

The Muley Canyon Sandstone of the Henry Mountains and Starpoint Sandstone of the Wasatch Plateau were deposited during an early Campanian third regression. This regression continued into the early-late Campanian as deltas shifted and a variety of nearshore environments were produced in the Henry Mountain region.

Nonmarine and interdeltaic deposits make up the lower Wahweap Formation of the Kaiparowits region (Peterson and Ryder 1975) and equate with the interdeltaic Masuk Shale of the Henry Mountain Basin. These two formations are similar and correlate with each other, but are not contemporaneous with the marine Masuk Shale of the Wasatch Plateau. The deltaic to lagoonal Blackhawk Formation was also deposited during this regression, but that delta system is not related to the Muley Canyon delta system since the Blackhawk delta was deposited later in the regressive phase and was probably derived from a northwest source (Balsley 1982).

A fourth Late Cretaceous transgression occurred after deposition of the Blackhawk Formation, but marine beds do not extend into the Henry Mountain region. The Tarantula Mesa Sandstone, exposed on Tarantula Mesa and nearby buttes, the Castegate Sandstone of the Wasatch Plateau, and the upper Sandstone Member of the Wahweap Formation in the Kaiparowits region were deposited during a late Campanian fourth regression (Peterson and Ryder 1975, p. 184). These three units were deposited by braided streams, and Peterson and Ryder (1975, p. 185) suggest that these units are isolated remnants of a once extensive braided stream sand sheet.

A fifth transgressive cycle seen in beds to the east is not documented in the Henry Mountains because rocks of that age are not preserved here. Peterson and Ryder (1975, p. 185) postulated that between 600 and 1,200 m of fluvial rocks may have been deposited on top of Tarantula Mesa beds but have been removed by erosion.

ECONOMIC POTENTIAL

Coal

Coal is the major mineral resource of the quadrangle and occurs in one to four seams in each of two intervals in the Muley Canyon Member. Most coal seams in the quadrangle are thin or lenticular and rarely exceed 1.3 m (4′); however, individual seams, located on north Cave Flat and south Swap Mesa near Muley Canyon, approach a 3-m (9.5′) thickness.

Underground mining in the quadrangle is impractical because coal seams are often thin or lenticular, but coal could be economically strip-mined in areas where overburden is thin. In order to determine possible areas within the quadrangle that could be economically strip-mined, isopach, interburden, and overburden maps were constructed.

Isopach maps (figs. 23, 24) of total coal thicker than 0.6 m (2′) within each coal interval were constructed, using surface and subsurface data (Doelling and Graham 1972; Law 1977, 1979a,b). Coals of the lower coal interval (fig. 23) are thicker and more widespread and, therefore, could be considered for strip-mining. The lowest seam within the interval rarely exceeds 1 m (3′), but additional upper seams, where present, cause the total coal to become thick. Thick seams cover areas of between 1 and 3 km². Local thick areas of interest occur on south Swap Mesa where minable coal reaches a 5-m (16′) thickness, at the head of Bitter Creek Canyon where total coal is 4 m (13′) thick, and on north Cave Flat where coal is often more than 3.3 m (10′) thick (fig. 23).

Total coal in the upper coal interval (fig. 24) rarely exceeds 2 m (6.4′), but coal up to 3.6 m (12′) thick occurs in sections 18 and 19, T. 33 S, R. 8 E. Coal within this interval would probably be considered for strip-mining only in areas where it overlaps minable coal of the lower coal interval, such as on north Cave Flat and upper Bitter Creek Canyon.

The overburden map (fig. 25) shows the amount of material above the lower coal interval and the interburden between individual coal seams within that interval. In areas where coal intervals overlap, an interburden map (fig. 26) shows interburden between the coal intervals as well as interburden within the lower coal interval.

There are several places within the quadrangle that contain thin overburden and thick coal, where coal could be economically strip-mined. An overburden of less than 24 m (80′) occurs over most of Cave Flat, and coal in the northern part of this area is thick enough to mine. Overburden on Swap Mesa is generally less than 48 m (160′) thick, and coal located in part of section 23, T. 33 S, R. 8 E, section 32, T. 33 S, R. 9 E, and section 5, T. 34 S, R. 9 E, is thick enough to mine as well. Although areas of thin overburden occur north of Muley Canyon, the coal there is generally too thin to mine.

Nearly all the overburden and interburden between coal intervals is sandstone. Interburden between coal seams within the coal intervals is either carbonaceous mudstone, siltstone, or fine-grained sandstone.

A sulfur content of between 0.46 and 0.78 percent in Cave Flat coals makes them additionally attractive (Doelling and Graham 1972, p. 174). The coal contains between 10,856 and 11,468 BTUs per pound (Doelling and Graham 1972, p. 174).

Although no mining has been done, exploratory holes have been drilled on Cave Flat, north Swap Mesa, and Tarantula Mesa, by one company and by the U.S. Geological Survey. Estimated and inferred reserves are about 45 million tons (Doelling and Graham 1972, p. 174).

Several factors presently impede development of these deposits. The area is remote, and more economical deposits occur in the more accessible areas of the Wasatch Plateau. Local environmental issues and a depressed coal market also pose problems. Because this area is one of the few in Utah presently feasible for strip-mining of coal, it may be developed in the future.

Oil and Gas

Some exploratory drilling has been done in nearby areas. Webb Resources drilled a well in 1971 on Cave Flat, 0.5 km east of the quadrangle, in section 24, T. 33 S, R. 9 E. The well was targeted for the White Rim Sandstone and produced fresh water. Two additional wells were drilled by Webb Resources 9.7 km north of the study area in section 22, T. 31 S, R. 9 E, and they also failed to produce oil or gas. Exxon Corporation is presently drilling a well 12 km northeast of the quadrangle in section 24, T. 31 S, R. 9 E. The target is also a pinchout of the White Rim Sandstone.

SUMMARY

The Late Cretaceous rocks of the Henry Mountain region were deposited in a variety of marine, nearshore, and continental environments (fig. 6). The Bluegate Shale was deposited in

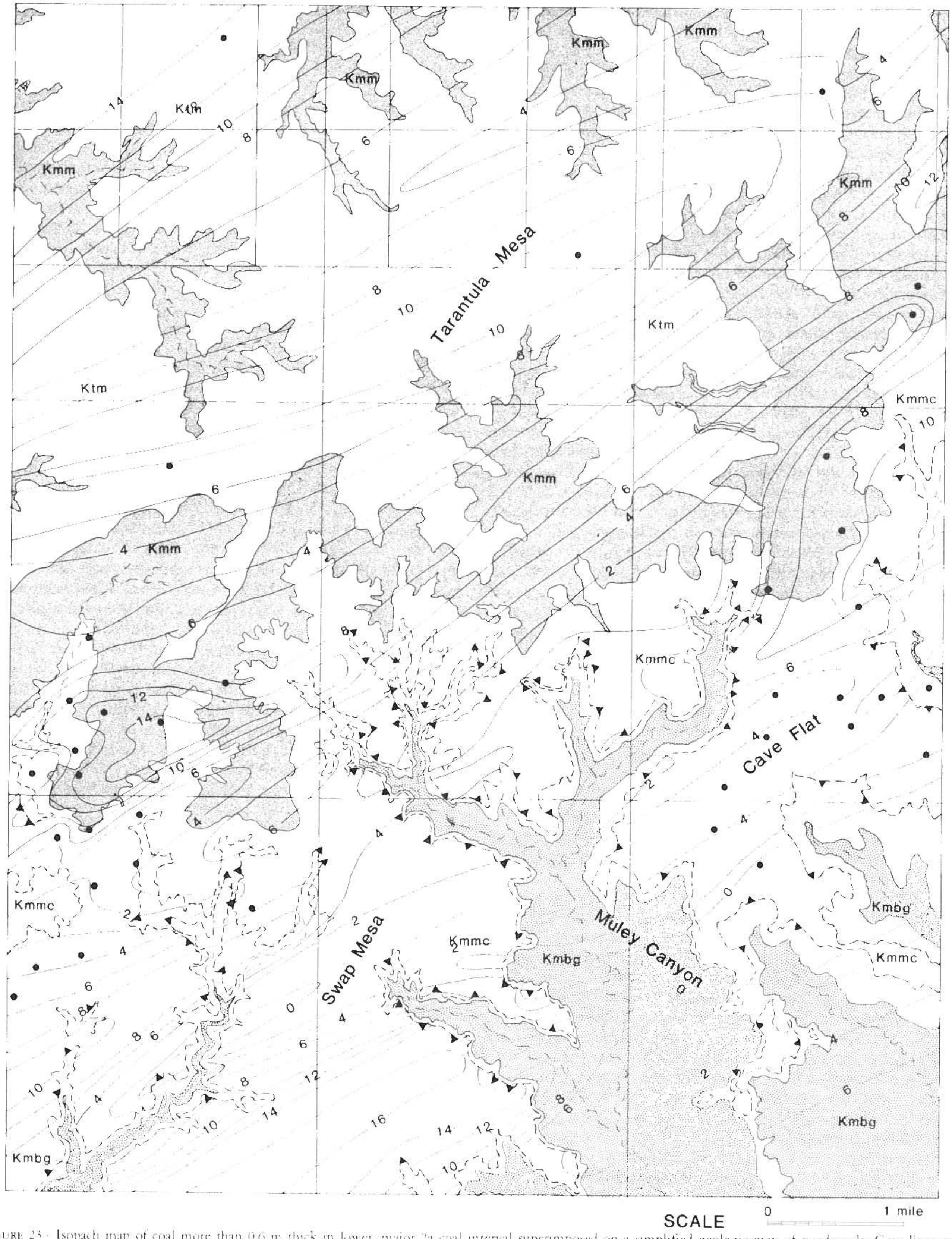


FIGURE 23. Isopach map of coal more than 0.6 m thick in lower, major 2a coal interval superimposed on a simplified geologic map of quadrangle. Gray lines = geologic contacts; Kmbg (light gray) = Bluegate Shale, Kmmc = Muley Canyon Sandstone, Kmm (dark gray) = Masuk Shale, Ktm = Tarantula Mesa Sandstone. Thick, light gray dashed lines = coal outcrops in Muley Canyon Sandstone. Circles = drill-hole data points; triangles = surface data points. Dark lines = coal thicknesses. Dotted lines = inferred thicknesses where coal has been eroded. Contour interval = 2 feet.

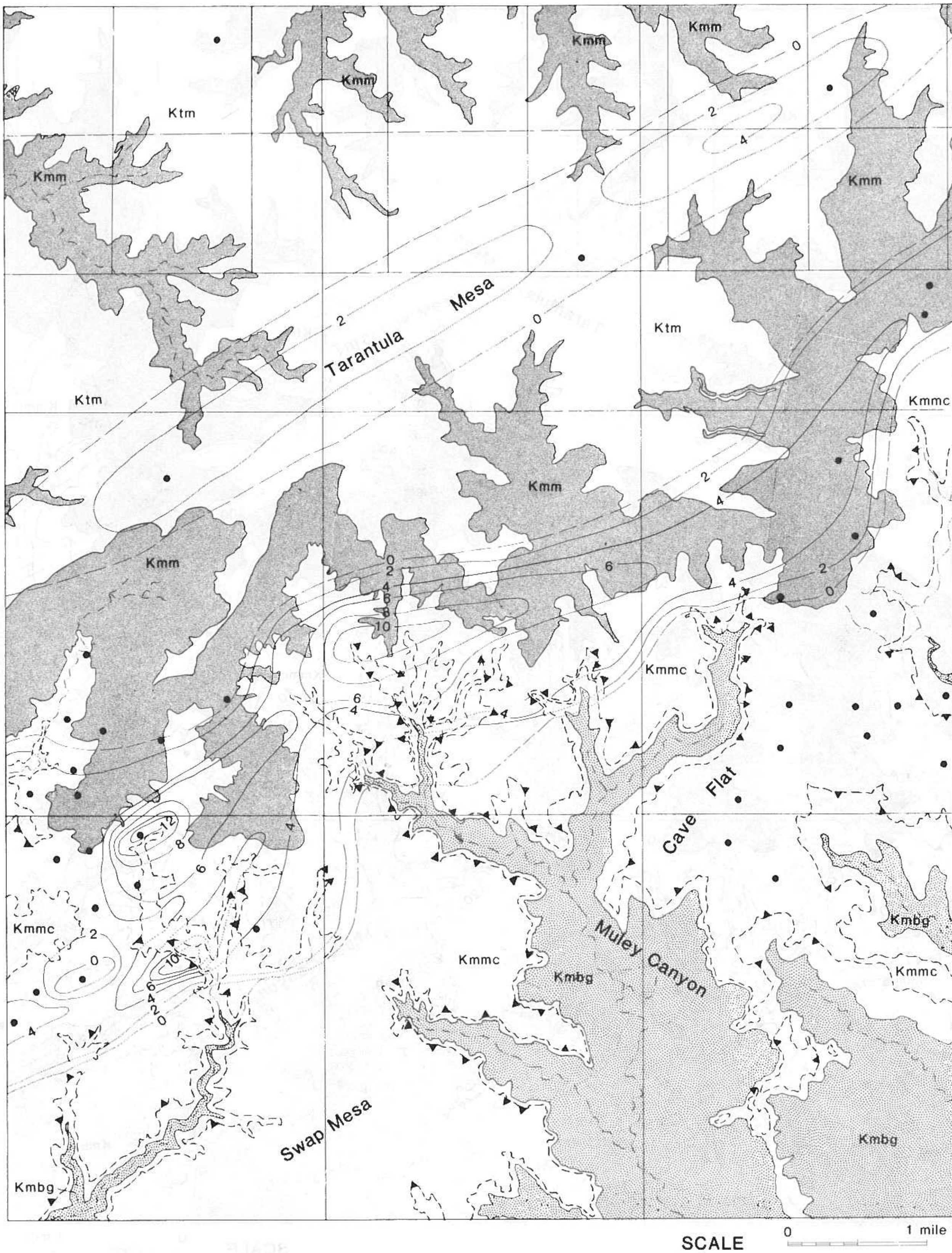


FIGURE 24.—Isopach map of coal more than 0.6 m thick in upper 2c coal interval superimposed on simplified geologic map of quadrangle. Gray lines = geologic contacts; Kmbg (light gray) = Bluegate Shale, Kmmc = Muley Canyon Sandstone, Kmm (dark gray) = Masuk Shale, and Ktm = Tarantula Mesa Sandstone. Dashed lines = coal outcrops in the Muley Canyon Sandstone. Circles = drill-hole data points, triangles = surface data points. Dark lines = coal thicknesses. Dotted lines = inferred thicknesses where coal has been eroded. Contour interval = 2 feet.

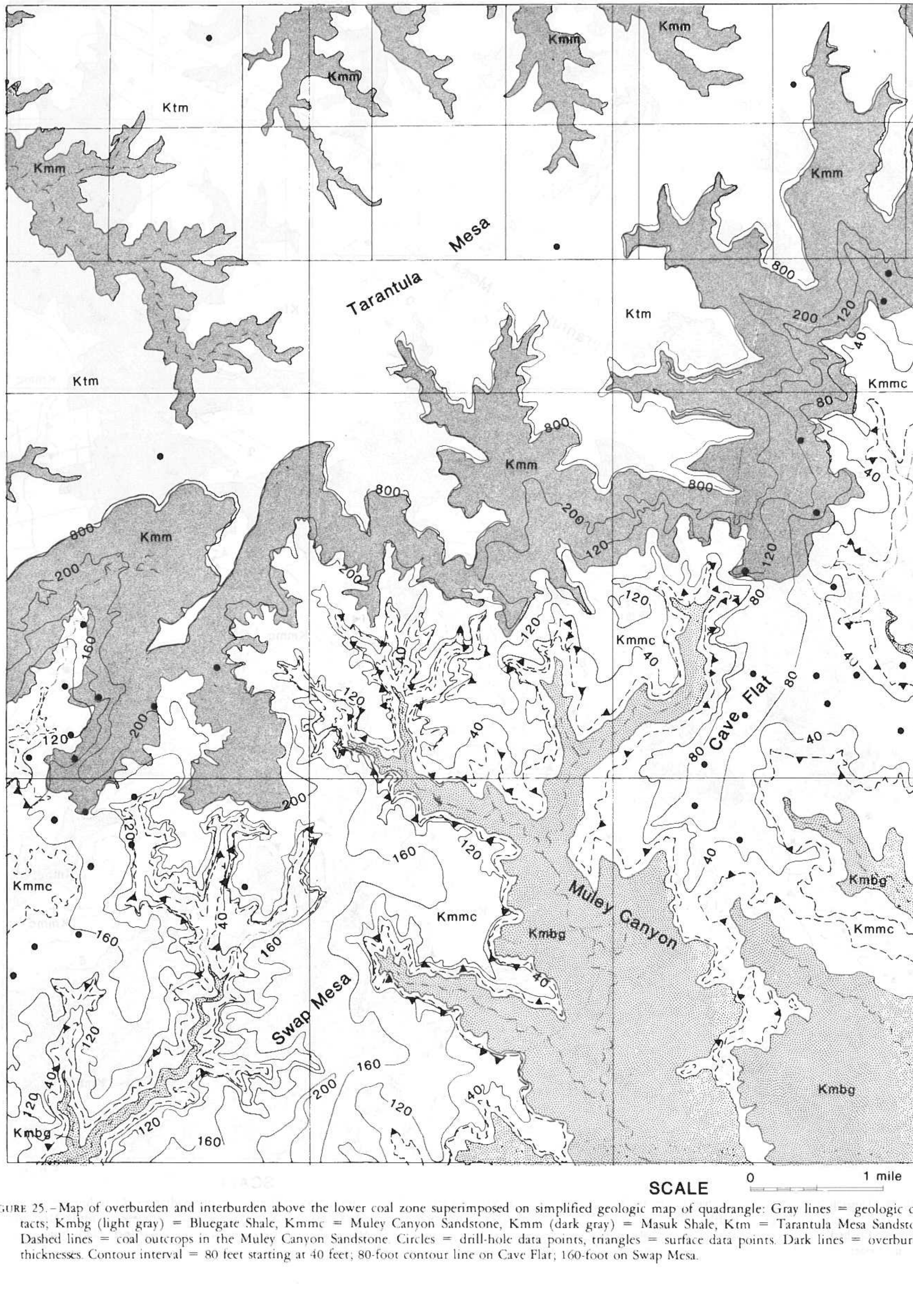


FIGURE 25.–Map of overburden and interburden above the lower coal zone superimposed on simplified geologic map of quadrangle: Gray lines = geologic contacts; Kmbg (light gray) = Bluegate Shale, Kmmc = Muley Canyon Sandstone, Kmm (dark gray) = Masuk Shale, Ktm = Tarantula Mesa Sandstone. Dashed lines = coal outcrops in the Muley Canyon Sandstone. Circles = drill-hole data points, triangles = surface data points. Dark lines = overburden thicknesses. Contour interval = 80 feet starting at 40 feet; 80-foot contour line on Cave Flat; 160-foot on Swap Mesa.

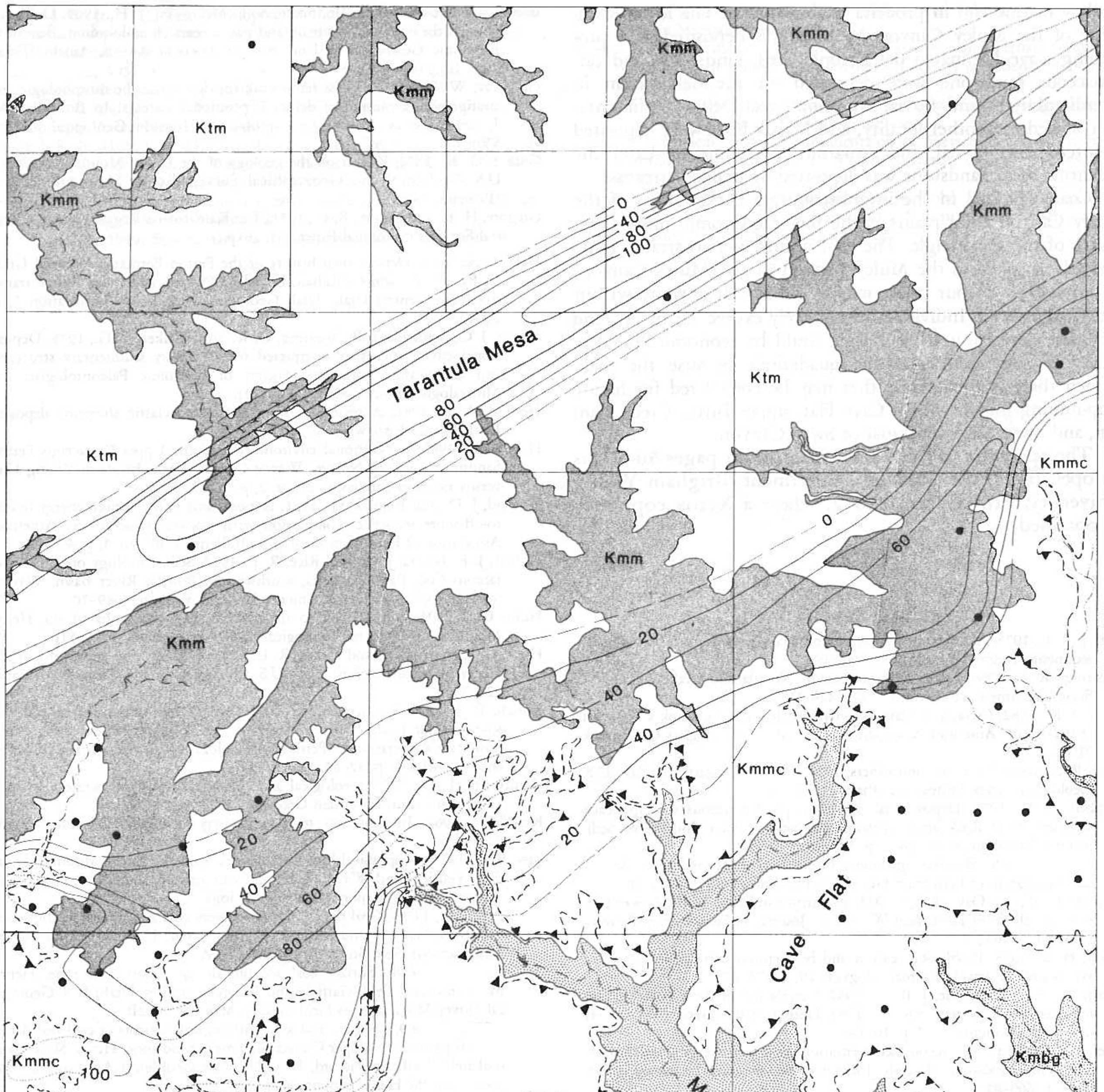


FIGURE 26.–Map of interburden between coal intervals and in lower coal interval where two intervals overlap; superimposed on a simplified geologic map of quadrangle: Gray lines = geologic contacts; Kmbg (light gray) = Bluegate Shale, Kmmc = Muley Canyon Sandstone, Kmm (dark gray) = Masuk Shale, and Ktm = Tarantula Mesa Sandstone. Dashed lines = coal outcrops in Muley Canyon Sandstone. Circles = drill-hole data points; triangles = surface data points. Dark lines = interburden thicknesses. Dotted lines = inferred thicknesses where interburden has been eroded. Contour interval = 20 feet.

shallow marine and in prodelta environments. The lower sandstone of the Muley Canyon Member was deposited as a prograding wave-dominated delta front. Coal, sandstone, and carbonaceous mudstone were deposited on the delta plain in interdistributary and fluvial environments. Deltaic sedimentation shifted to another locality, and Masuk beds were deposited in interdeltaic, fluvial, and estuarine environments. Later the Tarantula Mesa Sandstone was deposited by braided streams.

Coal deposited in the interdistributary backswamps of the Muley Canyon delta plains is the major economic mineral resource of the quadrangle. The coal occurs in two stratigraphic intervals, mapped as the Muley Canyon-2a and Muley Canyon-2c units. One to four seams may be present at any site within each coal interval. Individual seams rarely exceed 1.3 m (3′) and are often discontinuous, but they could be economically strip-mined in several areas of the quadrangle because the overburden there is thin. Areas that may be considered for future strip-mining include north Cave Flat, upper Bitter Creek Canyon, and Swap Mesa southeast of Swap Canyon.

The appendix to this paper, manuscript pages 50–71, is on open file in the Geology Department, Brigham Young University, Provo, Utah 84602, where a Xerox copy may be obtained.

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