Sedimentary Features of the Blackhawk Formation (Cretaceous) in the Sunnyside District, Carbon County, Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 688

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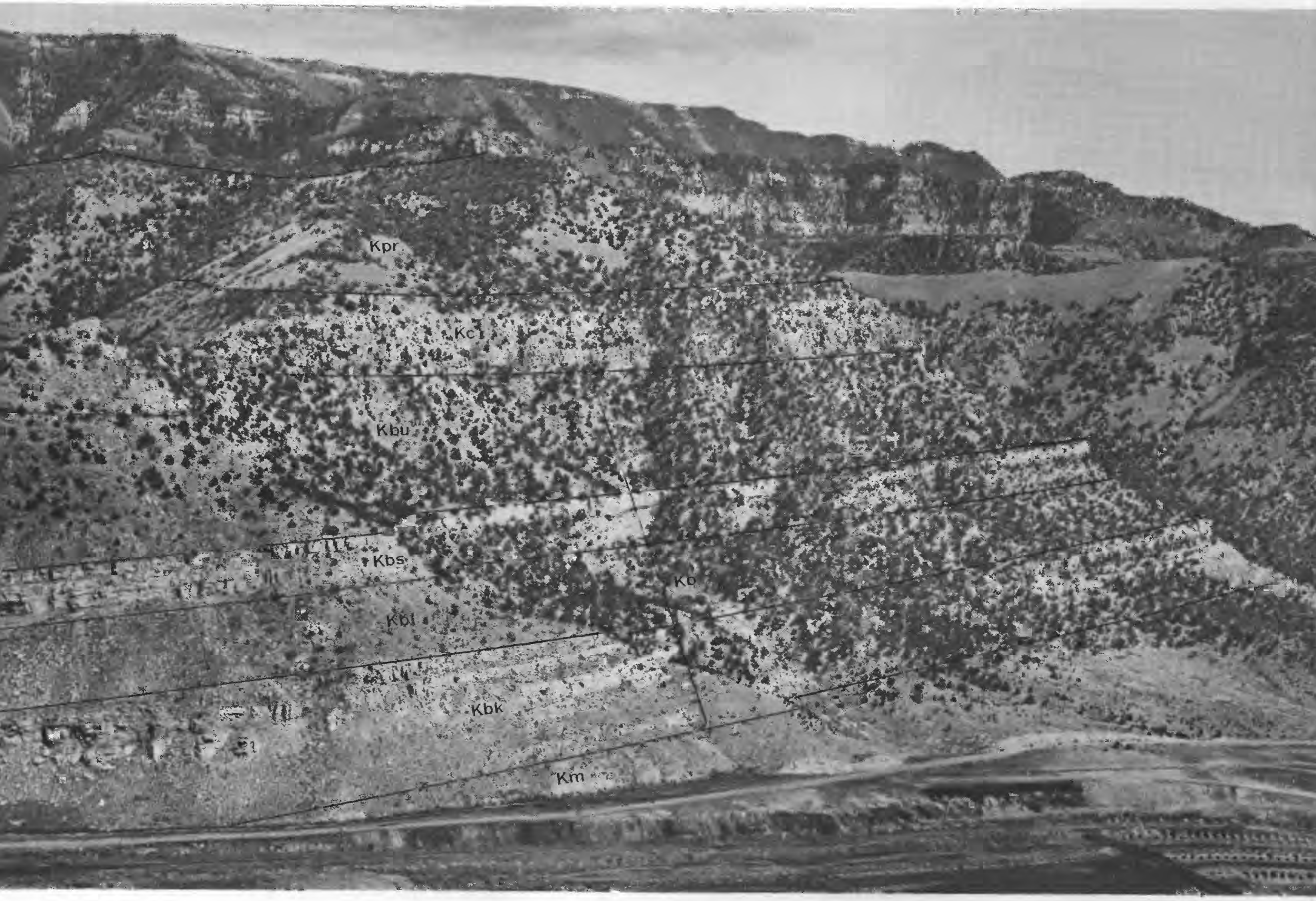

The Blackhawk Formation and associated rocks at the mouth of Whitmore Canyon, Sunnyside, Utah. Rock units shown are: Kpr, Price River Formation; Kc, Castlegate Sandstone; Kb, Blackhawk Formation (Kbu, upper mudstone member; Kbs, Sunnyside Member; Kbl, lower mudstone member; Kbk, Kenilworth Member); Km, Mancos Shale. Scale is indicated by telephone poles at base of hill. View looking southeast from West Ridge, above town of Sunnyside.

Sedimentary Features of the Blackhawk Formation (Cretaceous) in the Sunnyside District, Carbon County, Utah

By JOHN O. MABERRY

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A discussion of the trace fossils, stratigraphy, depositional paleoenvironment, and engineering geology of coal-bearing rocks in a part of the Book Cliffs coal field of central Utah

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CONTENTS

ILLUSTRATIONS

[Plates follow index]

TABLE

SEDIMENTARY FEATURES OF THE BLACKHAWK FORMATION (CRETACEOUS) IN THE SUNNYSIDE DISTRICT, CARBON COUNTY, UTAH

By John O. Maberry

ABSTRACT

The Blackhawk Formation in the Sunnyside district, Utah, was deposited along the west margin of the Western Interior Cretaceous sea during southeastward withdrawal of the sea. Sand was the dominant type of terrigenous sediment deposited in the Sunnyside district during the regressive phases. Sand bodies prograded seaward in response to changing sediment supply from a source west of Sunnyside. Where conditions were favorable for the accumulation of vegetable material, peat deposits formed landward of the sand bodies and were later changed by diagenesis to bituminous coal. The coals formed from accumulation of small low-growing plants and plant debris that was transported into the area of accumulation. Remains of large plants in the coals are rare.

Trace fossils, which are tracks, trails, and burrows formed by organisms and preserved in the rock, are extremely abundant in the Blackhawk rocks. These biogenic sedimentary structures are common in Cretaceous deposits throughout the Western United States. Trace-fossil distribution in the rocks is controlled by the depositional environment preferred by the organisms that created the traces. A study of the trace fossils of a locality allows a more precise determination of the conditions that existed during deposition of the sediments. Water depth, bottom conditions, salinity, current velocity, and amount of suspended nutrients are some of the environmental factors that may be reconstructed by studying trace fossils.

The Blackhawk Formation in the Sunnyside district comprises the Aberdeen, Kenilworth, and Sunnyside Members. The Blackhawk Formation is underlain by and pinches out into the Mancos Shale and is unconformably overlain by the Castlegate Sandstone. Sandstone units of the members of the Blackhawk form the basal units of the Book Cliffs and thereby effect an abrupt transition from the low topography of Clark Valley to the sheer cliffs.

Coal mining is the principal industry of the Book Cliffs region. Mines of the Sunnyside district are loci for coal-mine bumps, which are sudden, catastrophic releases of stress in the coal. Bumps often cause loss of life, property damage, and loss of profit to mining companies. Bumps occur when shear stress built up in the coal exceeds the shear strength of the coal. Differential overburden pressure, faulting and other tectonic activity, and lithology and structure of the enclosing rocks are among the factors that influence bumps. Petroleum and natural gas (methane), which occur locally in pockets in the roof rocks above coal beds, may be diagenetic products of organic-rich sediments.

Investigation at Sunnyside has revealed that many factors influence coal-mine bumps. Among these factors are differential compression of the coal and ease with which the coal can move into mine openings in response to pressure. Whether the coal continually creeps into the entry and spalls off or whether it bursts under an excess of stored stress depends upon the lithology of the enclosing rocks and the geometry of the interfaces between coal and rock.

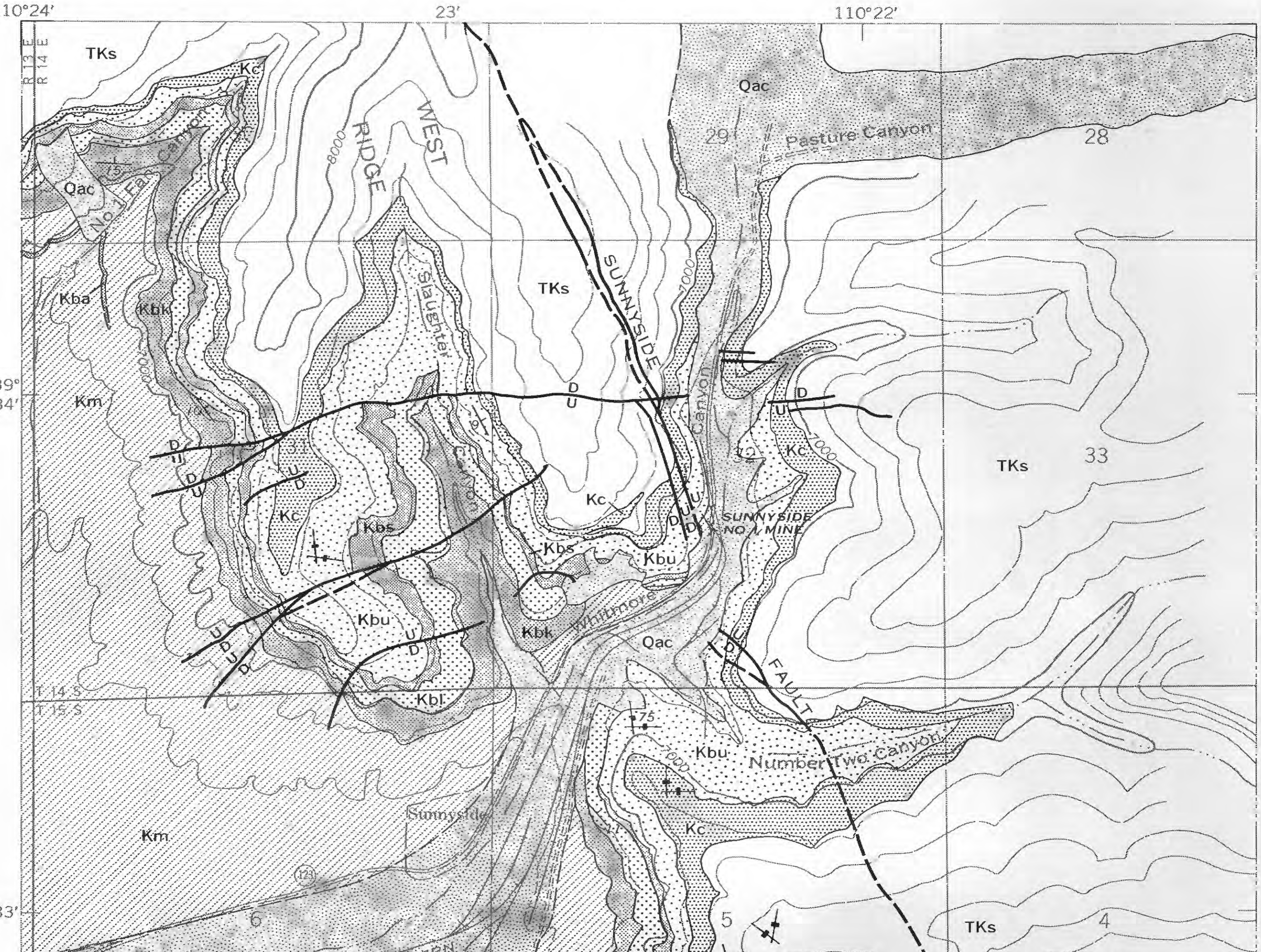
Where directional sedimentary structures are at large angles to entries, coal can slip relatively easily into the entries and continually relieve stress. Where friction builds between the roof or floor rock and the coal, stress may accumulate to the point of catastrophic failure of the coal. Such friction buildup may be due to structures oriented at small angles to the entries or to coarse-grained rocks enclosing the coal.

By studying inorganic and biogenic sedimentary structures and by mapping their trends, geologists may furnish a tool to help avoid mine bumps and rock bursts.

INTRODUCTION

This report stems from an investigation of geologic factors that may cause coal-mine bumps in the mines at Sunnyside, Utah. Future papers will discuss more comprehensively how these factors relate to mine bumps.

The coal mined at Sunnyside is in one of many thick coal beds that occur in the Blackhawk Formation. These beds are mined extensively in the Book Cliffs and Wasatch Plateau coal fields, and the coal industry is the basis for most of the economy of central Utah. Coal-mine bumps are sudden, catastrophic releases of stress in the rib, roof, or floor of a coal mine. These releases are of varying intensity, but all have the capacity to cause property damage (fig. 44) and work loss, as well as loss of life. Sunnyside mines long have been loci for violent bumps. Parallel goals of the present work were to ascertain the relationship of sedimentary structures to coal-mine bumps, to study and describe the trace fossils and inorganic sedimentary structures found in the rocks, and to ascertain the origin and mode of migration of petroleum and natural gas in the mines at Sunnyside.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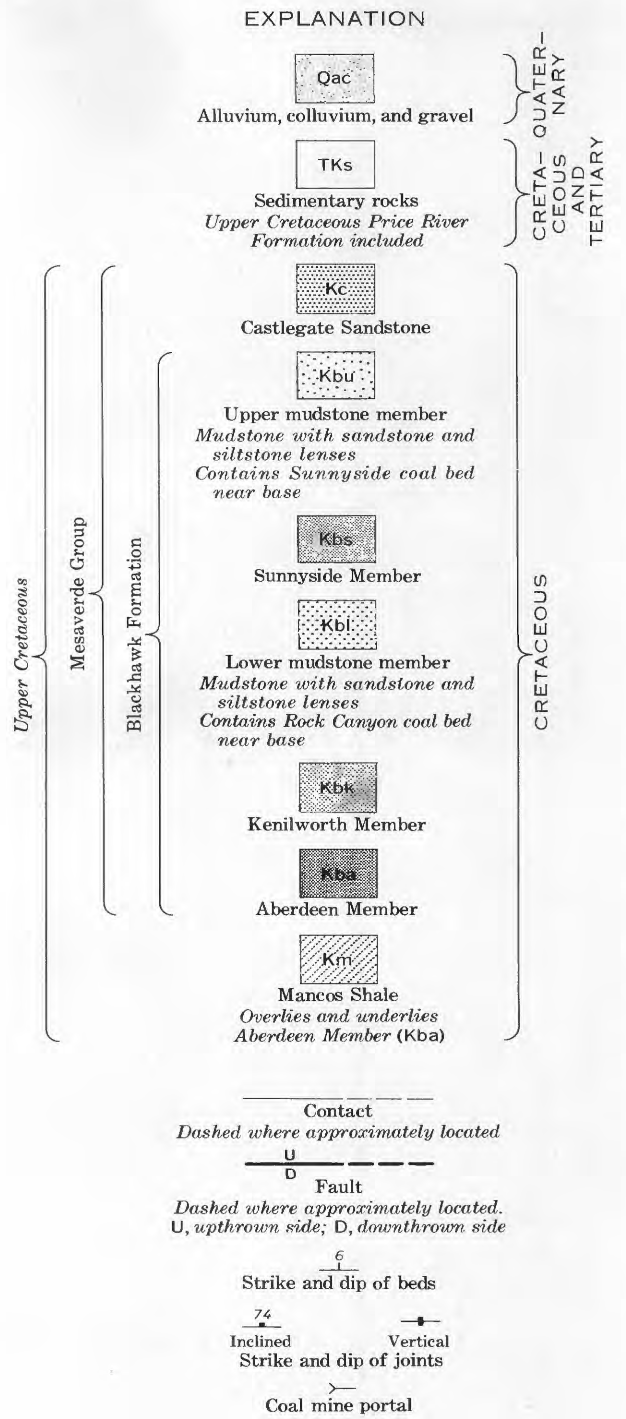

FIGURE 1.—Blackhawk Formation and associated strata at Sunnyside.

A major structural feature of east-central Utah is the San Rafael Swell, a northeast-trending asymmetrical anticline that plunges northeastward under the Book Cliffs (fig. 3). The swell probably is of pre-Triassic age and, therefore, probably caused localized depositional thinning of Blackhawk sediments at Sunnyside. The Blackhawk Formation crops out on the south- and west-facing scarps of the Book Cliffs. The cliff front is a faceted surface that resulted from erosion of the Roan Plateau. South of Sunnyside, strata strike northward; as the structural strike approaches the northeast end of the San Rafael Swell, the beds gradually change strike toward the west as they are gently folded over the crest of the swell. North of Sunnyside, beds strike westward and dip northward. Dips of the beds are as much as 15° N. and E. at the cliff front and decrease downdip to about 7°. The steeper dip at the cliff front probably is due to the proximity of the front to the crest of the swell, where the structural inclination is greatest. Traced downdip, the strata pass into the Uinta Basin.

The regional joint pattern is characterized by two major sets of joints at nearly right angles to each other, striking N. 75°–85° W. and N. 12°–20° W. (Osterwald and Eggleton, 1958, p. 13; Maberry, 1968, p. 9). Joint orientations are relatively constant throughout the area. As might be expected, joints are best expressed and best preserved in sandstone units.

Known faults in the Sunnyside area are alined subparallel to the regional joint pattern, and many major faults strike N. 12°–20° W. (fig. 1). All faults in the area are normal faults; fault planes dip 75°–90°. No known faults in the Sunnyside area effect more than 150 feet of stratigraphic separation at the surface. A buried northwest-trending fault south of the area, which was discovered by use of seismic methods (Tibbetts and others, 1966), may have as much as 2,000 feet of stratigraphic separation; the fault is downthrown to the northeast. The principal fault system at Sunnyside is the Sunnyside fault zone (Osterwald and Dunrud, 1966), which trends northwest and is downthrown to the southwest. It is a series of long northwest-trending faults with many short curving spurs (fig. 1). The Sunnyside zone causes difficulties in mining because the faults offset the coal bed, affect stress distribution, and necessitate changes in mining procedure.

Coal extraction underground commonly produces subsidence cracks at the surface. Most subsidence cracks are formed on spurs or noses above mine workings and trend subparallel to joints. Joint orientation controls alinement of subsidence cracks because many en echelon subsidence cracks closely parallel nearby joint trends. Extraction of the coal removes support for overlying rocks. The rocks immediately above the coal fail, and the failure eventually continues upward to the surface. Mine air issues from some of the cracks, and some cracks are visible at the surface, as much as 1,200 feet above the mine workings. Subsidence cracks range in size from splits one-fourth inch wide and a few feet long to crevasses 4 feet wide and 50 feet long (fig. 2).

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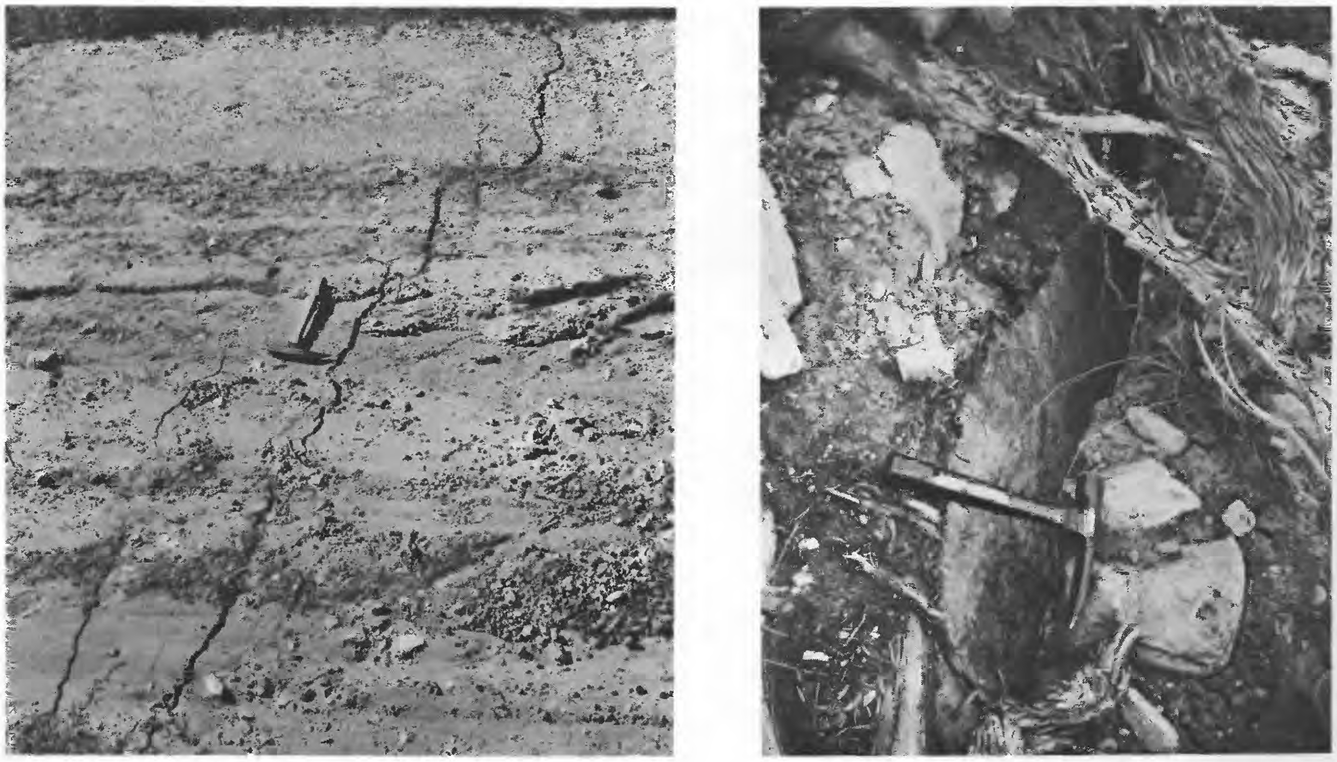

A B

FIGURE 2.—Subsidence cracks. *A*, Small en echelon cracks trending northwest at surface about 800 feet above Sunnyside coal, at junction of Pasture Canyon and Whitmore Canyon. *B*, Large crack trending northwest about 900 feet above Sunnyside coal in west wall of Whitmore Canyon; mine air issues from crack. Photographs by F. W. Osterwald.

LOCATION

The Sunnyside coal-mining district is in the western Book Cliffs, 27 miles east of Price, Utah (fig. 3). As described herein, the Sunnyside district lies wholly within Carbon County. The district was named for Sunnyside, the first and largest incorporated town in the district, with a population of approximately 800. The district is accessible by State Highways 123 and 124, which connect to the west and south, respectively, with U.S. Highway 6 and 50. The Denver and Rio Grande Western Railroad and the Carbon County Railway furnish freight service to the area. The district is northeast of the San Rafael Swell and at the base of the Roan Plateau, a maturely dissected high plateau in the Colorado Plateaus physiographic province.

PREVIOUS WORK

The Book Cliffs coal field has been the subject of much investigation. The coal deposits are thick and well exposed and have low dips. In the Sunnyside district, the coal in the Blackhawk Formation is high-quality bituminous coking coal, which is particularly valuable to industry. The Sunnyside district is also the locus of spectacular mine bumps, which have been studied intensively because they are hazardous to life and property.

Most investigators have concentrated on the economic geology of the area. Weimer (1960, 1961) defined regional stratigraphic relationships and correlations and set the framework for concepts of Cretaceous history in the area of Colorado, Utah, and Wyoming. Fisher, Erdmann, and Reeside (1960) discussed regional stratigraphy in a comprehensive paper on the Book Cliffs of Utah and Colorado.

Spieker and Reeside (1925) named and defined many Cretaceous and Tertiary units in central Utah, where Spieker and Reeside (1926) also investigated paleoshoreline orientations. Young (1955, 1957) studied the facies interrelationships in the Upper Cretaceous rocks of the Book Cliffs and based his work largely on Pike's (1947, p. 13–25) work south of Sunnyside. Young named and defined some of the members of the Blackhawk Formation, but his work was on a regional scale, and his conclusions are subject to some controversy.

The most detailed work in the Sunnyside district was done by Osterwald (1961; 1962a, b); Osterwald and Eggleton (1958); Osterwald and Brodsky (1960); Osterwald and Dunrud (1964, 1966); Osterwald, Dunrud, and Maberry (1968), who mapped much of the area at a scale of 1:6,000; and Brodsky (1960), who studied the general stratigraphic relationships of the

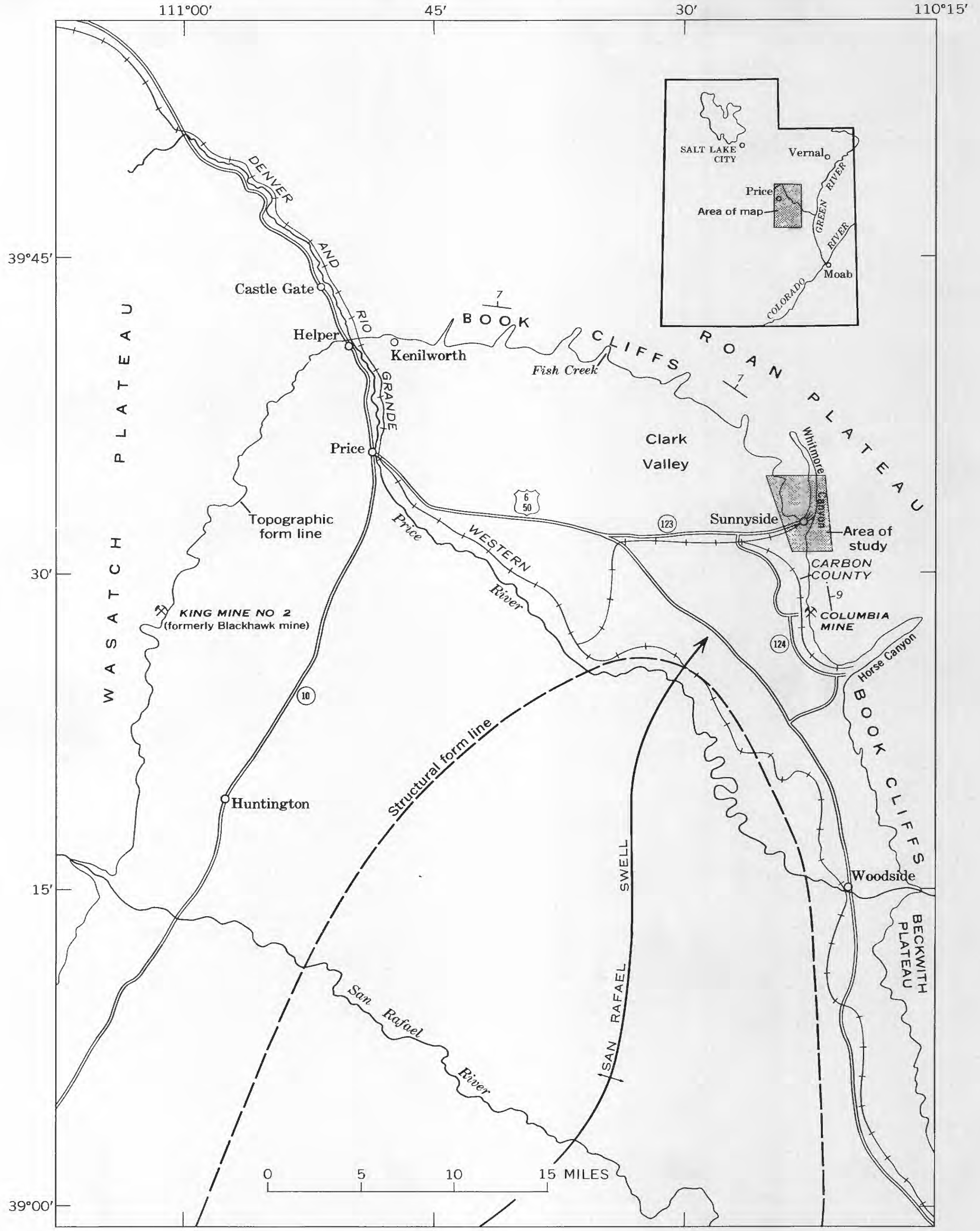

FIGURE 3.—Index map of the Sunnyside district. Axis of San Rafael Swell from Stam (1956). Topographic and structural form lines from Howard (1966a), Osterwald and Dunrud (1964), and Stam (1956).

Mesaverde Group. Most of these works, however, are based primarily on lithologic variation, with emphasis on the relationship of lithologies to the coal beds of the Blackhawk Formation.

Howard (1966a, b, c) studied trace fossils and sedimentary structures in Blackhawk strata in the Wasatch Plateau and western Book Cliffs, where the strata are stratigraphically lower than Blackhawk rocks at Sunnyside.

ACKNOWLEDGMENTS

I am indebted to W. A. Cobban and F. W. Osterwald, U.S. Geological Survey, for reviews of the manuscript. Osterwald's interest and direction during all phases of the work are particularly appreciated. James D. Howard, University of Georgia Marine Institute, instructed me in many aspects of trace fossils and sedimentary structures and furnished some illustrations. Discussions and field conferences with Dr. Howard were particularly valuable in understanding and interpreting the phenomena discussed herein. John Peperakis and Harry Elkin, Kaiser Steel Corp., allowed access to the study area and provided maps and other information regarding the coal beds. R. J. Weimer, John Hayes, and R. H. DeVoto, Colorado School of Mines, critically reviewed an earlier version of the report (Maberry, 1968). E. E. McGregor, U.S. Geological Survey, analyzed selected lithologic samples with an X-ray diffractometer. Artist's sketches of trace fossils were made by Roger B. Williams, University of Kansas.

BIOGENIC SEDIMENTARY STRUCTURES

Biogenic sedimentary structures, commonly called trace fossils, are tracks, trails, burrows, or borings made by organisms and preserved in rock strata. In short, trace fossils indicate where organisms have been. The lack of body fossils, particularly in sandstones, has been partly responsible for a lack of detailed paleoecological stratigraphic work in much of the Western United States. These trace fossils, or lebensspuren, are valuable paleoecologic indicators. Where body fossils are present, traces may be used to reinforce interpretations; where body fossils are scarce or absent, trace fossils may be used effectively to interpret the paleoenvironment. Body fossils may be transported from the living site, or they may be destroyed by diagenesis. Trace fossils, on the other hand, are found almost unquestionably in place, although J. D. Howard (oral commun., 1967) indicated that some *Ophiomorpha* burrow casts may be reworked. Most trace fossils are emphasized by diagenesis.

Trace fossils have been investigated mostly by Europeans, particularly the German geologists Häntzschel (1962) and Seilacher (1964, 1967). In the present report, much of the material included in the term "trace fossils" has heretofore been assigned to categories such as algae, fucoids, incertae cedis, problematica, inorganic structures, worms, or feces. The accurate description and classification of trace fossils may help bring to American geologists a valuable tool to be used in reconstructing the geologic history.

Howard (1966a, c) described trace fossils in the Blackhawk Formation near Helper, Utah. No other trace fossils from central Utah have been described; therefore, this report contains a detailed and extensive discussion of trace fossils to provide references for stratigraphic interpretations based on traces.

Häntzschel (1962) and Seilacher (1964, 1967) showed that trace fossils are grouped in sedimentary facies according to the environments preferred by their animal creators (fig. 6). Some traces definitely indicate shallow marine conditions; some indicate terrestrial deposition. The orientation of traces of the same type of organism indicates the relative rate of sedimentation. Seilacher (1967, p. 421) emphasized that vertical burrows in shallow-water deposits and the gradual tendency toward horizontal burrows in deeper water deposits correspond to a trend from suspension to sediment feeding. The type of feeding is a response to the amount of suspended nutrients at different levels in water and in sediment. In shallow zones, food for organisms is in suspension; at depth, in quiet water, nutrients settle out of suspension and become part of the sediment. Hence, in quiet waters the trend is toward horizontal intricately patterned burrows. By studying trace-fossil forms and associations on the outcrop, in mine workings, and in the laboratory, one can deduce the history and environment of deposition of strata. From these deductions, the positions of various strata in a depositional framework can be postulated with an increasing degree of accuracy.

The Upper Cretaceous strata of Wyoming, Colorado, and Utah have been the subject of intensive trace-fossil studies in recent years because of the paucity of body fossils and extreme wealth of trace fossils in these strata. Representative investigations are those by Toots (1961), who used trace fossils to delineate beach zones and strandlines in Wyoming, and by Masters (1966), who used trace fossils as environmental indicators in his study of the Mesaverde Group of northwestern Colorado. Howard (1966 a, b, c) exhaustively studied trace fossils in units slightly older than those discussed herein, and his work in the Wasatch Plateau west of Sunnyside dovetails with the studies described here.

The creators of all trace fossils described herein had an affinity for warm waters. Reeside (1957, p. 505) postulated a nearly tropical climate for the Western Interior for most of the Cretaceous Period, an interpretation based primarily on body fossils. Parker (1969) collected fossil flora from the Blackhawk Formation near Salina, Utah, and concluded from his study that the regional climate was subtropical during Late Cretaceous time. My interpretation, which is based on the presence of thick coal beds and palm-leaf fossils in terrestrial deposits within the Blackhawk Formation (fig. 4), agrees with the conclusions of Reeside and Parker.

USES OF TRACE FOSSILS

Most sedimentary syngenetic economic minerals are controlled by physical and chemical conditions extant at the time and place of deposition. Oil and natural gas in stratigraphic traps associated with nearshore marine sediments are well known. Trace fossils may be used as environmental indicators to predict areas that are favorable for entrapment of such deposits, and, consequently, loci for exploration may be delineated. Localization of sedimentary mineral deposits of manganese, phosphate, barite, iron, and evaporites is controlled by factors such as depth of water, temperature, salinity, circulation barriers, and organisms that facilitate precipitation. In the Western United States, most coal deposits are associated with marine or transitional-marine sedimentary rocks. When trace fossils can be recognized in drill cores, depositional conditions may be ascertained at some distance from the outcrop. Body fossils need not be present for one to interpret sedimentary environments. Geologists have become increasingly interested in trace fossils and their definition and uses (Howard, 1968). Some conditions of mining various commodities might also be predicted through knowledge of associated trace fossils.

DESCRIPTIVE NOMENCLATURE

Because it cannot be definitely known which genus and species of organisms made individual trace fossils,

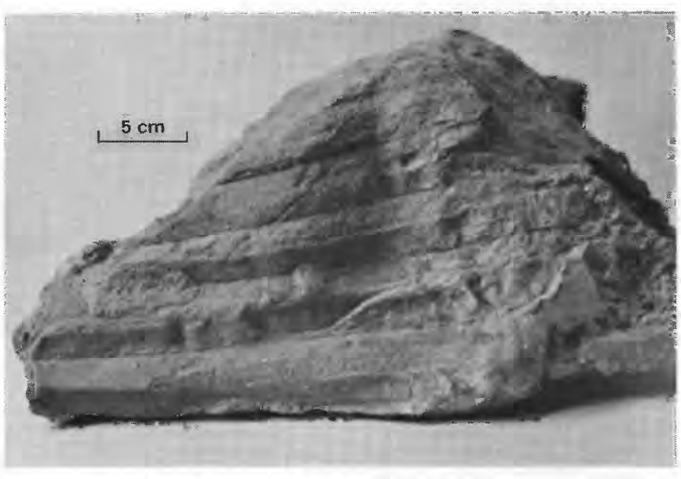

FIGURE 4.—Palm-leaf fossil found in upper part of the Sunnyside Member. On the basis of morphology, the fossil is inferred to be part of a leaf.

traces cannot be grouped into normal systematic taxonomic units. The trace-fossil nomenclature used in the present report was determined on the basis of the function, or ethology, of the fossil, according to the methods developed by Seilacher (1964). Traces are described partly on the basis of their relationship to the substrate on which they were formed.

ANIMAL-SEDIMENT RELATIONSHIP

Trace-fossil preservation is classed as epirelief, in which traces are present on the lower surfaces of beds (fig. 5); hyporelief, in which traces are present on the upper bedding surfaces; and full relief, in which traces are completely contained within the strata and are preserved as the original cavity or cavity filling. Original-cavity, full-relief trace fossils are very rare in the Book Cliffs. Epirelief and hyporelief trace fossils have convex and concave features. A convex feature is one that projects above the upper bedding surface or below the bottom of a bed. Conversely, a concave feature is one that is indented into the bedding surface.

Most trace fossils on bedding surfaces were formed either by locomotion of the animal, forming tracks and trails, or by excreta from the animal. Traces that are in upright positions were mostly living burrows, formed either by peristaltic contractions of the animal's body as it forced itself down into the substrate or by excavation accomplished by the animal's sediment intake. Walled or reinforced burrows were reinforced against a mobile substrate by excretions from the animal. Upright burrows that are interpreted as escape burrows (such as those that *Asterosoma* makes) were excavated by the animal and infilled with the sediment that passed through its system. Most horizontal trace fossils of infauna were formed by the animal by sediment intake and infilling with excretion, although some infaunal traces probably were informed by soft-sediment deformation.

SUBDIVISION OF BLACKHAWK TRACE FOSSILS

Every outcrop of Blackhawk rocks in the Sunnyside district exhibits some evidence of organism activity in the sediment at the time of deposition. The environment in which organisms responsible for trace fossils were most abundant and most varied is represented by interbedded siltstones and very fine to fine-grained sandstone. Some mudstones are also intensively burrowed, but preservation of trace fossils is poor in mudstone. The siltstone and fine-grained sandstone are rich in finely divided organic material and are very thinly and evenly bedded (fig. 6*A*). This environment was inhabited dominantly by detritus feeders (also called filter feeders or sediment feeders), which were organisms that prowled the surface of deposition and (or) bur-

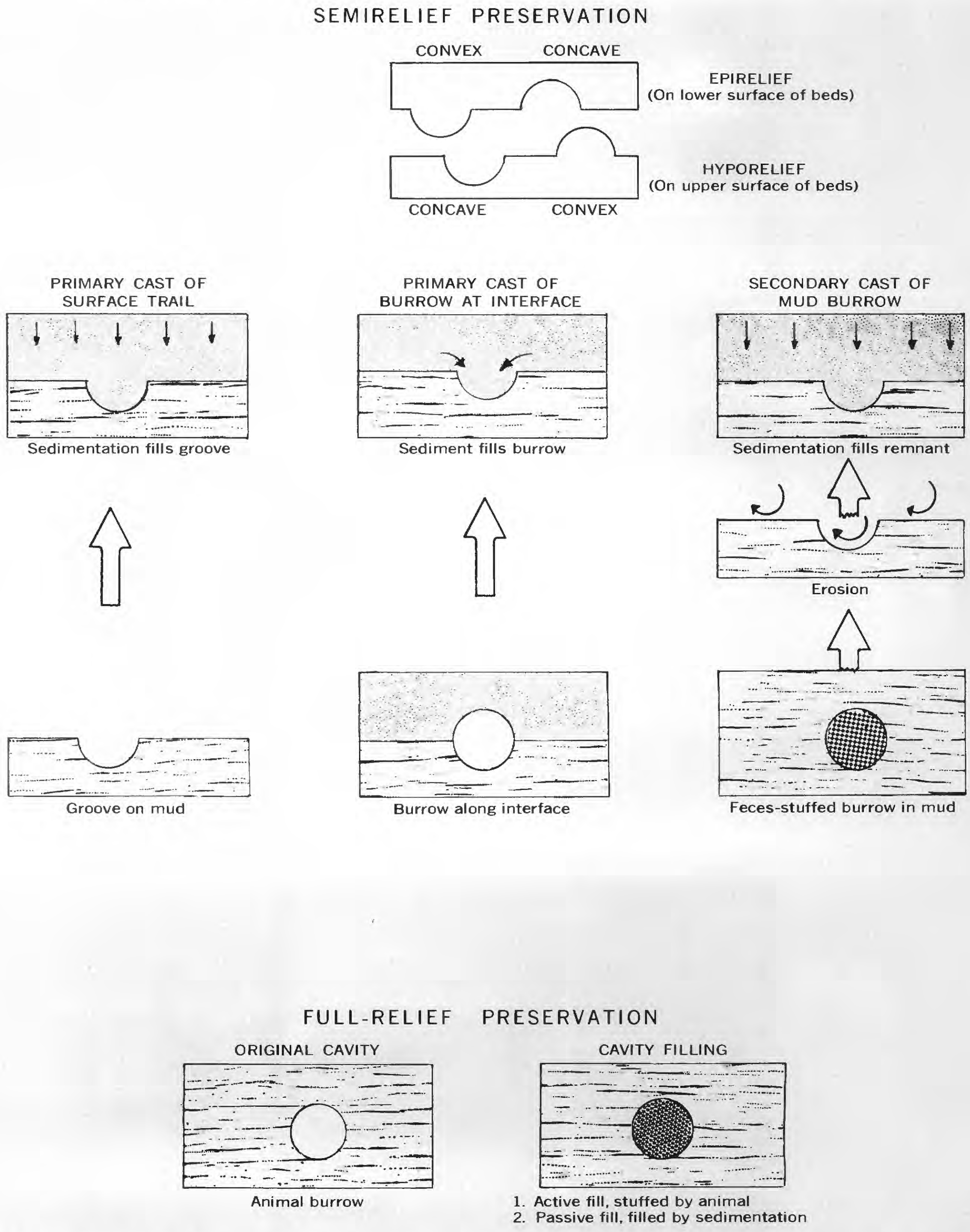

FIGURE 5.—Types of preservation of trace fossils, showing means of creation (modified from Sellacher, 1964).

rowed below the surface in search of food. They derived nourishment from nutrients, either living microorganisms or detrital organic material, that were part of the sediment. The actions of these detritus feeders in their search for food thoroughly altered the primary sedimentary structures and destroyed all but a few traces and suggestions of the morphology of the organisms themselves. Such alteration is called bioturbation. Evidence of primary lamination is scattered because the organisms churned the sediments before lithification.

The pattern of organic mottling suggests that the original sediments were thinly laminated and had little or no primary structural dip.

The smallest population of trace fossils is found in fine- to medium-grained moderately well sorted sandstone (fig. 6*C*). Sediments were often affected by currents that built ripple marks and cross-lamination and that shifted and reworked the sediments. The power of the transporting medium was sufficient to winnow out fine sediments and prevent deposition of organic detritus. Organisms in this environment were almost exclusively suspension feeders that built burrows which were strong enough or deep enough to exist in a mobile substrate. The organisms built their shelters upward to keep pace with sedimentation. Progressively fewer traces are found in rocks indicative of environments of increasingly stronger current velocity.

The environment in which organisms responsible for trace fossils lived in moderate abundance is represented by thin-bedded very fine to fine-grained sandstone that occurs above the interbedded siltstone and sandstone unit just described. The rocks of this sandstone unit are cross stratified in long low-angle wedge-shaped sets. Both complete and truncated large ripple marks are common in this interval. The depositional environment supported both detritus-feeding and suspension-feeding organisms. Suspension feeders obtain nourishment from pelagic microorganisms. In beds where detritus feeders were dominant, the strata are very bioturbate. These beds are not quite as intensively disturbed as in the siltstone and sandstone zone below, however; mottling commonly occurs in patches or pockets within a bed. Laterally, in the same bed, the sediments may be relatively undisturbed. Such strata commonly are described by geologists as clean-to-mottled strata. Where suspension feeders were the dominant organisms, sediments are moderately well sorted and slightly carbonaceous (fig. 6*B*). The current velocity was sufficient to winnow out the fine sediment, including carbonaceous matter, but not great enough to permit constant reworking and mobilization of the substrate. Trace fossils of detritus feeders in rocks of this environment indicate an attempt by these organisms to escape to a more favorable habitat.

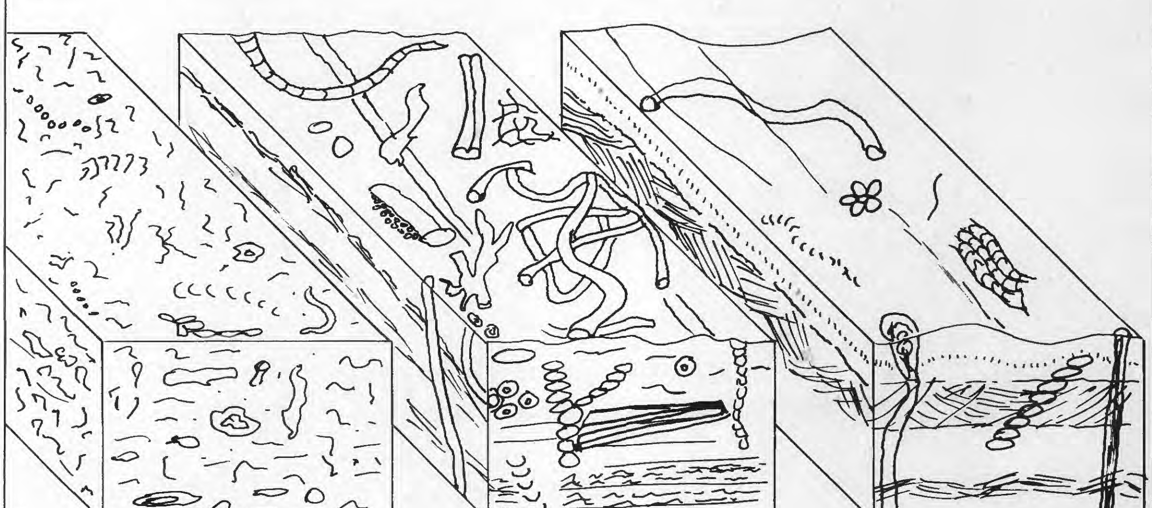

FIGURE 6.—Environmental grouping of trace fossils. No scale. (Modified from Howard, 1966a.) *A*, Very calm water, shallow and deeper neritic and lagoon environments with much silt, clay, very fine sand, and carbonaceous debris. Sediments thoroughly reworked and mottled by organisms; primary structures and bedding destroyed. Poorly preserved trace fossils. *B*, Shallow neritic environment, characterized by medium kinetic energy. Very fine to fine sand, moderately well sorted, low cross-stratification. Many trace fossils, most of which are well preserved. *C*, Environment of high kinetic energy, typical of the littoral zone. Well-sorted fine- to medium-grained sediments. Much cross-stratification. Few trace fossils; those present are mostly poorly preserved.

ETHOLOGICAL CLASSES

Seilacher (1964) established the following nomenclature for trace fossils on the basis of the function of the trace-fossil structure:

1. Repichnia: Trails or burrows left by vagile benthos forms during directed locomotion.
2. Pascichnia: Winding trails or burrows of vagile mud eaters, which reflect a grazing search for food by covering a given surface fairly efficiently and by avoiding double coverage.
3. Fodinichnia: Burrows made by hemisessile deposit feeders. These burrows reflect the search for food and at the same time fit the requirements for shelter.
4. Domichnia: As the root suggests, permanent shelters dug by vagile or hemisessile animals that procurred food from outside the sediment as predators, scavengers, or suspension feeders.
5. Cubichnia: Shallow tracks left by vagile animals that hid temporarily in the sediment, or lurked or rested on the sediment surface, that obtained their food as scavengers or suspension feeders.

BATHYMETRY OF TRACE FOSSILS

Seilacher (1964, 1967) grouped trace fossils according to the bathymetric conditions preferred by the organisms that made the traces (table 1). The universal ichnofacies, or trace-fossil groupings—based on a general, overall relationship between the ethological character of the trace fossils and the geological facies indicated by lithology and inorganic sedimentary structures—are:

1. Cruziana facies, in the littoral to sublittoral zone, above wave base. Dominant trace fossils are domichnia and cubichnia; fodinichnia of detritus feeders are found in deep water.
2. Zoophycos facies, in the sublittoral to bathyal zone, below wave base and without turbidite sedimentation. Dominant trace fossils are fodinichnia of detritus feeders.
3. Nereites facies, defined by Seilacher (1964, p. 311) as "bathyal with turbidite sedimentation." Dominant trace fossils are repichnia and pascichnia.

Interpretations of the environmental significance of trace fossils are based largely on the work of Seilacher; my interpretations that differ from those of Seilacher are noted.

Illustrations of these trace fossils were prepared by Roger B. Williams, Paleontological Institute, University of Kansas, Lawrence, Kans., and many were first published by Howard (1966c). Mr. Williams' illustrations are used with the permission of Dr. Howard.

SYSTEMATIC DESCRIPTION OF BLACKHAWK TRACE FOSSILS

A structure commonly observed in trace fossils is spreite, defined by Häntzschel (1962, p. W178) as "a German noun literally translated as 'spread' and meaning something spread between two supports, as the web of a duck's foot." Spreite are common in fodinichnia structures.

PASCICHNIA

CHEVRON TRAILS

Figure 7

Chevron trails occur as convex epireliefs on bedding surfaces of very fine grained sandstone. Width of track ranges from 10 to 15 mm (millimeters) and averages 12 mm. This trace fossil is commonly multitudinous. Trails are subparallel to parallel; many are aligned parallel to shoreline, as shown by measurement of associated ripple marks and sole markings and by alinement of detritus on bedding surfaces. Apparently, pascichnia formed by organisms grazing at the sediment-water interface. The fossil is a shallow neritic marine indicator (Howard, 1966a).

TABLE 1.—*Universal ichnofacies*

[Modified from Seilacher (1964, p. 310, 311)]

Ichnofacies	Dominant groups of trace fossils	Diagnostic inorganic sedimentary structures	Dominant lithology	Probable depth
Cruziana facies	Cubichnia; domichnia of suspension feeders (shallow, turbulent zone); fodinichnia of detritus feeders (deeper zone).	Oscillation ripples, foreset bedding in shallow zone, well-laminated bedding in deep water.	Well-sorted sandstone	Littoral to sublittoral, above wave base.
Zoophycos facies	Fodinichnia	Bedding and lamination poor.	Mottled siltsone and mudstone.	Sublittoral to bathyal, below wave base.
Nereites facies	Pascichnia; repichnia	Load casts, convolute lamination, other turbidite structures.	Mudstone and muddy and silty sandstone with high carbonaceous content.	Bathyal.

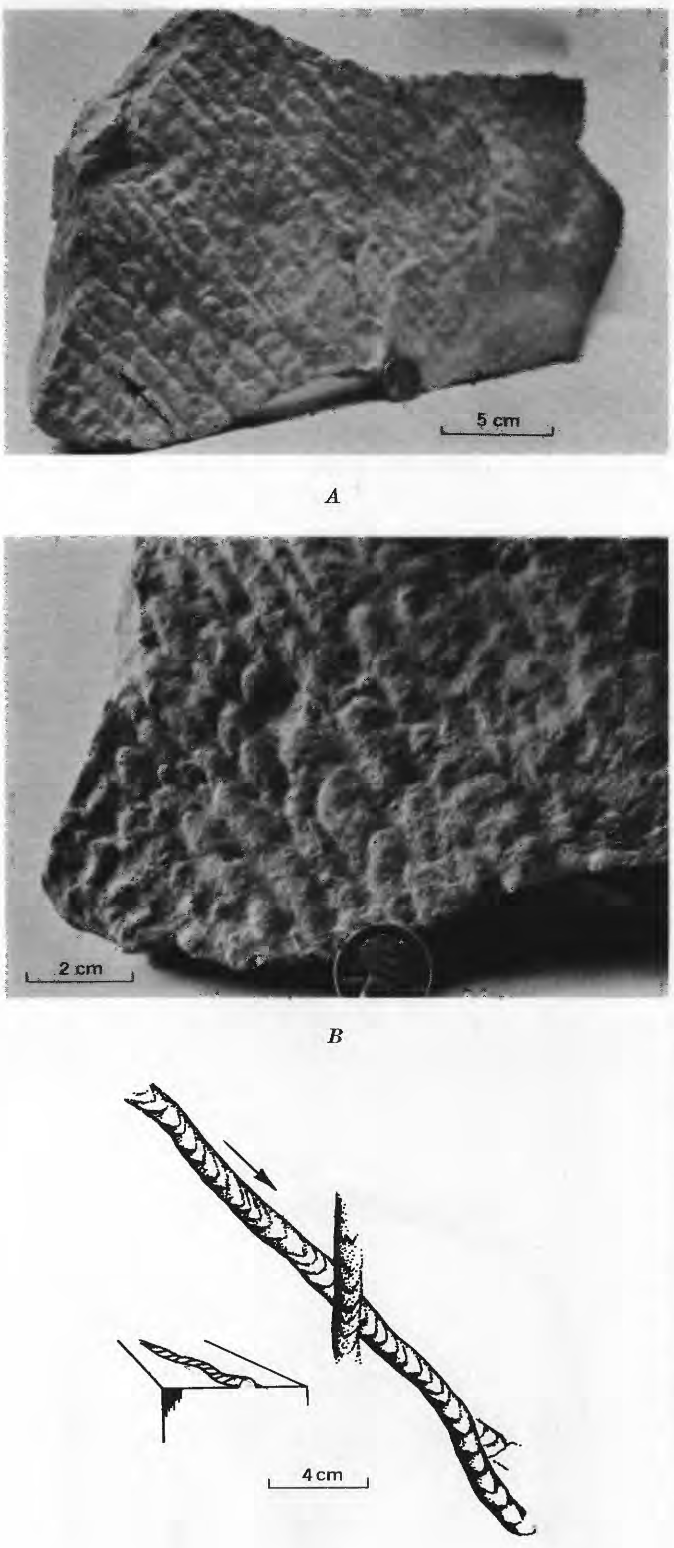

FIGURE 7.—Chevron trails; movement indicated by arrows. *A*, Trails on bedding surface; from middle sandstone tongue of Kenilworth Member. *B*, C'ose view of same specimen. *C*, Artist's illustration.

FODINICHNIA

TEICHICHNUS A

Plate 1, figures 1–3

Teichichnus A and *B* were differentiated by Howard (1966a, p. 145) on the basis of dissimilar morphological characteristics.

Teichichnus A is a burrow consisting of a series of spreite which form a vertical blade. When viewed from the side, the burrow resembles a narrow-angle "lazy" U. Interlayered with the spreite are carbonaceous silty laminae which have not been burrowed. The nonburrowed material is fine grained and not resistant and, hence, forms a constriction in the blade. The constrictions give *Teichichnus A* the gross appearance of a series of superposed round tubes, all emanating from a primary, or main, tube. The blades are 2–4 cm (centimeters) high and generally about 5 mm wide, blades more than 75 cm long have been observed on outcrops. The blade itself is always normal to bedding, but spreite of the blade vary from horizontal to vertical and commonly form a sinuous pattern. *Teichichnus A* is found in closely packed sandy siltstone deposited in marine neritic environments (Seilacher, 1964, p. 310). It is a feeding burrow of a detritus feeder, possibly a polychaete worm.

TEICHICHNUS B

Plate 1, figures 4, 5

Teichichnus B was possibly formed by the same organisms that formed type *A*, but *Teichichnus B* is a much larger structure; all specimens are in the form of vertical blades cutting across bedding with spreite forming superposed tubes. The individual tubes are oval in cross section and are commonly as much as 1 cm high and 5 mm wide; in all observed specimens, the tubes are subparallel throughout their length. Most blades are about 5 cm high and 1–5 cm wide and vary in length owing to the random grazing habit of their creators. A fodinichnia-type burrow was found in very fine to fine grained sandstone. Because of the increased size of the organism and better sorting of sediments where *Teichichnus B* is found, this fossil is believed to represent deposition in water shallower than that in which type *A* was formed.

ARTHROPHYCUS

Figure 8

Arthrophycus is a conduitlike segmented trace commonly normal to bedding. Preservation varies from full relief to convex epirelief; cavities are commonly filled. Some branching forms have a slight bulge at the point of branching, but these forms are uncommon. The trace

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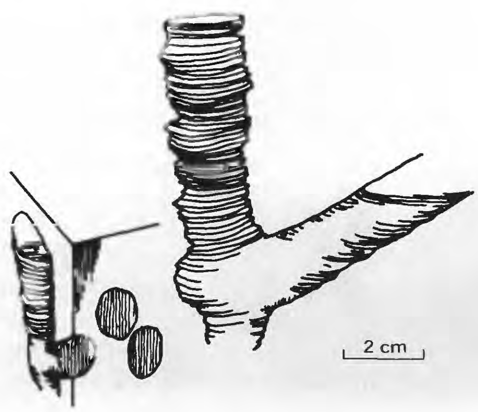
A



B

FIGURE 8.—*Arthrophycus*. *A*, In nodular carbonaceous siltstone of Sunnyside Member. *B*, Sketch showing typical mode of occurrence and morphology similar to that of *Ophiomorpha*.

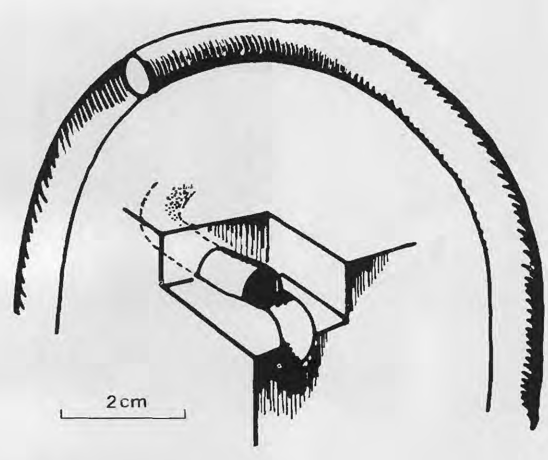
is round to flattened oval in cross section, 5–15 mm in diameter; its length is indeterminate where the trace passes into sandstone or turns away from the outcrop. *Arthrophycus* is often confused with *Ophiomorpha* because of its rough exterior and branching nature. It is most common in siltstone and very fine to fine grained sandstone. *Arthrophycus* is a fodinichnia burrow, indicative of a relatively wide depth range (Seilacher, 1964, p. 311).

SMOOTH TUBES

Figure 9

Some full-relief or convex-epirelief burrows are preserved as smooth curving unornamented tubes oriented at random throughout the rock .These smooth tubes may be *Arthrophycus*. Their cross section is round to oval and has a diameter of 8–15 mm; their length is indeterminate. Smooth tubes are found in finely mottled siltstone and clean-to-mottled fine-grained sandstone, and they are neritic marine indicators.

A



B

FIGURE 9.—Smooth tubes. *A*, From siltstone above Sunnyside coal bed. (One tube shown by arrow.) *B*, Sketch.

CHONDRITES

Figure 10

Chondrites is a concave-epirelief trace characterized by a plantlike appearance that results from the presence of numerous short branching segments. Horizontal branching trails reflect short excursions from a central vertical burrow. Diameter of the branches is 1–3 mm. *Chondrites* is found at Sunnyside in very fine grained sandstone, which is interpreted, on the basis of inorganic sedimentary structures associated with the trace fossil, to be very shallow neritic to littoral marine sandstone (Seilacher, 1964, p. 311).

ASTEROSOMA

Plate 2

A trace fossil previously named *Cylindrichnus* (Howard, 1966a, p. 73) was recently identified by Howard and H. W. Dresser (oral commun., 1968–69) as a variant of *Asterosoma* (Häntzschel, 1962, p. W184). *Asterosoma* is a full-relief burrow found in orientations from horizontal to vertical. Horizontal burrows are found in very fine grained carbonaceous sediments. They reflect a random contented grazing search for food in a hospitable environment in which the animals roiled and mottled the sediments intensively. Steeply angled burrows are escapeways from hostile environments. The *Asterosoma* animal built steep burrows as the current velocity increased and food was winnowed from the sediment, or as the rate of sedimentation increased and there was less food for the animal as the finely divided nutrients were winnowed out. High-angle and vertical burrows are common in clean well-sorted sandstone, where they are associated with *Ophiomorpha*. High-angle *Asterosoma* burrows culminate upward in what Howard (1966a, p. 70) called helicoid funnels (pl. 2, figs. 3, 4, and 6), full-relief vertically oriented funnel-shaped structures which at the top range in diameter from 4 cm to as much as 25 cm. These funnels seem to indicate a change in the animal's burrowing habits, a fresh influx of carbonaceous material into the environment, and a lowering of current velocity.

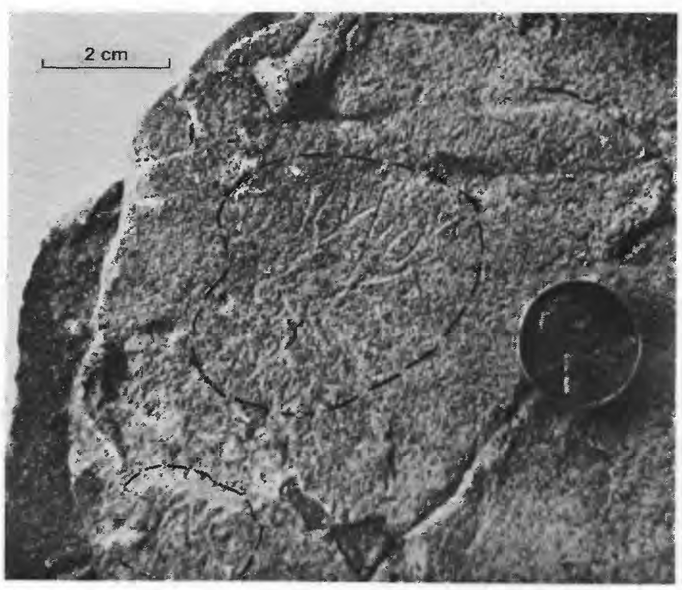


FIGURE 10.—Horizontal branching trails of *Chondrites* (circled), from middle sandstone facies of Sunnyside Member.

CYLINDRICHNUS REPTILIS BANDEL

Figure 11

Cylindrichnus reptilis was named by Bandel (1967, p. 6). This fossil is a vertical full-relief tube that is 1–3 cm in diameter and usually 8–14 cm high; its cylinder-shaped burrows are found in coarsely mottled siltly sandstone. *Cylindrichnus reptilis* Bandel is comparable in form to *Cylindricum* Linck (Häntzschel, 1962, p. W189), and it is common in thin-bedded sandstones in two members of the Blackhawk Formation. I believe this fossil to be an indicator of littoral to sublittoral marine zones.

LABYRINTH CASTINGS

Figure 12

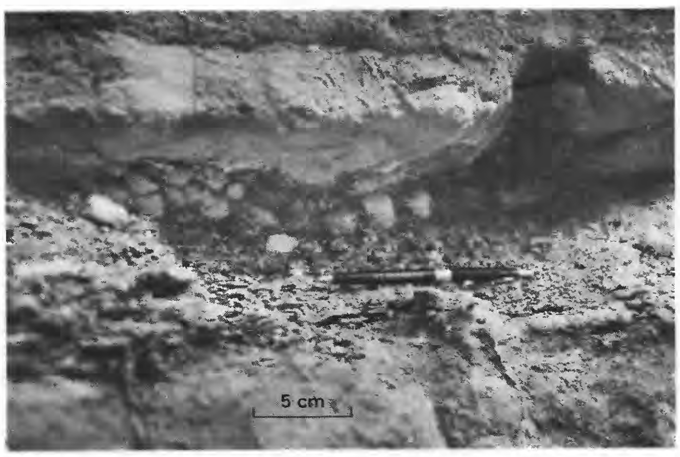
Local pockets of tightly interwound trails or castings are preserved as convex epireliefs on the bottom surfaces of fine- to medium-grained sandstone beds. These castings are similar morphologically to *Phycodes* (Häntzschel, 1962, p. W208). The small interstices between castings are filled with carbonaceous dust. The fossil is commonly associated with pieces of woody debris and is indicative of a littoral to flood-plain environment. The labyrinth trails possibly were made by polychaete worms, although W. A. Cobban (written commun., 1969) suggested that they are shipworm borings.

GYROCHORTE

Figure 13

Gyrochorte is a simple bilobate trail preserved as convex hyporelief in well-sorted fine-grained sandstone. It is characteriezd by a median furrow and superficially resembles *Aulichnites*. Trails are 1–7 mm wide, of indeterminate length, and 1–3 mm high. Surfaces are generally smooth; crossing burrows pass over or under each other, never destroying another burrow. Traces indicate random, meandering locomotion; there is no branching. *Gyrochorte* was described by Seilacher (1964, p. 311) as nondiagnostic of depth, but because of the traces with which *Gyrochorte* is associated (fig. 38), I believe

A



B

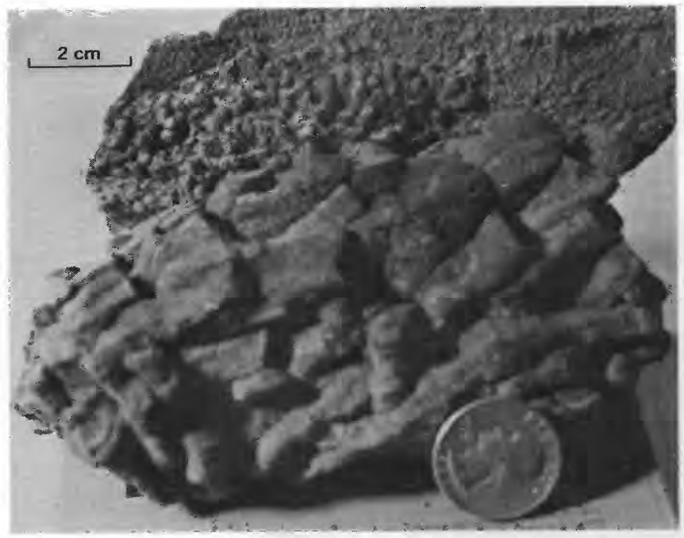
FIGURE 11.—*Cylindrichnus reptilis* Bandel. *A* and *B*, At interface between carbonaceous sandstone and overlying medium-grained well-sorted sandstone of the upper sandstone facies of Sunnyside Member.

that *Gyrochorte* indicates a sublittoral to littoral environment. This trace probably was made by gastropods (Häntzschel, 1962, p. W198).

AULICHNITES

Figure 14

Aulichnites is a simple bilobate crawling trail preserved as convex-epirelief forms in very fine- to fine-grained well-sorted sandstone. There is a median furrow in all trails. Meandering directions reflect a grazing search for food. Trails are 1–5 mm wide and 1–3 mm high, and they have smooth surfaces. Burrows were not reused and they do not branch. These trails probably were made by gastropods, perhaps the same genus as *Gyrochorte* but with different habits. *Aulichnites* indicates littoral deposits. (Description from Bandel, 1967, p. 4.)



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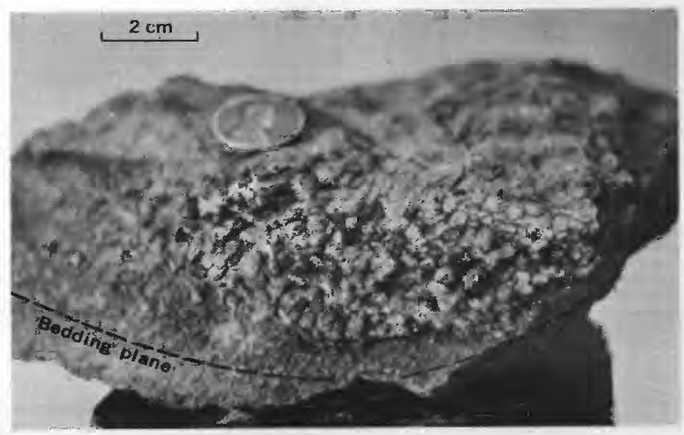

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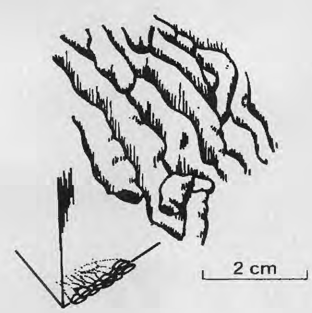


C

FIGURE 12.—Labyrinth castings in upright positions. *A*, Large castings; from upper part of Sunnyside Member. *B*, Smaller castings, similar morphologically to those shown in *A*; Castlegate Sandstone–Blackhawk Formation contact. *C*, Sketch.

FIGURE 13.—*Gyrochorte*; from lower sandstone facies of Sunnyside Member.

DOMICHNIA

OPHIOMORPHA

Plate 3

Known for many years as *Halymenites major* Lesquereaux, a European algal form which it superficially resembles, *Ophiomorpha* is one of the most widely distributed trace fossils in Mesozoic to Holocene sediments in the United States. The fossil is a full-relief burrow, many specimens of which are vertical, preserved as either cores or casts with characteristic bumpy surfaces. Casts of burrows found in deposits of shallow-water environments have a thick outer wall similar to that of burrows of the modern shrimp *Callianassa major* Say, which is considered the modern counterpart of the *Ophiomorpha* organism (Weimer and Hoyt, 1964; Hoyt and Weimer, 1965). *Ophiomorpha* burrows vary widely in size with variation in sedimentation. Well-sorted fine- to medium-grained sediments contain the largest burrows; burrows are smaller as the content of carbonaceous debris in the sediments increases. The animal that formed *Ophiomorpha* preferred environments with little suspended sediment for its role as a suspension feeder, because when there was an excess of suspended sediment the phytoplankton upon which the animal fed would not be present. *Ophiomorpha* is found in many different types of sedimentary rocks at Sunnyside, however. Several different species of *Callianassa* are found in modern estuaries, open lagoons, or tidal inlets, but burrows of species other than *C. major* Say cannot be confused with *Ophiomorpha*. Burrows of other species of *Callianassa* resemble *Arthrophycus*, smooth tubes, or large horizontal burrows (R. J. Weimer, written commun., 1968). Seilacher (1964, p. 313) pointed out the bathymetric inferences drawn from trace-fossil orientations.

FIGURE 14.—*Aulichnites*; from middle sandstone tongue of Kenilworth Member.

ARENICOLITES

Figure 15

Arenicolites is a full-relief vertically oriented U-shaped burrow with a diameter of 5–7 mm. Most burrows are oval in cross section, probably because of compression during lithification. The length of the burrow is controlled by the thickness of the enclosing bed. *Arenicolites* is preserved on bedding surfaces as pairs of depressions, usually 10–50 mm apart. This fossil is a domichnia- or fodinichnia-type burrow of a polychaete worm and is found in well-sorted fine- to medium-grained sandstone; the burrow indicates littoral environments (Seilacher, 1964, p. 311).

THALASSINOIDES

Figure 16

Thalassinoides is a convex-epirelief burrow and is very common in sandstones throughout the area. Burrows are a series of Y-shaped branching tubes that are intimately interwoven. Tubes are circular to oval and have a diameter of 5–15 mm. Burrows are developed at a sand-to-sand, sand-to-muddy siltstone interface. They were considered by Häntzschel (1962, p. W218) to be burrows of a decapod crustacean. Burrows indicate shallow neritic conditions close to the littoral zone.

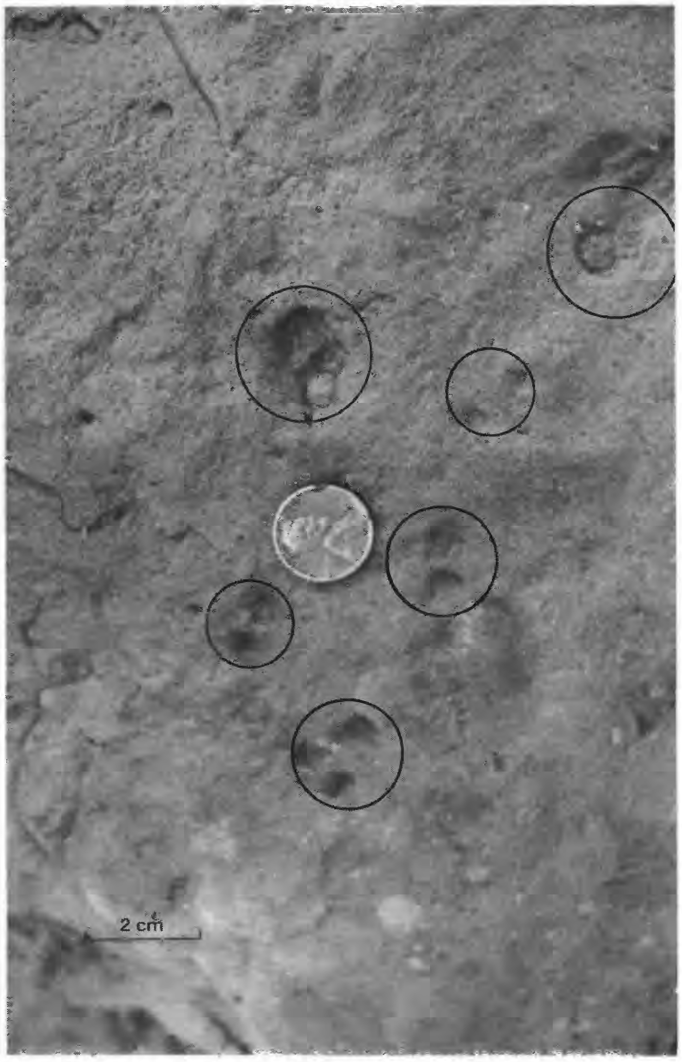
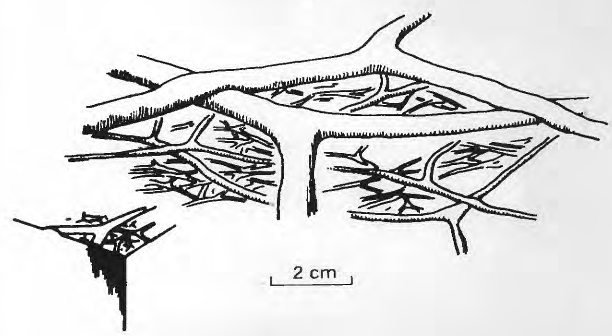


FIGURE 15.—End view of *Arenicolites* (circled), expressed as pairs of indentations on top of lower sandstone tongue of Kenilworth Member; view normal to bedding.

A



B

FIGURE 16.—*Thalassinoides*. *A*, Underside of bedding, lower sandstone tongue of Kenilworth Member. *B*, Sketch.

PLURAL CURVING TUBES

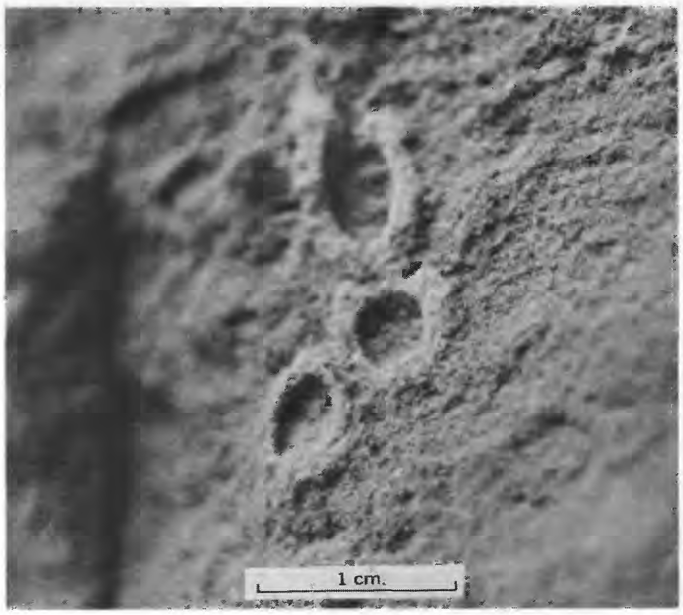
Figure 17

Howard (1966a, p. 76) described groups of subparallel curving vertically oriented full-relief tubes that have definite wall structure. Tubes are very light gray to white and are very noticeable on outcrops. Tube diameter is constant at about 7 mm, and the tube wall is 1–2 mm thick. Tubes are open at top and bottom. Grain size of the wall is the same as that of the enclosing rock, but organic matter and clay are absent. This fossil probably is the permanent burrow of a filter feeder in fine sands of the littoral zone (Seilacher, 1964, p. 311).

LARGE HORIZONTAL BURROWS

Figure 18

Large branching burrows are preserved in full relief and in convex epirelief in carbonaceous silty, sandy mudstones. Described by many writers as fucoids, the trace is similar to *Planolites montanus* (Häntzschel 1962, p. W210). In the Sunnyside district, these traces are found only above coal beds or above medium-grained sandstones. Many burrows are alined subparallel to the strike of ripple-mark crests, where the crests are associated with them, but there is no indication of mechanical reworking of burrows. Burrows are oval in cross section and have a maximum diameter of 10–60 mm. Burrows are filled with very fine to fine sand and some carbonaceous material in a clay matrix. Burrows are distinctive on the outcrops. I believe, on the basis of stratigraphic position and lithologic association of the trace fossil, that these burrows were constructed by detritus feeders in terrestrial subaqueous areas of peat swamps.



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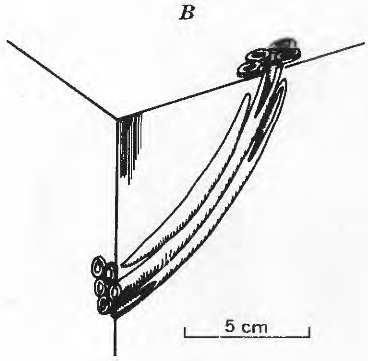


C

FIGURE 17.—Plural curving tubes. *A*, End view; from middle sandstone tongue of the Kenilworth Member. *B*, Longitudinal section; upper sandstone facies of the Sunnyside Member. *C*, Sketch showing typical mode of occurrence and morphology.

CUBICHNIA

PELECYPODICHNUS

Figure 19

Pelecypodichnus is a pelletlike structure preserved as convex epirelief or convex hyporelief at sandstone-to-sandstone interfaces. It is ovoid and has a major axis of 5–10 mm and minor axis of about 5 mm. Locally abundant, these fossils exhibit no interior structure. They were formed as casts of pelecypod resting places just below the water-sediment interface, and all known structures are composed entirely of well-cemented sand grains. First described by Seilacher in 1953 (Häntzschel, 1962, p. W208), the trace is similar morphologically to *Sagittichnus* Seilacher, 1953 (Häntzschel, 1962, p. W208) and is easily confused with it. No shells or shell remains have been found associated with the trace, and it is inferred that the fossils were formed by infilling after the pelecypod had deserted the resting place. Environment of deposition was in shallow neritic to littoral waters, but *Pelecypodichnus* also has been found in paludal deposits.

RUHESPUREN

Figure 20

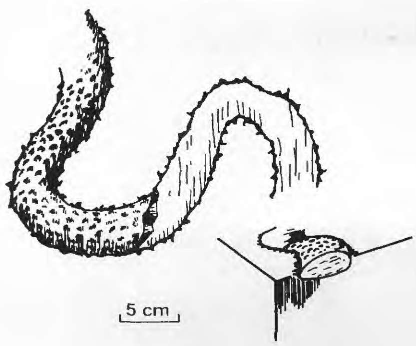
Ruhespuren are resting-place trace fossils preserved as concave hyporeliefs in fine- and medium- to fine-grained sandstones. Traces may form a circular pattern or an apparent trail, or they may occur singly. Howard (1966a, p. 78) suggested that they were made by "jellyfish or an animal with similar bottom configuration." Traces are oval and have a constant diameter of 10–15 mm. In cross section, they exhibit a peripheral trough 2–5 mm deep with transverse walls. The center of the trace is a raised boss slightly lower than the surrounding surfaces; the boss is 5–10 mm wide and is saucer shaped. The trace is uncommon, but its occurrence on outcrops probably is limited by the scarcity of horizontal bedding-surface exposures. The trace is indicative of a littoral to sublittoral environment (Seilacher, 1964, p. 311).

SEDIMENTATION AND STRATIGRAPHY

The Blackhawk Formation at Sunnyside is the lowest formation of the Mesaverde Group in the Book Cliffs. The unit was named by Spieker and Reeside (1925, p.

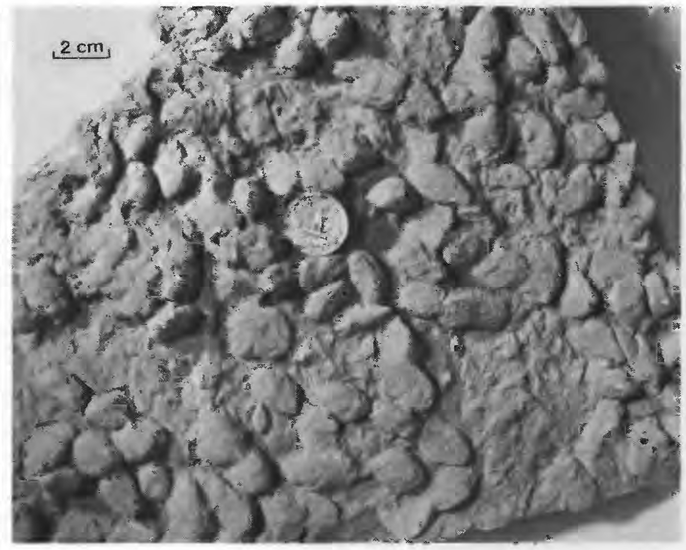
A

B



C

FIGURE 18.—Large horizontal burrows. *A*, Filled with light-colored sediment; in top of upper sandstone tongue of the Kenilworth Member. *B*, Light-colored fillings; from siltstone roof rock of the Sunnyside coal bed. *C*, Sketch. Burrow casts commonly are knobby on the surface.



A

B

FIGURE 19.—*Pelecypodichnus*. *A*, On top of middle sandstone facies of Sunnyside Member. *B*, Preserved as convex epireliefs on sandstone at base of Castlegate Sandstone; overhead view.

443) for an exposure of Cretaceous coal-bearing rocks near the Blackhawk mine in the Wasatch Plateau. The Blackhawk consists of arenaceous and argillaceous rocks and coal, deposited in a relatively complex sedimentational sequence (fig. 21). The term "Mesaverde Group" is subject to some controversy in Utah and Wyoming because there is some disparity in age between the section in those areas and the type Mesaverde at Mesa Verde National Park in Colorado (Young, 1955, p. 179). Abbott and Liscomb (1956, p. 120) and Brodsky (1960, p. 17) pointed out, however, that the term "group" has no time significance and that "Mesaverde Group" is the correct designation for the rocks under discussion. The term, therefore, is retained for use in this report.

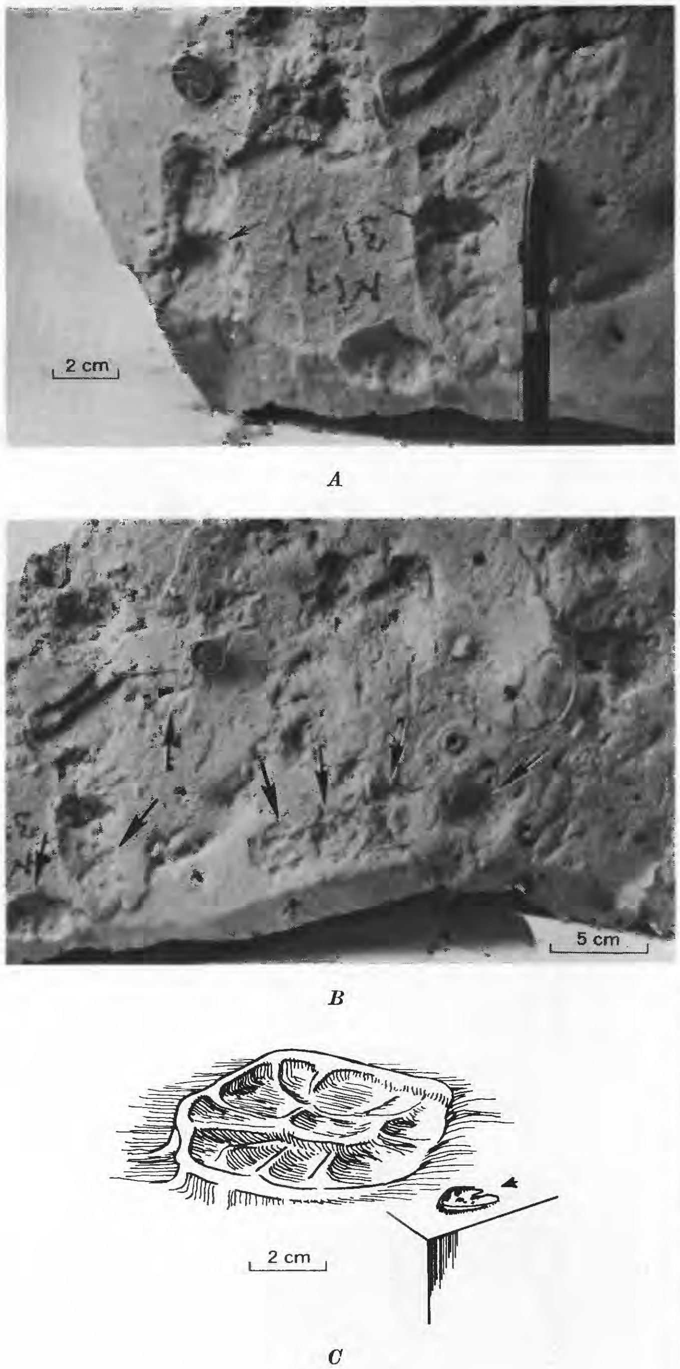


FIGURE 20.—*Ruhespuren.* *A*, Circular pattern (arrows). *B*, apparent trail of resting places preserved as concave hyporeliefs on top of lower tongue of Kenilworth Member. *C*, Sketch showing details of morphology.

TERMINOLOGY

The terminology used to describe sedimentation and stratigraphy in the present report follows:

Claystone, nonfissile indurated layers of argillaceous particles <0.004 mm in diameter.

Mudstone, poorly indurated indistinctly bedded sediments composed of grains <0.004 mm in diameter.

Sandstone, indurated sediments composed of arenaceous particles 0.062–2 mm in diameter.

Shale (capitalized), a group term indicating a collection of beds of dominantly argillaceous sediments.

shale (lowercased), fissile mudstone, claystone, or siltstone.

Siltstone, indurated arenaceous and argillaceous sediments composed of particles 0.062–0.004 mm in diameter.

Grain-size designations are in accord with the Wentworth (1922) scale for clastic sediments. Figure 22 shows current velocities necessary for erosion, transportation, and deposition of particles of these sizes and indicates the range of currents operating during the deposition of Blackhawk sediments.

Spatial relationships of the Blackhawk to strata of undoubted Late Cretaceous age define the age of the Blackhawk. Cobban and Reeside (1952) assigned the Blackhawk to the middle of the Campanian Stage (lower part of the Pierre Shale of the Western Interior) of the Late Cretaceous. Trace fossils that occur elsewhere in beds of undoubted marine origin occur also in the Blackhawk, and fossils of organisms that are known to be marine are found in the underlying Mancos Shale (Fisher and others, 1960, p. 26–31). Spore and pollen analysis of Mancos rocks by Sarmiento (1957, p. 1963) supports the conclusion that sedimentation of the Blackhawk Formation at Sunnyside was in the shallow water of a retreating epicontinental Late Cretaceous sea. The present report, therefore, attempts to determine how the sediments were transported to the site of deposition and what the environment was during deposition of the Blackhawk Formation at Sunnyside.

Spieker (1949) and Young (1955, 1957, 1966) interpreted the depositional environment of the Blackhawk as a series of sedimentational areas including eastward-prograding offshore-bar, shallow-marine, barrier, and beach-swamp–coastal-plain areas. A more detailed study of the sedimentary features leads to the conclusion that deposition was part of a deltaic sequence that included fluviatile, transitional, and marine environments. The delta during Blackhawk time probably covered an area much larger than the study area; field reconnaissance of Blackhawk rocks near Cisco, Utah, reveals a sedimentational sequence much like that in the Sunnyside area. The regional stratigraphic data necessary to reconstruct accurately the processes on and along the entire deltaic area are beyond the scope of this report. The paleoenvironmental interpretations presented herein are the simplest possible ones needed to explain the observed stratigraphic phenomena in the Sunnyside area.

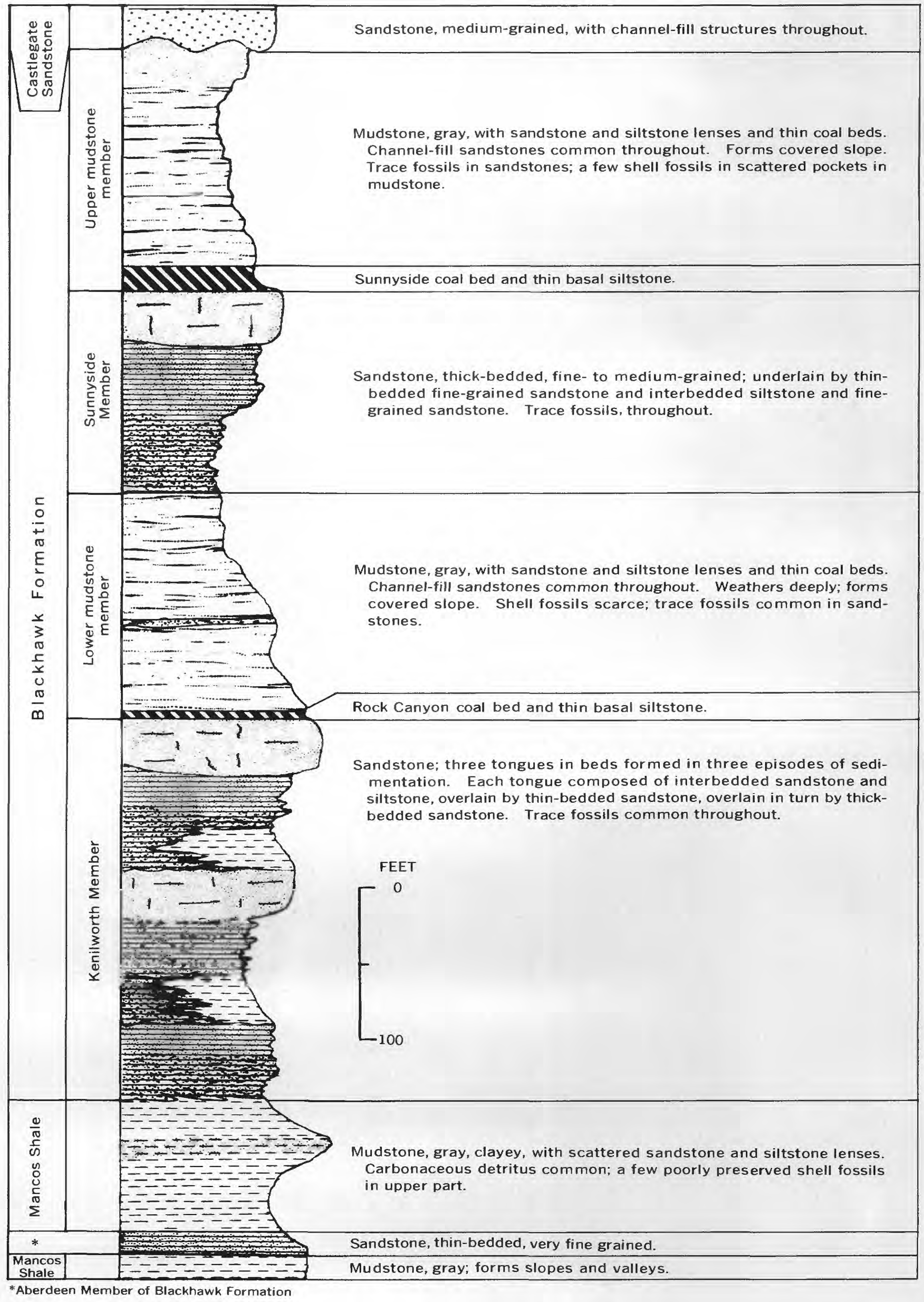


FIGURE 21.—Columnar stratigraphic section of the Blackhawk Formation and adjacent strata (Upper Cretaceous) at Sunnyside.

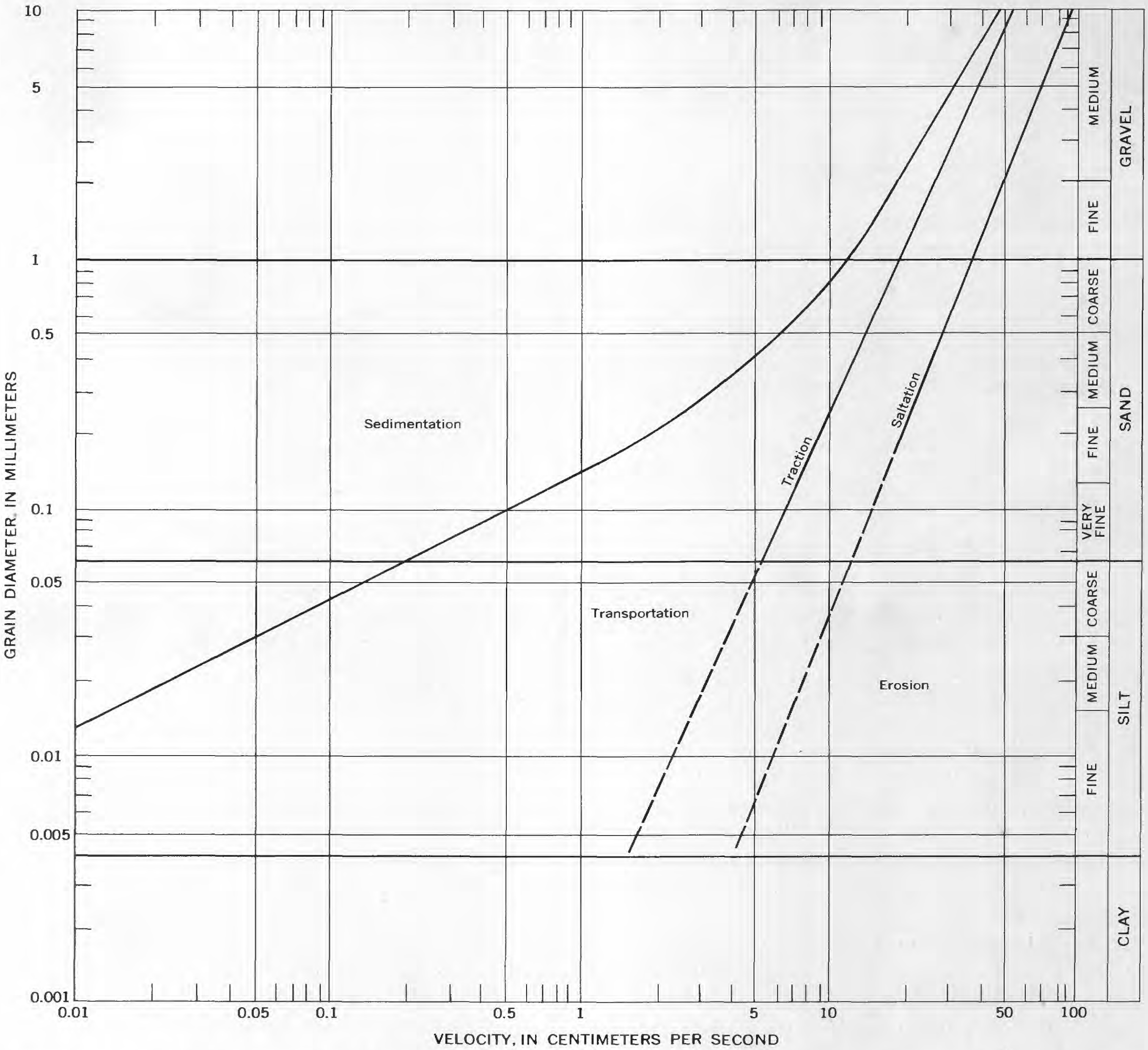


FIGURE 22.—Current velocities required for erosion, transportation, and deposition of sediments. Curves are based upon experiments with particles of specific gravity 2.60–2.65 (modified from Heezen and Hollister, 1964, p. 171).

Depositional environments that I recognized in the Blackhawk and associated rocks at Sunnyside include open-shelf, prodelta-slope, delta-platform, river-mouth-bar, beach, swamp-marsh-lagoon, estuary, and flood-plain environments. Each environment is discussed in the following pages in association with distinct units that are representative of those environments.

MANCOS SHALE

The upper part of the Mancos Shale Sunnyside is composed of massive and layered parts of dark-gray silty very carbonaceous mudstone. The rocks of this interval are soft and easily eroded and form faceted slopes from the floor of Clark's Valley up to the base of the Book Cliffs (fig. 3). Thin tongues and stringers of carbonaceous very fine grained sandstone and siltstone occur throughout the upper part of the Mancos, but they are discontinuous and rapidly pinch out laterally. The formation is most fissile in the uppermost part, where layering is most pronounced. Many bedding surfaces in the mudstone exhibit tracks and trails of vagile benthonic marine organisms and much plant debris.

Shell fossils also are found in the upper part of the Mancos (Fisher and others, 1960, p. 27–30). Mancos lithology becomes mostly arenaceous upward as the lower boundaries of overlying sandstone zones are approached.

The Mancos Shale represents sediment deposited as mud on the sea floor during regression of the Late Cretaceous sea from the continental United States. The seaway was filled with very fine sediments supplied by a southeastward-prograding deltaic complex. As filling progressed, sedimentation took place in shallower water; current velocity was such that fine silt and mud were swept farther seaward, while coarse silt and very fine sand were being deposited in their place on the shallowing shelf. In the deltaic framework, the Mancos sediments represent the deep-water to open-shelf environments, and these sediments grade laterally and upward into sediments of the prodelta-slope environment.

BLACKHAWK FORMATION

As originally defined, the Blackhawk Formation is a unit of "buff sandstone, shale and coal of the kinds common to the Mesaverde group throughout the Southwest" (Spieker and Reeside, 1925, p. 440). In the type locality, the Blackhawk conformably overlies the Star Point Sandstone and is overlain unconformably by the Castlegate Sandstone. Clark (1928, p. 18) extended the use of the name "Blackhawk" to the Book Cliffs (fig. 23). The Blackhawk is the lowest unit of the Mesaverde Group, as the name is applied to eastern Utah. At Sunnyside, the Blackhawk conformably overlies the Mancos Shale and is unconformably overlain by the Castlegate Sandstone (fig. 24).

Clark (1928) included the Panther, Storrs, and Spring Canyon Tongues in the Star Point. All these units are present in the Wasatch Plateau and westernmost Book Cliffs, but all tongue out into the Mancos Shale west of the Sunnyside district.

Fisher (1936, p. 10) redefined the Blackhawk Formation in the Book Cliffs and included in it, in ascending order, the lower sandstone member, middle shale member, middle sandstone member, and upper member. In 1955 Young (p. 183) redefined the Blackhawk, placing its base at the base of the Spring Canyon Tongue near the Wasatch Plateau and its top at the disconformable lower boundary of the Castlegate Member of the Price River Formation.

Young (1955, p. 185) recognized six members (four of them new with his report) of the Blackhawk. Of these, only the Aberdeen, Kenilworth, and Sunnyside Members are present in the section at Sunnyside (figs. 23, 24). Young's Spring Canyon Member tongues out northwest of Sunnyside, and his Grassy and Desert Members begin south of the district, in the area south of Horse Canyon.

ABERDEEN MEMBER

The Aberdeen Member was named by Clark (1928, p. 16) for a sandstone exposed near the Aberdeen mine near Kenilworth; the term Aberdeen was extended by Young (1955, p. 184) "to include the overlying coal-bearing rocks and associated offshore bar deposits." The Aberdeen contains five bar sandstones, according to Young; the next to the lowest bar sandstone is the most persistent—it disappears at Whitmore Canyon. At Sunnyside, the Aberdeen Member consists of a thin bed of very fine grained clayey organic-rich sandstone that is thinly laminated in ripple cross-stratification sets. The sandstone contains abundant trace fossils attributable to a neritic environment with a low sedimentation rate (*Arthrophycus*, *Teichichnus*, other nereites-facies structures). The sandstone is calcareous and slightly gypsiferous and is composed of well-rounded grains of very fine quartz. The Aberdeen extends into the Sunnyside area as far as the east side of Whitmore Canyon, where it is covered by colluvium. The Aberdeen may extend into the area southwest of Horse Canyon (fig. 3) (F. W. Osterwald, oral commun., 1968).

The southeastward extension of the Aberdeen probably is the transitional area between the open-shelf and prodelta-slope environments in the deltaic complex. In this transitional area, the distributary current was strong enough to lag fine quartz sediment, mixed with clay and mud, far out into the depositional basin to form a thin sheet of arenaceous sediment. The sandy environment was inhabited by burrowing and grazing organisms, and the sediment was shifted and slightly reworked by weak bottom currents. As the sediment supply dwindled, probably owing to a combination of environmental factors in the upland, sand sedimentation ceased and mud sedimentation of the lower prodelta slope resumed. At Sunnyside, the Aberdeen is unconformably overlain by 80–100 feet of mudstone of the Mancos Shale (fig. 24).

KENILWORTH MEMBER

The Kenilworth Member was named by Young (1955, p. 184) for an exposure near the coal-mining town of Kenilworth, Utah, the type locality, which is near the junction of the Book Cliffs and the Wasatch Plateau. According to Young, the unit consists of "a massive, cliff-forming, basal sandstone, an overlying series of coal-bearing rocks, and the offshore bar sandstones behind which they were deposited."

Young's definition of the unit derives from lithology, topographic expression, and inference of origin. Topographic expression of any unit is extremely variable

Clark (1928) Castlegate, Wellington, and Sunnyside quadrangles	Fisher (1936) Book Cliffs, south of Sunnyside	Young (1955) Book Cliffs, Utah and Colorado	Fisher, Erdmann, and Reeside (1960) Central and eastern Book Cliffs	This report
Price River formation Castlegate sandstone member	Price River formation Castlegate sandstone member	Price River formation Castlegate sandstone member	Price River Formation	Price River Formation
			Castlegate Sandstone	Castlegate Sandstone
Blackhawk formation: Coal-bearing member	Blackhawk formation: Upper member	Blackhawk formation: Desert member; Grassy member	Blackhawk Formation: Upper member	Blackhawk Formation: Upper mudstone member
	Middle sandstone member	Sunnyside member	Middle sandstone member	Sunnyside Member
Aberdeen member	Middle shale member	Kenilworth member	Middle shale member	Lower mudstone member
	Lower sandstone member	Aberdeen member	Lower sandstone member	Kenilworth Member
				Aberdeen Member / Mancos Shale
Star Point sandstone: Spring Canyon tongue	Not recognized	Spring Canyon member		Mancos Shale
Storrs tongue		Star Point sandstone: Storrs tongue		
Panther tongue		Panther tongue		
Mancos shale	Mancos shale	Mancos shale	Mancos Shale	

FIGURE 23.—Nomenclature used by various writers for Upper Cretaceous rocks in the Sunnyside area.

owing to differential weathering, and inference of origin is subject to controversy owing to various interpretations by other investigators of the depositional environment. My detailed field investigations show that the basal sandstone of Young's Kenilworth actually is the upper sandstone bed of an orderly upward succession of interbedded sandstone and siltstone, thin-bedded sandstone, and thick-bedded sandstone. All these rocks combine to make up a mappable unit of similar lithology. I here redefine Young's Kenilworth Member to include two underlying sandstone and siltstone sequences (fig. 21). The thin siltstone and coal are included in the overlying lower mudstone member.

Young (1955, p. 185) also stated that the Kenilworth "disappears into the Mancos shale near Sunnyside"; however, I traced the member as far south as the Beckwith Plateau (figs. 3, 24).

The Kenilworth Member, as here adopted for the Sunnyside district, is divided on the basis of the dominant morphology into three sandstone tongues, here informally designated the lower, middle, and upper sandstone tongues of the Kenilworth (fig. 24). The principal reference section here proposed for the Kenilworth Member in the Sunnyside district is on the north side of the mouth of Fan and Water Canyons, in the NW¼ sec. 8, T. 15 S., R. 14 E. (Salt Lake Meridian), in Carbon County (fig. 1). The basal part of each tongue consists of alternating layers of very thin bedded carbonaceous sandstone and sandy carbonaceous siltstone. The sandstone layers are evenly bedded and well sorted texturally and contain numerous trace fossils; most siltstone layers were thoroughly reworked by organisms and exhibit a bioturbate texture. Although the two lithologies are interbedded, boundaries between layers are sharp. The sandstone interbeds contain *Ophiomorpha* as the dominant trace fossil; siltstone interbeds contain *Asterosoma*, *Pelecypodichnus*, and labyrinth castings of carbonaceous material.

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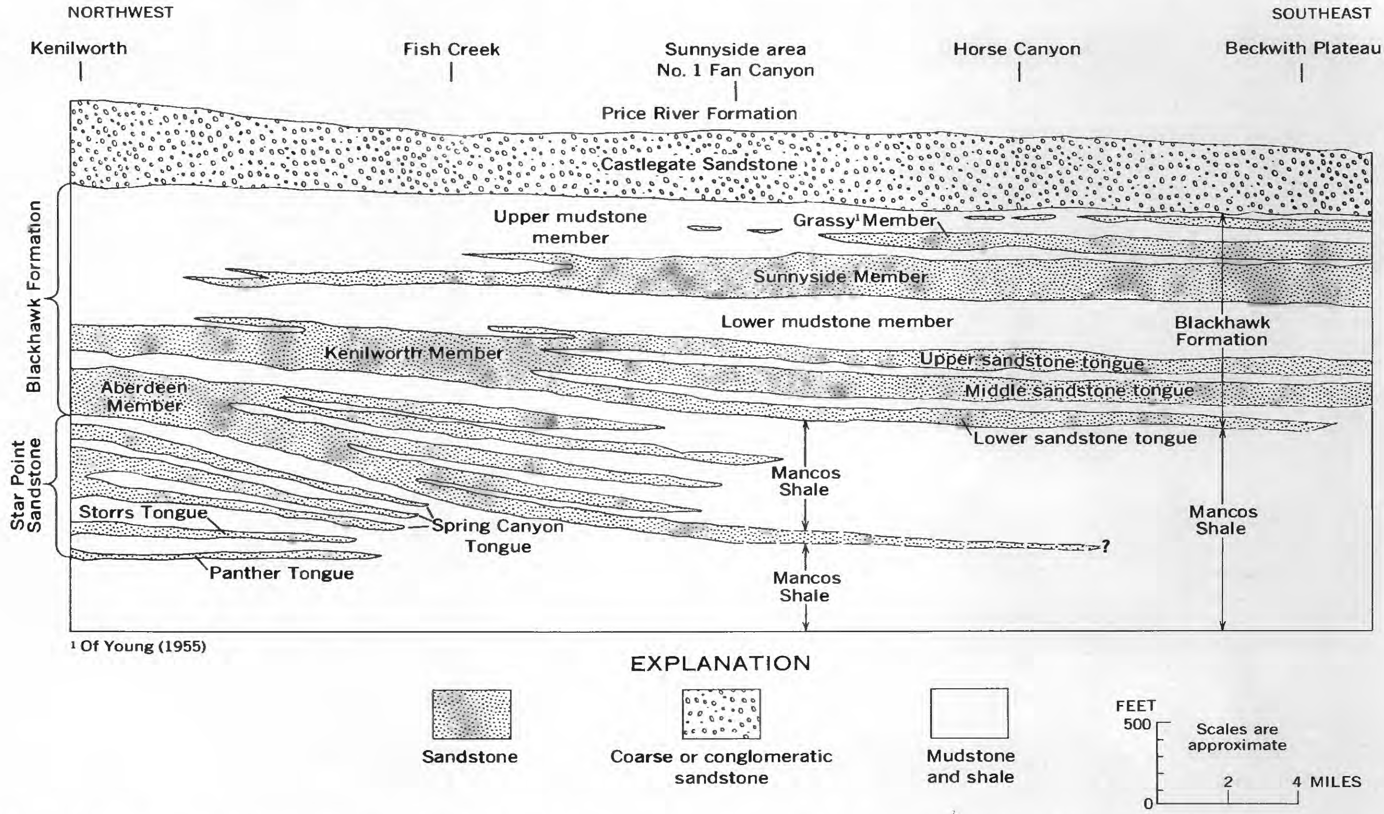


FIGURE 24.—Restored stratigraphic section of the Blackhawk Formation and associated rocks in the Book Cliffs area of east-central Utah.

Labyrinth castings are most abundant at the interface of siltstone and overlying sandstone, a horizon that represents a surface of deposition. The sediment in these beds was so intensely deformed by the infauna, as exemplified in figures 6*A* and 6*B*, that few identifiable trace fossils are preserved.

Principal reference section, Kenilworth Member, Sunnyside district: North side of mouth of Fan and Water Canyons, NW¼ sec. 8, T. 15 S., R. 14 E., Salt Lake Meridian, Carbon County, Utah

	Thickness (feet)
Blackhawk Formation:	
Lower mudstone member:	
Mudstone, dark-gray, sandy, with siltstone and ferruginous claystone interbeds. Scattered lenses and pockets of impure coal near the base.	
Kenilworth Member:	
Sandstone (upper sandstone tongue), light-gray to grayish-orange-pink (10*R* 8/2); very fine to fine grained at base; very calcareous; well-sorted layers interbedded with dark-gray coaly siltstone, 8–12 ft thick. Overlain by 32-ft-thick thin-bedded well-sorted calcareous fine-grained slightly carbonaceous sandstone that is intensely mottled in thin zones (clean-to-mottled texture). Contains *Ophiomorpha*,	

Principal reference section, Kenilworth Member, Sunnyside district: North side of mouth of Fan and Water Canyons, NW¼ sec. 8, T. 15 S., R. 14 E., Salt Lake Meridian, Carbon County, Utah—Continued

	Thickness (feet)
Blackhawk Formation—Continued	
Kenilworth Member—Continued	
Asterosoma, *Arenicolites*, and plural curving tubes; few labyrinth castings. Upper part consists of fine- to medium-grained sandstone, which coarsens toward the middle of the unit, and then becomes more fine grained upward. The upper part has discontinuous streaks of white sandstone. Trace fossils uncommon in upper unit. Root marks in uppermost part	72
Interbedded dark-gray carbonaceous silty shale and moderate-reddish-brown (10*R* 4/6) claystone lenses; unfossiliferous	12
Sandstone (middle sandstone tongue) light-gray to very pale orange (10*YR* 8/2), very fine to fine grained, well sorted, calcareous. Upper 22 ft is thick bedded and blocky and contains channel structures. Resistant, forms overhanging ledge; white zone 16 ft below top. Middle one-third composed of thinly bedded sandstone that is fine grained, crossbedded, and resistant, and has mottled zones. Contains abundant *Ophiomorpha* and *Asterosoma* and minor amounts of other trace fossils. Bedding	

Principal reference section, Kenilworth Member, Sunnyside district: North side of mouth of Fan and Water Canyons, NW¼ sec. 8, T. 15 S., R. 14 E., Salt Lake Meridian, Carbon County, Utah—Continued

	Thickness (feet)
Blackhawk Formation—Continued	
Kenilworth Member—Continued	
thickens upward. transitional with uppermost sandstone unit. Basal one-third is thinly interbedded sandstone and medium-gray carbonaceous siltstone, intensely mottled; contains carbonaceous debris on bedding planes	60
Interbedded dark-gray carbonaceous silty and sandy mudstone and dark-reddish-brown (10*R* 3/4) ferruginous claystone lenses	22
Sandstone (lower sandstone tongue), grayish-yellow (5*Y* 8/4) to light-yellowish-gray (5*Y* 8/2), fine grained, very calcareous, noncarbonaceous. Small channel bodies near base. Thin bedded, slabby; forms retreating ledge above lower interbedded part. Cross laminated in tangential foresets. *Ophiomorpha, Gyrochorte, Aulichnites, Teichichnus A*, and helicoid funnels are dominant trace fossils. Gradational with underlying sandstone	12
Sandstone, light-gray to grayish-orange-pink (10*R* 8/2), very fine grained, calcareous, carbonaceous; contains *Ophiomorpha, Asterosoma, Gyrochorte, Ruhespuren*, and *Teichichnus A* and *B*. Thin bedded and slabby; mottled; interbedded with very dark gray carbonaceous siltstone. Sandstone forms slump or rounder structures in the siltstone	42
Total Kenilworth Member	220
Mancos Shale:	
Mudstone, dark-gray, silty, calcareous, shaly.	

The next overlying part of the sequence in each tongue is mostly thin-bedded very fine grained sandstone with minor discontinuous lenses and pods of carbonaceous fossiliferous siltstone. The fine-grained sandstone commonly contains megaripples, current ripples, and oscillation ripples; most beds are crossbedded in tangential foreset sets. These sandstone beds contain abundant trace fossils of the kind interpreted by Seilacher (1967) to be indicative of shallow-water deposition. (See p. 10 of present report.) Thin-bedded sandstones are characterized by abundant trace fossils. *Thalassionoides*, *Ophiomorpha*, *Asterosoma*, *Teichichnus*, *Gyrochorte*, *Aulichnites*, and *Arenicolites* are some fossils that are preserved in the rocks of this type. One factor that governed the association of the animals that created the trace fossils was the amount of silt, mud, and organic debris in the depositional environment. Where much fine sediment and organic detritus were present during deposition, *Ophiomorpha* is small, most *Asterosoma* are horizontally oriented, and well-developed helicoid funnels are associated with *Asterosoma*. *Teichichnus* is common in rocks with a high content of carbonaceous detritus.

At Sunnyside, the three sandstone tongues of the Kenilworth Member are separated by variably thick deposits of dark-gray carbonaceous coaly, silty mudstone. The three sandstone tongues coalesce westward to form a single unit. The two sedimentational sequences just described—the basal interbedded sandstone and siltstone and the overlying thin-bedded sandstone—are in all three tongues. They form the entire arenaceous part of the lower sandstone tongue, the lower two-thirds of the middle tongue, and the lower half of the upper tongue.

The middle tongue of the Kenilworth Member at Sunnyside comprises the two sedimentational units just described and an upper sandstone bed which is moderately well sorted, thick bedded, and fine to medium grained and which commonly makes a massive cliff. The upper sandstone bed contains variable amounts of carbonaceous debris, and it commonly contains an abundant trace-fossil fauna. Channel-fill structures, which are common throughout the upper sandstone bed, cut out bedding laterally and vertically and exhibit multilateral and multistory trough crossbedding. They are composed of coarser grained sediments than the enclosing sandstone and have roughly graded bedding.

The upper sandstone tongue of the Kenilworth Member at Sunnyside comprises the three sedimentational units that occur in the middle tongue plus an uppermost unit of very light gray sandstone that normally is well sorted, fine to medium grained, and, in many places, nonfossiliferous; its stratification is mostly in tangential foreset crossbeds. Streaks of very light yellowish gray to very light gray sandstone are common at various intervals throughout the upper part of the upper tongue. Young (1955, p. 184) called these streaks whitecaps and ascribed their formation to leaching and bleaching action of acid swamp waters in the paleoenvironment. Thick-bedded well-sorted sandstones of this unit locally contain abundant trace fossils that include large *Ophiomorpha* burrows (3–5 cm diameter), vertical *Asterosoma* burrows, burrows of *Arenicolites*, and tracks and trails of other animals on bedding surfaces.

Any parts of the depositional sequence may be missing or unrecoverable from the stratigraphic section at a given point, depending upon a variety of factors ranging from conditions at the time of deposition to colluvial cover of part or all of the unit. All three sandstone tongues of the Kenilworth Member at Sunnyside contain variable amounts of calcareous cement, which probably was derived from oxidation of methane gas derived from carbonaceous debris. Differential weathering of the cement produces local pockmarked or honeycomb beds on the outcrop.

In the deltaic depositional framework that I propose for the Blackhawk Formation, the sandstone tongues of the Kenilworth were deposited in the delta-platform, river-mouth-bar, and beach-and-channel areas. Interbedded siltstones and very fine grained sandstones were deposited on the upper prodelta slope and lower delta platform under conditions of variable current velocity; sedimentation was relatively slow, and sediment and waterlogged organic debris were intimately mixed during transport and deposition. The environment was physically quiet; only small-scale ripple marks indicate any current. Bedding and lamination is thin and regular. Detritus-feeding organisms produced a severely mottled texture. Up the paleoslope, in the region of the delta platform, thin-bedded moderately well sorted sands were deposited in an environment in which the current velocity was sufficient to winnow out the fines and where sedimentation was usually moderately rapid. Currents worked the sediments into plane-bed forms such as megaripples and oscillation ripples. Organisms that built vertical burrows in pace with sedimentation left abundant trace fossils in the thin-bedded sandstones. *Ophiomorpha*, *Arenicolites*, *Teichichnus*, *Cylindrichnus reptilis*, *Asterosoma*, plural curving tubes, and smooth tubes are the most common trace fossils. Ripple-drift lamination is common on and within bedding.

The upper part of the thin-bedded sandstone sequence in each tongue locally contains channel-filled structures and is trough crossbedded. The channel-fill structures are small and pinch out laterally in a very short distance. These beds probably are representative of the river-mouth bar environment. Trace fossils are few, a condition common to areas of rapid sedimentation and energetic cutting and shifting of channels. That these areas are localized in the stratigraphic section further indicates that they formed under specialized environmental conditions, such as at the outlet of distributary streams at the lower part of the delta.

Thick-bedded medium-grained sandstone beds at the top of the middle and upper sandstone tongues are the result of beach deposits in interdeltaic areas. Depositional and postdepositional currents winnowed finer grains from the deposit and sent the fines farther seaward. Littoral currents produced low- to high-angle bimodal tangential crossbedding (fig. 25), and tidal creeks and inlets locally produced channel-fill structures in the top of a depositional set. Rill marks and swash marks occur on bedding planes. Trace fossils generally are confined to channel-fill structures in the thick-bedded well-sorted sandstones; *Ophiomorpha* is

FIGURE 25.—Bimodal tangential crossbedding in upper sandstone tongue of Kenilworth Member in Water Canyon (fig. 1), southeast of Sunnyside. Pen is 5 inches long.

the most common trace found in these deposits, and *Aulichnites* and *Gyrochorte* locally are found on parting lineation. The uppermost surface of the sandstone depositional sequence of the two upper tongues is planar, which indicates subaerial erosion prior to deposition of the overlying sediments. Root marks of plants commonly occur in the upper 1 foot of the sandstone beds; many of these structures are preserved down to rootlets and root hairs.

The sandstone sedimentational unit (Kenilworth Member as redefined) ends at the top of the thick-bedded well-sorted sandstone just described. The Kenilworth varies in thickness along the outcrop owing to environmental changes during deposition and to pinching out of the bed into the Mancos Shale down the paleoslope. At Kenilworth the sandstone is 190 feet thick; at Sunnyside it is 166 feet thick; at Horse Canyon, south of the district, it is 120 feet thick. Lapses in sand sedimentation during deposition of the Kenilworth are attributed by Young (1955, p. 177) to sharp pulses of subsidence of the depositional basin. I believe that these lapses were due to tectonic and climatic conditions in the upland source areas, which caused sediment starvation, landward invasion by the sea, and in turn the transport of mud and other fine sediments into the area.

LOWER MUDSTONE MEMBER

Overlying the Kenilworth Member is an upward sequence of very thin carbonaceous sandy siltstone, the Rock Canyon coal bed, a bed of siltstone or fine-grained sandstone, and dark mudstones that contain stringer beds of arenaceous rocks. This unit, here called the lower mudstone member of the Blackhawk Formation, forms a slope above the sandstone bluffs of the Kenilworth Member.

The basal siltstone is irregular in shape and thickness, is structureless, and locally contains tracks and trails of organisms interpreted to be worms. The siltstone, where present, usually contains root marks and carbonized plant remains. The bed is in unconformable contact with the underlying sandstone and with the overlying coal and other sediments. The coal, locally called the Rock Canyon coal bed, is discontinuous; and at Sunnyside it ranges in thickness from 0 to 4 feet and in many places is cut by channel-fill sandstone cutting down from above. The coal is hard, bright, slightly bony, and brittle, and it has cubic cleat. It is a detrital coal composed of small pieces of plant material derived from ferns, angiosperms, and conifers (Tidwell, 1966, p. 88). Where the coal is not present, the sediments of this interval are extremely carbonaceous owing to the presence of small pieces of carbonized reed and grass debris.

Overlying the coaly zone is a sequence of dark-gray to black mudstone of varying fissility, laced with thin discontinuous cross-stratified beds of claystone, siltstone, and very fine grained sandstone. These arenaceous beds occur at every level throughout the mudstone interval, but they are extremely lenticular and are not traceable from one side of a canyon to the other. Orientation of directional sedimentary structures within the stringer sands is dominantly east-southeast. Bedding is poorly preserved because of mottling by organisms. Large horizontal burrows are common in the interval immediately overlying the coal bed, and unidentifiable trace fossils of detritus-feeding organisms are very common throughout the interval.

The entire zone of argillaceous rocks overlying the sandstone sedimentational unit probably is the product of a swampy depositional environment. The environment was a large intertidal flat that sloped very gently seaward from the flood plain and in most places prograded seaward over older sediments. The flat was crossed and connected to the sea by an intricate network of small meandering streams and tidal channels that drained the delta area and resulted in the formation of small channel-fill sandstone bodies that are very lenticular and discontinuous. The water in the channels and streams was very brackish to saline, which allowed the landward migration of a few *Ophimorpha* and *Asterosoma* organisms, whose trace fossils occasionally are found in the resultant sandstones. Some areas of back swamp were bypassed by active sedimentation, and these were flooded at intervals by distributary streams. This flooding caused the formation of interbeds of black clayey siltstone and very fine grained sandstone over a greater areal extent than that of the stream channel. Swamp areas were occupied by a lush growth of plants, whose decay and compaction resulted in peat beds that later became coals. Large plant pieces, such as stumps or logs, are rare in the carbonaceous sequence.

Marine fossils, although locally present in the lower part of the argillaceous unit, are nearly ubiquitous in the upper part of the unit. There is no apparent break between nonmarine sedimentation and marine sedimentation, although the upper mudstone beds are slightly sandier. Young (1955, p. 181) identified the whole argillaceous part as Mancos Shale that was deposited during sharp pulses of basinal subsidence. The mudstone is indeed a Mancos facies; the unit is traceable into the Mancos on the outcrop. I believe, however, that tectonic and climatic conditions in the upland source area combined with slow, normal subsidence of the basin margin owing to superloading to allow transgression of the sea. Normal transgressive sequences of the Mesaverde include a standstone bed deposited as the sea swept landward; no such bed separates nonmarine from marine rocks at Sunnyside because there was not enough sand available for reworking and subsequent redeposition by the transgressing waters. The invading waters reworked only the marine mud and silt.

SUNNYSIDE MEMBER

The Sunnyside Member was named and defined by Young (1955, p. 185) to comprise "a massive, basal sandstone tongue and the overlying coal-bearing rocks which are replaced eastward by offshore bar sandstone." Young's definition derives from bedding characteristics, lithology, and inference of origin. My field investigations show that the "massive, basal sandstone" is the top unit in an orderly stratigraphic succession from interbedded sandstone and siltstone at the base to thick-bedded medium-grained sandstone at the top. The member forms an easily recognizable, mappable part of the stratigraphic section at Sunnyside and throughout the Book Cliffs; I traced the sandstone cliff of the Sunnyside Member as far south as Green River, Utah. I here redefine the Sunnyside Member on the basis of lithologic continuity, mappability, and topographic expression and place the lower boundary of the member at the base of the continuous cliff-forming sandstone above the Kenilworth Member. I place the upper boundary of the Sunnyside Member at the top of the same type of sandstone, just below the Sunnyside coal bed. The principal reference section I propose for the member is in the cliff just north of the town of Sunnyside in NE¼ sec. 6, T. 15 S., R. 14 E.

Principal reference section of the Sunnyside Member of the Blackhawk Formation, in the Blackhawk Cliff above the town of Sunnyside, Utah, in NE¼ sec. 6, T. 15 S., R. 14 E., Salt Lake Meridian

	Thickness (feet)
Blackhawk Formation:	
Upper mudstone member:	
Interbedded dark-gray silty mudstone and dark-red-brown (10*R* 3/4) ferruginous claystone and siltstone, with thick coal bed 0–1 ft above base.	
Sunnyside Member:	
Sandstone, light-gray to yellowish-brown (10*YR* 5/6), very fine grained, thin-bedded, and shaly. Contains *Ophiomorpha* and labyrinth castings. Ripple cross laminated on bedding surfaces	23
Sandstone, light-gray, fine- to medium-grained, sugary-textured. Contains channel structures, carbonaceous debris; trace fossils dominantly are *Ophiomorpha, Teichichnus, Asterosoma,* labyrinth castings, and large horizontal burrows. Undulating bedding surfaces contain ripple marks. Some crossbedding in tangential sets	36
Sandstone, light-grayish-yellow (5*Y* 8/5), fine-grained; well sorted within beds, contains carbonaceous debris on bedding surfaces. Tangential crossbedding throughout, in thick sets that have even upper and lower surfaces. Contains few trace fossils. Calcareous and silty	32
Sandstone, light-grayish-yellow to light-yellowish-gray (5*Y* 8/2), thin-bedded, and flaggy. Well sorted, with carbonaceous debris on bedding surfaces only; calcareous. Crossbedded in long sweeping tangential sets. Slump-and-founder structures on sandstone into underlying sandstone laminae, in ball-and-pillow forms. Honeycomb weathering	42
Sandstone, medium-yellow (5*Y* 7/4) to medium-grayish-yellow (5*Y* 7/4), very fine grained, silty, carbonaceous; intensively burrowed and mottled; contains *Ophiomorpha, Asterosoma,* plural curving tubes, *Arenicolites, Thalassinoides,* and rare *Ruhespuren.* Interbedded with dark-gray coaly and carbonaceous shaly siltstone. Siltstone has been mottled intensively. Siltstone contains disks and small lenses of coal, probably derived from bark. Interbed contacts are sharp	57
Total Sunnyside Member	190
Mancos Shale:	
Mudstone, silty, carbonaceous, dark-gray; weathers light gray to medium gray. Contains abundant trace-fossil infauna.	

The siltstone interbeds in the basal facies are medium to dark gray, sandy, clayey, and very carbonaceous. They are thin to very thin bedded and are crossbedded in trough-set beds. The siltstone beds have a highly mottled texture owing to action of burrowing organisms. Sandstone interbeds are very thin, very fine grained, clayey, calcareous, and very carbonaceous and contain numerous trace fossils. The beds are crossbedded in trough-set beds, and crossbedding and interbedding occur in every scale from large to microscopic. Rocks of the basal facies probably reflect the offshore, delta-platform environment, a place of low kinetic energy that was below wave base, and that received periodic surges of active sedimentation that carried sand-sized particles far seaward before depositing the load.

The Sunnyside Member comprises three lithologic facies, and each facies represents a different set of environmental conditions at the time of deposition. The basal facies of the member of Sunnyside is interbedded siltstone and very fine grained sandstone (fig. 26). The

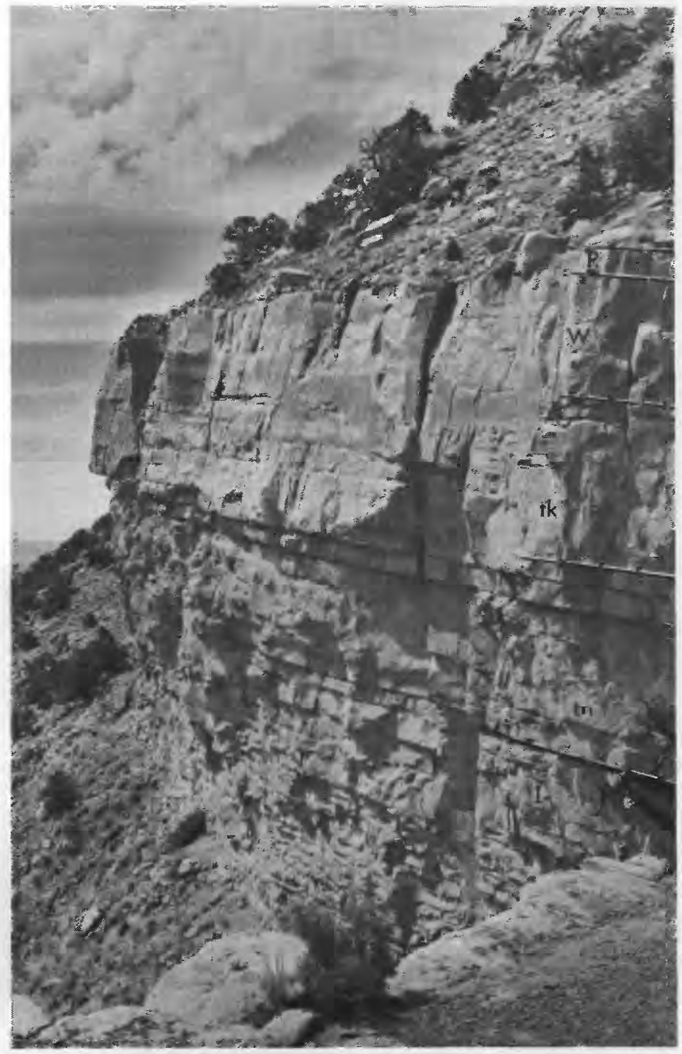


FIGURE 26.—Sandstone of the Sunnyside Member at the mouth of Slaughter Canyon (fig. 1), showing root zone (R), whitecap unit (W), thick-bedded sandstone (tk), thin-bedded sandstone (tn), and interbedded sandstone and siltstone (I). Thick-bedded sandstone, whitecap unit, and root zone—which are 45 feet thick in the area of the photograph—make up the upper facies of the member. View southward.

siltstone is extremely carbonaceous and has been so intensively reworked by organisms that remains of original bedding are rare. The thin siltstone and coal are included in the overlying upper mudstone member. Trace-fossil preservation in siltstones is uncommon, because the thoroughness with which the substrate was reworked either destroyed or altered the biogenic sedimentary structures. Trace fossils are abundant in the sandstones; *Ophiomorphia*, *Cylindrichnus*, *Asterosoma*, *Teichichnus*, *Thalassinoides*, *and Arthrophycus* are the most common types found in the thin-bedded sandstones.

The interbedded sequence of the basal facies is overlain by a thin-bedded cross-stratified sandstone facies that contains variable amounts of carbonaceous debris. Foreset and trough-set crossbedding are the most common types of cross-stratification. The rocks are light grayish yellow, fine to very fine grained, silty, clayey, and calcareous and contain abundant trace fossils. The individuals of the trace fauna vary with the amount of carbonaceous detritus in the sediment. The less carbonaceous beds contain *Aulichnites*, *Gyrochorte*, *Ophiomorpha*, vertical *Cylindrichnus*, plural curving tubes, and chevron trails. These trace fossils, with the exception of *Cylindrichnus*, were made by organisms that received their nourishment from sources other than carbonaceous detritus. Vertical *Cylindrichnus* burrows probably indicate an attempt by the animal to escape to a more favorable environment. Beds with a moderate to high carbonaceous debris content contain *Teichichnus*, *Thalassinoides*, *Arenicolites*, horizontal *Cylindrichnus*, and helicoid funnels. These traces reflect an intrasediment burrowing in search of the carbonaceous detritus for food.

The thin-bedded sandstone facies of the Sunnyside Member at Sunnyside reflects sedimentation in the upper delta platform, distributary-mouth-bar, and littoral subenvironments. Periods of low current velocity allowed deposition of carbonaceous detritus and fine sediment nearer to shore than periods of normally high transport velocity. During normal sedimentation, carbonaceous debris was winnowed out, and only clean fine sand was deposited in the area. The upper part of the facies is cross stratified in foreset crossbeds and appears to be the result of current action in the littoral zone.

The uppermost facies of the Sunnyside Member comprises thick-bedded medium- to fine-grained sandstone, which is moderately carbonaceous, clayey and calcareous, dominantly light gray to light grayish yellow with local streaks of very light yellow to white sandstone at varying intervals. The unit locally is brick red owing to oxidation by burning of the overlying coal. Bed forms are trough-set crossbeds, which contain directional sedimentary structures that indicate that the dominant direction of transport was east-southeast. Bimodal foreset crossbedding occurs locally in the upper part of the unit. Trace fossils are less common in this unit than in others; the scarcity probably is due to rapid sedimentation at relatively high velocity. Scattered *Ophiomorpha* occur in the uppermost unit of the Sunnyside, and labyrinth castings are found associated with local small pockets of carbonaceous debris that occur near the edges of troughs. *Gyrochorte* are found on bedding surfaces in the uppermost part of the upper sandstone unit. Other trace fossils are very rare. Root marks of plants that once grew on the sand commonly occur in the uppermost 2 feet (fig. 27). These root marks are preserved roots, rootlets, and occasional root hairs. Such features are carbonized limonite-stained branching tubes that terminate downward.

The uppermost unit of the Sunnyside Member represents channel-fill deposition in thick beds by distributaries in the upper delta area. As the transporting medium reached an open area at the end of its channel, current velocity decreased, which caused rapid sedimentation that constantly shifted direction as flow barriers were constructed and destroyed in the anastomosing channels. Local areas of beach sedimentation occurred, and these are indicated in the rocks by parts of the unit that are crossbedded in long sweeping foreset crossbeds that are tangential at their bases. These rocks exhibit no characteristics of channel-fill sedimentation. Rather, they contain trace fossils of the littoral zone such as *Arenicolites*, *Aulichnites*, *Gyrochorte*, and plural curving tubes. Large pieces of carbonaceous woody debris are common to the beach rocks, and the pieces of debris are oriented with their long axes normal to the long axis of deposition, which possibly indicates their

FIGURE 27.—Root marks in uppermost 1 foot of thick-bedded sandstone facies at top of Sunnyside Member; slt, siltstone which underlies Sunnyside coal bed.

deposition in tidal wash. Directional sedimentary structures in both the channel fill and the beach rocks indicate that the dominant direction of flow was eastward.

The upper limit of the Sunnyside Member is placed at the top of the thick-bedded sandstone unit. The thickness of the sandstone, which ranges from 100 to 150 feet at Sunnyside, makes the unit easily distinguishable on the outcrop and mappable at scales as large as 1:250,000.

UPPER MUDSTONE MEMBER

Overlying the Sunnyside Member is a basal thin discontinuous sandy siltstone, overlain by the thick Sunnyside coal bed and 250–300 feet of dark laminated shale and massive mudstone with lenticular bodies of sandstone and siltstone throughout. This unit is here informally called the upper mudstone member of the Blackhawk Formation. The mudstone is replaced southward by sandstone beds above the Sunnyside coal bed and is here delineated for continuity in mapping. I believe that the member is of continental origin at Sunnyside, although farther south it is of continental and marine origin.

The Sunnyside coal bed (Taff, 1906, p. 295) is a hard bright brittle coking coal of high-volatile A to B bituminous rank in the system of the American Society for Testing Materials. The coal has an irregular break, owing in part to the matting and interlayering of its plant parts. The Sunnyside coal is rich in spores and waxes. Fossil megaspores form resin blebs in the coal and are very common throughout the vertical and horizontl extent of the bed. The common spores and waxes, together with coal composed mostly of plant debris instead of woody material, indicate formation of detrital coal in shallow water (Tschudy, 1961, p. 57). The Sunnyside coal bed is split by siltstone and mudstone (fig. 28) which is a few inches to 75 feet thick in the deeper parts of the Sunnyside mines. In addition, many thin discontinuous coal beds occur in the coal-bearing interval. Because of the thickness of the split, miners and some earlier workers believed the coal to be two different beds. Detailed surface mapping and correlation of underground sections show that the upper seam and lower seam are splits of the same bed (Brodsky, 1960, p. 36). The split is not everywhere present in the area; it thins to the north and east and thickens to the south and west. The lower surface of the coal is irregular, owing to the irregular and discontinuous siltstone below. The upper part of the coal commonly is intertongued with overlying sediments (fig. 28). Locally, channel-fill deposits cut downward into the coal and affect the thickness of the bed.

The coal beds and carbonaceous sandy siltstone overlying the Sunnyside Member represent deposition in swamp and lagoonal areas peripheral to the coastline. Plants grew in shallow water and extended their root systems into the sandy soil below. Shifting distributaries brought additional carbonaceous detritus into the area; these channels also cut out the carbonaceous deposits and replaced them with channel-fill sands. Acidic waters that percolated downward from the swamp probably deposited sulfates in the sandy deposits, and the water also probably aided in local bleaching of the sediments. Bleached zones also occur most commonly where the coal has been burned on the outcrop, and this suggests that oxidation by burning also influenced bleaching of the sediments.

Overlying the coal zone is a sequence of interbedded very carbonaceous shales, mudstones, siltstones, and lenticular sandstones and siltstones. The only trace fossils observed in rocks of this sequence are large horizontal burrows, labyrinth castings, and rare *Ophiomorpha* in the lenticular sandstones. Large horizontal burrows are nearly ubiquitous in the rocks overlying the upper split of the coal. Labyrinth castings are associated with carbonized pieces of material of varying size which are stratigraphically above or below the coal. A sparsely populated fauna of thin-shelled poorly preserved mollusks was found in sandy mudstones at various intervals throughout the carbonaceous argillaceous sequence. A collection of this fauna from an interval 40–60 feet above the upper coal (USGS Mesozoic loc. D6221) was identified by W. A. Cobban (written commun., 1968) of the U.S. Geological Survey as:

Ostrea sp.,
Corbula sp.,
Anomia micronema Meek,
Brachidontes sp., and
bits of gastropod molds.

Cobban commented that the fauna was a brackish-water assemblage. A collection of shelly fossils from a sandstone unit 130 feet above the coal, at a locality 10 miles south of Sunnyside (USGS Mesozoic loc. D6722), was identified by Cobban (written commun., 1968) as:

Crassostrea sp.,
Brachidontes sp.,
Corbula undifera Meek, and
membraniporoid bryozoan.

Cobban commented that the fossils were obviously transported, but that they probably had been deposited in a brackish-water environment.

The arenaceous rocks overlying the coal at Sunnyside represent deposition in a lowland environment—a swampy, marshy area near sea level that occasionally was encroached upon by marine waters. Local estuaries and tidal channels allowed mixing of marine and nonmarine waters and allowed limited migration of marine

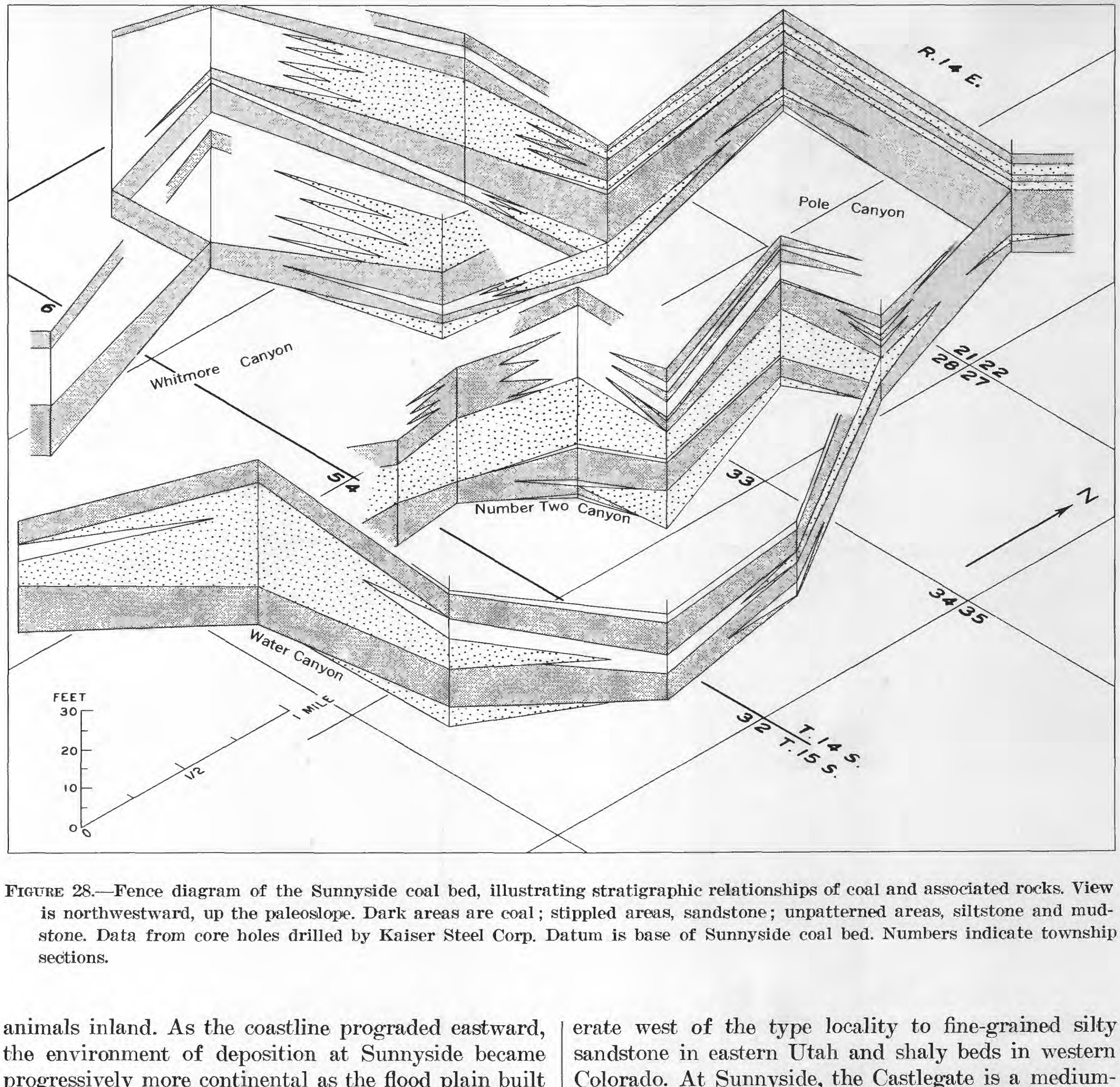


FIGURE 28.—Fence diagram of the Sunnyside coal bed, illustrating stratigraphic relationships of coal and associated rocks. View is northwestward, up the paleoslope. Dark areas are coal; stippled areas, sandstone; unpatterned areas, siltstone and mudstone. Data from core holes drilled by Kaiser Steel Corp. Datum is base of Sunnyside coal bed. Numbers indicate township sections.

animals inland. As the coastline prograded eastward, the environment of deposition at Sunnyside became progressively more continental as the flood plain built eastward. Meandering distributaries cut channels across the swamp throughout the period of deposition, and these channels became larger and more numerous as continental sedimentation progress.

CASTLEGATE SANDSTONE

The Blackhawk Formation at Sunnyside is unconformably overlain by the Castlegate Sandstone, a sandstone as much as 300 feet thick that forms a prominent cliff and dip slope throughout the Book Cliffs. Named for an exposure at Castle Gate, Utah (Spieker, 1946, p. 131), the unit varies in composition from conglomerate west of the type locality to fine-grained silty sandstone in eastern Utah and shaly beds in western Colorado. At Sunnyside, the Castlegate is a medium-grained light-grayish-yellow clayey sandstone that contains numerous clay galls and lenses of carbonaceous material. The formation is unconformable atop the carbonaceous rocks of the Blackhawk, and it fills local channels and interfingers into the top of the Blackhawk. The dominant sedimentary structures in the Castlegate are channel-fill sandstone bodies. Where the formation crops out in a direction normal to the direction of deposition, channel-fill structures occur throughout the unit.

The Castlegate in the Sunnyside area is the result of deposition of sand in a fluviatile and flood-plain environment. Where materials of more than one grain size occur, they are poorly graded. Local deposits of carbonaceous debris and large pieces of carbonized wood are the remains of detritus swept downstream and deposited on the flood plain and in eddies and backwaters.

In summary, the depositional history of the Sunnyside area was: offshore sea-floor muds (Mancos Shale); progressively shallower marine deposition of Aberdeen, Kenilworth, and Sunnyside Members, with periods of marine transgression and deposition interspersed between progradational sequences; transitional marine and continental deposition in low-lying areas behind the coastline; and fluviatile and flood-plain deposition as the final eastward regression of the sea took place near the close of the Cretaceous Period. Latest Cretaceous and Tertiary rocks are the result of continental sedimentation in flood-plain and lacustrine environments.

INORGANIC SEDIMENTARY STRUCTURES

Observable inorganic sedimentary structures of the Blackhawk Formation may be grouped into four categories: bedding structures, which are wholly contained within the limits of bedding surfaces; plane-bed forms, which affect only bedding surfaces; channel structures, formed by erosion of preexisting sediments and redeposition in the erosion channels; and load structures, formed by foundering of a superincumbent mass of sediment into less competent strata.

BEDDING STRUCTURES

Sandstone beds of the Blackhawk Formation commonly are cross-stratified. The nature of the cross-stratification varies with the current velocity. Thickness and type of stratification also depend mostly upon the velocity of the transporting medium. In strata deposited in quiet water, laminar bedding is dominant, and depositional cross-stratification is uncommon; deposits in environments of higher kinetic energy are thin to thick bedded (2 in. to 5 ft), and most are found in wedge-shaped crossbedded sedimentational units (fig. 29) 6 inches to 2 feet thick. Individual foreset beds within the sedimentational unit commonly are tangential to bedding planes at their bases and have planar tops (fig. 30). Sole markings in beds of this type are parallel to the direction of crossbedding. This parallelism indicates that the beds were built up in the direction of sediment transport. Primary dip of crossbedding varies with the energy of the environment, but measured primary-dip angles greater than 20° are rare. The primary dip of most crossbedding in Blackhawk sandstones at Sunnyside is 2°–15° SE.; measurements of direction of transport indicate a dominant direction of S. 80° E. The

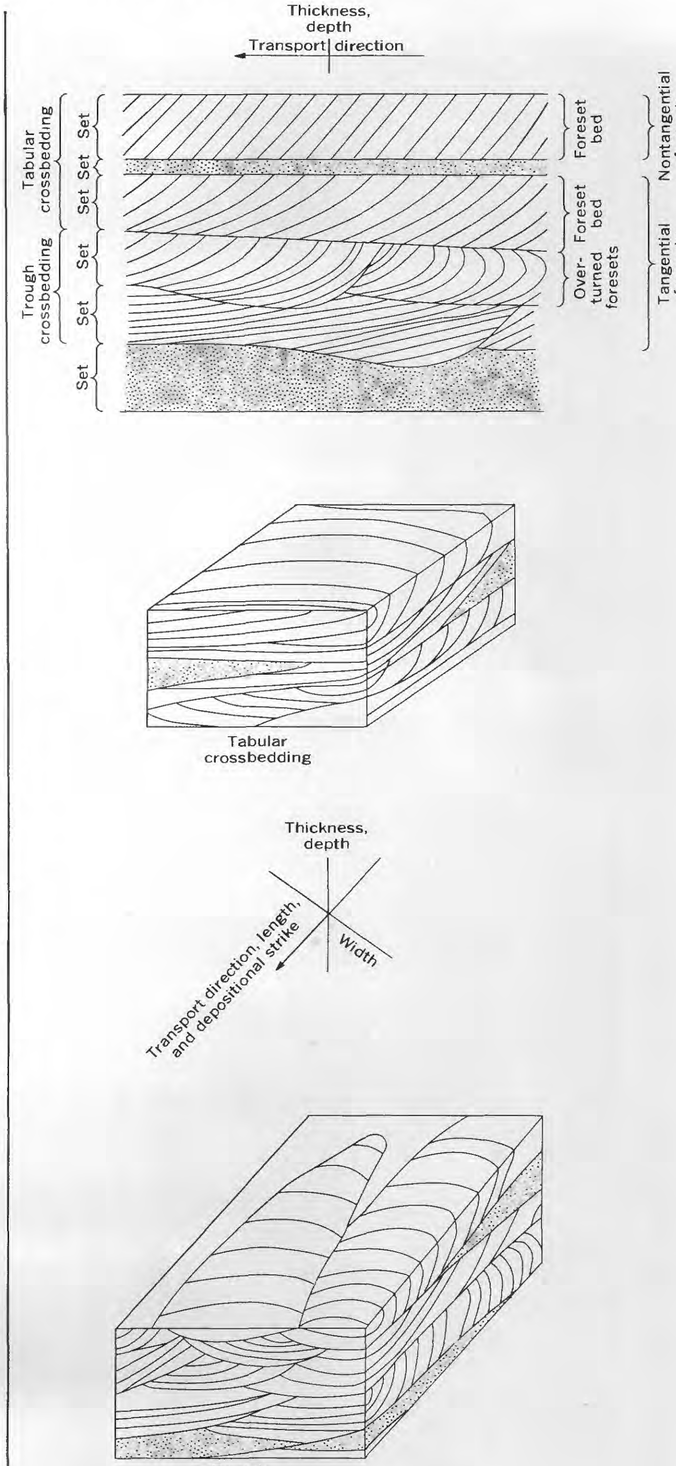


FIGURE 29.—Diagrammatic sketches illustrating terminology of crossbedding (modified from Potter and Pettijohn, 1963, p. 69). No scale.

directional features include crossbedding, flute casts and other sole markings, asymmetrical ripple marks, and orientation of plant debris on bedding surfaces. The

FIGURE 30.—Tangential crossbedding in lower sandstone tongue of Kenilworth Member.

nearly unidirectional sediment transport, which is discussed later in this report, is a major factor in the interpretation of depositional environment.

Many sandstone beds exhibit ripple cross-lamination (fig. 31), a bedding feature formed by low-velocity current drag penecontemporaneous with deposition (Potter and Pettijohn, 1963, p. 155). Laminae are built up by ripple marks migrating in one direction. Where this feature was found near Sunnyside, measurements of the direction of laminae buildup indicate ripple migration to the east-southeast.

Bimodal crossbedding, which indicates sediment transport in opposite directions in successively overlying sets of crossbeds (fig. 32), formed in local areas of deposition. This type of crossbedding is preserved in some outcrops of the Blackhawk Formation. In the upper sandstone of the Sunnyside in Water Canyon (fig. 32), particularly good outcrops of such beds display a vertical sequence of crossbedded units, each 6 inches to 1 foot thick, with foreset beds that dip in opposite directions at low angles. Potter and Pettijohn (1963, p. 96) pointed out that most crossbedding points down the paleoslope. The bimodal crossbedding probably was deposited in a backshore environment, landward of the beach. Seaward-dipping foresets were deposited by tidal and other currents in the lagoonal area; landward-dipping foresets were deposited by currents operating in a landward direction.

FIGURE 32.—Crossbedding in opposite directions in successively overlying sets of crossbeds in upper thick-bedded sandstone facies of Sunnyside Member, Water Canyon. View oblique to depositional strike.

The upper sandstone units of both the Sunnyside Member and the Kenilworth Member form a prominent cliff. The upper surface is planar at nearly every exposure (fig. 33). The planar surface may be an indication

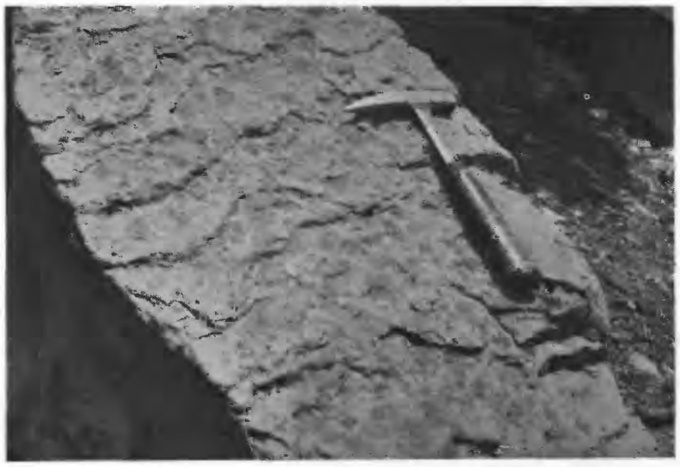


FIGURE 31.—Ripple cross-lamination in middle thin-bedded sandstone facies of Sunnyside Member. Current from upper left to lower right.

FIGURE 33.—Top of upper thick-bedded sandstone facies of Sunnyside Member, illustrating planar nature of bedding surface.

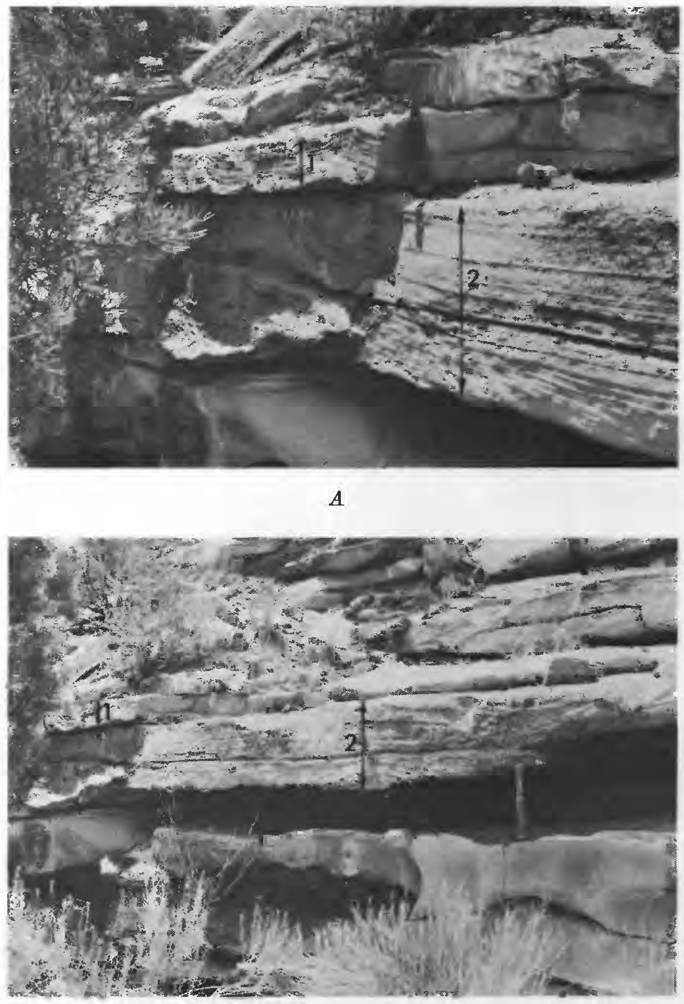
of subaerial erosion prior to deposition of the overlying sediments. Root marks occur in the upper foot of the uppermost sandstone bed in nearly all tongues of each member (fig. 27), which indicates that plants once grew at these horizons.

PLANE-BED FORMS

Ripple marks are the most common type of plane-bed form in the rocks at Sunnyside. Many are symmetrical (fig. 34) with relatively straight subparallel crests that are transverse to the oscillatory water movement that formed them (Potter and Pettijohn, 1963, p. 29). Current ripples (fig. 35), which are formed by directional movement or transport, are abundant in thin-bedded fine-grained sandstone in the Sunnyside area. Oscillation and current ripple marks vary widely in measured amplitude and wavelength. Megaripples with maximum amplitudes of 1.5 inches and wavelengths of 6–8 feet occur in the middle tongue of the Kenilworth Member in Slaughter Canyon (fig. 36). Megaripples are best preserved at this locality, although they are common elsewhere in the Sunnyside area. Gilbert (1899, p. 138) postulated that "ripplemarks are only half as broad as the waves rolling above them are high." If this postulate is true, waves that formed the megaripples described above were about 15 feet high. Heezen and Hollister (1964) have photographed current ripples on the sea floor at depths as great as 8,000 meters, however, thereby proving that fossil ripple marks have no bathymetric significance. Current ripples in the Blackhawk Formation are transverse to the direction of cross bedding; according to Potter and Pettijohn (1963, p. 94), these ripples aid in delineating the depositional strike. Interference ripple marks formed by currents operating at large angles to each other, and characterized by polygonal cusps, are found in some beds (fig. 37).

FIGURE 34.—Oscillation ripple marks in the upper thick-bedded sandstone facies of the Sunnyside Member.

FIGURE 35.—Current ripple marks in the upper thick-bedded sandstone facies of the Sunnyside Member. Overhead view.



A

B

FIGURE 36.—Megaripples in the middle tongue of the Kenilworth Member, Slaughter Canyon. *A*, Sharp-peaked ripple marks (1) overlying and truncating low-amplitude long-wavelength ripples (2). *B*, Same outcrop as *A*, showing megaripples with wavelengths of 6–8 feet and amplitudes of 1.5 inches (2).

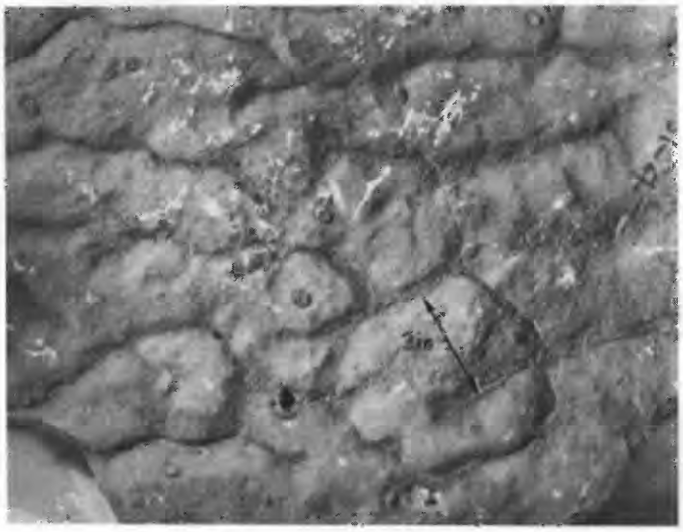


FIGURE 37.—Interference ripple marks on bottom of bed in middle tongue of Kenilworth Member, illustrating polygonal cusps.

CHANNEL STRUCTURES

Channel deposits occur in nearly all types of beds. They vary in width, depth, direction of transport, and orientation within beds. Few channel deposits can be traced for any appreciable distance laterally, however, because they commonly crop out high on inaccessible vertical cliffs and because they are covered by colluvium on north-facing slopes.

Channel deposits are found in two lithologic relationships: channels of sandstone that are scoured into mudstone beds and channels that are scoured into sandstone beds. Because these lithologic relationships may bear on interpretation of depositional environment, their data are presented separately.

Channel deposits of sandstone in mudstone (fig. 38) are commonly smaller than channel deposits of sandstone in sandstone. Most channel deposits in mudstone are bilaterally symmetrical about a thalweg at the center of the channel. Channel deposits of this type observed at Sunnyside are less than 50 feet wide and less than 20 feet deep. They are lenticular sandstone bodies, convex downward with nearly planar tops, and enclosed in and covered by the same general type of sediment into which the channels were cut. These channel deposits contain foreset crossbedding in trough-shaped sets that have their long axes parallel to the direction of dip of the foresets. The sets thicken in the direction of the foreset dip and truncate other sets throughout the depth and breadth of the deposit. Most trough sets display moderately graded bedding. No trace fossils were observed in units of this type.

Channels of sandstone in sandstone, which are larger than channels of sandstone in mudstone, are very common throughout the area. Nearly all sandstone sequences contain extensive channel deposits. The smallest observed channel of the sandstone-in-sandstone type (fig. 39) is at the mouth of Slaughter Canyon, in Whitmore Canyon (fig. 1). Although the northeast side of this channel deposit has been removed by erosion, the projected width of the deposit is 60 feet; it is 10 feet thick. The largest channel structure of this type observed in the area is in the south wall of Whitmore Canyon; it was measured by pacing and with steel tape and is 150 feet wide and 45 feet thick at the thickest point. These channels are asymmetrical in cross section, with the thalweg well to one side. Sediments in these channel fills are crossbedded in wedge-shaped sets that thicken laterally, normal to the long direction of the channel (fig. 40). Foreset bedding within sets dips in the direction of thickening of the sets. Forma-

FIGURE 38.—Sandstone channel deposit in mudstone (arrows) in upper unnamed shale member of Blackhawk Formation. Channel deposit at its center is 12 feet thick.

FIGURE 39.—Small sandstone-in-sandstone channel deposit in upper tongue of Kenilworth Member. Channel deposit is 10 feet thick at its thickest point and originally was about 60 feet wide. View northwest on west side of Whitmore Canyon, at mouth of Slaughter Canyon.

FIGURE 40.—Sandstone-in-sandstone channel deposit in upper unnamed shale member of Blackhawk Formation. View northeast. Channel outlines shown by dashes. Scale indicated by long arrow, which represents 13 feet. Sets of crossbedding in lower part repeat laterally, normal to the direction of flow.

tion of channel-fill structures of this type is well illustrated in a model of fluvial channels (fig. 41) that form the sets. Sandstone that fills scours in sandstone is coarser grained and contains less carbonaceous debris than the beds into which the channels were cut. The scoured beds commonly are thinly and evenly bedded and very carbonaceous; some beds consist only of sandstone, and some are interbedded with siltstone. Trace fossils are sparse in channel-fill sandstone but abundant in many scoured beds. Most channel deposits of the type described here crop out high on the cliffs; hence, they are easier to trace laterally than are the smaller channels. Measurements of sediment-transport direction indicate that the principal direction was east-southeast.

LOAD STRUCTURES

Ball-and-pillow structures and load casts are the most common load structures in the rocks of the Sunnyside district. Both are caused by foundering and settling of a sediment into a less-dense sediment while both bodies are still hydroplastic (Potter and Pettijohn, 1963. p. 145, 148).

Ball-and-pillow structures are individual segments of a stratum which have settled into the underlying sediment. Ball-and-pillows at Sunnyside most commonly are segments of fine-grained sandstone which have foundered into mudstone, with stringers of mudstone squeezed up around the segments.

Load casts are formed by settling caused by differential loading of irregular sediment surfaces. Initial depressions on hydroplastic mud beds are filled with sediment which results in unequal loading (Middleton,

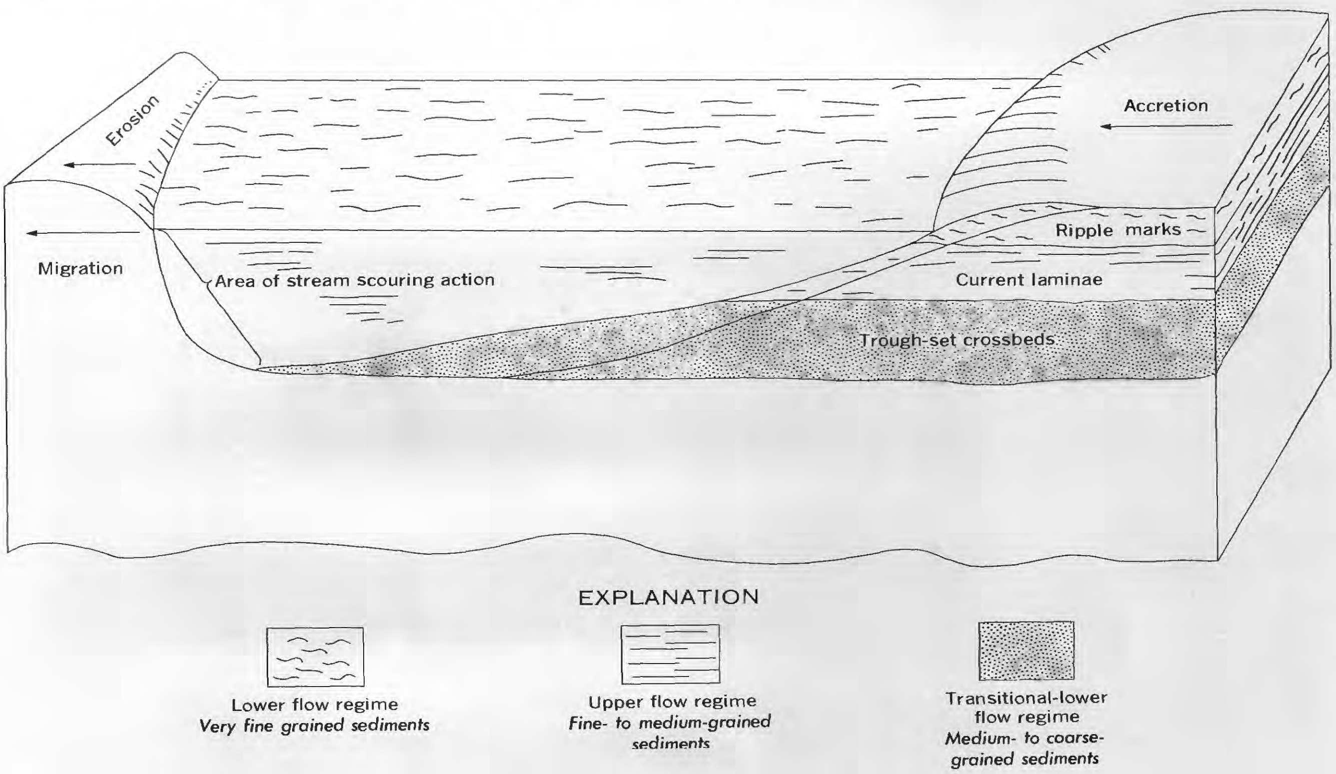


FIGURE 41.—Diagram of fluvial-channel environment, illustrating vertical distribution of sedimentary structures and sediment grain sizes and lateral formation of channel-fill deposits and structures (modified from Visher, 1963, p. 132).

1965, p. 249). Load casts do not break away from the parent bed as do ball-and-pillow structures; load casts form pendants into the less dense sediment. Load casts are most common where sands are deposited on argillaceous sediments (figs. 42 and 43) and reflect penecontemporaneous soft-sediment deformation.

ENGINEERING AND ECONOMIC GEOLOGY

Nearly all engineering and economic aspects of mining in sedimentary formations are related ultimately to the sedimentology of the rocks. Depositional environment and sedimentation pattern control engineering factors such as strength and homogeneity of the rocks, degree of lithification, and geometry of interfaces between lithofacies. The amount and extent of material deposited depend upon physical environmental conditions during deposition. Uninterrupted accumulation of vegetal material over a long period of time may result in a thick peat deposit; accumulation interrupted by inorganic sedimentation over a similar period may result merely in a thick carbonaceous zone. Sedimentary structures affect mining on many scales; directional sedimentary structures and other sedimentary phenomena, observable on the outcrop and traceable underground, may be predicted and their influence on mining may be forecast if such factors are respected as mining engineering parameters.

FIGURE 42.—Load casts of very fine grained dense sandstone extending into underlying carbonaceous mudstone, middle shale of Kenilworth Member in Slaughter Canyon. Current direction was from left to right.

FIGURE 43.—Load casts of fine-grained carbonaceous calcareous sandstone extending into underlying mudstone; Sunnyside coal zone in No. 1 Fan Canyon. Current direction was from left to right.

Some areas in the Sunnyside mines are characterized by coal that continually squeezes into the entries and spalls off, thereby continually releasing stress (fig. 44). Other areas are marked by floor anticlines, roof synclines, and buckled ribs—all conditions resulting from stress buildup in the coal (Osterwald, 1961, p. C349). The roof rock above squeezing areas commonly is a fine-grained siltstone or mudstone. The roof rock in other areas of coal deformation is a coarser grained siltstone or fine-grained sandstone. Osterwald (1962a, p. 65) showed that, other factors being equal, the difference in coefficient of friction with the coal between the finer grained and the coarser grained roof rocks determines the relative ease with which the coal can move laterally.

Where finer grained roof rocks allow the coal to move laterally with relative ease, the coal near the roof may spall off into the entry and effect the continual release of stress in the coal (fig. 45). Bumps that occur under these roof conditions are believed to be of lower

FIGURE 44.—Deformed roof bolts in the roof of Sunnyside No. 1 mine. Deformation resulted from the squeezing of the upper coal and intervening siltstone split into the entry owing to lateral pressure in the pillar at left. Photograph by J. C. Witt.

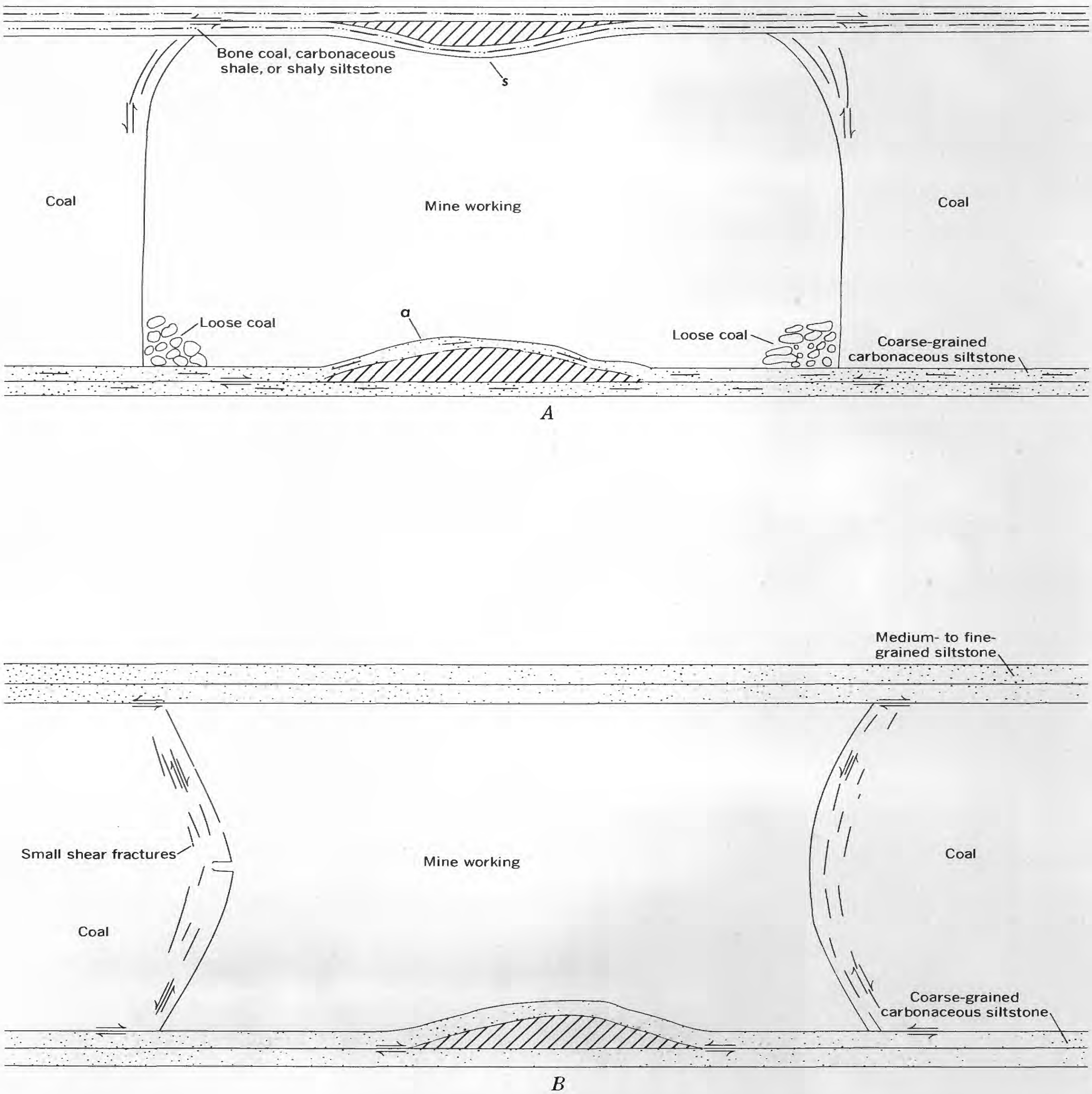


Figure 45.—Deformation around mine workings in Sunnyside No. 1 mine. Diagonally lined areas are hollow. Arrows show relative direction of movement. (Modified from Osterwald, 1961, p. C352.) *A*, Roof syncline (*s*) and floor anticline (*a*), which develop where coal slips along argillaceous roof but adheres to coarser grained rocks in the floor. *B*, Bulged and buckled ribs of coal where coal adheres to roof and floor.

magnitude than bumps that occur in areas of coarser grained roof rocks. The coarser rocks, which have a higher coefficient of friction with the coal, contribute to a high buildup of stress in the coal and thereby to conditions favorable for large bumps.

Osterwald and Brodsky (1960, p. B146) concluded that when entries intersect fault zones at a small angle, slippage will occur in the rib before much stress can accumulate. If the long axis of the entry intersects a fault or fracture at a large angle, slippage will be less likely to occur and a large stress concentration will be caused. If stress is allowed to continue to accumulate unabated, the plastic limit of strain will be exceeded, and a sudden, catastrophic release of stress will occur (fig. 46).

Coal-mine bumps partly are the result of vertical presssure on the coal from the overburden. The total stress on a point in space in a coal bed is a reflection of many factors. Surface topography and the thickness of overburden cause differential loading of the point; hydrostatic conditions, loading history and current geological conditions, manmade disturbances of the normal stress equilibrium, and other factors such as imposed heat gradients, vibrations, tidal forces, and the like all function together in varying degrees to form the sum of the stress (Corlett and Emery, 1959, p. 375). Spokes and Scott (1967, p. 46) showed that horizontal tensile stress is greatest near a caved area of a room-and-pillar mine. The magnitude of tensile stress is greatest near the surface, and it decreases to a neutral-stress axis somewhere near the middle point between the mined area and the surface. Downward from the neutral stress axis, horizontal compressional stress increases to a maximum in the area of mining. Stress tends to concentrate around the area of least support, which is the coal and rock surrounding the void created by mining. Much stress, therefore, concentrates around an entry, and the largest principal stress direction is at large angles to the axis of the entry.

Inorganic and biogenic sedimentary structures are three-dimensional. Both types of features commonly may have reliefs of as much as 18 inches in Blackhawk rocks, as do some load casts and ball-and-pillow structures, or they may be only films on the bedding surface, such as the trace fossil *Chondrites*. Locally, channel-fill sandstones completely cut out the coal. Most structures, however, are of sufficient relief to influence the friction at the interface of two rock bodies. A spatial and directional orientation of structures exists in the rocks at Sunnyside, but the continuity of orientation varies with the type of structure. The trace fossil *Thalassinoides* exhibits no preferred orientation, whereas current ripple marks and large horizontal burrows (fig. 47) both have highly preferred orientations. Rocks containing large horizontal burrows, which are tubes of sandstone in a carbonaceous siltstone or mudstone matrix, have lower shear strength than rocks that are structurally more homogeneous. Youash (1965, p. 96–98) performed triaxial and unconfined uniaxial compression tests on roof rocks from the Sunnyside No. 1 mine. He found that the shear and cohesive strength of roof rock which contains burrows and other lithologic and structural

FIGURE 46.—Aftermath of a coal-mine bump in the Sunnyside No. 1 mine, December 1957. Rib (coal face) at right failed catastrophically from right to left, pulling a part of the roof with it. Mine entry was closed for more than 250 feet. Roof bolts are 1-inch-diameter steel. Photograph by J. C. Witt.

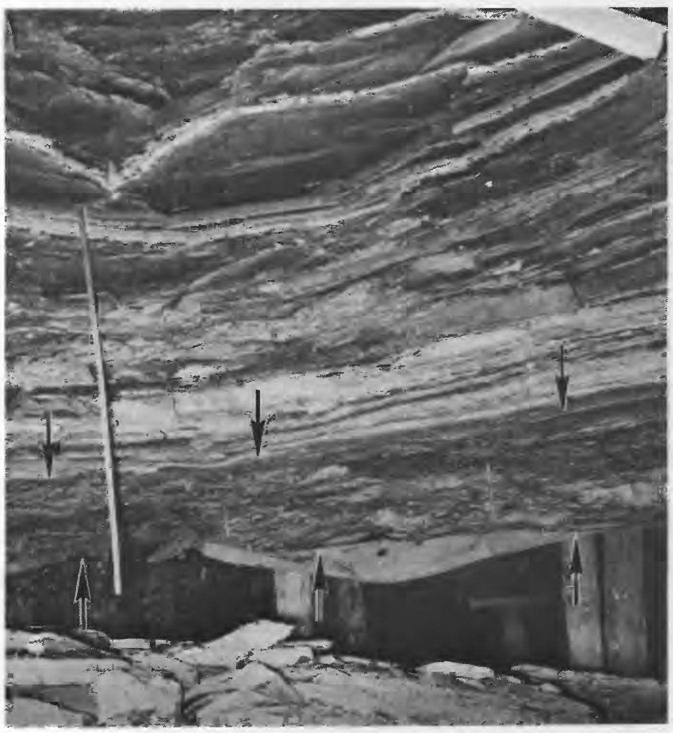


FIGURE 47.—Zone of large horizontal burrows (arrows) in roof rock, oriented at a small angle to the long axis of entry; Columbia mine, Utah. Burrows are light-colored sandstone structures in dark-gray shaly siltstone. This mine is approximately 3 miles south of Sunnyside and is developed in the Sunnyside coal bed. Photograph taken after a bump-related roof failure at intersection of mine workings. Entry runs obliquely from left foreground to right background. Timbers at lower right are 6 inches in diameter. Photograph by F. W. Osterwald.

discontinuities is less than that of rocks of similar lithology which do not contain structural inhomogeneities. Youash further found (1965, iii) that degree of failure of the rocks varies with the angular difference between the direction of principal stress and the direction of bedding surfaces in the rocks.

The relief and orientation of the sedimentary structures in the rocks of the roof and floor of a coal mine probably have a bearing upon the amount of stress that builds up in the coal seam. Where the preferred long direction of the sedimentary structures is parallel to or at a small angle to the long axis of the mine entry, these structures hinder movement of coal past rock at the interlithologic interface and cause the friction between the bodies to be greater. In areas where the dominant long direction of structures is normal to or at a large angle to the long axis of the entry, these structures form no barrier to movement and may actually aid movement by trapping and forming conduits for interformational and intraformational fluids that might be present in the rocks.

Sandstone-filled channels are sedimentary structures that affect mining on a larger scale than biogenic structures. Meandering channels are common to abundant in sediments above and below the Sunnyside coal. Regardless of their paleoenvironment, channel structures are composed of discontinuous layers of rock of irregular thickness. Individual layers in channels that are associated with the coal zone commonly are separated by thin films of coalified carbonaceous debris. Such films have nearly no structural strength and therefore cannot provide cohesion for the rock layers. When channel sandstones are encountered in the roof during mining, special roof-control measures should be taken to support the structures.

A channel sandstone represents a deviation from the usual lithologic pattern throughout the coal measures. Being a deviant, the channel body has a set of variables that influence the engineering characteristics of the body that are different from those of the surrounding rock. Among these variables are lithology, porosity, permeability, cement and degree of cementation, fluid content, strength, degree of homogeneity, and alinement of internal structures. Because of the physical and chemical differences between channel sandstones and their enclosing rocks, channel sandstones may be loci of mine bumps and other rock failures and should be regarded in mines with extreme caution.

A thick channel sandstone may completely cut out the coal locally and form a "want," or discontinuity in the coal. Such discontinuities are common in mines in the Wasatch Plateau coal field, in coal beds stratigraphically lower in the Blackhawk Formation than those at Sunnyside. The Wasatch Plateau coal field underlies most of the Wasatch Plateau from south of Huntington to near Helper. Also, coal near a channel may contain more impurities than coal elsewhere, owing to mixing of organic and inorganic sedimentation. Channel sandstone bodies commonly can be observed and mapped on the outcrop, and an indication of their general trend can be gained by measurement of internal structures. Then, on the basis of interpretation of the paleoenvironment, an area of mining where channels may be encountered can be forecast and precautions can be taken during development of a mine and extraction of coal.

Stratigraphic interrelationships are affected on a still larger scale by intertonguing facies contacts. Resistance to pressure release by horizontal sliding is increased at intertonguing contacts because of the irregularity of the contact surface. Contacts, therefore, may be foci of increased stress.

Because of environmental differences during sedimentation, it may be impossible to preclude danger from all the features mentioned herein. If, however, all aspects of the rocks are noted at the outcrop and in other exposures such as exploration pits and core holes, a pattern commonly can be determined that will serve as a guide to forecast the most potentially dangerous conditions, and planning can be guided by this additional information.

In 1964, an oil seep, which has long since dried up, was encountered during development work in the Sunnyside No. 3 mine. Earlier, 4 feet of saturated sandstone core was recovered from the coal interval in Pasture Canyon. Enough oil flowed from a channel-fill sandstone in the roof of the mine workings to cause a flurry of excitement among mine personnel. The oil at Sunnyside is believed to be a strictly local phenomenon. The oil probably was formed diagenetically either from organisms that inhabited the marsh or swamp areas or from the extremely carbonaceous sediments that surround the coal seam. The oil probably formed in discrete particles and then migrated into conduits formed by channels in the roof of the coal. When mining exposed the channels and disturbed the pressure equilibrium, the oil flowed into the opening. Asphaltic sandstones that may indicate proximity to petroliferous strata occur in association with coal beds in the Blackhawk Formation near Vernal, Utah, northeast of Sunnyside. Exploration for oil in the Blackhawk Formation at Sunnyside should concentrate on the stratigraphic traps formed where the sandstone-filled channels pinch out into the less permeable mudstones. Most such channels trend east-southeast.

At approximately the same time the oil seepage was encountered in the mine, fresh outflows of natural gas (methane) from the roof rocks were noticed. Methane, mostly derived from coal beds, in coal mines is very common throughout the world, and the appearance of oil in coal mines in the Book Cliffs is not uncommon; miners in the Castlegate mine in the Wasatch Plateau once encountered an oil seep that leaked enough oil to wet the haulage track (F. W. Osterwald, oral commun., 1968). I believe the methane is a product of decomposition of vegetable material during diagenesis and coal formation. Sedimentary structures such as channel-fill sandstones and trace-fossil horizons may have acted as a stratigraphic trap to concentrate the gas in the roof rocks. Other inflows of methane may be encountered when similar sandstone-filled channels are encountered.

Results of this investigation indicate that mining areas should be studied in minute geologic detail before drift or entry headings are laid out. In addition to the usual geologic information gathered, these studies should focus upon types of biogenic and inorganic sedimentary structures, their magnitude, mode of occurrence, and spatial orientation. If such studies were incorporated into the framework of a mining operation, they could contribute materially to the safety and economy of the venture. Because continual creep and spalling of the coal aids mining efficiency as well as contributing to safety, a mine should be opened with the mining entries driven at large angles to the trend of directional sedimentary structures but at small angles to tectonic structures to take advantage of the natural creep and spalling during mining. Such studies should make mining safer and more economical.

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INDEX

[Italic page numbers indicate major references]

PLATES 1–3

PLATE 1

FIGURE 1. *Teichichnus A,* indicated by arrows. Scale provided by encircled pencil.
2. Three-fourths view of *Teichichnus A;* arrow indicates up.
3. Sketch showing typical mode of occurrence and spreite construction of *Teichichnus A.*
4. *Teichichnus B,* from lower tongue.
5. Close view of same specimen of *Teichichnus B,* showing bladed structure.

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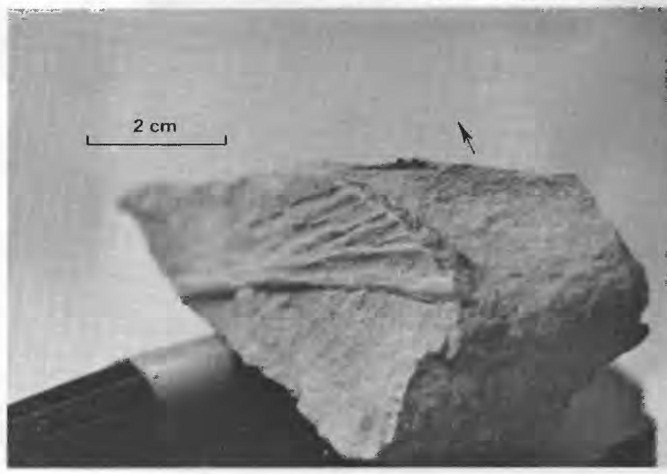

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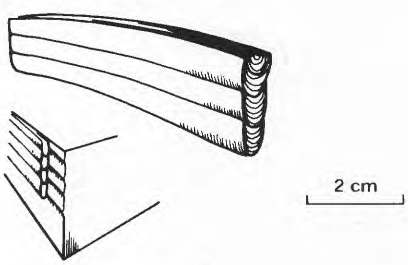

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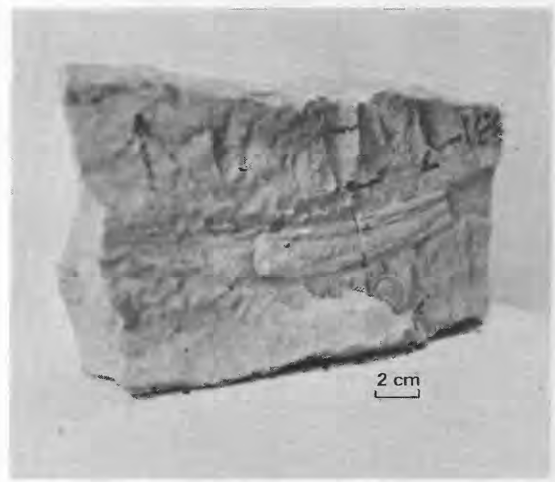

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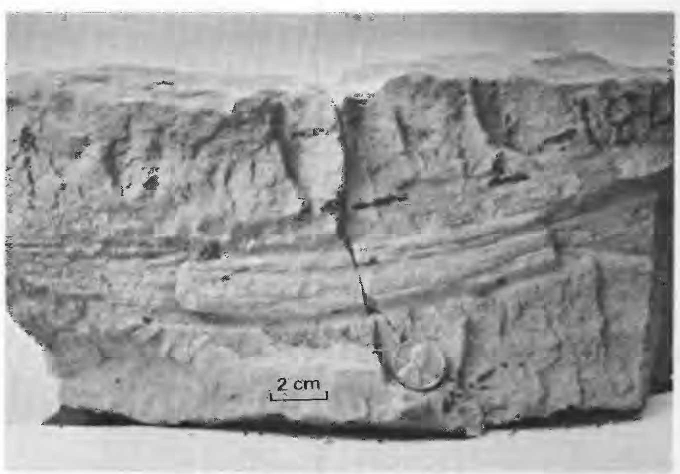


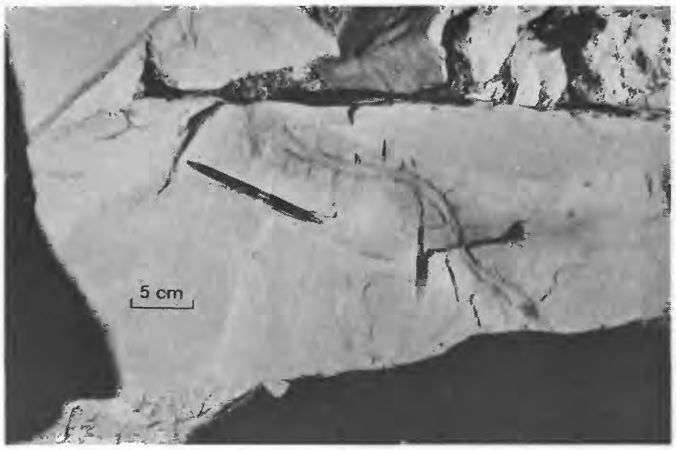
5

TEICHICHNUS IN THE LOWER SANDSTONE TONGUE OF THE KENILWORTH MEMBER

PLATE 2

FIGURE 1. *Asterosoma* burrow in fine-grained sandstone.

2. *Asterosoma* escape burrow in well-sorted sandstone.
3. Helicoid funnel at top of fine-grained sandstone bed; mouth of funnel is 20 cm across; specimen broken across trace fossil.
4. Helicoid funnels (arrows) at tops of *Asterosoma* burrows in sandstone.
5. Sketch of *Asterosoma*.
6. Sketch of helicoid funnel.



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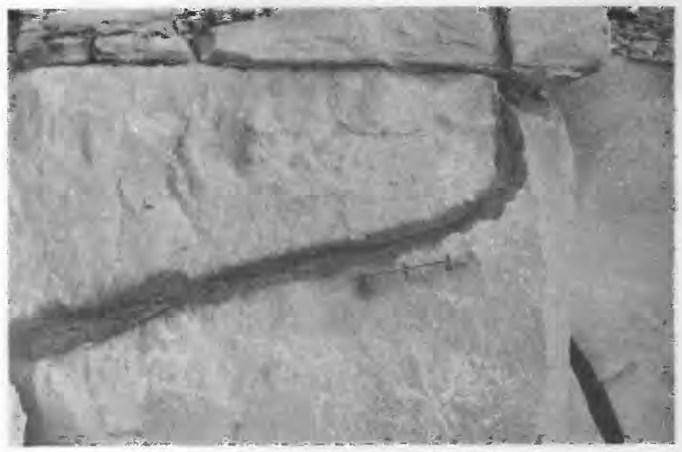

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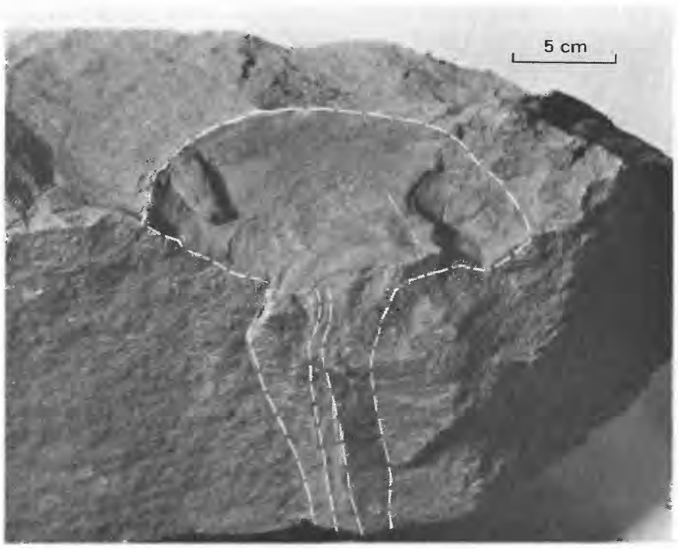

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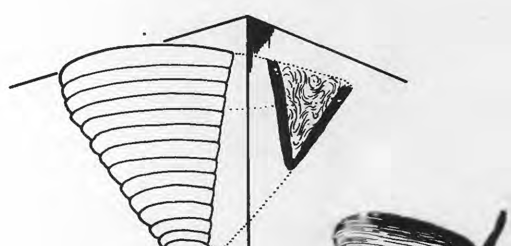


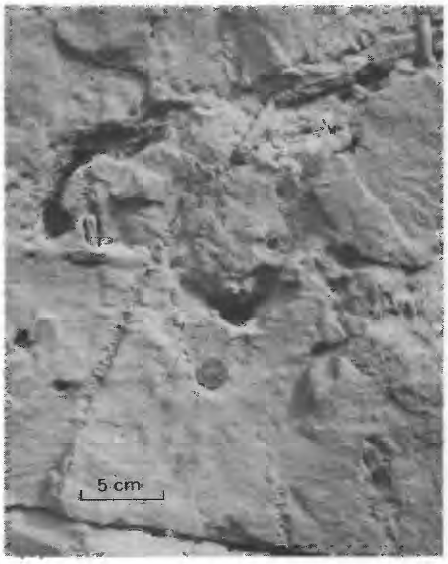
6

ASTEROSOMA AND HELICOID FUNNELS FROM KENILWORTH MEMBER

PLATE 3

[Specimens 1, 2, 3, 5, and 6 from upper sandstone facies of Sunnyside Member; 4 from upper tongue of Kenilworth Member]

FIGURE 1. External molds (center) and internal casts (upper right); view parallel to bedding surfaces.
2, 3. Longitudinal sections; view normal to bedding surfaces.
4. External mold.
5. External mold (scale in centimeters).
6. Filled burrow, illustrating branching nature; view parallel to bedding surfaces.
7. Sketch showing knobby external surface.



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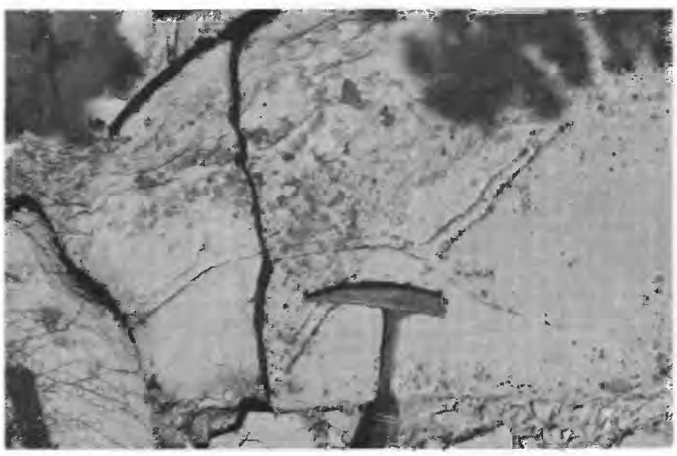

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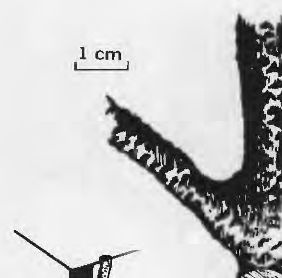

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