UNITED STATES
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THE MESAVERDE GROUP AT SUNNYSIDE, UTAH

By Harold Brodsky

Prepared in cooperation with the U. S. Bureau of Mines

1960

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2. Total intensity aeromagnetic profiles of the Yukon Flats-Kandik area, Alaska, by G. E. Andreasen. 7 sheets. On file at Brooks Memorial Mines Bldg., College, Alaska; Room 503, Cordova Bldg., Anchorage, Alaska; Room 117, Federal Bldg., Juneau, Alaska; State Division of Mines and Minerals, Territorial Bldg., Juneau, Alaska; So. 157 Howard St., Spokane, Wash.; Room 232, Appraisers Bldg., San Francisco, Calif.; Room 1031, Bartlett Bldg., Los Angeles, Calif.; Room 602, Thomas Bldg., Dallas, Texas. Copies from which reproductions can be made at private expense are available at Alaskan Branch, USGS, 345 Middlefield Road, Menlo Park, Calif.

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Contents

List of illustrations

THE MESAVERDE GROUP AT SUNNYSIDE, UTAH

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Abstract

The Mesaverde group of Late Cretaceous age at Sunnhside, Utah consists in ascending order; the Blackhawk formation, Castlegate sandstone and the Price River formation. The Mancos shale intertongues with the Blackhawk formation.

The Mancos shale formed in an offshore marine environment, the Blackhawk formation formed in a mixed marine and continental environment and the Castlegate and Price River formations at Sunnyside, Utah formed in a continental environment.

Thin even bedding characterizes the Mancos shale except where it extends as a thin tongue into the Blackhawk formation. Tongues of the Mancos shale in the Blackhawk formation have in places disrupted bedding and locally contain impressions of twigs and branches. Disrupted bedding with mottling, irregular and uneven bedding, and very thick bedding with cross stratification resembling lower foreshore laminae, are primary structures common in modern marine sediments and can also be found in the marine tongues of the Blackhawk formation. Massive, wedge-shaped, cut-and-fill structures characteristic of fluviatile deposits are found in the Castlegate-Price River formations.

Particle size distribution in the marine tongues of the Blackhawk formation shows an increasing coarseness as shoreline deposits are approached. Coal particles are generally absent in the marine sandstones of the Blackhawk formation but are commonly found in abundance in the continental sandstones in the Blackhawk.

The economic coal beds within the Blackhawk formation at Sunnyside have been reported as consisting of a "Lower" Sunnyside seam and an "Upper" Sunnyside seam. Stratigraphic sections and drill logs indicate that these seams may be splits of one major coal bed and that the term "Upper" Sunnyside seam refers to more than one major split.

The relationship of the splits in the Sunnyside coal seams and the lithologic characteristics of the coal indicate that the coal swamp existed on a low-lying coastal plain close to sea level where swamp accumulations were interrupted occasionally by fluviatile deposition.

Subsidence due to compaction of underlying sediments, aggradation as the shoreline regressed as well as slow tectonic subsidence or gradual eustatic rise in sea level are factors which may account for the thickness of the Sunnyside coal beds.

THE MESAVERDE GROUP AT SUNNYSIDE, UTAH

by Harold Brodsky

Introduction

Purpose of study

The purpose of this study is to reconstruct the depositional history of the Blackhawk and Price River formations of the Mesaverde group from data collected in the vicinity of Sunnyside, Utah. This paper is divided into four sections dealing with this problem. The first section is concerned with the regional stratigraphy and its relation to the section at Whitmore Canyon near Sunnyside, Utah. The second section describes the lithology and primary features of these sediments and their possible environmental significance. The third section deals with the configuration, lithology and structure of the major economic coal beds at Sunnyside. The fourth section integrates data and interpretation into a summary of the sequence of events that resulted in the vertical and lateral facies changes in the Blackhawk and Price River formations at Sunnyside.

This study was undertaken as part of the author's duties with the Engineering Geology Branch of the U. S. Geological Survey which, in cooperation with the U. S. Bureau of Mines, is investigating the occurrence of rock bursts, called "bumps" in coal mines.

Area of study

Outcrops of the Blackhawk and Price River formations extend from the Wasatch Plateau eastward along the Book Cliffs. The Blackhawk formation extends eastward to the vicinity of Cisco, Utah and the Price River formation extends eastward beyond the Colorado State line (Young, 1955). These two formations were studied in detail at Whitmore Canyon near Sunnyside, Utah. Figure 1 shows the trend of the Book Cliffs in central Utah and the position of Whitmore Canyon.

The upper Cretaceous formations strike north to northeast and dip gently (about 5 to 15 degrees) northward into the Uinta Basin. Several high-angle faults with a maximum of about 110 feet of displacement are visible along the cliff face. The axis of the San Rafael swell trends toward Sunnyside where it warps the beds into a broad anticlinal nose. This tectonic feature is probably responsible for the change in trend along the Book Cliffs escarpment. Broad re-entrants and salients along the Book Cliffs may correspond with the axes of anticlines and synclines respectively.

The area has economic importance because the coal beds mined at Sunnyside and elsewhere are of high-volatile bituminous B rank. Coal mined at Sunnyside is shipped by the Kaiser Steel Corporation to Fontana, Calif. where it is used as a coking coal.

Methods of study

Field work was done during the summer of 1959 and briefly during the winter of 1960. Sections were sampled and measured at Whitmore Canyon and other accessible points in nearby areas. Several coal sections were examined in the No. 1 mine at Sunnyside. Well log data obtained from

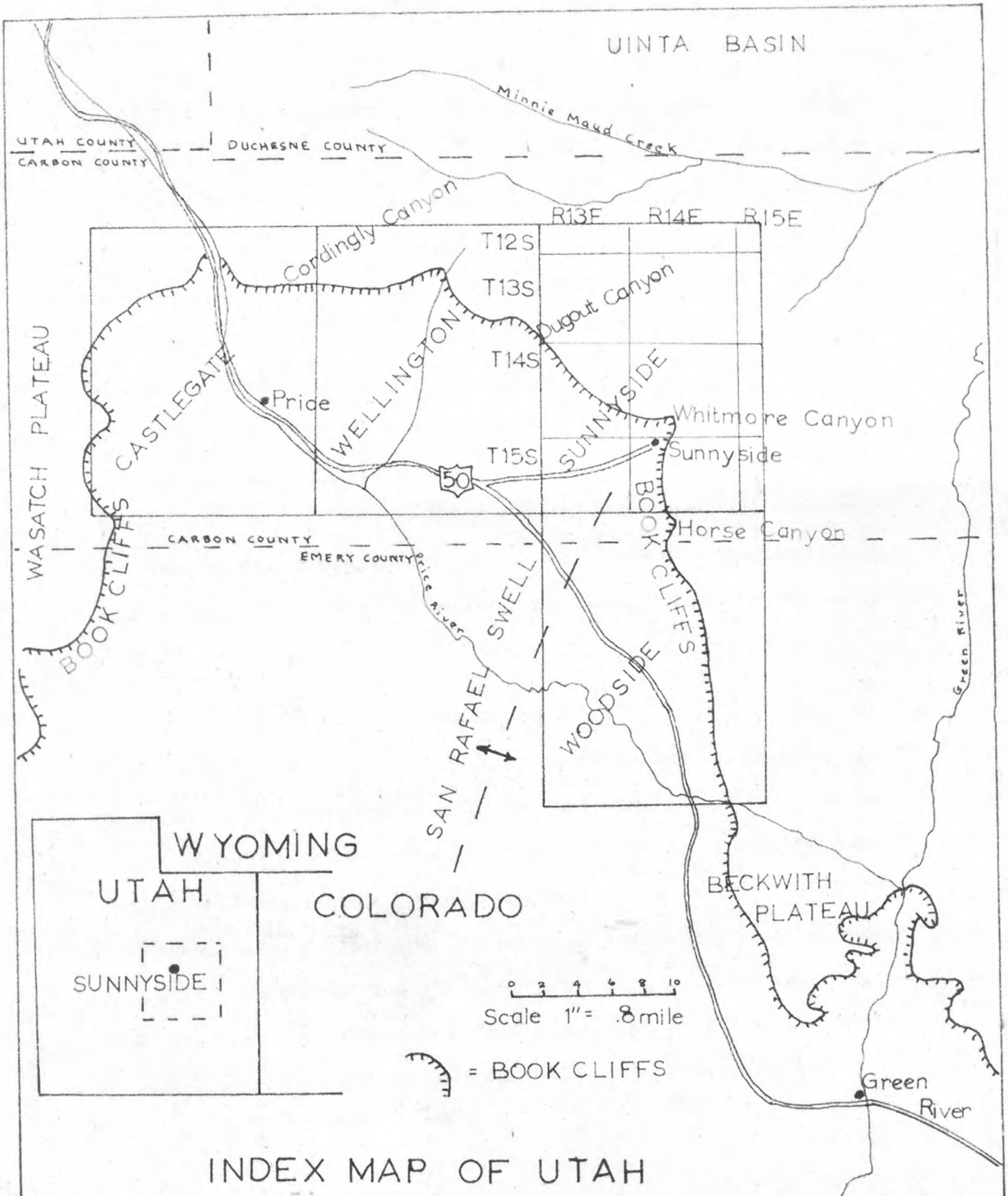

UINTA BASIN
Minnie Maud Creek
UTAH COUNTY
CARBON COUNTY
DUCHESNE COUNTY
Cordingly Canyon
R13E
R14E
R15E
T12S
T13S
T14S
T15S
Dugout Canyon
WASATCH PLATEAU
CASTLEGATE
Price
WELLINGTON
SUNNYSIDE
Whitmore Canyon
Sunnyside
50
BOOK CLIFFS
Horse Canyon
CARBON COUNTY
EMERY COUNTY
Price River
SAN RAFAEL SWELL
WOODSIDE
Green River
WYOMING
UTAH
COLORADO
SUNNYSIDE
BECKWITH PLATEAU
0 2 4 6 8 10
Scale 1" = 8 mile
= BOOK CLIFFS
Green River
INDEX MAP OF UTAH

Figure 1

the Kaiser Steel Corporation and the Columbia-Geneva Steel Division of the U. S. Steel Corporation were matched with outcrop sections to provide a more complete picture of variations in the coal seams and associated rocks. Hand samples of rock were selected to illustrate lithologies characteristic of a formation as a whole as well as lithologies that were obviously unusual variations of a formation. These samples were studied under a binocular microscope to determine general lithologic characteristics. Thin sections of coal from the Sunnyside seams were obtained from J. M. Schopf of the U. S. Geological Survey and examined under a petrographic microscope.

Terminology for grade sizes is the modified Wentworth grade scale (Dunbar and Rodgers, 1958, p. 161). Bedding thicknesses are described in accordance with the terminology used by Ingram (1954). The terminology used in describing sorting is based on the classification of Folk (1959, p. 102).

Acknowledgments

I wish to thank the Kaiser Steel Corporation and the Columbia-Geneva Division of the U. S. Steel ~~Steel~~ Corporation for permission to use their well logs. L. F. Huntsman, mining engineer, and Louis ~~Morse~~ Morris, geologist, both with the Kaiser Steel Corporation, assisted the author in collecting information.

Marsh Corbett helped with the layout of some of the drafting work. John Hill, Pete Schmidt and Bob Lester critically discussed aspects of this work with the author. Robert G. Young, geologist, U. S. Atomic Energy Commission, gave the author additional information concerning the stratigraphy in the Book Cliffs area.

Dr. W. O. Thompson directed this thesis and made valuable suggestions and criticisms. I benefited from suggestions made by Dr. W. F. Bradley, Dr. Eicher and Dr. T. R. Walker of the University of Colorado, Dr. J. M. Schopf of Ohio State University and Dr. Van Andel of Scripps Institute of Oceanography.

The U. S. Geological Survey provided financial assistance during the progress of this study.

I wish to acknowledge my indebtedness to Frank W. Osterwald, geologist, U. S. Geological Survey who made numerous suggestions, critically reviewed this thesis in its preparation, and provided several of the photographs. His encouragement, interest, and patience during the progress of this work are appreciated.

Stratigraphy

Previous work

The first detailed geologic work in the Sunnyside area was by Frank R. Clark from 1911-1913 for the U. S. Geological Survey, and was published in 1928 as Bulletin 793 "Economic Geology of the Castlegate, Wellington and Sunnyside quadrangles, Carbon County, Utah," Clark (1928, p. 11), divided the rocks of Late Cretaceous age at Sunnyside into the Mancos shale and the Mesaverde group, and subdivided the Mesaverde group into the Blackhawk and Price River formations. The basal sandstone of the Price River formation was named the Castlegate member (Clark, 1928, p. 20). Clark (1928, p. 21) correlated the sandstones and shales overlying the Price River formation with the "Wasatch" formation of Tertiary age.

Economic coal seams in the Blackhawk formation at Sunnyside were named the "Lower" and "Upper" Sunnyside seams (Clark, 1928, p. 34). Clark observed that the Blackhawk formation intertongued with the Mancos shale and thus recognized what are now called facies changes in the Book Cliffs area. He proposed that a barrier of some sort, possibly a sandbar, permitted coal accumulation near the shoreline. The source material for the Late Cretaceous sediments was thought to have come from a landmass to the west.

After the discovery of dinosaur bones in the lower part of the "Wasatch" formation, Spieker (1946) advocated that the name "Wasatch" formation be abandoned for the rocks overlying the Price River formation in the Book Cliffs area. Spieker named the lower part of the "Wasatch" formation the North Horn formation. The North Horn is considered to be transitional in age between Late Cretaceous and early Tertiary. Spieker (1949) later discussed criteria by which rocks of continental and marine environments in the Blackhawk and Price River formations could be recognized and stated that all the littoral marine sandstones within the Blackhawk formation were formed by regressive seas. Spieker (1949, p. 64) correlated the Castlegate member of the Price River formation with "Early Laramide" orogenic movements in the west.

Young (1955) traced the Blackhawk and Price River formations in detail along the Book Cliffs area and on the basis of the cyclic repetition of sedimentary units, subdivided the Blackhawk formation at Sunnyside into the Aberdeen, Kenilworth, and Sunnyside members. Young advocated that the term Mesaverde group be abandoned for the Book Cliffs areas because the Blackhawk and Price River formations are younger in some areas than the type Mesaverde at Mesa Verde National Park.

Fisher and others (1960), elevated the Castlegate member of the Price River formation to formational rank and called it the Castlegate sandstone. The Price River formation at Sunnyside, Utah was restricted by Fisher and others (1960) to rocks overlying the Castlegate sandstone but underlying the North Horn and Flagstaff formations undifferentiated.

Blackhawk and Price River formations at Sunnyside, Utah

A stratigraphic section of the Blackhawk and Price River formations at Whitmore Canyon near Sunnyside, Utah is shown in plate 1 and in figures 2 and 3. The nomenclature proposed by Young (1955) is used to subdivide the Blackhawk formation from bottom to top into the Aberdeen, Kenilsorth and Sunnyside members. The stratigraphic section at Whitmore Canyon shown in plate 1 of this paper differs from the stratigraphic section at Whitmore Canyon of Young (1955, pl. 3), in the following respects: 1) the nonmarine tongue of the Kenilworth member is believed to be thicker than Young has shown it, 2) the "Lower", Sunnyside and "Upper" Sunnyside seams of Young are shown as splits of one seam and 3) the "coal-bearing rocks" of Young (1955) are called the unnamed nonmarine member. Young's subdivision is based on a cyclic repetition of littoral marine sandstones overlain by nonmarine beds. Each member consists of, or can be traced westward into, a basal white-capped littoral marine sandstone tongue of wide lateral extent. Units of coal and other continental sediments as well as smaller tongues of littoral marine sandstone lying between two extensive littoral marine sandstone tongues are included as part of a lower member. The members are ordinarily separated by a thin tongue of Mancos shale which thins westward. Individual tongues of the Mancos were not given names by Young and only informal names are used herein.

Figure 2.--Book Cliffs near Sunnyside, Utah. Upper white band is the cliff-forming Castlegate sandstone. Middle white band is the Sunnyside member of the Blackhawk formation. The two lower bands are the upper and middle marine tongues of the Kenilworth member of the Blackhawk formation.

Figure 3.--Whitmore Canyon. Coal mine tipple at lower center of picture.

The oldest member at Sunnyside, Utah, the Aberdeen member as redefined by Young (1955), is represented at the base of the Book Cliffs by two thin tongues of siltstone and mudstone within the Mancos shale. The lowest tongue of the Aberdeen member is separated by 105 feet of Mancos shale from the upper tongue of the Aberdeen member. The two tongues thin and merge into the Mancos shale southeast of Sunnyside. To the northwest these tongues thicken, become more sandy and can be traced into units consisting of one basal white-capped littoral marine sandstone with overlying seams of coal. A tongue of Mancos shale separates the Aberdeen member from the overlying Kenilworth member.

The Kenilworth member of Young (1955) at Sunnyside consists of three littoral marine sandstone and siltstone tongues. The upper tongue is overlain by a coal-bearing nonmarine tongue. At the town of Kenilworth, the Kenilworth tongues merge into one white-capped littoral marine sandstone with overlying seams of coal. A thin tongue of the Mancos shale separates the Kenilworth member from the overlying Sunnyside member.

The Sunnyside member of Young (1955) at Whitmore Canyon consists of one basal white-capped littoral marine sandstone and siltstone tongue which has considerable lateral extent along the Book Cliffs. The tongue is overlain by the Sunnyside coal seams which are included as part of the Sunnyside member. Above the Sunnyside coal seams a coal-bearing, nonmarine member that is unnamed completes the Blackhawk section. The Blackhawk formation is 603 feet thick at Whitmore Canyon.

Overlying the Blackhawk formation is the Castlegate sandstone, which forms a prominent cliff. Overlying the cliff-forming Castlegate sandstone is the Price River formation consisting of two members a lower unnamed slope-forming member and an upper ledge or cliff-forming Bluecastle member.

The Bluecastle member is identified at the Whitmore Canyon section on the basis of regional tracing from its type section at the Beckwith Plateau where it was described originally by Fisher (1936, p. 18). The Bluecastle member was recognized by Vard Johnson (1951, written communication) in the Woodside quadrangle which adjoins the Sunnyside quadrangle to the south, and was extended to the Sunnyside area by Osterwald and Eggleton (1959, written comunication).

At Whitmore Canyon the Castlegate sandstone is 210 feet thick, the unnamed member of the Price River formation about 366 feet thick, and the Bluecastle member of the Price River 210 feet thick.

The contacts between the Castlegate sandstone and Blackhawk formations can be easily distinguished in the field even at a distance because the upper part of the Blackhawk forms a slope and the Castlegate sandstone forms a massive cliff, the most prominent cliff in this part of the Book Cliffs.

The contact between the Price River and the North Horn formation similarly is placed at the top of a massive cliff or series of prominent sandstone ledges above which are smaller sandstone ledges and mudstones of the North Horn formation. The contact between the Price River and the North Horn formation appears abrupt at a distance but seems transitional on close examination. Lithologic distinctions between the Mancos shale, the Blackhawk and Price River formations are described under the heading Lithology of this paper.

Unconformities

Numerous interruptions in the depositional history of the Mesaverde group result from repeated marine transgressions and fluvial channeling. Most of these breaks probably represent minor periods of erosion or nondeposition.

The disconformity noted by Spieker (1946) between the Castlegate sandstone and the Blackhawk formation in the Wasatch plateau is not apparent at Sunnyside. In the adjoining Woodside quadrangle, Johnson (1951, written communication) also could not recognize an important widespread disconformity at this contact.

A disconformity possibly exists at the Price River-North Horn contact at Sunnyside. Clark (1928, p. 20) stated that the upper surface of the Price River formation was considerably eroded before the overlying "Wasatch" formation, marked in places by a basal conglomerate, was deposited. This unconformity does not correspond to the Cretaceous-Tertiary boundary as Clark believed because later work by Spieker (1946) has disclosed that the Cretaceous-Tertiary boundary lies within the North Horn formation or within what Clark called the "Wasatch" formation.

Young (1960 oral communication) believes that a disconformity exists at the contact between the Price River and North Horn formations at Sunnyside and is due to tectonic activity on the San Rafael swell in Late Cretaceous time.

I was unable to find evidence of a disconformity above the Price River formation at Sunnyside but further study of this problem is needed.

Age of the formations

According to Fisher and others (1960) the Mesaverde group generally has not yielded faunas datable more closely than very Late Cretaceous age. The age of the North Horn and Flagstaff formations undifferentiated, at Sunnyside, Utah, may be transitional from Late Cretaceous to Paleocene age. A transitional Late Cretaceous to Tertiary age has been reported by Spieker (1946) for the North Norn formation on the Wasatch plateau.

Terminology

The use of the term Mesaverde group for the Blackhawk and Price River formations at Sunnyside, Utah has been questioned by Young (1955), although other geologists have found it a convenient designation. (Abbott and Liscomb, 1956). Young objected to the use of the term Mesaverde because the Blackhawk and Price River formations are not everywhere equivalent in time to the type Mesaverde at Mesa Verde National Park.

The term group like the term formation carries no concept of time and the same group name may be used even if the named formations within it change in time from one area to another (Dunbar and Rodgers, 1958, p. 261). Therefore, I believe there is no serious objection to using the term Mesaverde group to cover the Blackhawk and Price River formations in the Book Cliffs.

Lithology, primary features and environment

Mancos shale and Mancos shale tongues in the Blackhawk formation

The Mancos shale is a medium gray, carbonaceous, marine shale, which weathers purplish gray and forms slopes at the base of the Book Cliffs. It varies from clayey shale to silty shale and is commonly calcareous. Some small chips of selenite crystals glisten on weathered surfaces. Well-exposed outcrops disclose thin even bedding that commonly is considered characteristic of offshore marine shales (fig. 4).

Stratigraphically above the Mancos shale at Whitmore Canyon, in rising sequence, are the Aberdeen, Kenilworth, Sunnyside and unnamed members of the Blackhawk formation. Mancos shale intertongues with the Aberdeen and Kenilworth members and underlies the lower part of the Sunnyside member. According to Young (1955) the Mancos tongues represent rapid marine transgressions during periods of pulsating subsidences. At some localities it is difficult to discriminate between these Mancos shale tongues in the Blackhawk and the nonmarine shales of the Blackhawk on the basis of lithology and primary structures.

Thin even bedding with fine laminations and clay particle size grains is characteristic of offshore marine Mancos shales, but where thin tongues of the Mancos shale extend into the Blackhawk formation, the Mancos may be represented by mudstones with disrupted bedding, plant impressions and thin coal lenses one-fourth to one-eighth inch thick. During rapid transgression bottom sediments of continental origin containing coal and plant fragments could have been incorporated in the Mancos shale. Thus, although these reworked sediments were deposited in

Figure 4. Even bedding of Mancos shale. Northwest side of Whitmore Canyon.

a marine environment, they may retain many of the characteristics of their previous continental origin.

Evidence that the shale tongues in the Blackhawk are continuous with the Mancos is based on lateral tracing of the shale tongue outcrops to the place where they thicken eastward in the direction of unquestioned Mancos shale.

Mesaverde group

Blackhawk formation

Aberdeen member of Young (1955).--The Aberdeen member of the Blackhawk formation is represented at Sunnyside by two thin tongues of medium gray calcareous siltstone and mudstone. Both tongues form slightly resistant ledges in the scarp a few hundred feet above the base of the Book Cliffs and both merge lithologically upward and downward into Mancos shale.

On the northwest side of Whitmore Canyon the lower tongue of the Aberdeen member is 14 feet thick and consists of a 5-foot zone of calcareous siltstone overlain and underlain by transitional zones both of which are about 5 feet thick. These transitional zones grade into normal Mancos shale. The 5-foot calcareous siltstone is blocky and well indurated with calcareous cement. The siltstone is well sorted and composed mostly of detrital quartz grains with about 5 percent carbonaceous material and some pyrite. The siltstone contains laminations of carbonaceous material that are fine and even.

The upper tongue of the Aberdeen member is 12 feet thick and consists of a medium gray shaly mudstone that is streaked with one-half inch to one-eighth inch lenses and pods (mottled) of white siltstone. These mudstones have a fairly high carbonate cement content and have an average composition of about 50 percent detrital quartz and 50 percent clay-size particles. Coloring in the mudstones is the result of carbonaceous material.

Kenilworth member of Young (1955).--The lowest of the three marine tongues of the Kenilworth member at Sunnyside is about 22 feet thick and is made up of finely laminated siltstones and mudstones which are thin to medium bedded (one-tenth of a foot to one foot). Siltstones alternate with mudstones, regular persistant bedding and lamination prevails and the weathered outcrops manifest an etched or corrugated appearance.

Medium gray color dominates the siltstones, which contain about 5 percent very fine grained angular particles of vitreous coal (vitrain) and some coal particles which have the appearance of charred wood (fusain). Coal particles are most abundant along laminations but also can be found within the siltstones. Whereas 80 percent quartz dominates the siltstones they also contain minor amounts of weathered feldspar and muscovite flakes. The rock is well indurated with calcareous cement.

The middle and upper marine tongues of the Kenilworth member at Sunnyside are similar to each other in appearance and lithology. The total thickness of the middle tongue however is 55 feet whereas the upper tongue is 125 feet thick. The middle tongue is directly overlain by a tongue of marine Mancos shale but the upper tongue is directly overlain by a thin nonpersistant coal bed and fluviatile deposits of carbonaceous mudstones, siltstones, and very fine grained sandstones.

The uppermost 90 feet of the upper tongue and the uppermost 25 feet of the middle tongue consist of fine to very fine grained sandstones. The remaining 30 to 35 feet of both the upper and middle tongues grade downward from very fine grained sandstones to siltstones and mudstones. The type of bedding changes vertically within these tongues. The upper sandstone units of both tongues are thinly laminated and very thickly bedded (3 to 16 feet in thickness) but these beds grade downward into siltstones of irregular and uneven thin to medium bedding (3 inches to 1 foot in thickness). The siltstone beds in turn merge downward to siltstones and mudstones with disrupted bedding. About 10 feet of fine-grained sandstone at the top of the upper tongue of the Kenilworth is bleached. Colorless quartz with about 5 percent dark-brown to black chert dominates this fine-grained sandstone. The quartz grains are nearly equidimensional, subrounded, and uniformly sorted. No calcite or iron oxide cement appears and feldspars are absent. Below the bleached zone the sandstones are commonly enriched by iron oxide staining. Fossil roots appear in the bleached zone (fig. 5).

The very fine-grained sandstones in the upper and middle tongues of the Kenilworth are light gray to buff colored and composed of about 90 percent quartz, 5 percent dark black incipient chert with carbonaceous matter and some minor amounts of muscovite, feldspar and limonite. The rock is well sorted and moderately friable and porous but cemented with calcite.

The very fine grained sandstones grade downward into buff-colored siltstones 10 to 20 feet thick in both middle and upper tongues. The siltstones contain coal fragments ½ to 2 mm in length concentrated along

Figure 5.--Kenilworth sandstone, upper tongue, No. 1 Fan Canyon. Specimen found immediately underlying the Kenilworth coal seams. Shows roots from plants which grew in the coal forming swamp. This sandstone is an ancient soil and is evidence to indicate that the overlying coal formed in situ.

bedding surfaces and laminations. These siltstones intertongue along irregular bedding surfaces with medium gray mudstones with disrupted bedding in which coal fragments are scattered at random and in which are found one-eighth to one-half inch lenses and pods of white siltstone (mottled). The coal on the bedding surfaces of the siltstones and in the mudstones is identified under a binocular microscope as vitrain and fusain.

A thin layer of coal varying in thickness but with a maximum of 4 feet 7 inches at Sunnyside (Clark, 1928, pl. II) crops out above the white-capped sandstone of the upper Kenilworth marine tongue. The nonmarine tongue of the Kenilworth is made up of black hackly carbonaceous shale which weathers to a silvery white, and lenticular units of carbonaceous mudstones, siltstones, and very fine grained sandstones. Some of these units could not be traced more than 30 feet along an outcrop. Deep channeling was not observed. The nonmarine siltstones and very fine sandstones display a pinkish yellow color and are composed of about 90 percent quartz with limonite straining and calcite cement. The rock is well indurated and moderately to well sorted. Fragments of coal and streaks of carbonaceous material are abundant.

Sunnyside member of Young (1955).--The Sunnyside member of the Blackhawk formation overlies the Kenilworth member and is separated from it by a thin tongue of Mancos shale. The Sunnyside member consists of mudstones and siltstones that grade upward to very fine to fine-grained sandstones. Young (1955) includes the Sunnyside coal seams, the principal economic coals at Sunnyside, Utah as part of the Sunnyside member. The coal beds in the Sunnyside member are described separately with the Sunnyside coal beds in this paper. The Sunnyside member is about 105 feet thick in Whitmore Canyon.

Shaly mudstones at the base of the Sunnyside member may be a tongue of the Mancos shale. The shaly mudstones are calcareous, medium gray and contain fragments of both vitrain and fusain coal.

Shaly mudstones intertongue with light-gray to yellowish siltstones and very fine sandstones which contain coaly matter along bedding surfaces and laminations. The siltstones and very fine sandstones which make up the lower 40 feet of this member manifest medium bedding, (½ to 1 foot in thickness).

Fine sandstones comprise the uppermost 35 feet of the marine tongue of the Sunnyside member. These cliff-forming sandstones are thinly laminated and very thickly bedded. Whereas, some laminations commonly have low-angle dips, others dip 16 to 20 degrees.

The fine sandstones in the Sunnyside member which are well sorted, consist of 90 percent quartz, 3 percent dark-gray chert and 5 percent weathered feldspars as well as minor amounts of other minerals. The quartz grains are subrounded to subangular and nearly equidimensional. Secondary overgrowths on the quartz grains are common. The rock is fairly porous although moderately well indurated with calcite cement. No coal fragments appear, but in some specimens bits of amorphous black spongy matter, possibly resin, are visible.

The Sunnyside coal beds directly overlie these very thickly bedded sandstones or are separated from the sandstones by a few inches to a 1½ feet of siltstones and mudstones (fig. 6). A zone about 10 feet thick of bleached sandstone from which iron staining and carbonate cement have been removed underlies the coal.

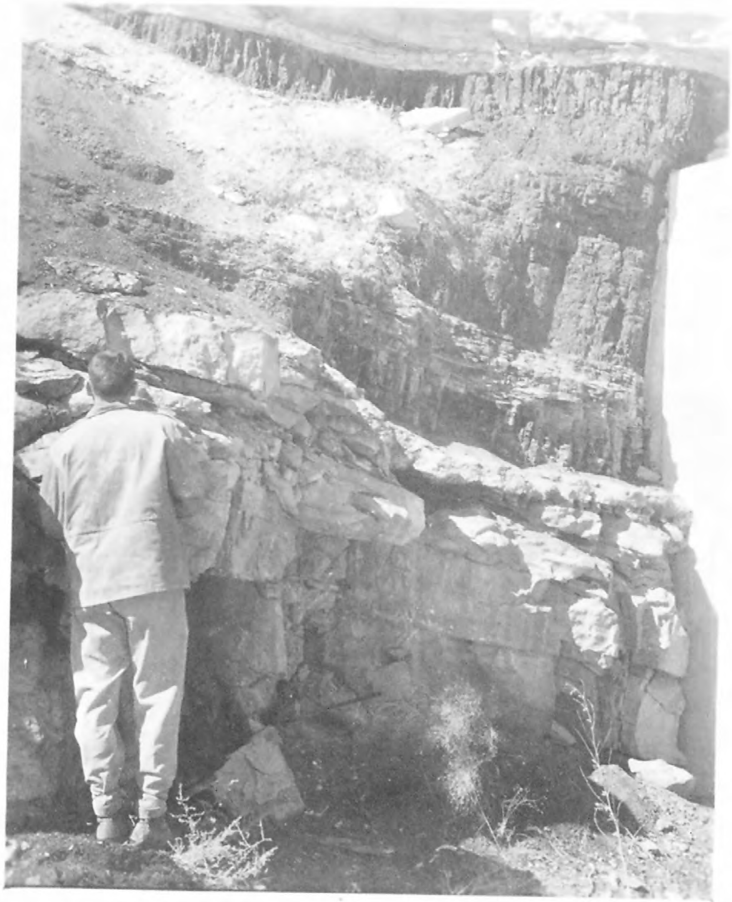


Figure 6.--Outcrop of Sunnyside coal. Split of bony coal is in lower part of coal bed. Sunnyside coal overlies littoral marine sandstone.

Unnamed, nonmarine member.--The unnamed, nonmarine member of the Blackhawk section at Sunnyside, Utah is made up of 160 feet of mudstone, siltstone, very fine sandstone and thin lenticular seams of coal.

The mudstones which are medium gray, carbonaceous and micaceous and well indurated by calcareous cement, have a conchoidal fracture. Individual units of mudstone may be 8 to 10 feet thick. Some of the mudstones which are associated with the coal beds in the Sunnyside member and with the unnamed member are noncalcareous and finely laminated.

The light tan carbonaceous siltstones are moderately well sorted and well indurated by calcite cement. Buff to pinkish yellow very fine grained sandstones consist of about 90 percent quartz with subangular rounding, and 10 percent minor constituents including weathered feldspars and angular coal particles. The rock is moderately to well sorted and well indurated with calcite and limonite cement. Sandstone units are lenticular and rarely more than 15 feet thick. Bedding is indistinct and cross stratification generally absent. Where thin coal seams overlie the sandstone units a thin bleached white cap is observed.

Discontinuous coal seams in the unnamed, nonmarine member of the Blackhawk rarely exceed more than 3 feet in thickness and in most places are only a few inches thick.

Sandstones, siltstones and mudstones in the unnamed, nonmarine member commonly display deep red, yellow, purple or green colors resulting from alteration of iron oxides during burning of the underlying Sunnyside coal beds. Only traces of burned carbonaceous material are left at burned outcrops. Slumping along numerous joint planes probably occurred almost simultaneously with burning.

Depositional history of Blackhawk formation

Lithology.--If Spieker's (1949) contention that each marine tongue in the Blackhawk formation formed during regressive conditions is accepted, the normal sequence in a vertical section should disclose a progressive downward decrease in grain size corresponding to increasing distance from shore. Marine tongues of the Blackhawk formation at Sunnyside show progressive decrease in grain size downward in section from fine to very fine grained sandstones to siltstones to mudstones. Nonmarine sediments in the Blackhawk reveal no such gradational lithologic changes in vertical section.

Where carbonaceous material of particle size in the Blackhawk sediments was distinguishable under a binocular microscope it was found to be composed of vitrain and fusain. In general coal particles are absent from the very fine and fine grained marine sandstones except where their presence is due to fossil roots. The absence of coal in these near-shore sediments probably resulted from the sorting and grinding action of active currents or waves which crushed the carbonaceous particles and winnowed them out to deeper quieter waters. Coal particles do appear along bedding surfaces in the coarse siltstones. During quiet intervals of nondeposition in the offshore environment, particles of carbonaceous matter probably drifted out to these areas and sank slowly to the bottom. The next epoch of agitated waters deposited a new layer of siltstone on this surface but without removing the carbonaceous particles which adhered to the bedding surface.

Coal particles concentrated along the bedding surfaces of the coarse siltstones were examined under a binocular microscope and many of them correspond with the description of fusain. These coal particles which have a maximum size of 2 mm occur as discrete black, prismatic, fragments with sharply angular terminations and a definite fibrous or woody structure.

According to Skolnick (1958), beach, bar, bay or lagoonal environment would be ideal for entrapment of fusain, provided the depositing area is near a source of fusain. Skolnick (1958) believes that a fusain-rich sediment is not likely to form in an offshore depositional environment because marine currents would disperse fusain fragments resulting on a marked dilution of fusain in environments distant from the landward source area.

The fusain-rich sediments in the Blackhawk, however, were formed in offshore environments which indicates that Skolnick's conclusions must be used with caution. Fusain-rich sediments can form in offshore environments if unusually large quantities of fusain are available in the source area as they probably were during the deposition of the Blackhawk formation.

Coal particles in marine siltstones tend to be concentrated along bedding surfaces whereas coal particles in the nonmarine siltstones and sandstones are uniformly distributed.

No obvious distinction in the sorting or rounding was noted between marine and nonmarine sediments in the Blackhawk although the data were not analyzed statistically.

Cementing material in the marine tongues is calcareous. Whereas some siltstones and mudstones associated directly with the Sunnyside coal beds contain no calcareous material, most of the mudstones, siltstones and sandstones do. Water in the coal-forming swamps probably was acidic and prevented deposition of or removed previously deposited calcium carbonate. According to Francis (1954, p. 148):

> "In peat deposits, the chief factor modifying acidity in the lime content of the water in which the peat is formed. Where calcium carbonate content of the water is high, the peat may be neutralized or made alkaline. Such a condition can be found only where drainage water collecting in hollows or basins is highly calcareous."

Alkaline conditions occurred in some Sunnyside swamps because calcareous shells of pelecypods appear in partings within the Sunnyside c oal beds.

The white capped sandstones which commonly underlie coal in the Blackhawk formation have been ascribed by Spieker (1949) as due to bleaching by acid water of the coal-forming swamps. It is possible, however, that the bleaching occurred after deposition.

Structure.--Primary sedimentary structures such as disrupted bedding with mottled, irregular and uneven bedding, and very thick bedding with cross stratification are found in the Blackhawk formation. Primary structures of this kind are common in modern marine environments.

According to Moore and Scruton (1957) mottled structures consist of irregularly shaped lumps, lenses or pods of sediment randomly enclosed in a matrix of contrasting textures. Moore and Scruton believe that bottom-living animals form mottles in the sediments and disrupt any bedding which might otherwise exist. They have been able to map recent sediments with mottled structures and they find that mottles are common in sediments deposited at certain distances from the shoreline where sedimentation is not too rapid for bottom-dwelling organisms to rework the deposits.

According to Rich (1951) irregular and uneven bedding is characteristic of certain marine environments where fluctuation in velocity of transportation tends to produce alternate scour and fill and hence irregular bedding. Ripple marks or current scours may produce uneven bedding in depositional environments characterized by agitated waters and discontinuous sedimentation. Very thick bedding is characteristic of near-shore environments where sediment supply is continuous. Very thick bedded sandstones in the Blackhawk formation are intricately cross stratified with foreset bedding dipping in all directions at angles approaching 30 degrees. Thompson (1937) has described similar cross stratifications in the lower fore shore of a beach.

A sequence of disrupted bedding with mottling, irregular and uneven bedding, and very thick bedding with cross stratification resembling lower fore shore laminae occurs in most of the marine tongues of the Blackhawk formation from bottom to top (figs. 7, 8).

This sequence of primary structures in a regressive deposit suggests an origin controlled by existing energy mediums at various distances from the shoreline during the time of deposition of the marine tongues of the Blackhawk formation.

In the Blackhawk, mottled structure may represent an offshore environment where sedimentation was not too rapid for bottom dwelling organisms to rework deposits. Uneven and irregular bedding which are

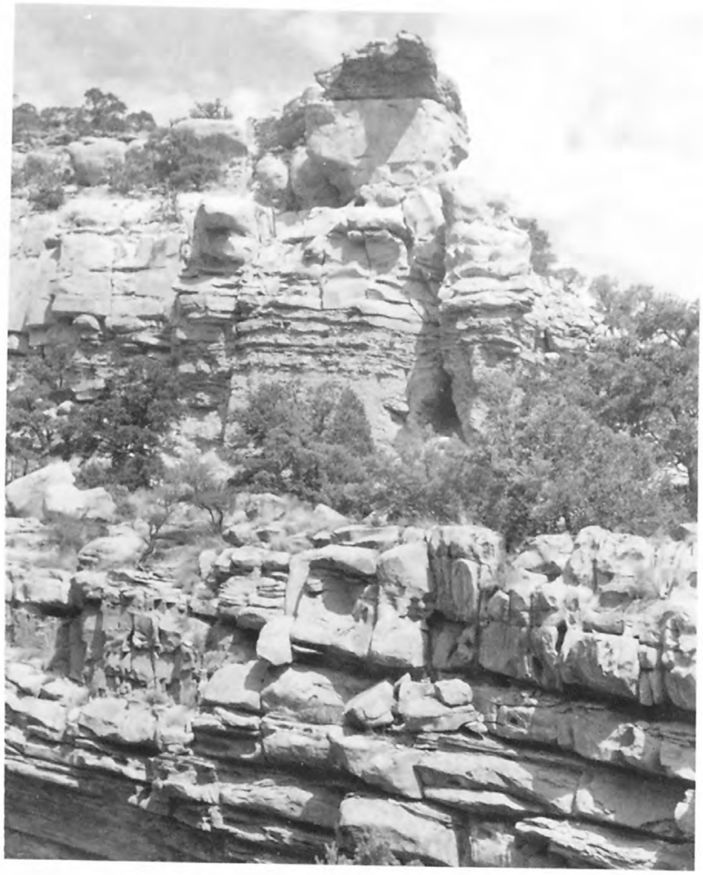


Figure 7.--Middle and upper Kenilworth marine sandstone tongues with gradational bases. Regressive sandstone tongue shows uniform decrease in grain size downward in section and change from very thick bedding to medium, irregular and uneven bedding to disrupted bedding.

Figure 8.--Upper Kenilworth tongue "A" Canyon. Cross stratification resembles lower foreshore laminations described by Thompson (1937).

closely associated may indicate a depositional environment somewhat c loser to the shoreline, characterized by velocity fluctuations and agitated waters and very thickly bedded sandstone tongues containing short steeply dipping laminae resemble lower fore shore laminae, may indicate a beach or near-shore deposit where deposition was continuous and characterized by currents fluctuating in strength and direction.

Castlegate sandstone.--The Castlegate sandstone is a massive cliff-forming sandstone that is 210 feet thick at Sunnyside. It is composed predominantly of very fine to fine-grained sandstones but contains lenticular units of mudstone up to 15 feet thick and lenses of coal several inches to 1½ feet thick. Freshly broken surfaces of the sandstones are normally light-creamy gray and friable; outcrop surfaces are distinctively yellowish gray and resistant to erosion. The ability of the Castlegate sandstone to form steep cliffs probably results from case-hardening by the addition of yellow iron oxide cement to the outer surface of the rock.

Fine-grained sandstones in the Castlegate consist of about 90 percent quartz, 2 percent black chert, 7 percent weathered feldspar as well as minor amounts of coal fragments and white clay galls. The subrounded quartz grains are almost equidimensional and the sandstones are moderately to well sorted. Secondary overgrowths on the quartz are common.

Large randomly orientated impressions and casts of tree trunks, twigs, and branches are abundant within some of the sandstone lenses. Casts are as large as 1 foot wide and 3 to 10 feet long (fig. 9). Small bits of coal are found with these impressions and casts.

Figure 9.--Impression of a log found in the Castlegate member of the Price River formation at Horse Canyon.

Locally the Castlegate contains lenses of very light gray, very fine grained sandstones. These lenses have a mineral composition similar to the fine-grained sandstones.

The Castlegate contains coal lenses that are commonly less than 6 inches thick. Wherever observed they are underlain by carbonaceous mudstones.

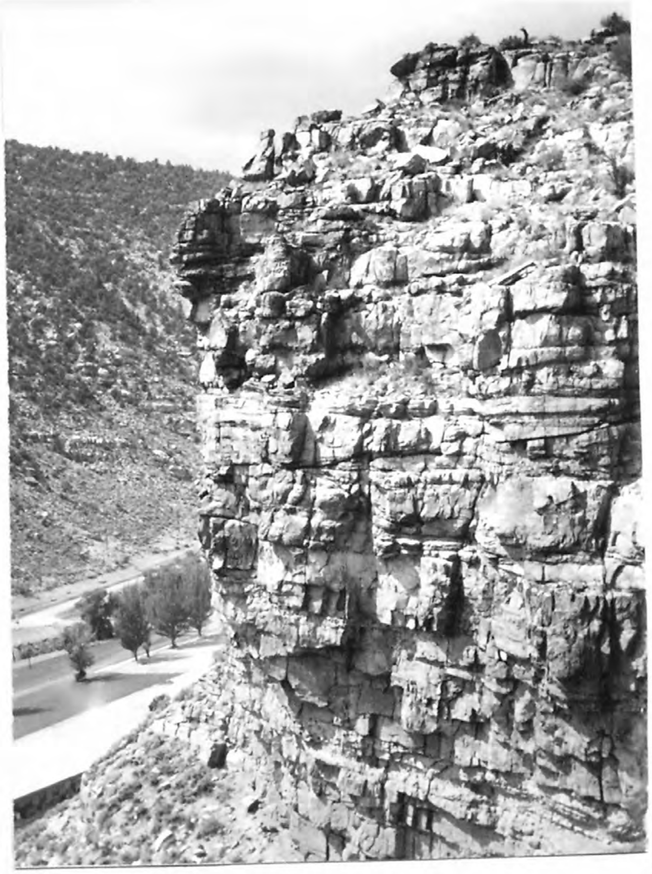
Units of finely laminated mudstones 3 inches to 6 feet thick are found locally in channels within the Castlegate (fig. 13).

The Castlegate sandstone has numerous wedge-shaped cut and fill structures as much as 6 to 10 feet thick. Bedding planes are commonly concave upward which indicates that units above the surfaces fill channels cut into previously deposited units (fig. 10).

Current ripple marks found in place at Horse Canyon have an amplitude of 1 inch and a wave length of 6 inches. The direction from which the current that formed these ripples came is N. 85° W. Penecontemporaneous folding resembling slump structures was noted in the sandstones at several localities. Folds vary from 1½ feet to 6 feet in height. The fold axes are nearly vertical or slightly tilted from the vertical (fig. 11).

Price River formation

Unnamed member.--The unnamed member of the Price River formation forms a slope between the Castlegate sandstone and the Bluecastle member of the Price River. This member consists of highly carbonaceous mudstone units and several lenticular sandstone units 2 to 15 feet thick. The sandstone units which are very fine grained consist of 90 percent quartz, 5 percent weathered feldspar and 3 percent dark chert with minor amounts of mica, coal particles and yellow iron oxide. The sandstones are pinkish yellow and moderately indurated with calcareous and iron-oxide cement. Mudstones are thinly laminated and contain coaly streaks



Figures 10a, 10b.--Castlegate sandstone member of the Price River formation. Pictures taken above Sunnyside No. 1 mine bathhouse in Whitmore Canyon. Note curved bedding surfaces and wedge-shaped cut-and-fill structures. Figure 10b has a 5-foot Jacob's staff at the lower left hand corner for scale.

Figure 11.--Penecontemporaneous slump structures in the Castlegate Member. Picture taken above Sunnyside No. 1 mine bath-house in Whitmore Canyon. Structure is about 2 feet in height.

and twig and branch impressions.

<u>Bluecastle member</u>.--Thick units of fairly well sorted, porous, friable medium-grained sandstone dominate the Bluecastle member which contains little or no calcite cement. Separation of the sandstone units by less resistant layers forms distinct, individual ledges and cliffs. Quartz grains, 20 percent of which are hematite stained, make up approximately 95 percent of the rock. Two percent dark-colored chert grains, 3 percent weathered feldspar and minor amounts of carbonaceous material constitute the remainder. The quartz and chert grains manifest angular to subrounded and almost equidimensional forms. Secondary overgrowths commonly coat the quartz grains. The fresh hand specimen of the rock displays a very light gray to pinkish tinge whereas outcrop surfaces of the rock appear yellowish gray and case hardened. Coarse grained sandstone lenses up to several inches thick appear in the Bluecastle.

The Bluecastle also contains lenses of carbonaceous mudstones up to 40 feet in thickness. Carbonaceous mudstones contain twig and branch impressions.

Like the Castlegate the sandstones in the Bluecastle contained wedge-shaped cut-and-fill structures. The Bluecastle can be distinguished from the Castlegate by its tendency to form two or more thick ledges, its larger sandstone grain sizes, and it lack of coal lenses.

Depositional history of the Castlegate sandstone and the Price River formation

The sandstones in the Castlegate and the Price River formations vary from orthoquartzites to subarkoses according to the usage of Pettijohn (1957). The chert and the lack of unstable or metastabel minerals indicate that sediments were present in the source area. Spieker (1949) believes that the Castlegate sandstone formed in response to the "Early Laramide" orogeny in the region to the west of Sunnyside.

The wedge-shaped cut-and-fill structures, thin coal lenses, the log casts, and clay galls suggest that the Castlegate was deposited in a fluviatile environment possibly as a braided stream deposit. The carbonaceous mudstones which underlie the thin coal deposits in the Castlegate sandstone were probably deposited in a lake which gradually filled, became a swamp and later was buried by the fluvial sandstones.

Log casts, twig impressions, and associated thin coal lenses within the sandstones suggest that fluvial currents were at times fairly strong and that sedimentation was rapid. The absence of a soil zone associated with these casts and impressions indicates that the logs were transported and burial was rapid enough to prevent complete oxidation so that some of the wood could be preserved as thin coal lenses. The slump structures may indicate adjustment of the sediments to rapid deposition on sloping surfaces such as the inside bend of a meander curve. The clay galls in the Castlegate probably were derived from the erosion of stream banks.

The large number of twig and branch impressions and thin coal lenses in the unnamed member suggests a probably nonmarine environment for this member.

Coal forming conditions progressively declined during the deposition of the Price River formation at Sunnyside, Utah and although the Bluecastle member seems to have been deposited in a similar environment as the Castlegate, it contains no coal. Sedimentation and erosion were probably too rapid and widespread for peat accumulation. Good drainage, as indicated by the coarseness of the sandstone deposits in the Bluecastle, probably prevented swamps from forming.

Depositional environment of finely laminated mudstones

Finely laminated mudstones with small-scale sedimentary structures occur in the nonmarine tongues of the Blackhawk and in the Castlegate sandstone (fig. 12). A quantitative mineral study of this rock by the U. S. Geological Survey (R. F. Crantnier, analyst) indicates that 70 percent of the material is silt-size quartz and that the remainder of the rock consists of carbonaceous matter with minor amounts of finely divided iron sulfides.. Laminations vary from less than 0.5 mm to 3 mm in thickness. Laminations thin and thicken and are not persistent. In some specimens minute cross bedding is visible.

Figure 13 shows a channel in the nonmarine Castlegate sandstone that contains finely laminated mudstones. The laminated rock within the Castlegate is probably of lacustrine origin and may have formed in an ox-bow lake. Similar lithologies can be found in modern tidal flats and delta margins (Potter and Glass, 1958, pls. 7 and 8), and thus are not in themselves reliable indicators of environment unless used in conjunction with other evidence.

Figure 12.--Finely laminated mudstones, from Castlegate sandstone. Minute faulting is penecontemporaneous and is probably due to differential compaction because the faults are high angle indicating vertical adjustment, and the downdropped blocks are in the direction of the thickening of the laminae. Photograph natural size.

Figure 13,--Channel of bluish gray mudstone 6½ feet by 40 feet, in the Castlegate sandstone in Horse Canyon, contains laminated mudstones similar to sample above. It possibly is an abandoned meander scar filled with finer overflow deposits from streams.

The angle of faulting in the mudstone, figure 12, varies from 76 to 69 degrees and fault planes dip to the left and to the right in the figure. A slight amount of drag is evident and displacement is from less than 0.5 to .5 mm. The faulting is penecontemporaneous because it is confined between two undisturbed laminae. Penecontemporaneous deformation has been attributed to many possible factors among which are slump, differential movement and differential loading (Rettger, 1935). Slump and differential movement usually result in folding with the majority of the fold axial planes dipping toward the moving force at 45 degrees or less. Uneven loading may produce faulting but the fault planes dip in one direction away from the point of loading. Since neither differential movements and slump nor differential loading explain the faulting in figure 12, differential compaction appears to be the most probable cause.

Carbonaceous material compresses more than clean silt and faulting as a result of differential compaction would cause the downdropped blocks to form in the same direction that the carbonaceous laminations thicken. Figure 12 shows that this is true of this specimen. The faulting probably occurred after the material had acquired some rigidity but before it was completely consolidated. Faulting rather than bending of the laminations occurred, probably because the load which resulted in the compression, was applied quickly.

Sunnyside coal beds

Splits and thickness variations

In his survey of the economic coals in the Castlegate, Sunnyside, and Wellington quadrangles, Clark (1928) distinguished the "Lower Sunnyside" and "Upper Sunnyside" coal seams. Clark traced the "Lower Sunnyside" seam from Cordingly Canyon in the Castlegate quadrangle where it is about 2.5 feet thick to the eastern end of the Sunnyside quadrangle where it averages 7 feet 9 inches. The "Upper Sunnyside" seam, according to Clark (1928, p. 35), is not as persistant in length or thickness as the "Lower" seam but can be traced from Dugout Canyon where it is 3 inches thick southeastward to Whitmore Canyon where it averages 2 to 4 feet in thickness.

Mining operations at Whitmore Canyon and Horse Canyon are generally confined to the "Lower Sunnyside" seam except where the "Upper" and "Lower" Sunnyside seams join and are mined together or where only the "Upper" seam can be mined efficiently.

The Sunnyside seams vary in thickness from place to place and contain numerous splits and partings. A split is a coal bed which is, part of the main coal seam but which in certain places is separated from the main coal seam by a parting of rock. A rider is a thin seam of coal overlying a thicker one or main bench. A rider may laterally connect with the main bench in which case it is a split or the rider may be an independent seam.

In order to illustrate the splits and thickness variations encountered in mining operations and to provide a basis for interpreting the geological factors responsible for their origin, a fence diagram plotted on an isometric base was constructed from drill-hole data and outcrop sections (pl. II). An isometric base was used to increase the illusion of perspective and to present nearly northwest-southeast panels in full view. The nearly northwest-southeast panels are approximately perpendicular to the Late Cretaceous shoreline which trended northeast (Young, 1955, p. 179), and illustrate lithologic changes which are significant for the reconstruction of environments at the time the coal swamps existed.

Datum for the logs and sections is the top of the Sunnyside marine sandstone tongue which directly underlies the coal or is separated from the coal by several feet or less of mudstone or bony coal. This datum is not a time-stratigraphic marker because it is the top of a regressive sandstone, but it is a reliable litho-stratigraphic horizon because it can be traced continuously for many miles along outcrops.

Where possible, sections and logs were matched by continuous tracing of coal beds along outcrops or within mine workings. Most of the drill logs were matched indirectly by noting the thickness of the main coal benches, the thickness and number of rider seams and the thickness and lithology of the partings. For example, a rider was drawn up as a split off the main bench if the total thickness of coal in the main bench **of an adjoining area** /and rider equaled or was less than the total thickness in the main bench and a rider thinned and lithologically graded from siltstone to mudstone to bony coal in an adjoining area. Where the thickness of a rider and parting in one section or log was similar to the thickness of a rider and parting in an adjoining section or log, the rider was drawn as independent of the main bench within the local area.

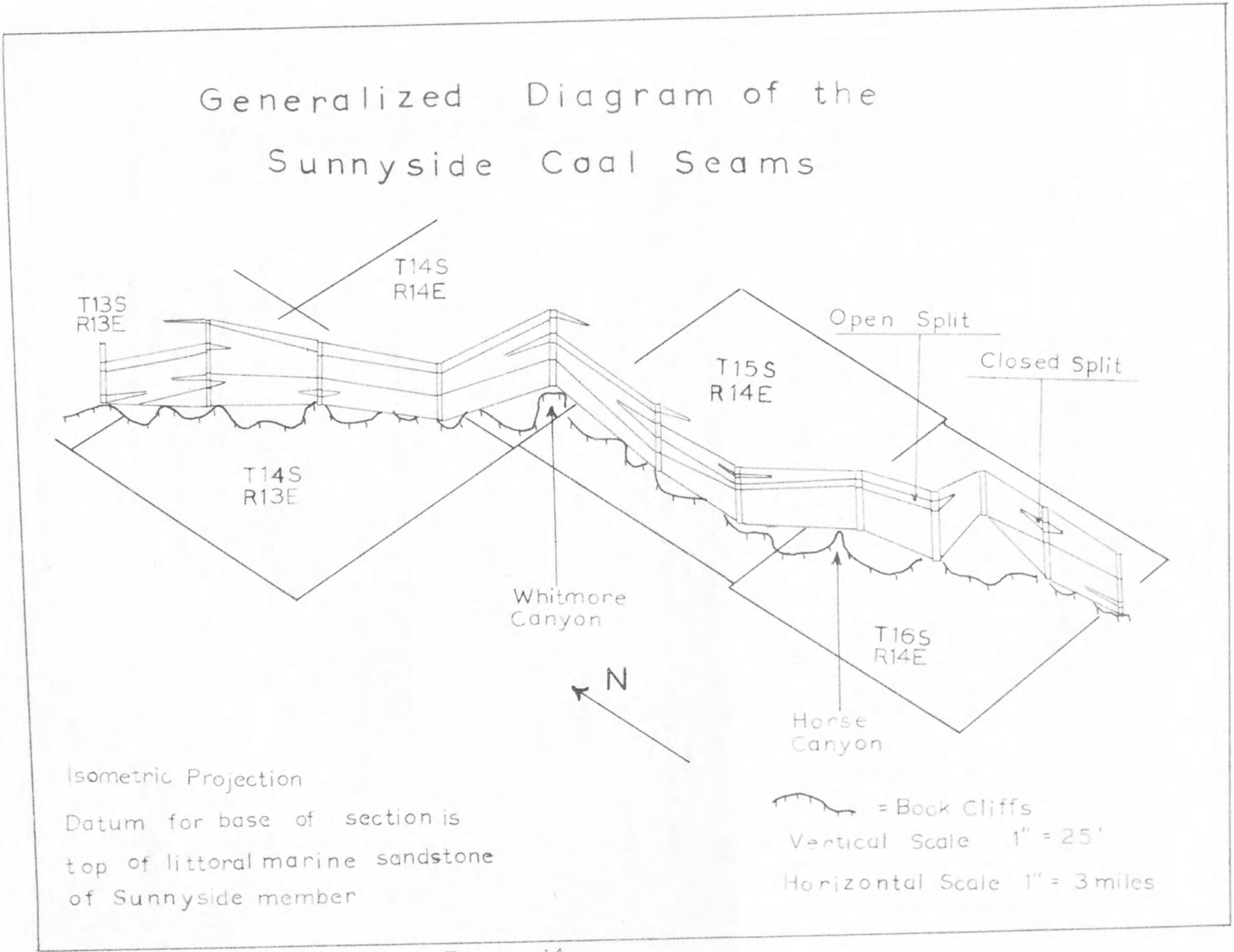
Open and closed types of splits are shown in plate II and figure 14. In open splits the coal seams join in one direction only, but in closed splits coal surrounds the parting. Where two seams are laterally continuous for some distance the partings between the seams may vary from 10 to 30 feet in thickness.

Major factors responsible for the nature of the splits and the thickness variations in the seams and the partings are: 1) the ancient drainage system existent at the time of coal swamp accumulation, 2) differential compaction of coal and interbedded sediments, 3) relief on the land surface that was partly covered by swamp water or differing rates of clastic and coal accumulation.

The open and closed splits in the Sunnyside seams are similar to splits described by Haites (1951) in the Sydney Coal field in Canada where he states:

> "Closed splits are connected with avulsions or abandonment of river channels, for instance, in case of a cut-off meander. Here, the river interferred temporarily with the vegetation. After the oxbow lake was developed, the vegetation re-established itself on the channel-fill deposits. In a coal-bearing succession, this feature is represented by sandstone lenses in the coal seam.
>
> A lateral migration of the river by progressive bank-cutting on the outside bends may be connected with the establishment of vegetation on the deposits of the inside bends. In coal seams, this phenomenon may be represented by splits opening in one direction."

The ancient drainage system existent during the accumulation of peat in the swamps which formed the Sunnyside coal seams was probably a low-lying coastal swamp where meandering streams deposited mud and very fine grained sand. The apparently random pattern that this ancient



Generalized Diagram of the
Sunnyside Coal Seams
T13S
R13E
T14S
R14E
T14S
R13E
T15S
R14E
Open Split
Closed Split
Whitmore
Canyon
N
T16S
R14E
Horse
Canyon
Isometric Projection
Datum for base of section is
top of littoral marine sandstone
of Sunnyside member
= Book Cliffs
Vertical Scale 1" = 25'
Horizontal Scale 1" = 3 miles

Figure 14

drainage system assumed caused major and minor splits in the Sunnyside seams and is responsible for lithologic variations found in the partings and in the roof rock.

Previous geological investigations, for example (Young, 1955), have suggested that the shoreline was close to the swamp. Some of the sediment associated with the coal may therefore be of tidal flat or lagoonal origin because these rocks in a broad way resemble fluviatile deposits (Dunbar and Rodgers, 1958, p. 73).

A fluvial origin for most of the sediments associated with the coal is more likely than a tidal flat or lagoonal origin because: 1) the Sunnyside coal is directly above a littoral marine sandstone with little or no intervening mudstones or siltstones that would indicate lagoonal filling or tidal flat sedimentation prior to major coal accumulation, 2) the partings in the coal splits most commonly wedge out in a seaward direction indicating that clastic debris probably came from a landward direction.

Where a parting between two seams varies in thickness, differential compaction of the material in the parting was probably a factor in determining its present thickness. Lenses of coal and carbonaceous mudstone in the parting will compact more after burial than siltstones and very fine grained sandstones of the same original thickness.

The importance of differential compaction in determining the thickness of the parting is difficult to estimate because some relief probably existed on the material that accumulated in the coal swamp and deposition was not uniform over wide areas.

Some thickness variations in coal seams are the result of "washouts" which are sandstone lenses that extend down into the underlying coals. Washouts probably are the result of local erosion at some period during or soon after the formation of the coal seams (Raistrick and Marshall, 1948, p. 79). A few "washouts" have been noted at the mines in Sunnyside, but are not common (Louis Morse, oral communication, 1960). The rarity of washouts in the Sunnyside coal seems to indicate that the streams flowing through the swamps were graded most of the time but that occasional periods of increased flow corresponding either with exceptional rainfall or with slight uplift caused rejuvenation and down cutting into underlying swamp accumulations; increased rainfall is the probable cause.

Minor variations in coal thickness are due to "rolls" or "swells." "Rolls" or "swells" are best observed in the roof rock where according to Moore (1922, p. 217), "these masses of rock resemble nothing more closely than the waves on the sea when running as a ground-swell". Moore favors the theory that these features are due to small folds in the roof induced by pressure applied when the sediments were still in a plastic state. The difference in specific gravity between the coal and the overlying sediments would favor the growth of these irregular contact surfaces. "Rolls" and "swells" along the Motor Road in the Sunnyside No. 1 mine have no more than several inches of relief.

The matched sections and drill logs in plate II reveal that the seams called "Upper" and "Lower" Sunnyside seams by Clark and in local usage at Sunnyside, Utah, refer to more than one major split. It is also evident from plate II that no one parting persists throughout the entire lateral extent of the Sunnyside coal interval. It is thus probable that peat accumulation was never entirely interrupted during the period when the major coal beds formed and that even those seams drawn in plate II as independent of the main coal seam could be drawn as splits if additional data were available. Consequently the "Upper" and "Lower" Sunnyside are not two separate seams, but rather, as presently used refer to the Upper and Lower workings of one seam.

Petrography

The petrographic characteristics of coal are influenced by the environment in which the vegetable matter originally accumulated. The splits in the Sunnyside coal suggest a fresh-water environment and the petrographic characteristics of the coal provide a means of confirming this conclusion.

The nomenclature for the rank of coal (lignite, bituminous, etc.) is familiar to most geologists. The nomenclature for type of coal (bright, splint, cannel, etc.) is less familiar, although the type of coal is most significant for determining the original depositional environment. Several different classes of nomenclature for the type of coal are currently used in coal petrography and no classification is universal among coal geologists. Some confusion also exists as to the meaning of certain terms because they are variously defined in different classifications. For this reason the terminology and petrographic features are briefly reviewed below.

The classification used at the present time by the U. S. Bureau of Mines divides the megascopic type of coal into banded (bright, semi-splint, splint) and nonbanded coal (cannel, boghead, etc.). The microscopical composition of coal is divided into three main components, anthraxylon, attritus, and fusain (Parks and O'Donnel, 1956). Anthraxylon appears in thin section as bright orange to red or brownish bands, and commonly shows well-preserved cell structure. This component of coal originated from the woody parts of the original vegetation such as stems, twigs, branches, etc. Attritus is a mixture of finely macerated plant debris and contains among other material, spores, pollen, seeds, cuticles and resinous bodies. Fusain is a minor component of coal and in thin sections is opaque with carbonized cell walls closely resembling charred wood.

European nomenclature uses the terms vitrain, clarain and durain for coal rock types. Vitrain and clarain are closely analogous to bright and semisplint coal and durain is similar to splint coal (Francis, 1954, p. 261).

Bright (vitrain, clarain), splint (durain), and possibly semisplint coal types are found in the Sunnyside coal beds. According to Raistrick and Marshall (1948, p. 195):

> "There is little doubt that whereas clarain resulted from the accumulation of vegetable debris derived from generations of plants which grew in sutu, and so gave rise to coal peat, the durain layers have formed during periods when the peat was inundated by water. Then, instead of normal peat formation, there would be produced a mud of the finest plant and mineral debris resulting from the accumulation of washed-in plant fragments and sediment, together with material derived from the coal peat. When the waters retreated, normal peat accumulation was resumed. This view as to the origin of durain is supported by the high proportion of sedimentary mineral matter which is characteristic of that type of coal."

Figure 15 shows the microscopic features of bright (clarain) coal from Sunnyside with anthraxylon and attritus. Figure 16 shows a particle of fusain in bright (clarain) coal.

Splint (durain) coal in the Sunnyside beds in the No. 1 mine at Sunnyside is random and discontinuous in section, and for this reason, is more likely due to fluviatile inundation than sea level rise.

No cannal coal is known at Sunnyside (L. F. Huntsman, oral communication, 1960) indicating that open water conditions were rare or absent because cannel coal probably originates in open water environments such as fresh-water lakes or lagoons (Francis, 1958, p. 20).

Several factors suggest a fresh-water rather than a brackish water environment during peat accumulation. Most plant debris accumulations under near marine conditions such as tidal deltas or shallow lagoons have high sulfur contents and are free from all evidence of fungal attack (Francis, 1958, p. 180). Thiessen and Sprunk (1937, p. 34) in a petrographic study of Sunnyside coal from Horse Canyon, concluded that fungi plays an important part in the formation of the coal. Sunnyside coals lack significant amounts of pyrite and marcasite and hence have a low sulfur content.

Structures

Some of the structures in the Sunnyside coal are banding and a particular type of cleavage known as "eye coal" (fig. 17). Banding in coal is due to alternate layers of different texture and/or composition. Banding in the Sunnyside coal varies from microscopical size to layers several inches thick. "Eye coal" according to Stutzer (1940) gets its

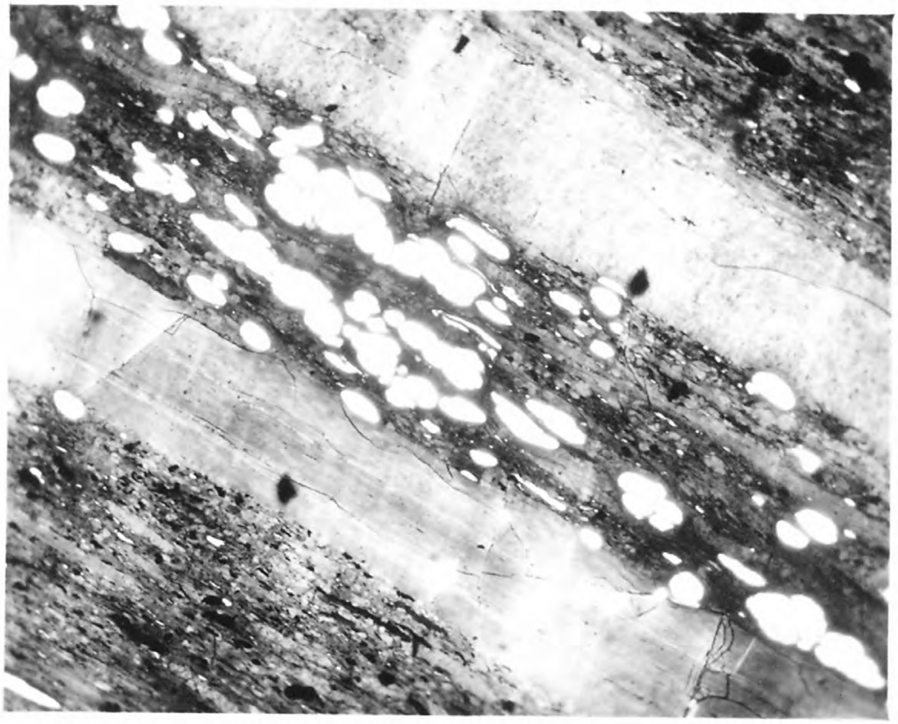


Figure 15. Photomicrograph of Sunnyside coal. Transparent clear bands are anthraxylon. Macerated bands are attritus. White spots are resin. This is bright coal or clarain.

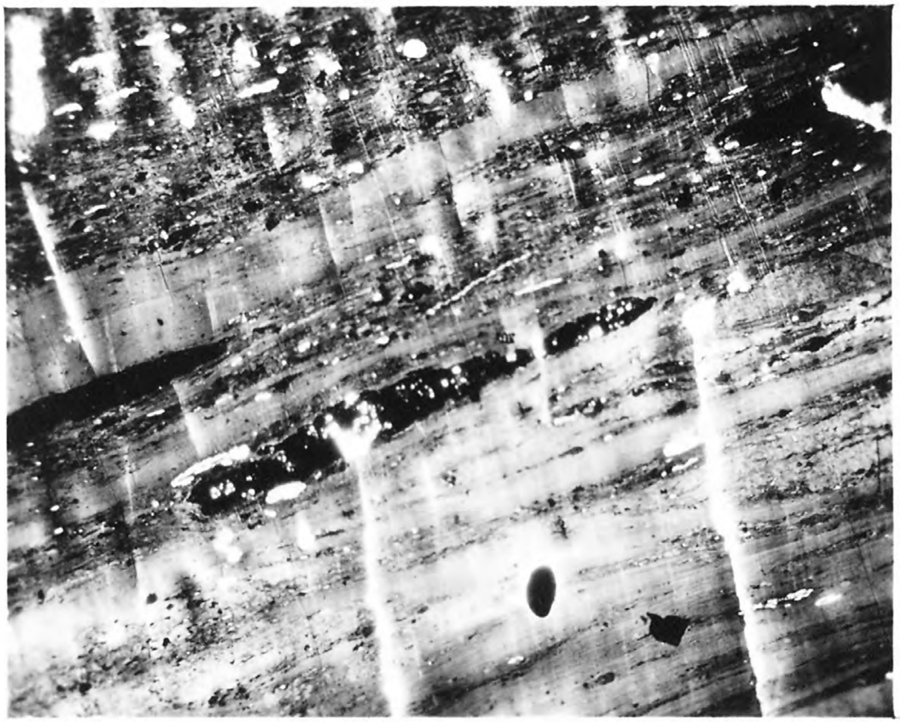


Figure 16.--Photomicrograph of Sunnyside coal. Dark opaque cellular particle is fusain.

Figure 17.--"Eye coal," Sunnyside coal seams.

name from numerous smooth and shining circular or elliptic disklike cleavages which lie in parallel planes. The size of individual "eyes" in the Sunnyside coal vary from 0.7 inch to disks more than 6 inches in diameter.

Banding in coal is of problematical origin. Some coal geologists believe that it has an environmental significance. Banding according to White and Thiessen (1913, p. 29) is due to changes in water level of forest moors and consequent influence of aseptic solutions and oxygen content upon the rate that plant debris decomposed. Davis (1946) believes that banding was inherited from original differences in plant constituents. Lahiri (1951), observed that banded structure is usually absent in low rank coals such as lignite and concludes that banding is more likely due to differentiation during compaction when more mobile constituents were squeezed out of the less mobile constituents and segregated into bands. However, according to Schopf (oral communication, 1960), it is doubtful if the vitrain component in banded coals could have preserved its cell structure if segregation during the metamorphism of the coal had occurred. Considerable variety in the thickness of the banding in the Sunnyside coal was noted in the Sunnyside No. 1 mine, but a detailed examination was not made to determine the possible origin of this structure.

The origin of "eye coal" cleavage is not well understood. According to Stutzer (1940) the origin of "eye coal" is the same as slaty fracture which is produced normal to the direction of pressure. It is also possible that "eye coal" may originate during the diagenesis of coal when shrinkage occurs. The "eye coal" cleavages in the No. 1

mine at Sunnyside have been mapped (Osterwald, and Eggleton, 1959, written communication), but the origin of these structures is as yet unknown.

Depositional history

Reconstructing the depositional history of the Sunnyside coal beds is a difficult problem because there are few swamp areas in the world at the present time that could give rise to thick, extensive coal seams. The Dismal Swamp of North Carolina and Virginia however is somewhat analogous to the type of depositional environment that may have existed during the time the Sunnyside coal swamps formed. According to Moore (1922, p. 137), if the accumulated peat in the Dismal Swamp turned to coal it would form a seam 1 inch to 20 inches in thickness. The Dismal Swamp stands near such a critical level that a slight uplift might produce dry land or a slight lowering might produce a transgression of the sea. Base level control therefore is of primary significance in maintaining coal-swamp conditions. A theory of the depositional history of the Sunnyside coal beds should consider the influence of this factor.

The theory of Young (1955) concerning the depositional history of the coal beds in the Book Cliffs area is summarized below:

Coal forming swamps in the Book Cliffs area began to form after deposition of each of the major sandstone tongues had almost ceased. This period of coal deposition corresponds with a time of diminished supply of sediment and to tectonic stability. A barrier bar, beach or vegetative barrier existed at the seaward edge of the sandstone tongues and prevented the sea from interfering with the swamp growth in the coastal plain or lagoonal areas. One or more sharp pulses of subsidence that were not of large magnitude caused the sea to flood the margins of the swamp. An increase of sediment after these small subisdences allowed a rapid building of offshore bars either at the site of the previous barrier or slightly farther inland. Swamp areas not affected by this marine incursion continued to grow and are responsible for the unusual thickness of the coals in certain areas such as at Sunnyside.

When the lagoons created by these sharp pulses of subsidence were filled, coal forming conditions resumed. The larger coal swamps were formed during periods of successive subsidences and all the major coals of the Book Cliffs lie at horizons which correspond almost exactly with the tops of these offshore bars or barriers. The result of such a sequence of events probably would be a coal bed which thins landward, is thickest where it corresponds with the tops of the successive offshore bars and splits seaward into two or more seams which were buried beneath successive overlying tongues of sandstone.

Young's conclusion that offshore bars, barrier beaches, vegetative barriers or some other type of barrier probably existed during the formation of the Sunnyside coal appears to be correct because lithologic facies indicate that the marine shoreline was close to the swamp at times, and because shorelines in the zone of tidal fluctuations are not as favorable for peat growth as are protected shorelines behind barrier bars (Auer, 1930). White and Thiessen (1913) believed that offshore bars were a possible barrier behind which coal could form.

Clark (1928) proposed a sandbar theory to explain the origin of the coal seams in the Book Cliffs.

Young's conclusion (1955, p. 196) that coal forming swamps began to form after the growth of the sandstone tongues had almost ceased does not appear to be correct. Sears, Hunt and Hendricks (1941), thought that analogous coals in the Late Cretaceous sequence in the San Juan basin were formed during regressive conditions and grew seaward as the regressive shoreline emerged.

If the coal swamps formed after regression was nearly complete then the contact between the coal and the underlying littoral marine sandstones probably should be a marked unconformity indicating a period of nondeposition or erosion. A period of nondeposition on an emergent coastal plain probably should result in the formation of a soil zone. Unlike many of the coals of Pennsylvanian age in Eastern North America, the Sunnyside coal beds lack a widespread thick soil zone at the base. A period of subareal erosion could have occurred prior to the deposition of the coal if there was an upward movement of the emergent area or if sea level dropped eustatically. Tectonic upward movement or a drop in sea level would have to be large enough not only to counter the tendency of streams to aggrade on a regressive shoreline but also to balance subsidence caused by the weight of the newly deposited sandstones compacting underlying mudstones and coal. ~~The evidence for and against underlying mudstones and coal~~ The evidence for and against uplift or sea level drop during a regression has been discussed by Sears, Hunt, and Hendricks (1941), who maintain that if uplift occurs during a regression sandstone tongues would have little tendency to grade smoothly downward into shale because the shallowing of water would allow the underlying shale to be disturbed by wave erosion. Spieker (1949) thought that there was no uplift during the regression of the sandstone tongues in the Book Cliffs because this would have resulted in erosion of previously formed sandstones and the sandstone tongues would have thinned landward. There is no evidence for such thinning in the Book Cliffs.

The truncated tops of sandstone tongues observed by Spieker (1949) in the Blackhawk formation near Helper, Utah suggest that some areas have had a minor amount of subareal planation prior to coal swamp accumulation. This erosion however could have taken place almost simultaneously with regression. In some areas of the Book Cliffs, Young (1957) observed channeling near the tops of the sandstone tongues. These channels could have resulted from tidal inlets or other types of marine scour as well as stream erosion.

Since there is little evidence for an unconformity below the Sunnyside coal beds, the Sunnyside coal beds probably represent regressive coals deposited behind retreating shorelines. There is also no reason to suggest that the growth of the swamp corresponds with a period of diminished supply of sediment to the littoral marine environment. It is true that the purity of the Sunnyside coals which have a low ash content indicates that streams which flowed through the swamps could not have provided more than a minor fraction of the sediment responsible for regression of the shoreline. Dense vegetation, however, could provide an effective barrier to overbank deposits of such streams as did flow through the swamp. Sedimentation in the littoral marine area was probably the result of longshore currents and thus large quantities of sediment need not have been transported through the swamps.

Young's(1955) interpretation of the origin of the major splits in the Sunnyside coal also appears to be inadequately founded. The major splits the "Upper Sunnyside" and the "Lower Sunnyside" seams as designated by Clark (1928, p. 34), likely resulted as a consequence of interruptions in swamp accumulation by stream deposits rather than by marine incursions.

The factors responsible for the thickness of the Sunnyside coal seams have not as yet been adequately explained. For accumulation and preservation of sediment, room must be made below the base level of erosion. For substantial thicknesses of sediment this can be accomplished only by tectonic subsidence in the depositional area. However, on a smaller scale, room can be made for sedimentary buildup by: 1) subsidence due to compaction, 2) regression which allows infilling of an existing basin and aggradation in the subareal portion of the depositional area, and 3) eustatic rise in sea level.

Deposits of coal in the Sunnyside member of the Blackhawk formation commonly are 15 feet thick. According to the estimates of Weller (1959) a coal bed 15 feet thick is equivalent to a thickness of 210 feet of new peat. Making allowances for some compression of peat in the lower portions of the deposit and loss of substance due to biochemical alteration possibly 75 to 125 feet of altered peat may be required for a total of 15 feet of coal.

During the buildup of peat the rate of accumulation and the rate at which room is made for the buildup of the organic deposits must be nearly equal. According to Francis (1954, p. 4):

> "During the extensive coal-forming periods, accumulation of vegetable matter and associated mineral matter, generally clays and sand, is balanced by the subsidence of the area on which these materials are accumulating. When this balance is disturbed, the accumulation of coal-forming vegetable debris ceases. If the area is near the sea, as in a coastal swamp or delta, and the rate of subsidence exceeds the rate of accumulation of vegetable matter, the area sinks below the sea level and the invading sea covers the deposit with sand and calcareous muds. If the area is inland and the subsidence is excessive, the area is flooded by fresh water and the debris is covered with soil or clay. When the rates of subsidence and deposition are about equal plant debris continues to accumulate and the deposit is substantially free from extraneous mineral matter. When no subsidence occurs, the area gradually rises, due to the continued growth of plant life, but accumulation of plant debris eventually ceases due to rapid decay by microbial agencies and erosion by wind or rain."

Thus, possibly 75 to 125 feet of altered peat which accumulated during a period when subsidence and rate of accumulation must have been nearly balanced.

To explain the rapid transgressions recorded in the Blackhawk formation, Young (1955, p. 197) proposed that subsidence occurred in sharp pulses. Sharp pulses of subsidence, however, would not account for the thick accumulation of peat. Also, it is possible to account for the rapid transgressions in the Blackhawk by other means, such as change in the rate of subsidence, or change in the rate at which sediments were supplied to the littoral zone.

The steady, gradual subsidence during the accumulation of the peat could be explained as a result of tectonic subsidence, gradual eustatic rise in sea level subsidence due to compaction of underlying sediments. Aggradation of sediments under regressive conditions could also assist in the accumulation of peat.

Compaction of sedimentary material, and resulting differential subsidence probably occurred during the deposition of the littoral marine sandstone tongue of the Sunnyside member because it is underlain by 120 feet of formerly highly compactable sediments--the Mancos shale and the nonmarine mudstones and coals of the Kenilworth member. Unknown factors such as the porosity of the sediments and the proportionate amount of sandstone, siltstone; mudstone and coal contained within the nonmarine tongue of the Kenilworth make it difficult to estimate the amount of compaction that must have occurred as the overlying sandstone was deposited. Subsidence from this cause probably was slow and continuous.

According to Weller (1959) compaction due to dewatering occurs in mudstones and coal at an early stage before the sediment is buried more than about 500 feet. Thus, sibsidence due to compaction may have initiated swamp conditions soon after the emergence of regressive beaches in the Sunnyside member and before any significant subareal erosion could occur.

Exposed land newly emergent from the regressive sea probably had a low gradient, and if rainfall was moderately heavy and well distributed, swamp conditions could have extended inland for considerable distances. To a certain extent drainage probably was obstructed by luxuriant, dense plant life. Some streams probably flowed through the swamps to the sea.

As the sea regressed stream profiles were lengthened and average stream
consequently flattened. The effect of lengthening stream gradients
gradients could cause aggradation. As a consequence of an aggrading stream, water tables may have risen and swamps adjusted to a newly built up water level. This factor, which is independent of subsidence, may account in part for a slow gradual buildup of peat. The amount of sedimentary buildup that can be accounted for by aggradation is difficult to estimate and may be of only negligible significance.

In conclusion, the Sunnyside coal formed as a regressive deposit during which the rate of accumulation of vegetable material was nearly balanced by the room made available for buildup. Gradual tectonic subsidence, slow eustatic rise in sea level, or subsidence due to compaction could account for the peat accumulation. Stream aggradation under regressive conditions may have assisted. No quantitative estimate of the relative importance of these factors can be made on the basis of available data.

The "Upper Sunnyside" and "Lower Sunnyside" seams of Clark (1928) probably are splits of one major coal bed and the nature of the splitting indicates interruption by fluviatile rather than marine deposition.

Conclusions

Depositional history of the Mesaverde group at Sunnyside

Depositional history of the Mesaverde group at Sunnyside

During Late Cretaceous time the sea in the Western Interior of North America gradually retreated eastward. Successive pulsations of subsidence in the basin, changes in the rate of subsidence or possibly the rate at which sediments were supplied to the littoral zone, caused repeated invasions of the sea westward which are now reflected in the intertonguing relationships of continental, littoral marine, and offshore marine deposits as seen in cross section along the Book Cliffs in central Utah.

The Late Cretaceous shoreline in this region had a northeast trend, (Young, 1955). The direction of the shoreline is suggested by isopach maps of tongues of the Mancos shale.

After a rapid invasion of the sea westward the shoreline regressed slowly eastward. Only regressive marine deposits are known in the Book Cliffs area (Spieker, 1949). Regressive deposition of littoral marine sandstones is inferred from the fact that these sandstones grade downward to shales but show no similar gradation on their upper surfaces. Young (1955) has established the cyclothemic nature of the Blackhawk formation. According to Spieker (1960) these cyclical variations are of the (1, 2, 3, 4, 1, 2, 3, 4) type rather than the (1, 2, 3, 4, 3, 2, 1) type which indicates that the deposition was interrupted periodically rather than alternating regressive and transgressive deposition. Particle size in marine tongues shows a progressive increase in coarseness as the position of the ancient shoreline is approached.

The character of the bedding also progressively changes, disrupted bedding with mottling, irregular and uneven bedding, and massive bedding with laminae resembling those found by Thompson (1937) on the lower foreshore beach appear in marine tongues of the Blackhawk formation, in the same sequence, in environments progressively closer to the shoreline.

Sandstone units in nonmarine tongues of the Blackhawk are lenticular and lack the fine laminations observed in the marine sandstones. Coal particles are abundant in the nonmarine sandstones, but generally are lacking in the fine-grained littoral marine sandstones.

Thin even bedding and clay-size particles characterizes the Mancos shale except where thin tongues extend into the Blackhawk formation. Tongues of the Mancos shale may have disrupted bedding and may contain impressions of twigs and branches.

During Late Cretaceous time geological conditions were favorable for the accumulation and preservation of vegetable matter which later formed the Sunnyside coal and other coal deposits. Favorable geological conditions require a delicate balance between the rate of accumulation of coal-forming vegetable matter and the rate of subsidence in the area of accumulation. Gradual tectonic subsidence or slow eustatic rise in sea level could have provided the proper base level control during the time of coal-swamp accumulation. Subsidence due to compaction and subareal aggradation as the sea regressed are factors which also may have assisted to maintain a uniform balance in the areas of swamp accumulation.

Since the Sunnyside coal is directly above a littoral marine sandstone which shows primary sedimentary structures found in present day beaches, swamp conditions were probably initiated soon after new land was added to the regressive shoreline and before signigicant subareal erosion had occurred. Gradual subsidence due to compaction of the underlying sediments may have been responsible for rapid development of swamps on the newly built up land surface.

The open and closed splits found in the Sunnyside coal indicate numerous interruptions in the accumulation of vegetable matter due to fluvial deposition. The absence of cannel coal, the relative absence of sulfur and presence of fungi indicate that the vegetable matter probably accumulated in fresh-water conditions. A low-lying coastal swamp is the most probable depositional environment of the Sunnyside coal. Peat accumulation was probably never entirely interrupted during the period when the major coal beds formed and therefore the "Upper" and "Lower" Sunnyside coal seams as designated by Clark(1928) are believed to be splits of one major coal bed.

In response to orogenic movement environment changed during the time of the deposition of the Castlegate sandstone and Price River formation at Sunnyside, Utah. The sea retreated eastward and the Castlegate sandstone and Price River formation at Sunnyside, Utah was deposited in a continental environment. Rapid deposition of the sediments and better drainage conditions probably prevented extensive swamp accumulations in the Castlegate sandstone and Price River formation. Wedge-shaped cut-and-fill structures, log, branch and twig impressions and casts, clay gails and thin coal lenses indicate that the depositional environment was continental.

Finely laminated mudstones are commonly found in the Blackhawk and Price River formations. Although similar lithologies originate in marine or brackish water environments, in the Castlegate sandstone the laminated mudstones are associated with nonmarine fluvial deposits.

"And what might have been,
And what might be, fall equally
Away with what is, and leave
Only these ideograms. . ."

From "Lyell's Hypothesis Again"
by Kenneth Rexroth

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