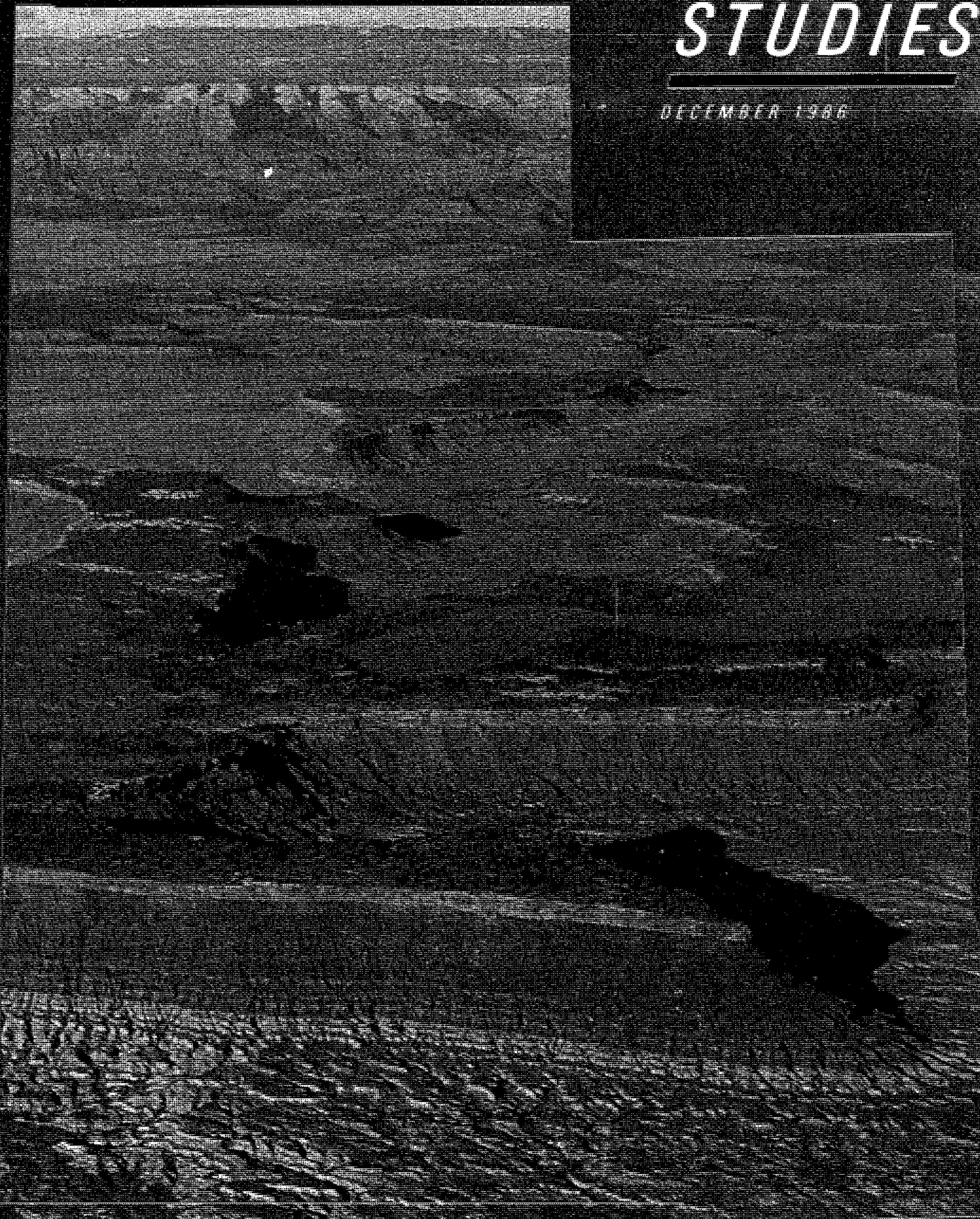
BRIGHAM YOUNG UNIVERSITY

GEOLOGY STUDIES

DECEMBER 1986



VOLUME 33, PART 1

BRIGHAM YOUNG UNIVERSITY GEOLOGY STUDIES

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THE GLORY OF GOD IS INTELLIGENCE

A publication of the
Department of Geology
Brigham Young University
Provo, Utah 84602

Brigham Young University Geology Studies is published by the Department of Geology. This publication consists of graduate student and faculty research within the department as well as papers submitted by outside contributors. Each article submitted by BYU faculty and outside contributors is externally reviewed by at least two qualified persons.

Cover: Moenkopi Formation, Southern Utah

ISSN 0068-1016
Distributed December 1986
12-86 600 24422

Geology, Depositional Environment, and Coal Resources of the Sego Canyon 7½-Minute Quadrangle, near Green River, East Central Utah*

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ABSTRACT

The Sego Canyon 7½-Minute Quadrangle is located in the Book Cliffs of eastern Utah and contains an exposed section of Upper Cretaceous through Eocene rocks approximately 1110 m (3640 ft) thick. Lowest exposed strata are the upper part of the Mancos Shale, which were deposited in a shallow open-marine environment during part of the maximum transgression of the interior Cretaceous seaway. Overlying units were deposited along the western regressive margin of the seaway in wave-dominated delta systems, backshore delta-plain swamps, and fluvial and lacustrine floodplains. Deposition was interrupted by two, or possibly three, major periods of erosion, possibly one after deposition of the Farrer Formation, another after deposition of the Tuscher Formation, and another after deposition of the conglomerate beds of Dark Canyon.

The quadrangle is near several north–northwest-trending Precambrian structural lineaments. Faults along the lineaments have been reactivated periodically, affecting structure and stratigraphy in the area. Salt diapirism in the Paradox Basin, controlled by these faulted lineaments, has resulted in long linear salt anticlines, such as the Thompson Anticline. Drape folding caused by the largest Precambrian lineament, the Uncompahgre Fault, formed Sagers Wash Syncline.

Coal deposits up to eight feet thick accumulated in backshore delta-plain swamps during the regressive phase of Mancos Sea deposition. Three seams within the quadrangle contain significant minable thicknesses. These have been exploited in the past but proved only marginally profitable. High ash content, splits, poor roof rock, and changing economic conditions were the main problems encountered. The coal is primarily low sulfur, high volatile bituminous B. The quadrangle is adjacent to several producing oil and gas fields and there is good potential for hydrocarbon discoveries, both in Mesozoic reservoirs and in deeper Paleozoic structures related to the Paradox Basin. Drilling in the quadrangle has resulted in several shows and minor production.

INTRODUCTION

The Sego Canyon 7½-Minute Quadrangle contains significant coal deposits and has good potential for substantial hydrocarbon discoveries. A better understanding of the depositional and structural history of the quadrangle is important to the future location and development of these resources. Because the quadrangle is located in the foredeep basin of the Sevier orogenic belt, overlies the Uncompahgre Fault, and has deeply incised canyons with excellent exposures, it is important to the study of the Late Cretaceous and early Tertiary history of east central Utah. Also, the thickest known coal beds in the Sego Coal Field are in Sego and Thompson Canyons in the central part of the quadrangle.

The primary purpose of this study is to map the surface geology of the quadrangle, but it also emphasizes coal resources, the descriptions and environments of deposition of exposed formations, structural history, subsurface geology, and hydrocarbon potential of the quadrangle.

*A thesis submitted to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree of Master of Science, March 1984.

Previous workers have documented that structural history of the area, including salt diapirism, has been controlled in large part by recurrent movement on a series of northwest-trending faults that first developed during the Precambrian. The largest of these, the Uncompahgre Fault, bisects the quadrangle and had a major impact on depositional systems, especially in the late Paleozoic (Baars 1966, p. 2082–2111; Baars and Stevenson 1981, p. 23–31, and 1982, p. 131–158).

LOCATION AND ACCESSIBILITY

The Sego Canyon Quadrangle is located in Grand County, Utah, and includes part of the south-facing Book Cliffs. The area is about 40 km (25 mi) east of Green River, Utah, and 50 km (30 mi) west of the Utah-Colorado border (fig. 1).

The town of Thompson is 4 km (2.5 mi) south of the quadrangle. U.S. 70 parallels the southern quadrangle margin, 5 km (3.2 mi) to the south. Access into the area is by a maintained dirt road that bisects the quadrangle through Sego Canyon, and by four-wheel drive roads in Upper Thompson Canyon, near Sagers Wash, in Nash Canyon, in Left Hand Bull Canyon, and along a wide bench in the southern part of the quadrangle.

METHODS

Mapping was done on aerial photographs with a scale of 1:20,000. In addition, field mapping and correlation was done on a preliminary topographic map of the 7$^1/_2$' series with a forty-foot contour interval. The final map was prepared from these two field sources. Formation boundaries shown on maps by Doelling and Graham (1972) and maps of parts of the Sego Canyon, Thompson, Crescent Junction, and Floy Canyon Quadrangles by Gualtieri (1981b, 1982) were evaluated during the present study.

Stratigraphic sections were measured through all formations at several locations using a Jacob's staff and Brunton compass. Fossils and trace fossils were collected. Detailed coal sections were measured at locations not already documented by Doelling and Graham (1972). Coal channel samples were collected through sections or partial sections of the three significant coal seams at seven locations throughout the quadrangle. These will be ana-

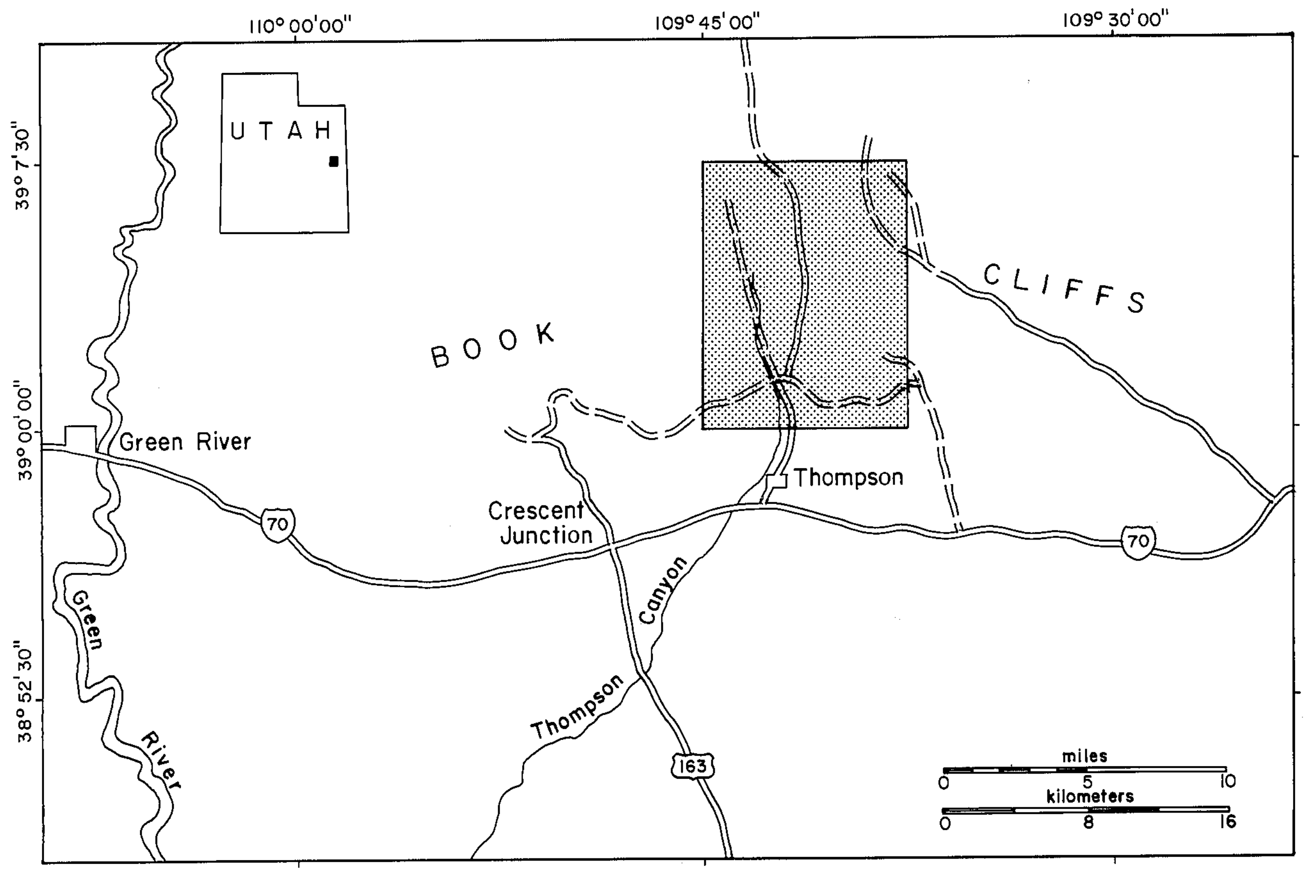

FIGURE 1.—*Index map of the Sego Canyon 7$^1/_2$' Quadrangle, Grand County, Utah.*

lyzed by the Utah Geological and Mineral Survey. Results were not available at the time of this writing.

Geophysical logs and well data on file with the Utah Department of Oil, Gas, and Mining were used to help select unit boundaries, correlate units, develop cross sections, determine structure, and locate salt concentrations.

The geologic map, structural contour map, and coal maps, along with an abbreviated version of this report will also be published by the Utah Geological and Mineral Survey (Willis 1986).

PREVIOUS WORK

Geology of the Book Cliffs was first documented by Peale (1878) as part of the Hayden Survey. The next important paper was by Richardson (1909), who included a generalized map of the Book Cliffs coal field. Four units were differentiated on his map, including the Dakota Sandstone, Mancos Shale, Mesaverde Formation, and Eocene rocks.

Fisher (1936) completed the most detailed study of the area to date. He concentrated on coal-bearing units.

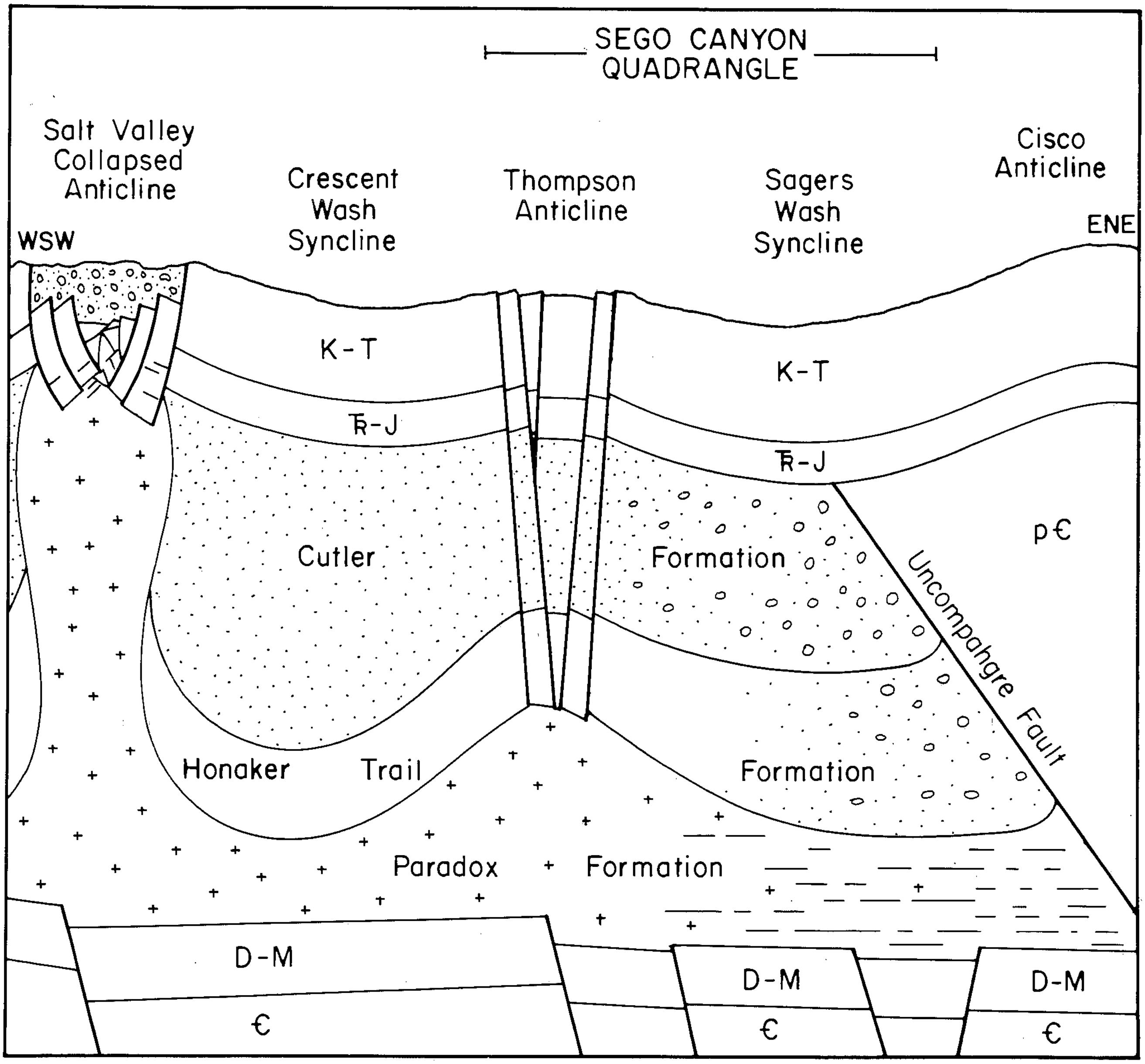

FIGURE 2.—*Schematic cross section showing relationship of structural geology of the Sego Canyon Quadrangle to regional structures. No scale, but vertical is greatly exaggerated. After Baars and Stevenson (1981) and Frahme and Vaughn (1983).*

Fisher, Erdmann, and Reeside (1960), the main workers in the area at that time, compiled information on the stratigraphy, paleontology, and nomenclature of the eastern Book Cliffs. Doelling and Graham (1972) reviewed the coal resources of the region and published a generalized geologic map at a scale of approximately 1:50,000 and several measured sections through coal horizons. Gualtieri (1981b) mapped the southern and eastern parts of the quadrangle at a scale of 1:62,500 and showed more detail than previous workers.

Other pertinent studies on stratigraphy or regional geology include Clark (1914), Spieker and Reeside (1925), Erdmann (1934), Spieker (1946, 1949), Young (1955, 1966), Walton (1956), Sanborn and others (1956), Gross (1961), Baars (1966), Balsley (1980), Baars and Stevenson (1981, 1982), Lawton (1983), Frahme and Vaughn (1983), and Fouch and others (1983).

GEOLOGIC SETTING

PRECAMBRIAN

Geology in the Sego Canyon Quadrangle has been strongly influenced by two long-lasting, related tectonic structures, the north–northwest-trending Olympic-Wichita lineament, and the northeast-trending Colorado lineament (Baars and Stevenson 1981). The two lineaments intersect near Moab, Utah, and together form a conjugate shear set, the Colorado lineament being subordinate. These have been dated at 1700 mybp (Baars and Stevenson 1981, p. 23). Study of Precambrian faulting and folding patterns show these to be the result of continental-scale north–south compression or right lateral wrench faulting (Baars and Stevenson 1982, p. 136). Strain ellipsoid studies show that such stress should produce north–northwest-trending normal faults. Such faults have been documented in the Precambrian basement in the subsurface in the quadrangle and nearby areas (Baars and Stevenson 1982; Frahme and Vaughn 1983). These normal faults, along with the Olympic-Wichita lineament that became the boundary fault of the Uncompahgre Uplift, have controlled structure in the area since Precambrian time (fig. 2) (Baars and Stevenson 1982).

Precambrian rocks underlying the quadrangle are included in the Uncompahgre complex (Hintze 1973, p. 157), a thick accumulation of sedimentary and volcanic rocks deposited prior to 1700 mybp (fig. 3). The basement rocks on which they were deposited is unknown but may be part of the Farmington Canyon–Uinta Mountain protocontinental group with an age of about 2500 mybp. Intense metamorphism culminated about 1700 mybp, obscuring previous history and resetting radiometric clocks. Subsequent intrusions of the Vernal Mesa Quartz Monzonite and related rocks occurred 1480 mybp and 1400–1450 mybp (Hedge and others 1968, p. 95).

LATE PRECAMBRIAN TO MIDDLE PALEOZOIC

Late Precambrian to Middle Paleozoic time was a period of relative quiescence across all of western North America. The quadrangle was situated inland of the miogeosynclinal shelf margin and received a relatively thin sequence of shelf deposits (Hintze 1973). Baars and Stevenson (1982) documented minor reactivation along the proto-Uncompahgre line and other normal basement faults during Cambrian, Devonian, and Mississippian times.

Cambrian deposits in the subsurface include undifferentiated sandy limestones, possibly the Ignacio Formation ("Lynch" and "Maxfield" equivalent) (fig. 3) (Baars 1958). The Ignacio Formation is a sandy or shaly unit in contrast to the Lynch and Maxfield carbonate units and is indicative of local Cambrian clastic sources (Baars and Stevenson 1982).

No Ordovician through Middle Devonian rocks are preserved in eastern Utah, probably due to a Late Devonian erosional period (Hintze 1973, p. 23). The Upper Devonian McCracken Sandstone represents renewed deposition adjacent to the rejuvenated Uncompahgre platform. Mississippian reactivation was minor along the ancient faults, creating shoals to the east, but may not have affected the study area (Baars and Stevenson 1982).

LATE PALEOZOIC

A radical tectonic change, perhaps related to collision of North America and Africa, began in Middle Pennsylvanian (Atokan) time. Proceeding from south to north, the Uncompahgre area was uplifted thousands of feet. Uplift of the central part of the Uncompahgre Plateau, from the Sego area south, began in Desmoinesian time and continued well into the Permian (Baars and Stevenson 1982, p. 140). Significant uplift of the northern part, from the Sego area to the Wasatch Plateau, did not begin until early Permian time (Baars and Stevenson 1982, p. 141). The compressive event forced the Uncompahgre Uplift up along a high-angle reverse fault that placed Precambrian rocks over Paleozoic rocks (fig. 2). Mobile C-1 McCormick Federal well in section 11, T. 21 S, R. 22 E, penetrated 4267 m (14,000 ft) of Precambrian rock before entering Mississippian rocks (Gries 1983, p. 4). During the Pennsylvanian and Permian, Precambrian-basement normal faults were reactivated in the basin area west of the uplift.

A thick wedge of alluvial clastic sediments accumulated along the edge of the uplift. Mobil-American Petrofina Elba Flats Unit 1-30 penetrated 2502 m (8209 ft) of

Honaker Trail Formation and 1134 m (3720 ft) of Cutler Formation just east of the study area in section 30, T. 21 S, R. 22 E (fig. 3). A deep basin formed to the west and southwest, in which the Hermosa Group, including 1524–2400 m (5000–8000 ft) of salt, was deposited. Thickest salt deposits accumulated in the inclined half grabens formed by the rejuvenated normal wrench faults (Baars and Stevenson 1982). Thick salt underlies part of the study area and was involved in subsequent flowage and structural deformation (fig. 2).

MESOZOIC TO EOCENE

The Uncompahgre Uplift was reduced to near sea level by the Late Triassic and was part of a large arid flatland during much of the Mesozoic. This part of Utah and Colorado was intermittently inundated by shallow seas, developed tidal mudflats, swept by broad dune fields, covered by extensive floodplains, or exposed to erosion.

The Uncompahgre Uplift was the primary source area for the silt and clay of the Early Triassic Moenkopi Formation, the lower part of which abuts against the uplift. Overlying Mesozoic formations were relatively unaffected by the uplift, except for minor thinning over the old positive area (Blakely and Gubitosa 1983). Overlying Cretaceous units exposed in the quadrangle are discussed later.

The Laramide Orogeny first affected the area in latest Campanian (Lawton 1983). Rejuvenation on basement faults caused minor salt movement and drape folding throughout the area. Post-Laramide erosion removed sediments deposited in the area from Maestrichtian to late Paleocene (Fouch and others 1983).

EOCENE TO PRESENT

Several large lakes covered this area during the early Tertiary, but the deposits from these have since been eroded from the quadrangle. Sediments from the largest of these, the Green River Formation, form an erosional escarpment about a mile north of the study area. There the formation is about 457 m (1500 ft) thick (Hintze 1973, p. 145).

Northward tilting of the Colorado Plateau began in Eocene time. Subsequent uplift of the plateau during the last 10 million years was the last tectonic event to affect the area. This movement resulted in a homoclinal dip to the north, erosion to the present topographic configuration, and increased groundwater circulation with resultant salt dissolution.

STRATIGRAPHY

GENERAL STATEMENT

Exposed rocks in the quadrangle range from the upper part of the Upper Cretaceous Mancos Shale through the

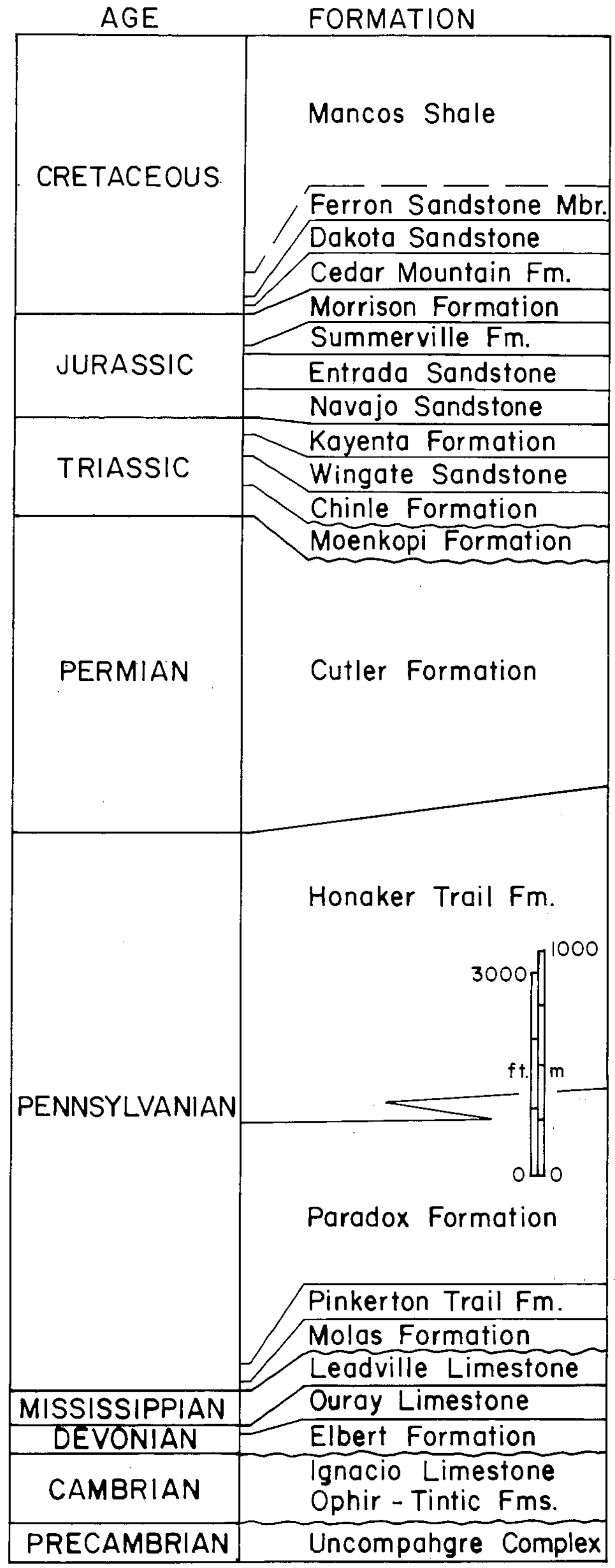

FIGURE 3.—*Stratigraphic column showing rocks underlying the Sego Canyon Quadrangle, after Hedge and others (1968), Hintze (1973), Molenaar (1981), Baars and Stevenson (1982), Frahme and Vaughn (1983), and Young (1983b).*

lower part of the Tertiary (probably Eocene) Wasatch Formation (fig. 4). Rock units that have been mapped include the Mancos Shale (of which only the upper part and the Buck Tongue crop out in the study area); Blackhawk Formation; Castlegate Sandstone; Sego Sandstone; Neslen, Farrer, and Tuscher Formations; the conglomerate beds at Dark Canyon; and the Wasatch Formation (Willis 1986). During mapping, the Sego Sandstone was divided into lower, middle, and upper members, the Neslen Formation into lower and upper members, and the Wasatch Formation into three units, with the conglomerate beds at Dark Canyon included in the lower Wasatch unit (Willis 1986). These various map units are considered only as informal units in this paper. The three Wasatch units were separated on the basis of their mappability in this area and do not correspond to the three divisions of the Wasatch Group of Spieker (1946) to the northwest.

The Neslen Formation contains all important coal resources in the quadrangle. These occur in three intervals called the Palisade coal zone, the Ballard coal zone, and the Chesterfield coal zone (Clark 1914) (fig. 4). There are also several additional minor coal zones in the formation.

Fouch and others (1983) summarized the latest available research on age and timing of the Upper Cretaceous–lower Tertiary stratigraphy of the Book Cliffs, and their data are generally used for this study. They concluded that all units from the upper Mancos Shale through the Tuscher Formation are Campanian. An unconformity between the Farrer and overlying Tuscher Formations has been described to the west by Fisher (1936), but was not recognized by later workers (Fouch and others 1983; Lawton 1983).

A conglomeratic unit 10–30 m (33–48 ft) thick occurs at the base of the Wasatch Formation. It is here considered equivalent to the conglomerate beds of Dark Canyon (Fouch and Cashion 1979). These conglomeratic beds are considered late Paleocene and are separated from the underlying Tuscher Formation by an unconformity that represents a gap of approximately 15 million years. Fouch and others (1983) showed another unconformity separating the conglomerate unit from the overlying Wasatch Formation with a five million-year hiatus. The Wasatch Formation is considered early to middle Eocene in this area.

Paleontology

Fossils are generally not abundant in the rocks in the area and few were collected. Tiny inarticulate brachiopods 2–5 mm long were collected from the Mancos Shale. Shark teeth were collected from the Blackhawk-Castlegate beds and from the Upper Sego Sandstone. Impressions of small oph[illegible] l in the Castlegate Sandstone (fig. 5). Several mollusks were also collected from the Castlegate Sandstone and the Sego Sandstone. Plant impressions and carbonized plant films are common in the Neslen Formation but none were studied in detail. Freshwater gastropods were collected from the Farrer Formation. Fisher and others (1960) and Fouch and others (1983) list fossils collected from the quadrangle. No new fossils were collected during this study except the shark teeth which have not yet been identified.

Terminology

Terminology used in the Upper Cretaceous of the western United States has evolved from many independent sources and units do not correlate well from one area to the next. The status of the Sego, Neslen, and Farrer units is the main problem in the study area. Most papers have grouped these as members of the Price River Formation. The Price River Formation is then part of the Mesaverde Group. Fisher and others (1960, p. 11), who along with Spieker and Reeside (1925) and Spieker (1946), developed most of the terminology used in the central Book Cliffs, elected to use formation rank for the Sego, Neslen, and Farrer units. They then limited the term "Price River Formation" to beds west of the Green River where the Sego, Neslen, and Farrer units are not generally recognized (Fisher and others 1960, p. 14). I agree with their reasons for this usage and have mapped the Sego, Neslen, and Farrer Formations and some subdivisions of these rocks in the quadrangle (Willis 1986). Young (1955) called the Castlegate, Sego, Neslen, and Farrer units "facies" because they are time transgressive. His usage has not generally been accepted and will not be used here.

A sequence of conglomerate and conglomeratic sandstone beds at the base of the Wasatch Formation is called "conglomerate beds of Dark Canyon" in this paper (fig. 4). The informal term was first used by Fouch and Cashion (1979) in a correlation chart they constructed through the Uinta Basin, at approximately T. 15 S, using well data. A lithologically similar conglomeratic sandstone in western Colorado occurs in approximately the same stratigraphic position as the unit in the Sego Canyon area. Lee (1912, p. 48) applied the term "Ohio Creek Conglomerate" to this unit. Correlation outside Lee's locality is not documented, however (Fisher and others 1960, p. 22). As such, the term "conglomerate beds of Dark Canyon" is preferable because the closer geographic location lessens the possibility of error. The term "Ohio Creek Conglomerate" could be adopted if positive correlation is established in future studies.

SUBSURFACE STRATIGRAPHY

Rocks of Precambrian to Cretaceous ages, except Or-

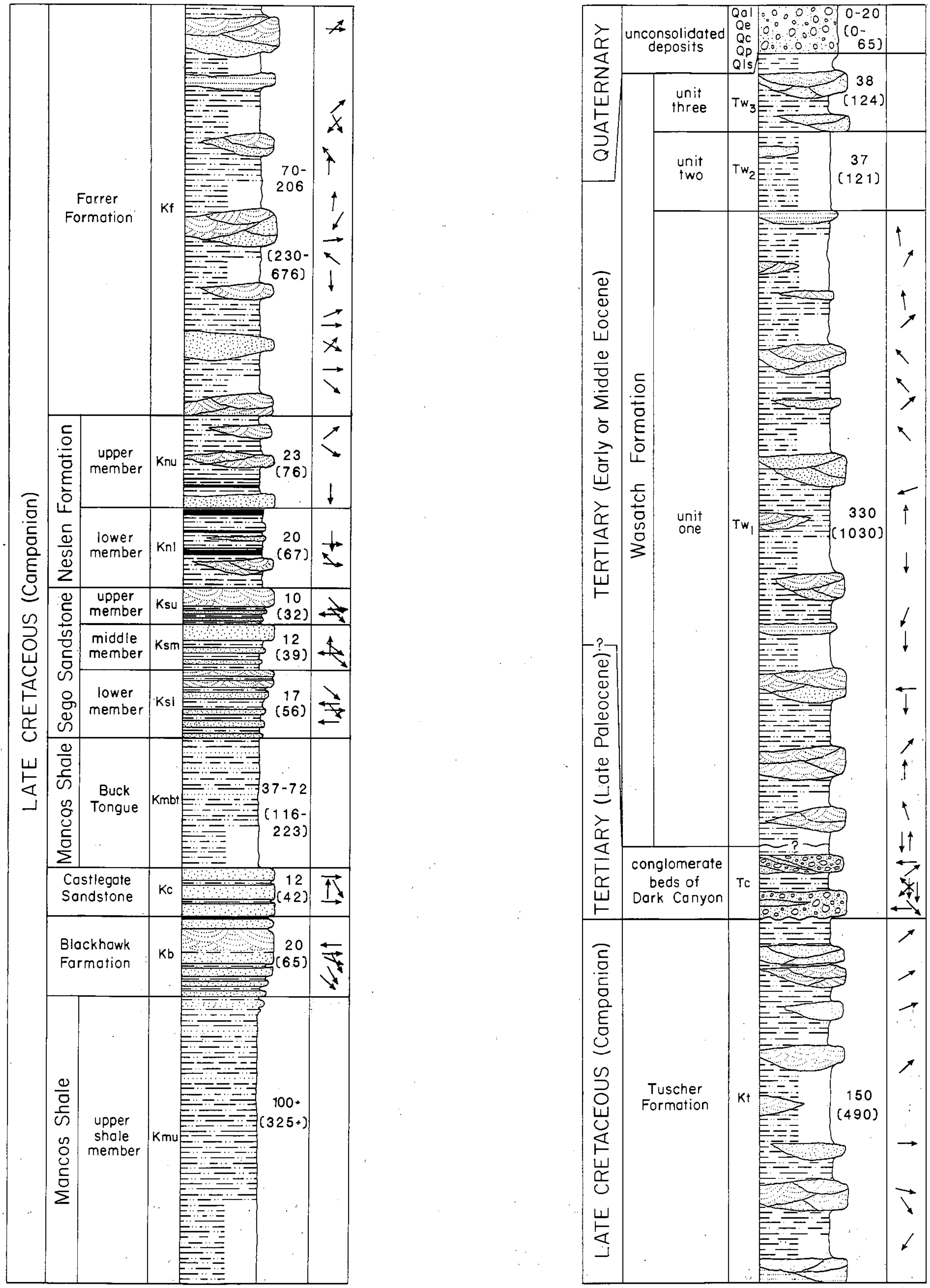

FIGURE 4.—*Stratigraphic column of exposed rocks in the Sego Canyon Quadrangle.*

FIGURE 5.—*Ophiuroid impressions on interference-rippled sandstone bed, probably lithology IV (Nethercott 1986), in the upper part of the Blackhawk Formation in lower Thompson Canyon.*

dovician and Silurian units, underlie the quadrangle (fig. 3). These are known from drill data and by projection from surrounding areas. Drill holes within the quadrangle have penetrated into the Cambrian in the Paradox basin and through the Precambrian on the Uncompahgre Plateau. Middle and lower Paleozoic strata are best known from Mobil American Petrofina No. 1-30 Elba Flats well in section 30, T. 21 S, R. 22 E, and Pacific Western/Equity No. 1 Thompson in section 33, T. 21 S, R. 21 E. Precambrian rocks are well exposed east of the Uncompahgre Fault in eastern Utah and in Colorado. Mobile No. 1 McCormick Federal "C" penetrated 4267 m (14,000 ft) of Precambrian rocks in section 11, T. 21 S, R. 22 E. Rocks from the Permian Cutler Formation to the Cretaceous Mancos Shale are well exposed in the Salt Valley Collapsed Anticline to the southwest (Gard 1976; Hite 1977) (fig. 6). Diapiric masses of Paradox Formation are also exposed there. Rocks as old as the Honaker Trail Formation are exposed in the Colorado River Canyon near Dead Horse Point. No middle or lower Paleozoic rocks are exposed in the region of the Paradox Basin (Hintze 1980). A summary of subsurface geology is shown diagrammatically in figure 3.

MANCOS SHALE

The lowest exposed unit in the quadrangle is the Upper Mancos Shale, which crops out along the base of the cliffs in the southern part of the quadrangle (fig. 7) (Willis 1986). Cross and Purington (1899) first applied the name "Mancos" to gray bentonitic shales exposed in the southwestern part of Colorado. The name has since come to define all thick marine shales overlying the Cretaceous Dakota Formation (Fisher and others 1960). In the Sego Canyon area it is overlain by the Blackhawk Formation (fig. 4). The Mancos Shale averages 1160 m (3800 ft) thick in this area, but only the uppermost 95 m (312 ft) is exposed within the quadrangle in lower Thompson Canyon. Lesser thicknesses are also exposed in Blaze Canyon, Sagers Canyon, and two smaller unnamed canyons between Sego and Sagers Canyons.

The Mancos Shale easily erodes to a wide "badlands" topography that is utilized for highway and railway routes throughout much of the Colorado Plateau. It is often veneered with alluvial and colluvial deposits that cause a series of dissected pediments to form.

The uppermost 95 m (312 ft) of the Mancos Shale is a coarsening upward sequence increasing both in quantities of sand and silt and in sandstone beds. It is predominantly medium to dark gray to brownish gray, gypsiferous, and bentonitic mudstone. It is crumbly, lacks fissility, and weathers to a "popcorn" soil. Gypsum is common both as veinlets and as crystals on parting surfaces. Internal sedimentary structures are rarely seen in the rocks due to their crumbly weathering. A stringy, braided texture on a 1–10 cm scale occasionally occurs. Extent of bioturbation is difficult to determine because of the homogenous nature and slope-forming characteristic, but a few 1–3 mm smooth-wall burrows were found.

Several 5–10 cm (2–4 in) thick horizons of laterally continuous, clean, orangish to yellowish brown bentonitic clay are interbedded in the formation. These form a sticky ball and swell considerably when moistened.

Two types of sandstone beds occur near the top of the section. The first type is dense, quartzitic sandstone. It occurs in laterally persistant 3–30 cm (1–10 in) thick beds. The other type is more friable, lighter colored, more laterally variable in thickness, and has sedimentary structures preserved. The later type occurs near the upper contact and resembles Blackhawk units.

The contact with the overlying Blackhawk Formation is gradational but was selected at the base of the lowest laterally continuous, thick-bedded sandstone (fig. 7). Occasionally this criterion is not appropriate. In that case the

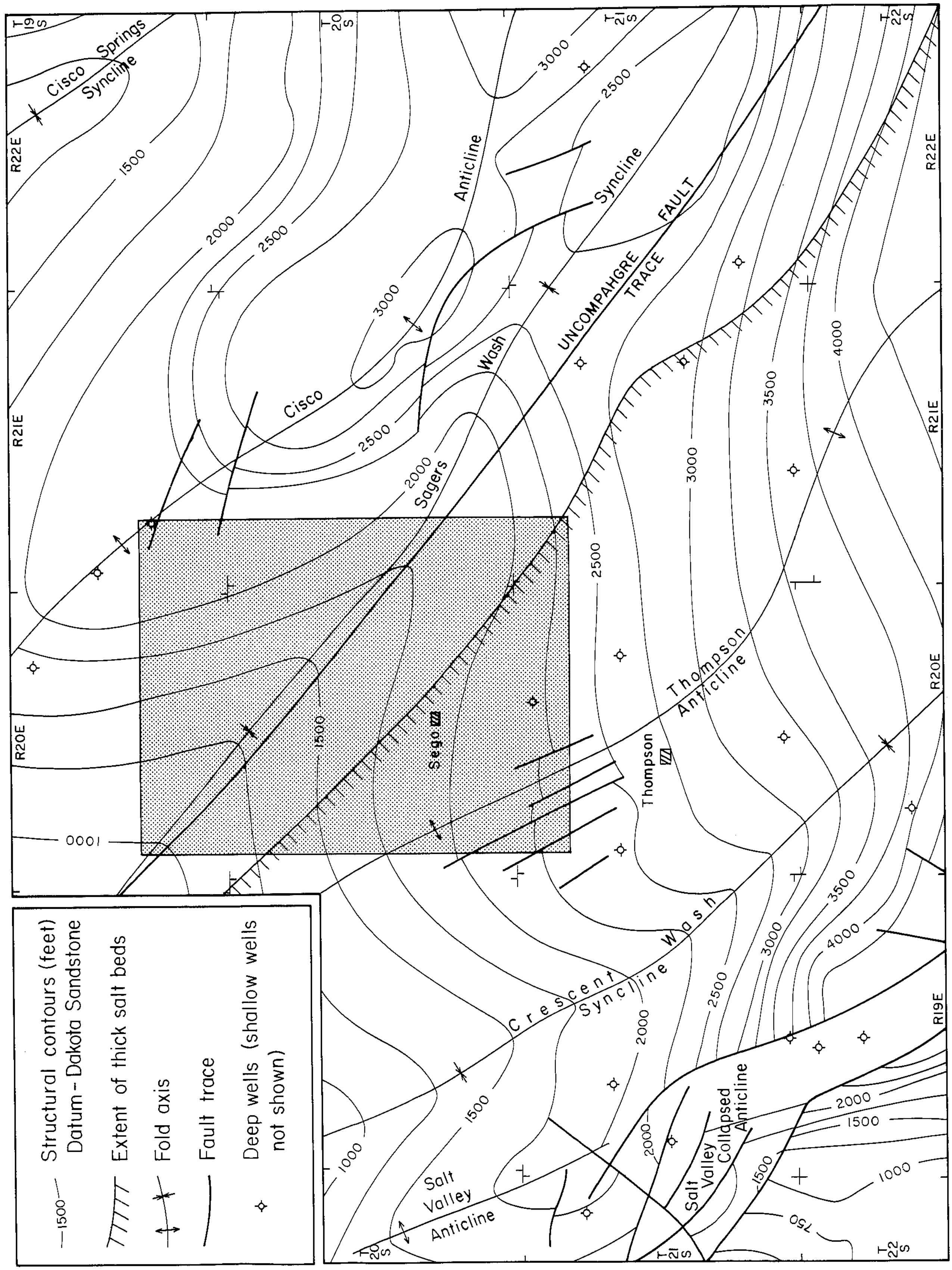

FIGURE 6.—*Regional structural contour map showing relationship of the Sego Canyon Quadrangle to regional structures of the area, to the limit of thick salt accumulation, and to the trace of the Uncompahgre Fault. After Walton (1956), Frahme and Vaughn (1983), well data, and data from this study.*

FIGURE 7.—*Mancos Shale, Blackhawk Formation, and Castlegate Sandstone showing facies change from shallow open-marine to distributary channel (capping unit) depositional environments. Steep, vegetation-free, intricately dissected slope at the base of the cliff is the Mancos Shale.*

contact was selected as the point in the coarsening upward sequence where sandstone became dominant over mudstone. This contact is generally definable to within 2 m (6 ft).

The Mancos Shale is of undoubted marine origin (Maxfield 1976; Balsley 1980). Its broad areal extent over several states, homogeneous lithology, black anaerobic appearance, and marine fauna all bespeak this setting. As mentioned, only the uppermost part of the Mancos Shale is exposed within the quadrangle. It has a higher mudstone/shale ratio than the lower part of the Mancos Shale and contains relatively abundant sandstone layers that increase in number upward. This part was deposited in a prodelta environment. The increased sand and silt is due to storm pulses reaching the area with increasing frequency as the regressive shoreline encroached from the west. The fine sediment, black color, high gypsum content, and rarity of fossils suggest a muddy, hypersaline, stagnant basin in which living conditions were very harsh.

BLACKHAWK FORMATION AND CASTLEGATE SANDSTONE

The Blackhawk Formation and Castlegate Sandstone are resistant sandstone units which, in this area, form the cuesta termed the "Book Cliffs" (fig. 7). The Blackhawk Formation was deposited under different depositional conditions and is distinctively different than the Castlegate Sandstone in the Price, Utah, area, where both units were named. However, in the Sego area, 160 km (100 mi) to the southeast, both are greatly reduced in thickness, have undergone major facies changes, are part of the same depositional sequence, and are difficult to distinguish. As such, they will be discussed together in this study.

The Blackhawk Formation was defined by Spieker and Reeside (1925, p. 443) as "the coal-bearing unit of the Wasatch Plateau." In that area it is 275 m (900 ft) thick, contains several important coal beds, and is divided into several members. It thins eastward, losing coal beds and sandstone members and changing facies. It ranges from 218 m (714 ft) thick and three sandstone members near Green River to 113 m (370 ft) and two sandstone members in Tuscher Wash (approximately 24 km (15 mi) west of the study area), to 65 m (214 ft) and one member north of Crescent Butte (13 km (8 mi) west of the study area) (Fisher and others 1960). The Blackhawk Formation is 37 m (121 ft) thick in Thompson Wash in the southwest part of the study area and is 28 m (91 ft) thick near Sagers Wash in the southeast part. It is 17 m (51 ft) thick east of the study area near Nash Wash and disappears west of Cottonwood Creek, which is 16 km (10 mi) farther east (Fisher and others 1960).

The Castlegate Sandstone was named for a 120 m (400 ft) thick lenticular bedded sandstone unit directly overlying the Blackhawk Formation near Price, Utah. It ranges from conglomerate on its west end near Price to mudstone and siltstone 250 km (150 mi) to the east where it feathers out near the Utah-Colorado border (Fisher 1936). It is 20 m (66 ft) thick in Blaze Canyon and 27 m (89 ft) thick near Sagers Wash. It is 30 m (93 ft) thick near Nash Wash, 25 m (72 ft) thick near Westwater Canyon, and grades into mudstone a few kilometers east of that point (Fisher and others 1960).

Some confusion exists in the Sego-Thompson area concerning the contact between the Blackhawk Formation and the Castlegate Sandstone. The distinctive facies, lithology, and physical appearance used to distinguish them west of the study area lessen and disappear eastward until no real distinction exists in the quadrangle. The problem lies in the definition of the upper boundary. Spieker (1949, p. 72), working west of the study area, said that "nowhere does the Castlegate Sandstone contain coal." Fisher and others (1960, p. 12–13) stated that the uppermost coal zone of the Blackhawk Formation, the only one present in the quadrangle, "often reduces to a single carbonaceous shale zone." Thus, because of the lack of other distinguishing criteria, they use this zone as the top of the Blackhawk Formation. In tracing this carbonaceous shale horizon across the quadrangle it is apparent that it is not a single zone but instead consists of a series of shingled zones. In section 6, T. 21 S, R. 21 E, near Sagers Canyon and in section 5, T. 20 S, R. 21 E, in Bull Canyon, the Buck Tongue lies directly upon the carbonaceous shale zone with no intervening sandstone. Thus, if this definition is used, the Castlegate Sandstone pinches out in the quadrangle and the Blackhawk Formation continues as a thinning wedge 40 km (25 mi) to the east. This opposes all current literature on the area and is

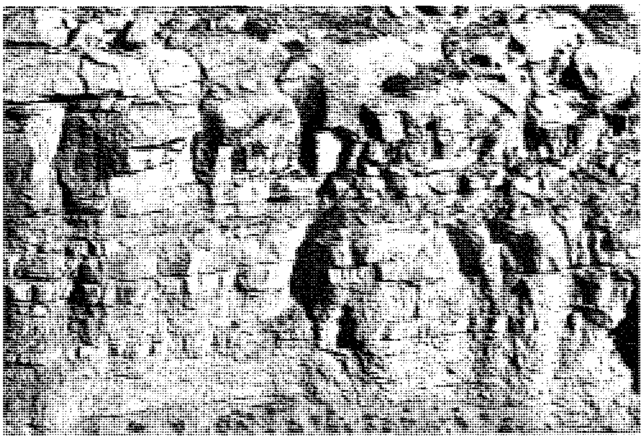

FIGURE 8.—*Mancos Shale (near bottom of photograph), Blackhawk Formation (middle), and Castlegate Sandstone (top) in Blaze Canyon. Lithologies I, II, and III are repeated in the lower part of the cliff (Blackhawk Formation). The thin coal that caps lithology IV (foreshore deposits) marks the contact between the formations. The uppermost part of photograph may be lithology IV through distributary channel facies.*

FIGURE 9.—*Blackhawk Formation and Castlegate Sandstone, greatly reduced in thickness, separated by a mudstone slope-forming unit near Sagers Wash in the southeast corner of the quadrangle. Note the gently inclined bedding near the top of the Castlegate Sandstone.*

incorrect. Gualtieri (1981b, 1982) avoided the problem by mapping them as separate formations in the Floy Canyon Quadrangle, west of the Sego area, but by mapping them as a single combined unit in the Sego area. Other literature is divided as to the eastern extent of the Blackhawk Formation (Young 1955; Fisher and others 1960; Kidson 1971, p. 14; Van De Graaff 1972, Balsley 1980).

The problem lies in the use of the coal-carbonaceous shale zone as the upper contact of a formation. This type of deposit is seldom laterally extensive and often splits or shingles. In addition, the Castlegate Sandstone does contain carbonaceous shale and coal zones that often exceed a thickness of 0.3 m (1 ft). The major coal zone does correspond with the formational contact in the west part of the quadrangle (fig. 8), but in Thompson Canyon it does not. However, there is a break in the cliff face that seems to correlate with the coal zone contact near Blaze Canyon. That break can be traced eastward with some difficulty to Sagers Wash, where it becomes a prominent slope between two sandstone cliffs (fig. 9). The lower cliff is here considered Blackhawk Formation. It grades out 16 km (10 mi) east of the quadrangle. The slope zone and upper cliff are the Castlegate Formation which continues into Colorado. This conforms to the work of Fisher and others (1960). The contact was "dashed in" on the map east of the Thompson Wash area where its continuity is questioned (Willis 1986).

Bedding in the two formations is thick to massive with varying amounts of mudstone and thin-bedded sandstone interlayered above the gradational lower contact of the Blackhawk Formation (fig. 8). Grain size is typically very fine. Composition is 97% angular to subangular unfrosted quartz grains, 2%–3% weathered feldspars, and 1%–2% dark chert and other minerals. Gypsum and limonite occur as secondary minerals. The unit is generally a massive cliff-former, but mudstone zones do form ledges and slopes in some areas (figs. 8, 9). As mentioned, one to three coal/carbonaceous shale zones occur (figs. 8, 9). They are less than two meters (6.6 ft) thick, with coal never exceeding 30 cm (12 in) thick. Carbonaceous and bituminous plant fragments occur on bedding surfaces throughout the formations. Cement is mainly iron carbonate. Extensive leaching has occurred in the highly porous units, as evidenced by the friable nature and the occurrence of bivalve molds with no original material remaining.

Cross-bedding is dominant throughout the formations with lesser amounts of laminar bedding, convolute bedding, and areas of no apparent bedding. Hummocky bedding is very common in the lower part of the sequence. Current directions primarily range from northeast to southeast (fig. 4).

Bioturbation ranges from absent to intense. Burrows are primarily 0.5–1.0 cm smooth-walled types, but *Ophiomorpha*, *Ruhespuren*, and other types also occur. *Thalassinoid*-type burrows are especially abundant in a thin carbonaceous shale zone that caps the coal horizons. *Ophiomorpha* occur in the upper parts of some sandstone beds. A single fallen block 1 by 2 m (3 by 6 ft) in Thompson Canyon has 49 ophiuroid impressions on a single rippled bedding surface (fig. 5).

Channeling and scour-cut surfaces are common throughout the formations (fig. 10). Clay pebbles and rip-up clasts often occur near the base of the channels.

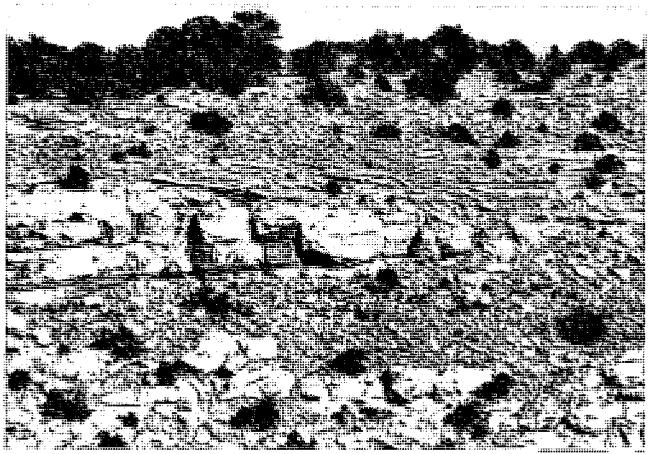

FIGURE 10.—*Meandering channel sequence cutting underlying massive sandstone in the Castlegate Sandstone, west of Sagers Wash. Note coal-carbonaceous shale zone at the base of the sandstone.*

FIGURE 11.—*Large depression postulated to be a distributary channel cut into the Castlegate Sandstone and subsequently filled by the less resistant Buck Tongue of the Mancos Shale. Channel is about 25 m (80 ft) deep by 100 m (325 ft) wide. Near mouth of Thompson Canyon.*

These occasionally contain shark teeth and bone fragments. Inclined or shingled bedding can be observed in some areas on a scale of hundreds of meters to kilometers (figs. 9, 10). Hardened sandstone and ironstone concretions are locally common. Some are more than 10 m (30 ft) long. An unusual soft sediment structure was observed in section 6, T. 21 S, R. 20 E. This appears as numerous flattened, tapered sandstone rods splayed out inside a wood impression. This was attributed to soft sandy mud being forced through 1–2 mm borings in a hollow log by the pressure of overlying sediment.

Fossils found in the Blackhawk-Castlegate Formations include various wood and leaf impressions, a few small bone fragments, none of which could be identified, a few isolated coquinoid mounds of bivalve shells, a few isolated bivalve molds, and shark teeth. Three tracks of an unidentified three-toed dinosaur measuring 8–10 cm (3–4 in) long were observed near the top of the Castlegate Sandstone.

Both formations thin eastward and increase in mudstone content (compare figs. 7–10). The cliffs also become less formidable in this direction. The contact with the overlying Buck Tongue is sharp with mudstone resting on the underlying Castlegate Sandstone. A pronounced dip slope bench is formed by the erosion of the nonresistant Buck Tongue mudstone from the resistant underlying unit (fig. 7).

The lower part of the Blackhawk Formation/Castlegate Sandstone sequence was deposited along the strandline of a wave-dominated delta complex. It has the characteristic facies I, II, and III of Nethercott (1986) or transition, lower shoreface, and upper shoreface deposits of Balsley (1980) (fig. 8). The lower part of the measured section (see appendix) is composed of these facies. (Unit numbers discussed henceforth refer to measured sections in the appendix, available at the Department of Geology, Brigham Young University.) Units 1, 2, 3, 6, and parts of 5 and 7 are facies I. Parts of units 5, 7, and 8 are facies II. Units 9, parts of 10, 13, 14, and 15 are facies III. These facies occur at the base of the formation throughout the quadrangle and are usually repetitive, occurring several times in parts of the quadrangle. Facies IV, the foreshore deposits, is less developed in the formations. Unit 16 may contain this facies.

The coal and carbonaceous shale zone overlies the strandline sequence and probably represents deposition in swampy or marshy areas directly behind the shoreline deposits (fig. 8). Young (1955) suggested that lagoonal conditions existed behind the shoreline (i.e., that the shoreline was a barrier beach sequence), but little supporting evidence was found in this study. The area definitely was low, stagnant, and rich in plant growth. Units 17 to 19 contain deposits of this facies.

Following and possibly partially contemporaneous with the swampy units, the facies became highly variable, with meandering-channel sandstone beds, carbonaceous shale and mudstone units, thin to thick interbedded sandstone and mudstone units, and massive sandstone beds (compare figs. 8–10). Shingled or inclined bedding, cross-bedding, horizontal bedding, and convolute bedding are common in these units. The ophiuroid impressions and shark teeth were found in these units in Thompson Canyon, and three-toed dinosaur tracks 8–10 cm (3–4 in) long were seen in correlative beds near Blaze Canyon. This sequence, which varies from 0–50 m (0–150 ft) thick, is interpreted as a lower floodplain and distributary system composed of numerous small migrating channels

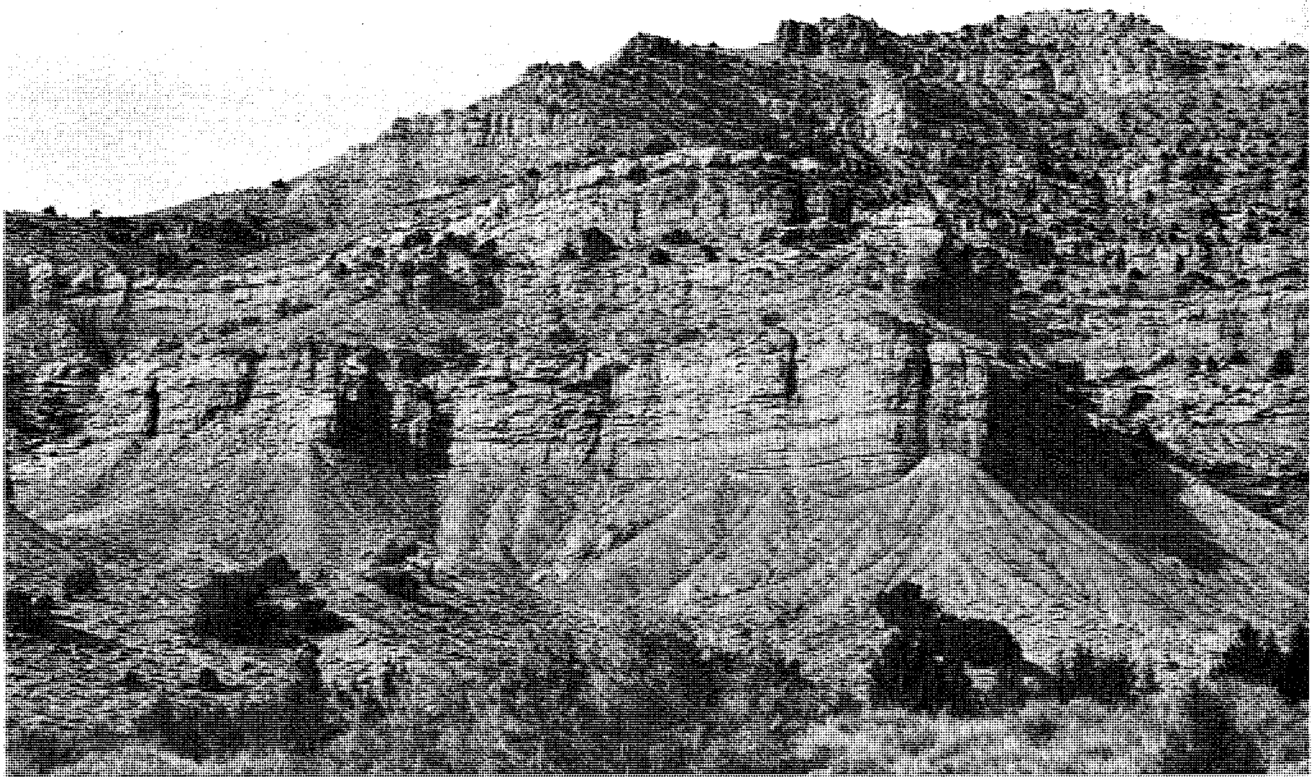

FIGURE 12.—*The three repeated members of the Sego Sandstone overlying the Buck Tongue of the Mancos Shale. The Neslen Formation forms the slope zone on the left side of the photo and the Farrer Formation is the steep interbedded sandstone and slope zone in the upper half of the photograph. Approximately one mile east of Sego Canyon.*

with associated interdistributary deposits. There must have been both positive areas and areas influenced by marine waters to allow all the associated facies to occur together. The front of this system was probably still a wave-dominated shoreline.

A large depression in the top of the Castlegate Sandstone in Thompson Canyon may have been a distributary channel subsequently filled by the transgressive Buck Tongue that immediately followed (fig. 11). The Thompson Canyon area has thicker sandstone units throughout all the formations than occur laterally. This may be due to minor tectonic activity directing deposition toward this area.

BUCK TONGUE OF THE MANCOS SHALE

Fisher (1936) first used the name "Buck Tongue" to describe Mancos Shale-like gray bentonitic mudstones and shales overlying the Castlegate Sandstone and underlying the Sego Sandstone. The name applies from the point on the east near the Utah-Colorado border where the Castlegate Sandstone feathers out, leaving the unit indistinguishable from the Mancos Shale, westward to near Woodside, Utah, where the tongue dies out (Kidson 1971). In the study area the Buck Tongue ranges from 37 m (116 ft) near Blaze Canyon to 72 m (223 ft) near Sagers Wash.

The Buck Tongue forms a sharp contact with the underlying Castlegate Sandstone. The mudstone is generally deposited directly on a sandstone bed, but near Sagers Wash it is deposited on the coal/carbonaceous shale horizon of the Castlegate Sandstone.

A wide bench is usually formed by erosion of the nonresistant Buck Tongue (fig. 7). This bench ranges up to 3 km (1.8 mi) wide and is generally covered by alluvium, colluvium, eolian deposits, erosional remnants of the Buck Tongue, and active and beheaded pediments.

The Buck Tongue, like the upper part of the Mancos Shale, consists predominantly of mudstone, with varying amounts of silt and occasional interlayered thin sandstone beds (fig. 4). It also has a few 5–10 cm (2–4 in) interbedded bentonitic layers. Bedding is usually poorly preserved, but appears thinly laminated to thin bedded.

FIGURE 13.—*Hummocky bedding in the basal part of the Sego Sandstone. Similar bedding is typical of lithologies I, II, and occasionally III of the lower Blackhawk Formation and the lower part of each member of the Sego Sandstone.*

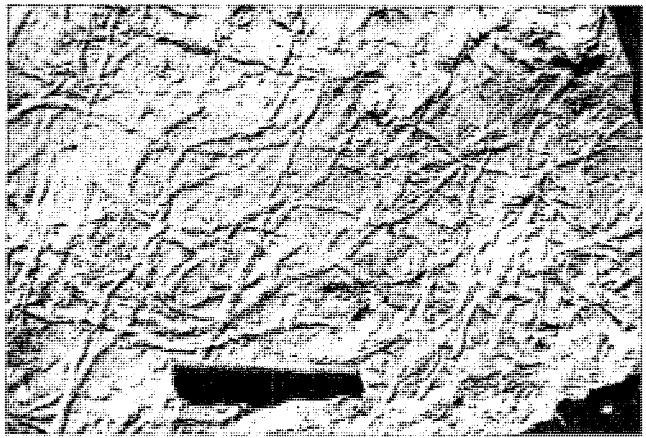

FIGURE 14.—*Intense bioturbation in the Sego Sandstone. Trails are primarily gastropod. The sandstone beds of the Sego Sandstone are usually heavily bioturbated. The Blackhawk has similar trace fossils, but in lesser quantities.*

Light and dark silt create a discontinuous, stringy appearance on a 1–10 cm scale. Bioturbation is rarely observed, but occasional small 1–3 mm diameter burrows were found. A zone of large round orangish gray mudstone concretionary balls occur one-half to two-thirds up the section (unit 5, appendix). This zone is traceable across the entire study area. Several of these concretions were examined in the field but no internal structure or identifiable cores were observed. The few fossils found in the Buck Tongue are inarticulate brachiopods.

The Buck Tongue was deposited following a rapid transgression over the area, under conditions similar to those that produced the upper part of the Mancos Shale. That the transgression was a very rapid event is evident as there are no significant transgressive shoreline deposits, the underlying Castlegate Sandstone appears not to have been reworked, and the Buck Tongue was deposited across different facies of the Castlegate Sandstone with no apparent effect on the underlying units. The tongue was deposited in this shallow open-marine transgressive pulse and in the slow regression that followed. Bentonite beds are probably reworked ash from distant volcanics. The large concretions must have required a unique set of conditions, probably related to groundwater, and mud of just the right consistency to form.

The upper part of the tongue (units 6 through 11, appendix) is a slowly coarsening upward sequence, similar to lower beds of the Blackhawk Formation and shows progradation of the shoreline over the area (fig. 12). These beds are lithology I of Nethercott (1986) or the transition zone of Balsley (1980).

SEGO SANDSTONE

The Sego Sandstone was named by Fisher (see Erdmann 1934) but first published by Erdmann (1934) and is mappable from near the Green River to the Colorado border. The type locality is in Sego Canyon in the central part of the study area and includes strata from the first thick-bedded sandstone overlying the Buck Tongue upward to the top of the last laterally continuous massive sandstone below the coal-bearing Neslen Formation (fig. 4). The Sego Sandstone contains significant coals in Colorado (Erdmann 1934; Young 1983b), but does not in this quadrangle. However, the coals in Colorado may actually be equivalent to part of the Neslen Formation of the Sego Canyon area. The formation consists of 1 to 4 minor cliffs, separated by mudstone-dominated slope-forming units (Fisher and others 1960, p. 15). In the Sego Canyon Quadrangle it consists of three coarsening-upward sequences similar to the base of the Blackhawk Formation (fig. 12). The lower part of each sequence is slope-forming mudstone and thin-bedded sandstone. Sandstone content and bedding thickness increase upward. The top of each sequence is a massive sandstone. The sandstone is fine to very fine grained, well sorted, and composed almost entirely of quartz grains. Ironstone concretions, wood impressions, macerated bituminous plant material, and occasional clay pebbles occur in many of the units.

The Sego Sandstone contains a large variety of sedimentary structures. Hummocky bedding is common in the lower part of each of the three coarsening upward sequences (fig. 13). Cross-bedding, convolute bedding, ripple laminations, and horizontal laminations occur higher up in the sequence. Oscillation and directional ripple marks occur in most units. Units more than a couple of meters thick can be traced laterally for large distances but individual bedding planes are discontinuous.

Bioturbation varies from absent to intense through the formation. Trace fossils are extremely varied and abun-

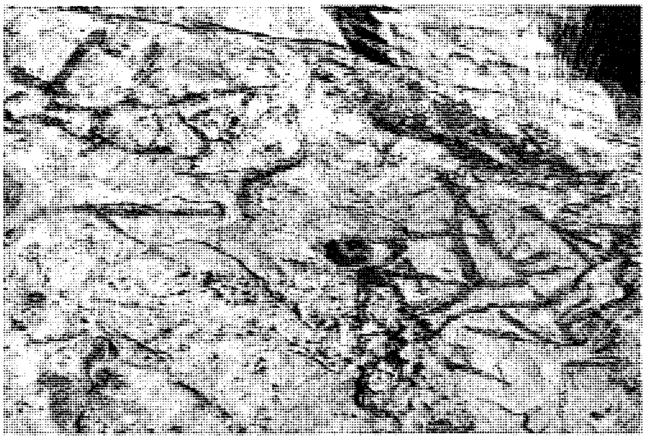

FIGURE 15.—*Horizontal* Ophiomorpha *burrows in fallen block of the Sego Sandstone.* Ophiomorpha *is the most abundant trace fossil in the Sego Sandstone and also occurs in the Blackhawk Formation.*

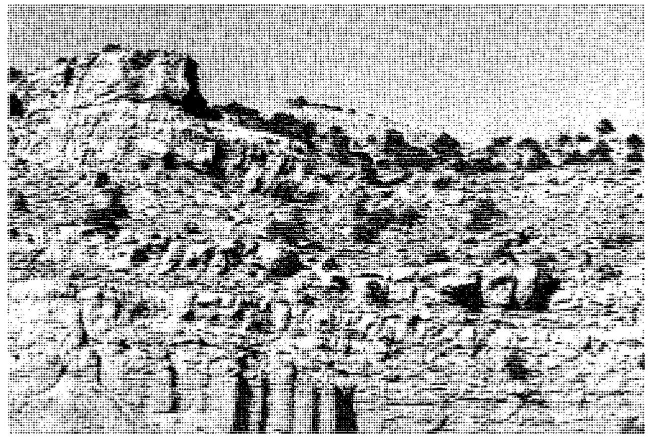

FIGURE 16.—*The Sego Sandstone near Blaze Canyon on the west side of the quadrangle. Note the increase in thick sandstone ledges (lithology III) compared to figure 13.*

dant. They include horizontal, vertical, and branching *Ophiomorpha*, gastropod trails, smooth tubes and trails, and *Thallassinoides* (figs. 14, 15).

Mounds composed of a coquina of bivalves are locally common near the top of the upper unit. These mounds are discontinuous, only occurring in a few localized areas. Shark teeth were found in this coquina in Blaze Canyon and in fallen blocks from unknown Sego Sandstone units 0.4 km (0.25 mile) east of Blaze Canyon.

The upper contact of the Sego Sandstone was mapped at the top of the highest laterally continuous, massive sandstone bluff and below any coal units. This contact is sharp and is easily seen from a distance due to the slope-forming carbonaceous shales that directly overlie it and the distinctive morphology of sandstone units in the Neslen Formation (fig. 12). Sandstone ledges in the Neslen Formation are channel shaped, discontinuous, and not as abundant as sandstone beds in the Sego Sandstone, which are planar and laterally continuous. The Sego Sandstone is occasionally stained by red oxides from overlying clinkered coal zones of the Neslen Formation.

Lateral variation is evident in the Sego Sandstone. The formation consists of three coarsening-upward sequences made up of three slope zones capped by massive sandstone cliffs in the central part of the quadrangle (fig. 12). The three slope zones become more prominent and the cliffs less so toward the east. The middle cliff especially loses prominence, thinning and eventually pinching out 40 km (25 mi) to the east near the Utah-Colorado border. The resulting thicker mudstone unit then becomes the Anchor Mine Tongue of the Mancos Shale, named by Erdmann (1934). The Sego Sandstone is divided into lower and upper members east of that point (Young 1983b, p. 9). The number of sandstone beds increase westward so that near the west side of the study area the slope-forming parts of the two upper sequences become hard to distinguish (fig. 16).

The three similar repeated coarsening-upward sequences of the Sego Sandstone (fig. 12) represent parts of three rapid transgressions and three slow regressions across the area. The lowest transgression resulted in deposition of the Buck Tongue of the Mancos Shale. The three sequences have been divided into three members for the purpose of mapping. These three repeated sequences have similar depositional histories judging by the similarity of their lithologies and sedimentary structures. Each cycle began with a rapid transgression over the area. Deposition of the slope-forming mudstones in shallow open-marine conditions resulted. Thin hummocky sandstone beds follow that were formed by storm influx which deposited and reworked sediment below the normal wave base (Dott and Burgeois 1982). This interbedded sandstone-mudstone zone is the transition zone of Balsley (1980), or lithology one of Nethercott (1986) (units 1 to 5, and 8 to 10, measured section, appendix). Beds representative of the different facies of the strandline of a wave-dominated coastline followed. These are the lower shoreface (units 6, 7, 11, 12, and possibly 14, appendix), upper shoreface (units 13, 15, 16, and 17), and foreshore (possibly the upper part of unit 34) of Balsley (1980) or lithologies 2, 3, and 4 of Nethercott (1986). Foreshore beds are poorly developed or absent in most areas and may not have been deposited until the final regressive cycle. Figure 17, a detailed photograph of part of the Sego Sandstone, shows the transition zone through upper shoreface zones. The major difference between this area and the system described by Balsley (1980) is the distance from the active source area. Since this area was much farther away, the surface gradient was much shallower and sediments are finer grained. The units are also thin-

FIGURE 17.—*Close-up photograph of part of the lower member of the Sego Sandstone showing the transition zone (lithology I) (up to backpack), a thin lower shoreface zone (II), and a massive, bioturbated, cross-bedded, upper shoreface zone (III). SE 1/4, section 35, T. 20 S, R. 20 E.*

ner than he described and more laterally persistent.

Young (1955, p. 190) interpreted the sandstone beds as barrier bars. Barrier bars and strandlines are identical except for associated deposits (Balsley 1980, p. 113). The strandline interpretation is preferred since no tidal inlets or tidal delta deposits were seen. This also concurs with the occurrence of fluvial-associated coal deposits directly over the Sego Sandstone.

Bioturbation is more intense than in the Blackhawk Formation described by Balsley (1980) in the Price area or than exists in the Blackhawk-Castlegate Formations in this area. This is probably due to slower sediment influx, a wider inhabitable zone due to the lower profile, a good supply of organic material, and water conditions which created ideal environments for bottom-dwelling organisms.

Facies in the Sego Sandstone have only minor lateral variation. The gradual increase in sand beds toward the west was due to the closer proximity to the source area and higher position topographically. There are also less transition zone deposits and a proportional increase in the lower and upper shoreface deposits westward. The third regressive sequence proceeded beyond shoreline deposits to backshore delta-plain swamp conditions, resulting in deposition of the coal beds of the Neslen Formation. The conspicuous absence of coal or carbonaceous shale associated with the Sego Sandstone strandline deposits contrasts with coals associated with strandline deposits in the Price area (Balsley 1980) and in the Grand Junction, Colorado, area (fig. 2 of Young 1983b). In those areas thick coal deposits accumulate directly on and behind the strandline or beach ridge deposits. These are typically the thickest and most economically minable coal deposits in the Book Cliffs. They are the lower delta-plain coals of Nethercott (1986). The lack of lower delta-plain coal deposits suggests that regression never proceeded to back-swamp conditions and that no lagoons existed during Sego time. The Sego Canyon area was also more stable, without repetitive stacked beach ridge deposits extensive enough to restrict marine influx, and without subsiding areas where coal could form. The locally present bivalve coquina is probably a lag deposit associated with storm surge in the foreshore zone.

NESLEN FORMATION

The Neslen Formation was named by Fisher (1936) for "a series of shales and sandstones overlying the Sego Sandstone that has an average thickness of 106 m (350 ft) and carries valuable coal beds." It has been traced west to the Green River and is equivalent to part of the undifferentiated Price River Formation. It is probably equivalent to Erdmann's (1934) Mount Garfield Formation to the east (Fisher and others 1960, p. 17).

The Neslen Formation is notably different from the Blackhawk Formation, the only significant coal-bearing formation in the Book Cliffs northwest of Green River, in the "absence of continuous cliff-making sandstone beds and in the inferiority of coal beds, which are thinner and of lower rank and grade" (Fisher and others 1960, p. 17). The Neslen Formation forms a slope zone with several channel-shaped sandstone lenses scattered throughout and one laterally continuous sandstone unit near the middle of the formation (fig. 18). The latter was called the Thompson Sandstone Bed by Fisher (1936, p. 18). The formation was mapped as two units, using the base of the Thompson Sandstone bed as the contact (Willis 1986). Three major coal zones, the Palisade zone, the Ballard zone, and the Chesterfield zone, and several insignificant coal zones occur in the formation (fig. 4). The Palisade and Ballard coal zones are contained in the lower member and the Chesterfield zone in the upper.

The formation is composed of slope-forming mudstone, shale, carbonaceous shale, sandstone, and coal with minor channel-shaped sandstone ledges interspersed. Thin to medium bedded sandstone beds occur in varying numbers. A few thick to massive channel-fill sandstone lenses also occur. They are usually cross-bedded, ripple laminated, convoluted bedded, and often have inclined bedding (fig. 19). The upper member is similar to the lower except for having a higher proportion of channel sandstone lenses, especially in its upper part.

The Neslen Formation shows a strong regressive tendency with only minor "short-lived" transgressive pulses. This is indicated by a relatively short period conducive to coal accumulation, the lack of repetitive beds, and the consistent increase in sandstone beds upward. All indicate an upward regressive tendency with increased fluvial influence. Thus it appears that the regression proceeded

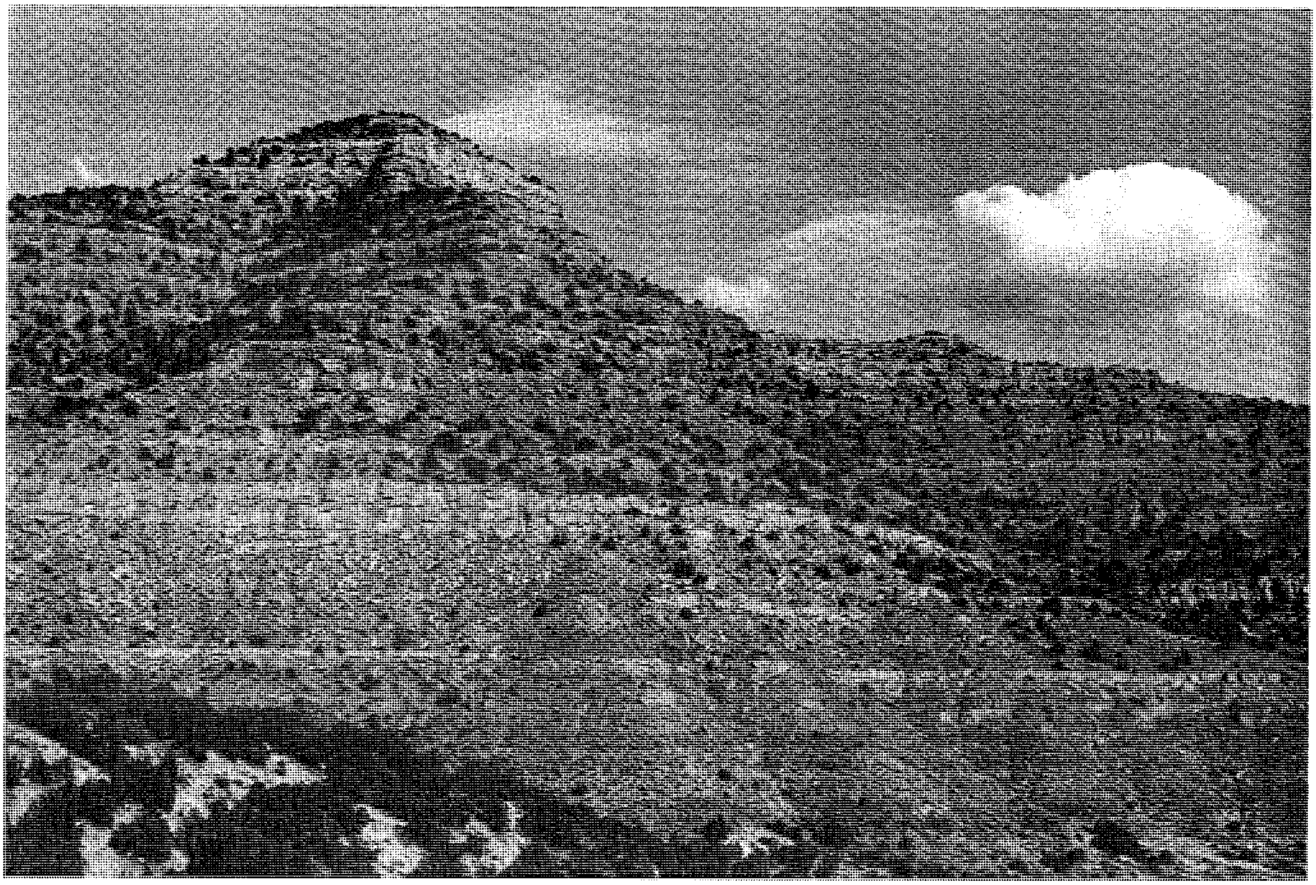

FIGURE 18.—*Typical slope-forming outcrop pattern of the Neslen Formation overlain by ledgy sandstone and mudstone of the Farrer and Tuscher Formations. Note the lenticular nature of the sandstone beds in the fluvial Farrer Formation. The Farrer and Tuscher Formations appear very similar in black-and-white photographs. The light colored laterally continuous sandstone ledge one third up from base of photograph is the Thompson Sandstone bed. Coal zones are subtle, slightly darker bands. Note the occasional fluvial channel deposits in the Neslen Formation. The slope zone, which is composed of coal, carbonaceous shale, thin-bedded mudstone, and fluvial channel sandstone are typical of upper delta plain coal zones. See Nethercott (1986) to contrast coal outcrop appearance of lower delta plain coals.*

through the Sego shoreline phase, across the backshore, coastal plain, and lower delta plain, and directly to the fluvial plains of the Farrer Formation, leaving the Neslen coals in the process.

Coals of the Neslen Formation in the Sego area are upper delta-plain to lower fluvial-plain coals as opposed to lower delta-plain coal deposits. Upper delta-plain coals are typically associated with mudstone, carbonaceous shale, and fluvial deposits, and are thinner and less economically minable than lower delta-plain coals. The upper delta-plain coal deposits of the Sego area probably grade laterally into lower delta-plain coals eastward in Colorado (see fig. 2, Young 1983b).

Lack of thick sandstone units, especially large channel-shaped beds, suggest that this area was remote from any active distributary system. The small channels (fig. 19) were deposited by minor rivers that meandered through the swamps. The extensive sheetlike Thompson Sandstone bed is interpreted as a major splay break in a distributary channel, probably located to the north, as suggested by current directions (fig. 4). It seems to have spread evenly across the entire swamp area represented by the Ballard coal zone in the quadrangle. The presence of sandstone instead of the expected Ballard seam in drill hole BC-2-SC in section 15, T. 20 S, R. 20 E (Albee 1979), to the north may be because drilling encountered the channel responsible for the Thompson Sandstone bed. The splay apparently healed itself as suggested by the fact that coal-forming conditions followed immediately.

FARRER FORMATION

The Farrer Formation, named by Fisher (1936), is the highest stratigraphic unit in this area equivalent to part of the Price River Formation and is mappable as a belt parallel to outcrops of the Neslen Formation. Thickness of the Farrer Formation ranges from 70 m (230 ft) to 360 m

FIGURE 19.—*Inclined point-bar deposits of a meandering stream associated with the Neslen Formation.*

FIGURE 20.—*Basal clay pebble rip-up clasts are common in the base of scour surfaces in all formations from the Blackhawk to the Wasatch.*

(1180 ft) across the area between the Green River and the Utah-Colorado border, and averages 230 m (750 ft) (Fisher 1936, p. 19). In the Sego Canyon Quadrangle it ranges from 70 m (230 ft) in the northeast part of the quadrangle to 206 m (676 ft) in Sego Canyon (Willis 1986). The thinning correlates with the projected crest of the Cisco Dome and is probably due to penecontemporaneous arching, which caused less deposition and/or erosion over the arch. The formation is composed of alternating resistant sandstone ledges and slope zones (fig. 18). The ledges are up to 30 m (98 ft) thick and are seldom traceable laterally more than a few kilometers and often only a few hundred meters.

The ledge-forming sandstone units are typically composed of fine- to medium-grained, subangular to subrounded quartz sand with minor chert and weathered feldspar, and form ledgy to massive cliffs. They are light to dark brown to orangish brown. Desert varnish and iron oxide stains are prevalent. Bedding is usually massive but occasional interbedded mudstone layers occur.

Trough and planar cross-bedding, ripple laminations, convolute bedding, climbing ripples, and laminar bedding all occur within these sandstone ledges. Scour bases and channeling are prevalent, especially in the lower part of the sandstone cliffs. Scour zones have abundant wood and plant impressions, poorly preserved flute casts and sole markings, and mud rip-up clasts (fig. 20). Current directions are primarily south to east (fig. 4). Where observable, the sandstone layers are incised into the underlying units. Cement is primarily calcium and iron carbonates and is usually leached from exposed units. The ledges gradually increase in size in the upper part of the formation.

Slope zones in the Farrer Formation are covered by talus, soil, and vegetation, except near the base of some of the sandstone ledges and over the shoulders of a few ridges. The slope zones constitute about two-thirds of the total Farrer Formation and are primarily siltstone, mudstone, and shale. A few one- to two-meter-thick sandstone beds commonly occur within the slopes. These are thin to massive bedded, and contain sedimentary structures similar to the larger sandstone layers. They can often be traced laterally into one of the larger sandstone beds. The siltstone, mudstone, and shale are light to medium gray, or shades of brown, orange, or yellow. Bedding is usually absent but where present is thin laminated to thin bedded.

Carbonaceous and bituminous plant fragments are common, especially in the lower part of the formation. An occasional carbonaceous shale or thin coal layer also occurs. Evidence of rooting is common. Calcite and gypsum occur occasionally as secondary minerals. The only fossils found in the Farrer Formation are a few freshwater gastropods and plant and wood impressions.

The upper contact of the Farrer Formation was previously considered as an unconformity, based on rapid variations in thickness (Spieker 1946, p. 20). Studies in the Sego area show thickness variations but no other evidence of an unconformity. Fouch and others (1983) showed no unconformity between the formations and give them the same age. Lawton (1983) also suggested a continuous sequence from Farrer to Tuscher Formations. The two formations are similar in appearance and part of the thickness variation may actually be contained within the Tuscher Formation. Nature of the upper contact is discussed later in treatment of the Tuscher Formation.

The Farrer Formation represents deposition in a low-relief floodplain and includes meandering and braided river systems. The large sandstone ledges, which invariably thin and finally pinch out, and which have incised scoured bases, are deposits of meandering rivers. These sandstones can usually be traced laterally into reddish back-levee or "bog iron" sandstone beds that were deposited along edges of back swamps. Bedding inclination changes laterally, showing progression from channel deposits to levee to back-levee deposits. Traced farther, the back-levee deposits grade into lacustrine or bog deposits.

Channel sandstones with clay pebble rip-up clasts are probably braided stream deposits (see units 13 and 39, appendix) (Keighin and Fouch 1981). These typically have more lenticular bedding, and less predictable sedimentary structures. The Farrer Formation, as a whole, accumulated in environments transitional between the two stream types with meandering streams being dominate. Channels were small but increased in size and became braided upward (Keighin and Fouch 1981).

Slope-forming units represent deposition in back swamps and floodplain lakes. The low organic content suggests oxidizing conditions and sufficient energy to remove or destroy organic material. The carbonaceous shale and coal beds in the lower part of the formation show a gradual change from the lower floodplains of the upper Neslen Formation to the middle floodplains of the Farrer Formation. The quiet-water deposits are invariably heavily rooted, often show some burrowing, and are much finer grained than the channel-fill deposits.

TUSCHER FORMATION

The Tuscher Formation was named by Fisher (1936) to describe nonfossiliferous, light gray beds above the Farrer Formation and beneath the Wasatch Formation. It is traceable from the Green River on the west to the Utah-Colorado border on the east (Fisher and others 1960, p. 18).

The Tuscher Formation ranges from 70 m (230 ft) to 200 m (650 ft) (Fisher and others 1960, p. 18). Measured thicknesses within the quadrangle are 150 m (490 ft) near Sego Canyon and 151 m (495 ft) near Left Hand Bull Canyon. The Bull Canyon thicknesses reported here for the Farrer and Tuscher Formations are inverted from those reported by Fisher and others (1960, p. 60) for the same area (Tuscher Formation 81 m (267 ft) and Farrer Formation 143 m (470 ft)). The difference is due to the choice of their mutual contact. Overall thicknesses correlate well, however, and show that thinning over the Cisco Dome did occur during deposition of the Farrer and/or Tuscher Formations.

Fisher first defined the Tuscher Formation in Tuscher Canyon (spelled "Tusher" on new maps). However, he did not define a type section, making proper resolution of the formation difficult (Keighin and Fouch 1981). It is distinctive from the Farrer Formation in Tuscher Canyon, but as the formations are traced laterally, differences decrease so that in the Sego Canyon area the two formations are difficult to distinguish. This has created a problem in mapping the two units. As a result much of the contact is "dashed" on the geologic map (Willis 1986). More work needs to be done to distinguish the two formations in the field. Distinctions observed in this study include: (1) the sandstone ledges of the Farrer Formation have a slightly more brown to brownish gray appearance while those of the Tuscher Formation have an orangish or brownish orange tint, (2) sandstone ledges of the Tuscher Formation tend to be thicker than those in the Farrer Formation and occasionally weather more rounded, (3) the lower part of the Tuscher Formation is more resistant than the middle part, forming a slope or bench above a steep ledgy slope, thus creating an often recognizable pattern, and (4) the upper sandstones of the Tuscher Formation are lighter colored and more friable than any in the Farrer Formation. These differences are generally subtle, and nonexistent in places. Lawton (1983) encountered the same problem near the Green River. He elected to divide the two formations on the basis of sand/shale ratios with the Farrer being less than 0.50 and the Tuscher being over 0.50. This method also fits the Sego area but still gives a highly arbitrary contact. A measured section in Sego Canyon (appendix) gives a ratio of 0.34 for the Farrer Formation and 0.57 for the Tuscher Formation. The large difference in ratios is due primarily to a significant change from the lower Farrer to the upper Tuscher Formation and is not as distinctive near the contact.

The ancient rivers that deposited the Farrer and Tuscher Formations became more stable as they flowed eastward, changing from braided to meandering. However, the Tuscher beds do show more evidence of braided stream deposition upward. Thus the zone of change between meandering and braided-stream deposits appears to climb upsection in an eastward direction through the formation.

The upper contact of the Tuscher Formation is unconformable with the "conglomerate beds of Dark Canyon" of Fouch and Cashion (1979).

CONGLOMERATE BEDS OF DARK CANYON

A 10–30 m (33–98 ft) thick conglomeratic sandstone unit, probably of late Paleocene age, unconformably overlies the Campanian Tuscher Formation. It is tentatively correlated with conglomerate beds of Dark Canyon of Fouch and Cashion (1979). Clasts range from 1–4 cm in diameter, are rounded to subrounded, rest in a sandy matrix, and are grain supported. They are mostly multicolored quartzite and chert. A few chert pebbles contain fossils of probable Mississippian age. Pebbles average 50% light colored, 30% black, 10% pink, and 8%–9% other colors. Some horizons also contain 1%–2% mudstone pebbles. Cross-bedding, imbrication of pebbles,

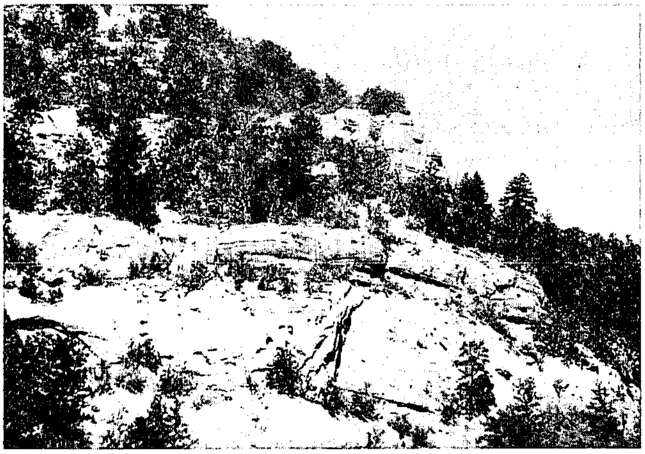

FIGURE 21.—*Conglomerate beds of Dark Canyon exposed in the upper part of Sego Canyon. Base and upper contact are erosional surfaces. The upper contact is obscured by trees. Note the interfingering sandstone stringers.*

FIGURE 22.—*Unit 1 of the Wasatch Formation in northeast part of quadrangle showing slope zones and massive lenticular sandstone beds. Looking southeast into Nash Canyon from near the north central boundary of the quadrangle.*

and cross-bedded lenses of sandstone and conglomerate are common. Current directions vary, but the most common are west and southwest. Channelling is evident but individual channels can rarely be identified. Bedding is massive. The conglomerate generally forms a cliff, except in the northeast part of the study area where it forms a protective cap on most of the ridges. The conglomerate unit forms a distinctive olive green to olive gray ledge when observed from a distance (fig. 21).

The conglomerate generally overlies a clean, very well sorted, friable quartz sandstone. In a few places the upper 1–5 m (3–16 ft) of the underlying sandstone has been reworked and has pebbles incorporated. Interbedded sandstone, conglomerate, and slope zones overlie the basal conglomerate ledge with the coarsest conglomerate near the base. The unit fines upward, both in pebble size and in increasing percentage of sandstone, until near the top it is 95% sandstone with a few stringers of 1 cm (0.4 in) or smaller pebbles and granules. The conglomerate occasionally occurs in two layers separated by a 5- to 10-meter (16–32 ft) thick, pale yellowish gray, friable sandstone.

The conglomerate beds represent a high-energy fluvial system in which gravel was transported from the rejuvenated Uncompahgre Uplift to the east. The beds have a braided-stream pattern, with numerous interfingering stringers of conglomerate and sandstone. No well-defined meander-type shingling or lensing beds with finer interchannel deposits were seen. There are many channels or scour surfaces but most lack well-defined slip bank deposits. Clast diameters range, but there is a well-defined modal peak of 3–5 cm (1–2 in). Some imbrication of pebbles occurs but it is not extensive.

Fouch and others (1981) assigned the conglomerate beds to a late Paleocene age on the basis of palynology. The overlying Wasatch Formation is unconformable on the conglomeratic beds and follows an approximately five-million-year erosional hiatus. No evidence was seen for the unconformity, and the contact, in fact, appears conformable in the Sego area. This may be due to reworking of the conglomerate beds or to covered slopes obscuring diagnostic evidence. The conglomerate beds are mapped as part of unit 1 of the Wasatch Formation (Willis 1986).

WASATCH FORMATION

The term "Wasatch" was first applied by Hayden (1869) to early Tertiary rocks in Wyoming. Since that time the name has gone through a multitude of revisions and reassignments. These are best covered in Spieker (1946, 1949), and Williams (1950). In the Sego area, the term has been applied to undifferentiated rocks that rest unconformably on the conglomerate beds of Dark Canyon and that are overlain by the Green River Formation. Only the lower third of the total Wasatch Formation is present in the Sego Canyon Quadrangle (fig. 22). The rest has been removed by erosion. The lower Wasatch beds have been divided into three units for mapping and discussion (Willis 1986). These three divisions should not be interpreted to correlate in any way with the North Horn, Flagstaff, or Colton Formations of the Wasatch Group to the west of Spieker (1946) other than they represent part of the same time in the Tertiary. The Flagstaff Limestone pinches out near Green River, Utah. East of that point the Wasatch unit maintains formational status and has not been formally divided. Two of the three mappable units are a lower and an upper interbedded, variegated mudstone, siltstone, and sandstone that form cliffs and slopes. These two units are separated by a wide slope-forming unit that supports a distinctive vegetation. The lower unit is 328 m (1075 ft) thick in the central part of the quadrangle, the middle unit is 37 m (121 ft) thick, and a maximum of 38 m (124 ft) of the upper unit is preserved in the quadrangle (fig. 4).

The Wasatch Formation, as a whole, fines upward. This is well illustrated by a comparison of the sand/shale ratios of lower and upper beds. The first 100 m (328 ft) of the section in Sego Canyon (appendix) has a ratio of 0.66. The ratio from 0–150 m (0–492 ft) is 0.58. Wasatch unit 1, as a whole, has a ratio of 0.55. The total exposed formation has a ratio of 0.34 within the quadrangle. This is especially noteworthy when compared with areas to the north where the total ratio within the Wasatch Formation was determined by Murany (1964). The sand/shale ratio is highest in the southeast part of his map (fig. 3 of Murany 1964), nearest the Sego Canyon Quadrangle. Such a relationship indicates that the primary source area for the Wasatch Formation was to the southeast, probably the Uncompahgre Uplift.

Wasatch Unit 1

Unit 1 is composed of interbedded, variegated mudstone, siltstone, and sandstone slope-forming units, with thick to massive bedded ledge-forming sandstone units. Slope-forming units are typically dark red to brownish red, often with a pale yellow or orange mottling. Some units are purple, green, gray, or yellowish-orange. Murany (1964) mentioned dark gray or black beds, but such rocks were not seen in the quadrangle. Bedding is poorly preserved or destroyed in the slope-forming units. Root impressions are very common and some burrows are occasionally seen. These slope-forming units weather into crumbly or chippy fragments and are poorly exposed, except where protected by overlying sandstone ledges. Silty mudstone is prevalent, but silt-free argillaceous material is rarely seen.

The cliff-forming sandstone units are typically pale yellowish gray to dark brownish gray and are fine to medium grained. They are composed primarily of clear or frosted quartz grains with minor dark chert grains and kaolinized feldspars which appear as white powdery fragments. Numerous incised scour or channel surfaces occur within the sandstones. They typically have a clay pebble zone 1 cm to 1 m (0.5 in to 3 ft) thick near the base. The clay pebbles are typically pale gray or yellowish gray mudstone and are subangular to subrounded. Bedding within the sandstone units is trough or wedge cross-bedded, or convolute. Current directions vary greatly but are most commonly north to northwest (fig. 4).

The high sandstone cliffs are lense shaped, pinching out in both directions along the outcrop. They persist laterally from hundreds of meters to two to three kilometers. There is no apparent preferred orientation or stacking of beds. No vertebrate or invertebrate fossils were found in the Wasatch Formation. Some plant impressions were seen, but none preserved well enough to identify.

Wasatch unit 1 was deposited in a floodplain similar to that in which the Farrer and Tuscher Formations accumulated. It was heavily vegetated and had extensive lakes and marshes or swamps. Channel sandstones are more massive than the Farrer and Tuscher units, indicating larger, better established rivers. Both braided and meander-type fluvial deposits are seen. Quiet-water silt and mud probably accumulated as overbank and back-swamp deposits.

The distinctive reddish coloration associated with the Wasatch Formation is intriguing since the formation directly overlies beds of apparently similar lithology and depositional conditions that are not red. Friedman and Sanders (1978, p. 235) discussed five possible mechanisms for red beds. It is likely that the Wasatch red beds are due to a combination of change in climate and change in source rock. There is a 20-million-year hiatus after the deposition of the Tuscher Formation and the source area did switch from west to east.

Wasatch Unit 2

Wasatch unit 2 is a distinctive, mostly covered slope-forming unit 37 m (121 ft) thick (fig. 22). A roadcut near the top of Sego Canyon exposes partially weathered float from the unit, which suggests that it is primarily mudstone similar to slope-forming parts of unit 1. Unit 2 was mapped on the basis of its wide slope and contrasting vegetation that it supports. Wasatch units 1 and 3 support a climax flora of Douglas fir, pinyon pine, juniper, and oak brush. Wasatch unit 2, though in a similar topographic setting, supports only oak brush. Wasatch unit 2 was deposited in an area not crossed by a major river for an unusually long time and was lacustrine, marsh, or swamp dominated.

Wasatch Unit 3

Wasatch unit 3 is preserved only in the highest part of the quadrangle, where it caps a few ridges. A maximum thickness of 38 m (125 ft) remains within the quadrangle. It is similar in lithology and depositional environment to unit 1.

QUATERNARY DEPOSITS

Alluvium and Colluvium

Most of the washes in the quadrangle are choked with sediment, including sand, silt, clay, and fallen blocks. The stream in the lower part of Thompson Canyon has eroded sufficiently lateral to create small areas suitable for cultivation. They are currently utilized for dry-land pasture. Colluvium occurs mainly on the bench formed on the Castlegate Sandstone and consists primarily of detritus eroded from the Sego Sandstone and overlying units. A small amount of colluvium has also collected at the base of the cliff-forming Castlegate Sandstone.

Eolian Deposits

Loess and eolian sand blanket much of the "Castlegate bench." The deposits are especially extensive in the graben-produced depression in the southwest part of the quadrangle where sand is up to 10 m (32 ft) thick and forms a few small dunes, now partially anchored by vegetation. Elsewhere sand and loess are only a few meters thick and are mostly stabilized by vegetation.

Landslide Deposits

Landslide deposits are rare in the quadrangle even though the terrain is steep. This is due primarily to the resistant sandstone ledges and vegetation that anchor the slopes. A landslide approximately one kilometer long is located in a side canyon of Nash Canyon in the SW 1/4, section 7, T. 20 S, R. 21 E. There are also a few small landslides in Thompson and Sego Canyons. In addition, a few landslides too small to be mapped occur in some of the other canyons. The latter are primarily colluvial features and do not involve the underlying bedrock.

Pediments and Beheaded Pediments

Pediments and beheaded pediments are veneered by detritus caps that protect the less resistant Mancos Shale and Buck Tongue. They occur locally on benches at the base of the Blackhawk Formation and more extensively on the Castlegate bench. The most prominent pediments are in the areas around the mouth of Thompson and Sego Canyons.

The only significant active alluvial fan pediments in the quadrangle are at the mouth of an unnamed wash about two kilometers east of Sego Canyon, and between Thompson and Blaze Canyons, on the Castlegate bench.

STRUCTURE

The Sego Canyon Quadrangle includes part of or is near several regional structural features that affect the geology of the area (figs. 2, 6). It is situated on and includes part of the northeast margin of the Paradox basin off the flank of the Uncompahgre Uplift. The quadrangle also includes north-dipping beds that form cuestas rimming the southern margin of the Uinta Basin. The La Sal Mountain intrusive complex is 56 km (35 mi) southeast of the quadrangle and the San Rafael Swell is 64 km (40 mi) to the west. Beds in the quadrangle generally have a regional dip of one to five degrees northward. This regional dip is in turn overprinted with a series of gentle northwest-trending folds parallel to the major salt anticlines of the Paradox Basin (fig. 6). Minor faulting is associated with some of the anticlinal folds.

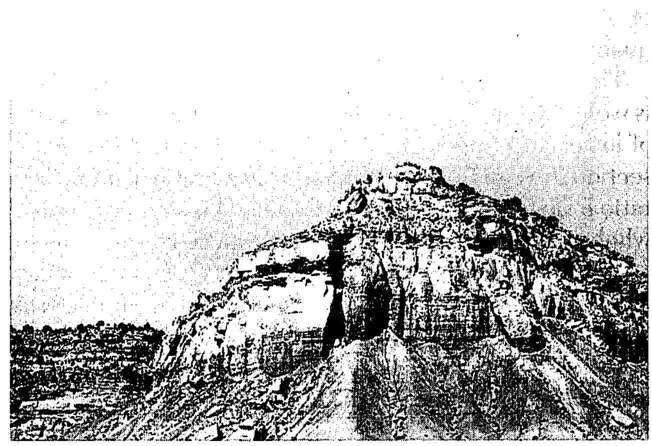

FIGURE 23.—*Major east-bounding fault of the Thompson Collapsed Anticline exposed in the Buck Tongue of the Mancos Shale and the overlying Sego Sandstone. Section 5, T. 21 S, R. 20 E.*

The extreme western flank of the elongate Cisco Dome occurs on the east edge of the quadrangle where dips are westward and northwestward at up to nine degrees. These quickly flatten to one to three degrees within the quadrangle. A very gentle synclinal trough near Sagers Wash, on the east side of the quadrangle, and an anticlinal nose to the west, near Thompson Wash, trend north to northwest through the quadrangle. These are very low broad features that deflect strike measurements only a few degrees and are not evident on casual observation.

Faults are limited to the southwest part of the quadrangle, except for a small fault in Left Hand Bull Canyon (Willis 1986). The Bull Canyon fault trends westward off of the Cisco Dome and dies near the quadrangle boundary.

Faults in the southwest part of the quadrangle are subparallel, high-angle, normal faults that trend N 20 W. Offset ranges up to 26.5 m (86.9 ft). Maximum offset is on the western boundary fault of a 600 m (2000 ft) wide graben that is mappable through sections 5, 6, and 8 of T. 21 S, R. 20 E, and sections 31 and 32 of T. 20 S, R. 20 E. The eastern boundary fault of this graben has an offset of only 9 m (30 ft) (fig. 23). Four smaller grabens and several additional even smaller faults occur to the east. From west to east these have measured offsets of 10.7 m (35.1 ft), 3.8 m (12.5 ft), 14.9 m (48.9 ft), 2 m (6.6 ft), 4.7 m (15.4 ft), 2 m (6.6 ft), 2–3 m (6.6–10 ft), 1–2 m (3.3–6.6 ft), and 3 m (9.8 ft) on the Sego Sandstone and adjacent units. One small horst occurs to the west of the main graben and has faults with 5 m (16 ft) of offset. Similar minor faults continue into the South Floy Canyon Quadrangle to the west.

The mechanism responsible for faulting and folding in the quadrangle is controversial. Folds south and southwest of the quadrangle are well documented as related to salt movement (Walton 1956; Shoemaker and others

1958), but those on the northeast overlie Precambrian rock (Frahme and Vaughn 1983). Thick salt deposits occur west of the quadrangle while Mobile C-1 McCormick Federal well on the Cisco Anticline, which lies just east of the quadrangle, drilled up to 4,267 m (14,000 ft) of Precambrian rock (Gries 1983). Thus the Cisco Anticline is definitely not salt related (fig. 2). Mechanisms responsible for the Thompson Anticline and Sagers Wash Syncline, which lie in between, are less certain.

Walton (1956) discussed this problem. He suggested that the Thompson Anticline is on trend with the Onion Creek–Sinbad Valley salt structures and had a similar origin. The pattern of keystone collapse faulting in the Thompson Anticline is characteristic of salt structures. Mobil-American Petrofina Elba flats well 1-30 penetrated 54 m (178 ft) of salt a short distance east of the quadrangle, showing that salt does extend beneath the Thompson Anticline. Walton also suggested that the Cisco Anticline is directly related to faulting along the steep western flank of the Uncompahgre Uplift and is a drape fold over that structure. He further suggested that the Sagers Wash Syncline coincides with the eastern edge of the Paradox, Hermosa, and Cutler Formations, indicating either compaction folding or salt movement. Additional subsurface data made available since 1956 (Frahme and Vaughn 1983) suggests that the Uncompahgre Fault coincides with the Sagers Wash Syncline. The syncline is thus a drape fold. The origin of the Cisco Dome is unknown but it is possibly due to drape-over faults in the underlying Precambrian crystalline rocks.

Timing of folding relative to deposition of the Wasatch and Green River Formations is uncertain. Lenticular bedding in the Wasatch Formation does not permit accurate enough strike and dip measurements to determine if it has been gently folded. The basal contact is an unconformity and thus is not dependable. However, overall outcrop patterns suggest that folding has affected the Wasatch Formation. The Green River Formation crops out too far north of the quadrangle to answer the question but gross map patterns do not show local folds. This would suggest, but certainly not confirm, that folding was Late Cretaceous to early Eocene. This seems likely since folding was probably initiated by Laramide disturbances in the area. The thick accumulation of Mesozoic sediments destabilized salt diapirs, which had nearly ceased movement in Triassic or Jurassic time, and Laramide-related movement then triggered minor renewed flowage and draping, forming the Thompson Anticline and Sagers Wash Syncline. Baars and Stevenson (1982) have shown that the linear nature, as well as timing, of salt structures in the area is linked to basement fault movement.

A careful study was made to determine if the faulting associated with the Thompson Anticline was penecontemporaneous with deposition or later occurring, and to determine the responsible mechanism. Stratigraphic sections were measured on both sides of the faults and amount of offset was measured at low and high stratigraphic intervals in the Sego Sandstone, Neslen Formation, and Farrer Formation to determine if any growth faulting had occurred. Fault surfaces were examined for any evidence of soft sediment deformation that would indicate that faulting occurred before lithification. Depositional patterns were examined to see if faulting might have caused abrupt or unusual changes. Modern drainage patterns were also studied to see what effect faulting had on them.

All evidence indicates that faulting occurred after lithification of at least the Tuscher Formation (the Wasatch Formation does not occur close enough to be diagnostic), and probably in late Tertiary or later. Walton (1956) had earlier concluded that deformation was a late event. Depositional patterns of the Blackhawk through Tuscher Formations do not seem to be altered in any way by faulting. Measured offset on high and low stratigraphic markers did not vary in amounts that could not be explained by lateral variations along the fault traces. At all observed locations, fault movement appeared brittle with jagged, broken sandstone blocks and small splintery branching faults extending off of the major faults.

Drainage patterns also suggest late movement. If faulting had occurred before drainage patterns were well established, that drainage would be controlled by faulting. There is little control in this area. Generally, orientation of washes is unrelated to fault patterns. Tributaries of Blaze Canyon, for example, cross several of the larger faults with no major deflections along fault traces (Willis 1986). The tributary of lower Blaze Canyon, in the NW 1/4 of section 8, T. 21 S, R. 20 E, is just beginning to be deflected parallel to the faults. In the north central part of section 9 the cliff-forming Castlegate Sandstone is just beginning to be notched where a four-meter (13 ft) fault cuts the unit. These evidences of minor drainage control suggest that faulting was late and that, with time, drainage will adjust. Doelling (personal communication, 1984) observed Quaternary sediments that had been highly tilted by salt movement in the Salt Valley Anticline to the southwest. Late faulting also fits the scenario of Baars and Stevenson (1982). They suggested that uplift of the Colorado Plateau increased groundwater flow, which caused salt solution and subsequent collapse.

ECONOMIC GEOLOGY

Potential economic resources of the Sego Canyon Quadrangle are primarily coal and hydrocarbons. The quadrangle has produced coal in mining operations since 1900, and considerable reserves remain. Hydrocarbons have been produced from adjacent structures similar to

Table 1. Proximate analyses of selected coal samples from the Sego Canyon Quadrangle. All BTU measurements are calculated on the basis of moist, mineral matter-free samples (Wood and others 1983). The first six samples are from Doelling and others (1979). The remaining samples are calculated from analysis "B", Doelling and Graham (1972, p. 230). Seams are: C-Chesterfield, B-Ballard, u-upper, l-lower, P-Palisade. M-moisture, VM-volatile matter, FC-fixed carbon, S-sulfur (all in percent).

Location	Seam	M	VM	FC	Ash	S	Moist Mm-Free BTU/lb
NW15, 20S, 20E	C	4.2	36.9	47.6	11.3	0.6	13712
NW15, 20S, 20E	C	4.4	38.4	49.4	7.8	0.5	13891
NW15, 20S, 20E	B?	4.3	39.3	47.7	8.7	0.7	14012
SE17, 20S, 20E	B (u)	6.3	39.2	51.8	2.7	0.6	13461
SE17, 20S, 20E	B (1)	5.3	38.4	44.8	22.5	0.6	13528
SE17, 20S, 20E	P	5.1	36.4	47.1	11.2	0.6	13719
NW27, 20S, 20E	C	8.5	35.6	49.9	12.0	0.7	13992
NW27, 20S, 20E	C	2.5	37.2	48.7	11.0	0.6	13931
NW27, 20S, 20E	C	2.3	37.6	48.4	11.0	0.7	13888
NW27, 20S, 20E	C	2.8	37.9	49.2	9.5	0.6	13880
NW27, 20S, 20E	B	4.1	32.6	43.8	19.5	0.6	13764
NW27, 20S, 20E	B	1.9	35.0	46.8	15.7	0.6	13685
NW27, 20S, 20E	B	5.3	37.8	46.3	10.6	0.67	13513
NW27, 20S, 20E	P	5.1	38.3	45.9	10.7	0.62	13608
NW17, 20S, 20E	P	2.0	38.2	49.4	9.7	0.7	13928

those in the quadrangle, and considerable potential exists in this area. Sand and gravel show minor potential for development.

COAL

Coal seams in the quadrangle are part of the Sego Coal Field, an eastward extension of the Book Cliffs Coal Field (Doelling and Graham 1972, p. 191). The Book Cliffs Coal Field makes up that part of the Book Cliffs from near the Price River east and south to the Green River. The Sego Coal Field constitutes the Book Cliffs eastward to the Colorado state line (Doelling and others 1979, p. 25, 37). The two fields are differentiated because all economic coals in the Sego Coal Field occur in the Neslen Formation, while those in the Book Cliffs Coal Field are contained in the Blackhawk Formation. Four main coal zones, the Palisade, Ballard, Chesterfield, and Carbonera, plus several minor zones make up the coal units of the Neslen Formation. Of these, the first three, plus several minor zones, are present in the Sego Canyon Quadrangle.

Practically all mining in the Sego Coal Field has been in the central part of the quadrangle near Sego and Thompson Canyons. Coal has been removed from all the major seams, but usually as a marginal venture. An estimated 2.4 million metric tons (t) (2.65 million tons) had been removed from this area as of 1972 (Doelling and Graham 1972, p. 207). Poor roof rock, splits, and high ash content combined to frustrate profitable operations. No active mining is being done at this time.

Coal in the quadrangle is high volatile bituminous B as determined from proximate analyses but ranges from subbituminous B to high volatile bituminous B (table 1). Doelling and Graham (1972, p. 229, 230, 237) and Doelling and others (1979, p. 9–11, 19–20) reported results of proximate and ultimate analyses and other tests made on samples from various parts of the quadrangle for the Palisade, Ballard, and Chesterfield seams in the quadrangle. Proximate analysis results are given in table 1.

Palisade Coal Zone

The lowest of the three main seams, the Palisade, occurs 10–20 m (33–66 ft) above the base of the Neslen Formation (fig. 24). It averages 0.9 to 1.2 m (3 to 4 ft) thick but reaches a maximum measured thickness of 2.0 m (6.8 ft) near Thompson Canyon. It thins eastward so that in parts of Sagers Canyon and Nash Canyon it is completely missing. It also thins on the west side of the area. Near Blaze Canyon a thickness of 0.4 m (0.9 ft) was measured. Figure 25 shows thicknesses of the coal based upon a wave-dominated shoreline depositional model.

Doelling and Graham (1972, p. 242) estimated total coal reserves in the Palisade seam in the Sego Canyon Quadrangle at 45 million metric t (49.5 million tons). Of that amount, about 10 million metric t (12 million tons) are in seams greater than 1.2 m (4 ft) thick.

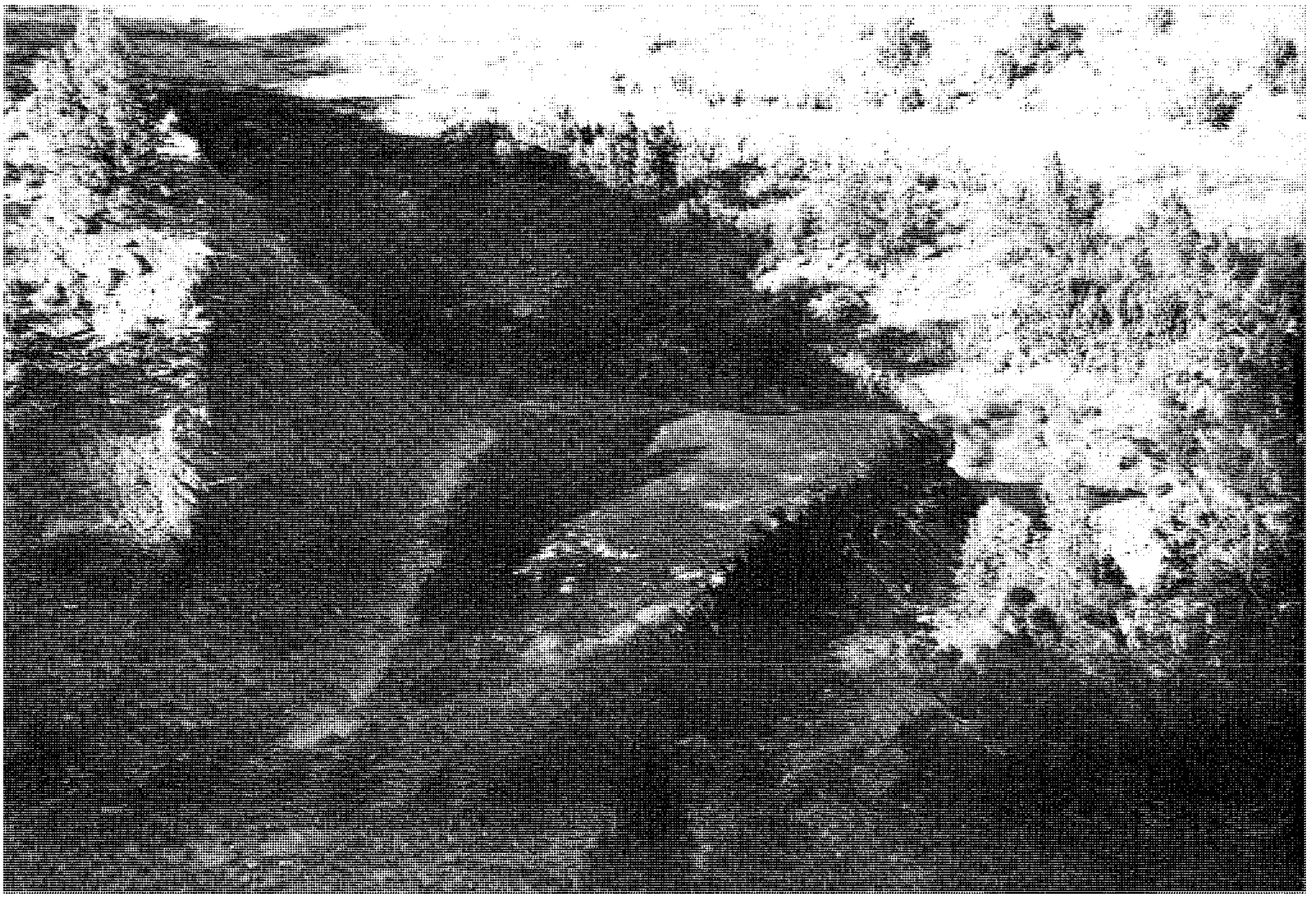

FIGURE 24.—*Palisade coal bed in section 29, T. 20 S, R. 20 E. Coal is about 1 m (3 ft) thick. Note the underlying carbonaceous shale and overlying thin-bedded sandstone beds that are typical floor and roof rock of the Palisade seam.*

As mentioned, high ash content, mainly the result of numerous splits, rendered the Palisade zone uneconomical to mine. Figure 25, showing typical measured sections through the Palisade and other coal zones, illustrates this problem. Poor roof rock is another problem associated with the Palisade seam. It is generally overlain by thinly laminated carbonaceous shale, mudstone, and thin interbedded sandstone and mudstone, all quite susceptible to roof collapse (figs. 24, 26, 27). Thick to massive channel sandstone lenses locally overlie the coal beds, providing more stable roof rocks.

Ballard Coal Zone

The Ballard coal zone is located at the top of the lower member of the Neslen Formation, at the base of the Thompson Sandstone (fig. 28). It is often exposed in a cliff face held up by the resistant Thompson Sandstone bed.

The Ballard seam averages 1.2 m (4 ft) thick, with a maximum measured thickness of 2.3 m (7.5 ft) in Nash Canyon. It thins to a feather edge between Nash and Sagers Canyons. Other thick loci are in Sego Canyon and Sagers Wash (fig. 29).

Doelling and Graham (1972) estimated 156.1 million metric t (171.7 million tons) of reserves remain in the quadrangle in the Ballard seam. Of that, 78.7 million metric t (86.6 million tons) are in beds over 1.2 m (4 ft) thick. Results of proximate analysis (table 1) show that the Ballard seam is similar to the Palisade seam but with higher moisture and ash content and lower volatile matter, fixed carbon, and sulfur content.

Roof rock for the Ballard coal zone is good because the Thompson Sandstone everywhere overlies the seam, usually with less than 10 cm (4 in) of carbonaceous shale between. The Thompson Sandstone bed is thick to massive bedded and has considerable internal strength. Splits are a problem with this seam as with the others (fig. 29).

Chesterfield Coal Zone

The Chesterfield coal zone is located 5–10 m (15–30 feet) above the Ballard coal zone. It was the last of the three seams to be mined in the quadrangle but eventually proved to be most economical, mainly because it had a greater split-free thickness (Doelling and Graham 1972). The Chesterfield zone is overlain by a thick sequence of

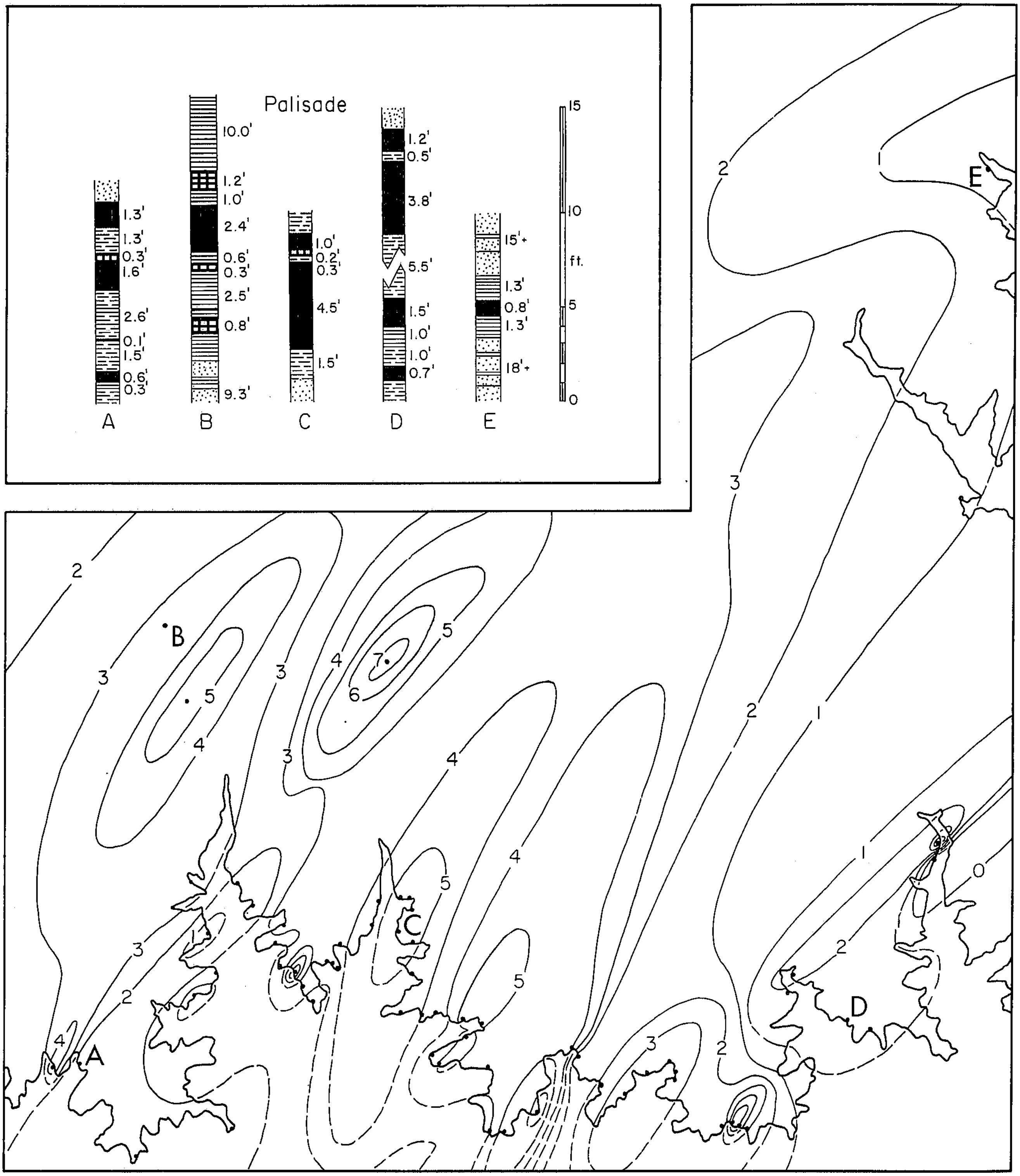

FIGURE 25.—*Total coal isopach map of the Palisade coal zone based on a model with coal thickness controlled by repeated underlying wave-dominated shoreline sequences. Inset shows representative measured sections through the seam. From Doelling and Graham (1972), Albee (1979), and data from this study.*

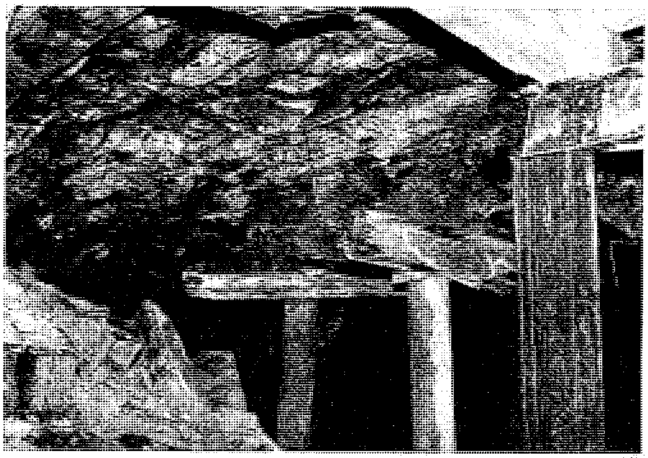

FIGURE 26.—*Poor roof rock is a constant problem with the Palisade and Chesterfield coal zones. This mine is in the Chesterfield seam in Thompson Canyon.*

FIGURE 27.—*Poor roof rock in the Chesterfield coal zone. Even well-reinforced roof rock is prone to collapse. This mine is in Thompson Canyon.*

carbonaceous shale, mudstone, and thin-bedded sandstone, and an occasional channel sandstone (fig. 28). As such it is usually poorly exposed, occurring in a grassy slope zone (figs. 18, 28) although it occasionally is exposed in cliff faces.

The Chesterfield seam averages 1.2 to 1.5 m (4 to 5 ft) thick within the quadrangle. It is up to 2.4 m (8 ft) thick, with split-free intervals up to 2 m (6 ft) thick in Thompson Canyon. Thickest sections occur in the Thompson and Sego Canyons area, near Sagers Wash, and near Nash Canyon (fig. 30). Thicknesses of less than a foot occur in the Bull Canyon area.

Doelling and Graham (1972, p. 242) estimated 153.8 million metric t (168.6 million tons) of reserves in the Chesterfield seam in the quadrangle. Of this, 97.5 million metric t (107.3 million tons) are in seams averaging more than 1.2 m (4 ft).

As mentioned, roof rock is probably the greatest hindrance to development of this seam (figs. 26, 27). Overlying rocks are similar to those overlying the Palisade seam, consisting of interbedded sandstone, mudstone, carbonaceous shale, and thin-bedded coal. It is the best of the three seams for lack of splits, low ash content, and low sulfur (table 1).

Minor Coal Zones

Other coal seams worthy of note occur below the Palisade zone, between the Palisade and Ballard zones, and above the Chesterfield zone. These are typically lenticular and small in areal extent. Correlation between them is difficult because they are poorly exposed and discontinuous. The seam between the Palisade and Ballard zones is most extensive, reaching thicknesses up to 1.3 m (4.3 ft) thick. Doelling and Graham (1972, p. 242) estimated that 3.5 million metric t (3.9 million tons), averaging 1.1 m (3.7 ft) thick, occur in sections 35 and 36, T. 20 S, R. 20 E, in this seam near Sagers Wash. A few fingers or splits off the three main seams may also have locally minable thicknesses.

HYDROCARBONS

The Sego Canyon Quadrangle is located in an area of at least 28 oil and gas fields in which 445 producing wells have been drilled (Young 1983a, p. 4). Production has been realized from structural, salt intrusion, structural/stratigraphic, and stratigraphic traps (Young 1983a, p. 4), but no significant hydrocarbon production has been realized from the quadrangle. The nose of the Cisco Dome, which produces just east of the quadrangle, extends into the northeast corner of the quadrangle and has been drilled in both Nash and Left Hand Bull Canyons (fig. 6). Shows were reported but no significant production was achieved. The Cisco Dome is a shallow field with most production from thin sandstone beds in the Mancos Shale and the Dakota Formation. Production has also been reported in the Cedar Mountain, Morrison, and Entrada Formations (Young 1983a, p. 5). These formations all underlie the study area and may yet produce there.

The quadrangle overlies part of the Paradox Basin, which is well known for its yield to the south. Several companies are actively exploring for Paleozoic-related traps in the basin around the study area (Krivanek 1981, p. 77–81).

Faulting in the Thompson Anticline is probably due to Paradox salt movement. As such, the anticline shows considerable promise for shallow or deep fault bounded or diapir-created traps. Additional potential exists for stratigraphic or stratigraphic/structural traps in several of the subsurface formations. Deeper traps related to the Precambrian faults should also be considered (Baars and

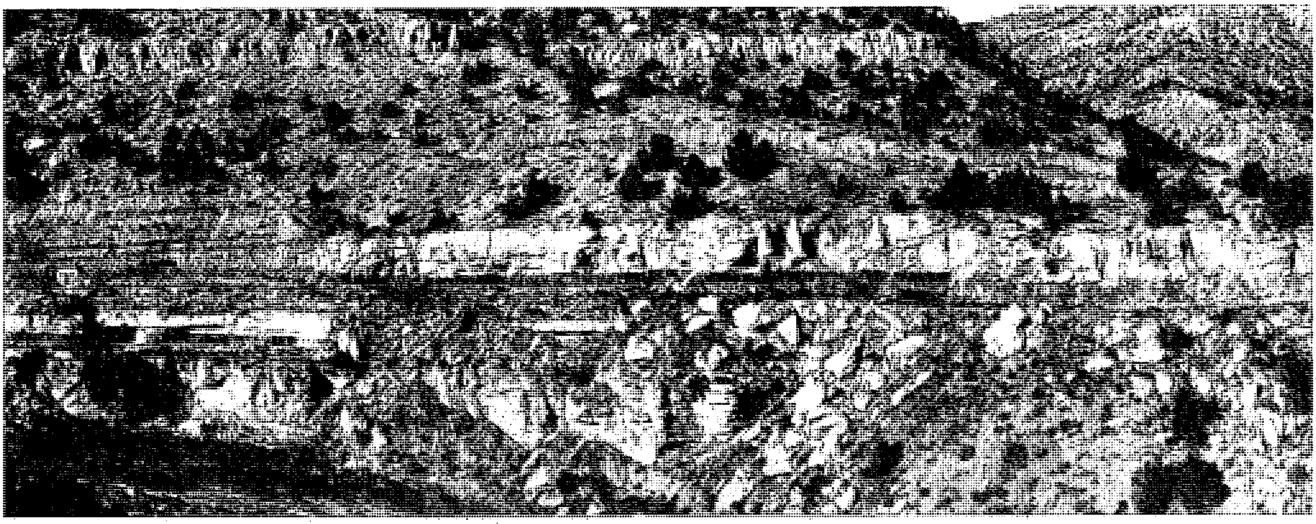

FIGURE 28.—*The Neslen Formation near the Knight Mine in Thompson Canyon. The Palisade zone occurs near the road at the bottom of the photograph and is overlain by a meandering stream deposit. The Ballard seam is being mined near the left of the photograph and is capped by the thick unjointed Thompson Sandstone bed. The Chesterfield seam is overlain by mudstone and carbonaceous shale in the left of the photograph and a thick meandering channel deposit in the center and right of the photograph. The channel has cut out the seam near the right side. A thin coal seam overlies the channel sandstone. The Farrer Formation is exposed in the upper part of the photograph (sandstone ledges). Figures 26 and 27 are from the upper mine in the left part of this figure.*

Stevenson 1982, p. 131–58). Source rocks are abundant in the area and include the Mancos Shale for shallow reservoirs and the Paradox Formation for deeper traps.

SAND AND GRAVEL

Eolian sand deposits and sandstone beds in the quadrangle generally contain too much clay, silt, and iron to be utilized for quartz. There are no significant alluvial gravel deposits in the quadrangle, but small amounts do occur in the bottom of Thompson and Sego Washes. The conglomerate beds of Dark Canyon, located at the base of the Wasatch Formation, could conceivably be crushed for gravel. They generally crop out on steep slopes and cliffs (fig. 21) far from existing roads, but in Thompson and Sego Canyons access is better and some limited production could be realized.

SUMMARY OF ECONOMIC GEOLOGY

Coal and hydrocarbons are the main potential economic mineral resources for the area. Doelling and Graham (1972) estimated the quadrangle contains 187.2 million metric t (205.9 million tons) of coal in seams greater than 1.2 m (4 ft) thick that have potential for underground mining. Though the lenticular nature, poor roof rock, high ash content, and thin beds may hinder underground mining, such mining has been done in the past, and with proper economic conditions and modern techniques may be profitable in the future. There are an additional 180 million metric t (200 million tons), and probably over 360 million metric t (400 million tons), in seams less than 1.2 m (4 ft) thick. These beds have potential for in situ gasification, as economic conditions dictate. Potential for surface mining is limited as most coal beds are covered by thick overburden (Willis 1986, p. 14). A small area near Thompson Canyon could possibly be surface mined.

Hydrocarbon potential for the quadrangle is good and merits more study, especially in the area of the faulted Thompson Anticline. Gravel from the crushed conglomerate beds is the only other geologic resource with any potential at the present time.

WATER RESOURCES

The Green River, 30 km (20 mi) to the west, and the Colorado River, 40 km (25 mi) to the southeast, are the large perennial water bodies closest to the quadrangle. There are two small perennial spring-fed streams in the quadrangle. One is in Thompson Canyon and is the water supply for the small town of Thompson. The other is in Nash Canyon and is utilized by a small agricultural and ranching operation at the mouth of the canyon. Sego Canyon, Sagers Wash, and Left Hand Bull Canyon have small seeps or springs that flow intermittently. Most of these springs surface at impermeable carbonaceous shale layers near the top of the Neslen Formation. There are also a few small seeps in the higher canyons in the Wasatch and Tuscher Formations. Precipitation in the quadrangle ranges from 21.6 cm (8.5 in) at the lowest

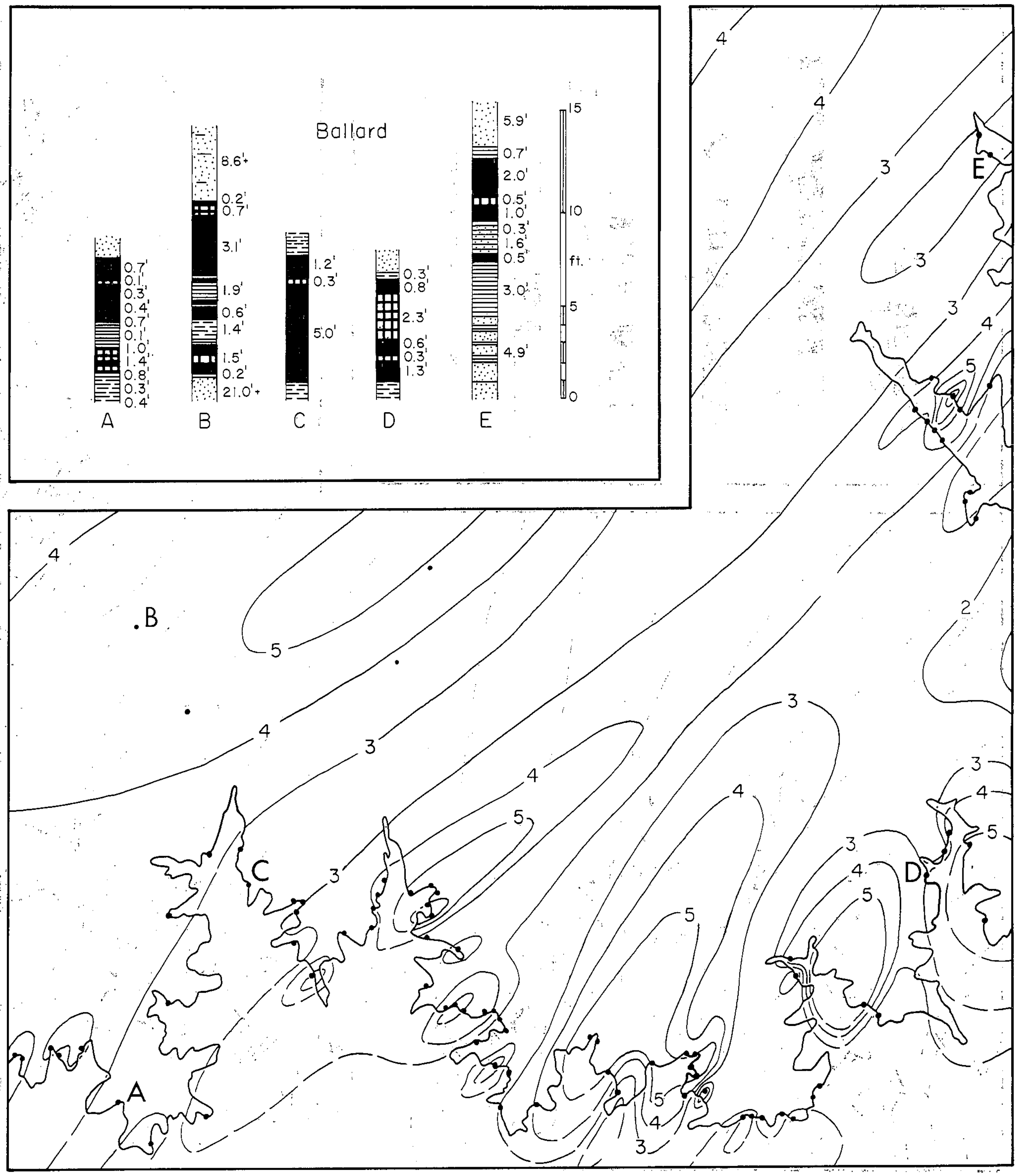

FIGURE 29.—*Total coal isopach map of the Ballard coal zone based on a model with coal thickness influenced primarily by repeated underlying wave-dominated shoreline sequences and secondarily by a fluvial system. Inset shows representative measured sections through the seam. From Doelling and Graham (1972), Albee (1979), and data from this study.*

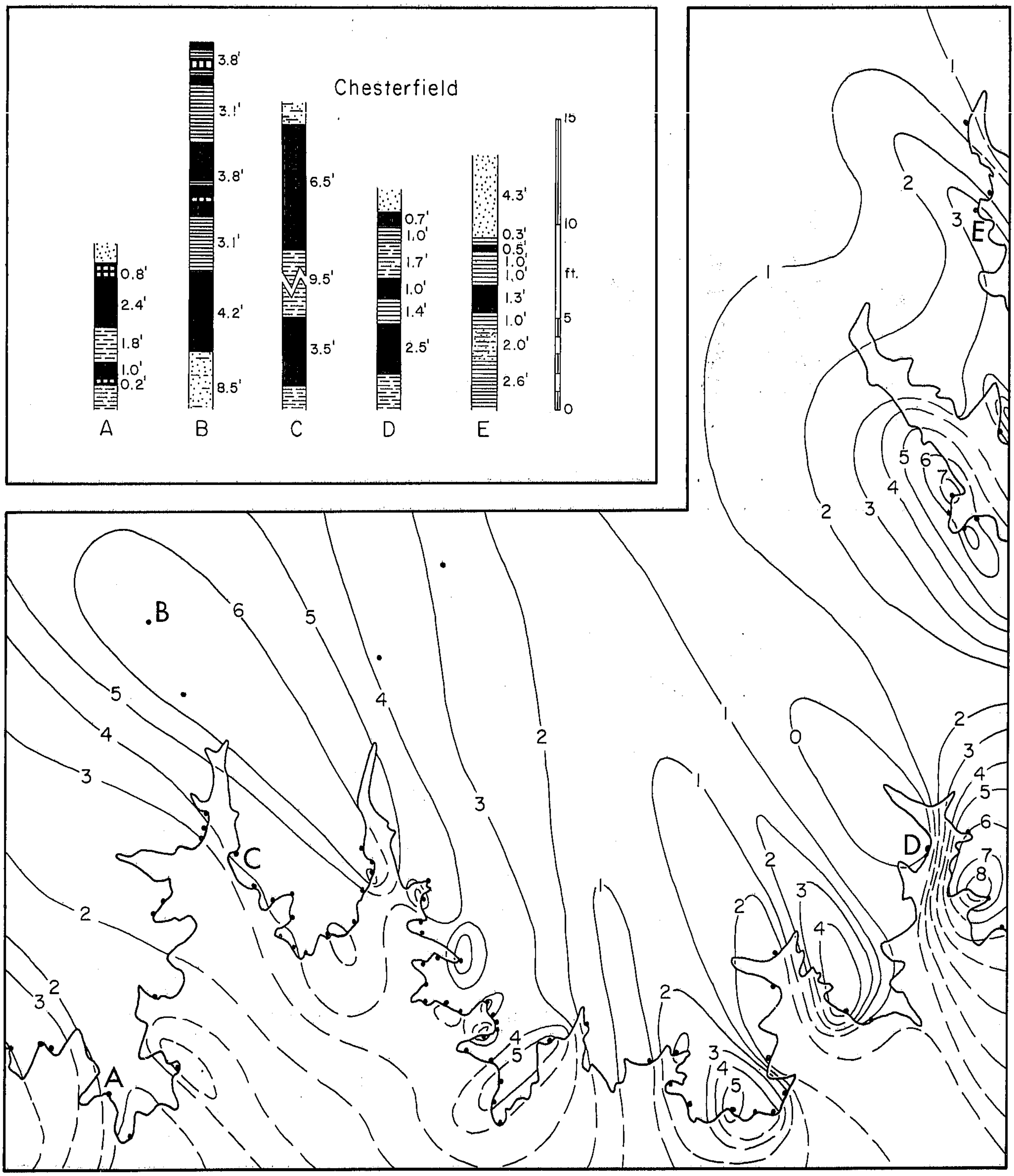

FIGURE 30.—*Total coal isopach map of the Chesterfield coal zone based on a model with coal thickness controlled by a fluvial system. Inset shows representative measured sections through the seam. From Doelling and Graham (1972), Albee (1979), and data from this study.*

elevations near Thompson to about 41 cm (16 in) in the highest areas (Waddell and others 1981).

There is limited potential for subsurface water in the shallower formations because most subsurface water flows down the north-dipping slope of the impermeable beds away from the area. There is also limited potential for deeper subsurface water because the quadrangle is underlain by 1160 m (3800 ft) of impervious, highly alkaline Mancos Shale. Hydrocarbon exploration has located water in porous sandstone beds beneath the Mancos Shale but these are too deep to be pumped economically. Attempts have been made to locate water along the fault traces in the quadrangle but they were found to be sealed (Les Rogers personal communication 1982). There are no alluvial aquifers in the area.

SUMMARY OF CHRONOLOGY

Significant advances have been made in understanding the chronology of geologic events in the Sego Canyon area. The following outline contains only those events pertinent to geology discussed elsewhere in this report and affecting the Sego area. A brief discussion of effects on the area, or evidences within the area, is included in some cases. Sources include Walton (1956), Hintze (1973), Fouch and others (1981), Baars and Stevenson (1982), Frahme and Vaughn (1983), Fouch and others (1983), Lawton (1983), Molenaar (1983), and new information collected in this study.

Age (m.y.b.p.)	Events
Precambrian 1780 to 1460	Basement complex established. Northwest-trending Olympia-Wichita and northeast-trending Colorado lineaments established. Faults associated with these trends have controlled structure in the area since.
Early Pennsylvanian 320 to 285	Major uplift on the Uncompahgre and other basement faults. Paradox evaporite deposition. Salt flow begins due to loading. Flow is horizontal until basement faults are encountered which divert flow upward, creating parallel, linear diapirs.
Pennsylvanian to Permian 300 to 245	Salt flow maximizes.
Triassic 245 to 210	Salt flow wanes as salt supply is depleted and loading equalized. Formations are slightly affected by salt movement.
Triassic to Jurassic 210 to 145	Salt flow is minimal. Diapirs are stable with respect to host rock. Thick Mesozoic sediments are deposited over the area with negligible influence by salt flowage or faulting.
Cenomanian 95–90	Advance of the Mancos Sea, the last of many marine invasions that inundated parts of Utah.
Campanian 76–72	Regression of Mancos Sea from the area. Deposition of all units exposed in the Sego Canyon Quadrangle through the Tuscher Formation.
Latest Campanian 73	Rapid onset of the Laramide orogeny. The Farrer and/or Tuscher Formation thins over the Cisco Dome (Uncompahgre Fault) due either to uplift reducing rate of deposition, or erosion after the Farrer Formation and prior to deposition of the Tuscher Formation.
	The San Rafael Swell begins rapid uplift, resulting in changes in sediment pattern of the Tuscher Formation (Lawton 1983). The Tuscher Formation deposits have only subtle differences in the Sego area but are significantly different farther to the west.
Maestrichtian to Late Paleocene 72 to 58	An unconformity resulting from the Laramide orogeny has removed all record of this time period from the area.
	The Uncompahgre Uplift is rejuvenated enough to expose Mississippian-age sediments.
	Laramide activity triggers minor renewed movement on dormant salt diapirs that had been rendered unstable by thick Mesozoic sediment accumulation and minor renewed faulting on the Uncompahgre Fault. Drape folding of the Cisco Dome and salt doming of the Thompson Anticline resulted.
	Folding may possibly have occurred as late as late Tertiary.
Late Paleocene to Eocene 58 to 56	Conglomeratic sandstone shed from the Uncompahgre Plateau is deposited in the area. An unconformity may have followed deposition of these beds but evidence in the area is inconclusive.
Early to Middle Eocene 56 to 48	Deposition of the Wasatch Formation. Sediments derived from Uncompahgre Uplift to southeast. Tectonic activity and salt movement is dormant.
Eocene to Recent 48 to present	Green River Formation deposited, then subsequently eroded from the quadrangle. During this time the Colorado Plateau was tilted toward the north, shedding sediments into Lake Uinta.
Late Miocene to Recent 10 to present	Major uplift of the Colorado Plateau. This resulted in increased groundwater flowage and subsequent solution and collapse of salt structures, including the Thompson Anticline and erosion to the present topographic configuration.

CONCLUSIONS

Geologic history represented by stratigraphy exposed within the quadrangle began with the regressive phase of the epicontinental Mancos Sea. The Blackhawk Formation and the Castlegate Sandstone, which are stratigraphically adjacent and similar in appearance in this area, were deposited in a regressive wave-dominated delta and shoreface sequence. The Buck Tongue of the Mancos Shale was deposited during the last major transgressive pulse of the Mancos Sea into the area and is marine. The lower, middle, and upper Sego Sandstone members are three lithologically similar sequences, each of which coarsens upward from marine to shoreface deposits. These represent three minor regressive pulses separated by two transgressions and are wave-dominated delta deposits. The middle Sego Sandstone member wedges out east of the area and the two transgressive mudstone sequences combine to become the Anchor Tongue of the Mancos Shale. These minor pulses were the last marine influence in the area.

The Neslen Formation is composed of near-shore transition sediments deposited in the area between marine and fluvially dominated lower floodplain facies. These transition deposits were then overlain by the Farrer and Tuscher Formations, which are meandering and braided stream, back-levee swamp, and lacustrine deposits. A disconformity may exist between the Farrer and Tuscher Formations and between the Tuscher Formation and conglomerate beds of Dark Canyon. They are probably due to renewed uplift on the Uncompahgre Fault. The conglomerate beds of Dark Canyon were derived from the resulting positive area to the east. All previous deposition originated from the west. The Wasatch Formation was deposited in a fluvial-lacustrine environment similar to the Farrer and Tuscher Formations, but of lower energy.

The Uncompahgre and smaller northwest-trending faults, which originated in the Precambrian, and salt diapirism have been the major structural controls in the area. Movement on the Uncompahgre Fault resulted in deposition of thick late Paleozoic clastic and evaporite sediments in the adjacent Paradox Basin. Subsequent periodic movements on the faults have caused parallel salt flowage, as well as subsidence and drape folding. The Thompson Anticline was formed by salt movement. The Sagers Wash Syncline was caused either by salt flowage out of the area or differential compaction due to drape over the Uncompahgre Fault. The Cisco Dome may have been caused by minor faulting east of the Uncompahgre Fault.

Economic resources of the quadrangle include coal and hydrocarbons. Approximately 2.40 million metric t (2.65 million tons) of coal have been removed from the quadrangle. An estimated 187 million metric t (206 million tons) remain in seams greater than 1.2 m (4 ft) thick. Of that amount, 11 million metric t (12 million tons) are in the Palisade seam, 79 million metric t (87 million tons) in the Ballard seam, 98 million metric t (108 million tons) in the Chesterfield seam, and small amounts in the remaining minor seams.

Hydrocarbons have been produced in adjacent quadrangles, and shows have been reported in drill holes in the quadrangle. Best prospects are associated with faults and intrusive salt-related traps of the Thompson Anticline and Paradox Basin-related structures.

ACKNOWLEDGMENTS

The writer expresses appreciation to J. Keith Rigby, who served as thesis chairman, and to Lehi F. Hintze and James L. Baer, who served as committee members. Hellmut Doelling and Archie Smith of the Utah Geological and Mineral Survey provided much helpful advice and information. George Stancliff, Layne Smith, Jonathon Morten, my brother Bryce Willis, and my parents, Curtis and Winona Willis, provided much appreciated field assistance. Students in the Brigham Young University Geology Summer Field Camps (1981, 1982) measured several stratigraphic sections in the area that aided in interpretation of the geology. Julie, my wife and fellow geologist, provided unending support and advice.

Partial funding was provided by grants from the American Association of Petroleum Geologists and the Utah Geological and Mineral Survey. Brigham Young University provided computer time and laboratory facilities.

The appendix to this paper is on file at the Department of Geology, Brigham Young University, where a copy may be obtained.

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