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CRETACEOUS SEDIMENTATION AND TECTONISM IN THE SOUTHEASTERN KAIPAROWITS REGION, UTAH

By

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ABSTRACT

Upper Cretaceous strata in the southeastern Kaiparowits region of south-central Utah consist of approximately 3,500 feet of interfingering sandstone, mudstone, shale, and coal in the Dakota Formation (oldest), Tropic Shale, Straight Cliffs Formation, and Wahweap Formation (youngest). The formations consist of several depositional facies that can be recognized by characteristic lithologies, bedding structures, and fossils; these are the alluvial plain, deltaic plain, lagoonal-paludal, barrier sandstone, and offshore marine facies. The distribution of facies clearly defines the paleogeography of the region during several cycles of marine transgression and regression.

The nonmarine beds were deposited on a broad alluvial coastal plain that was bordered on the west and southwest by highlands and on the east and northeast by the Western Interior seaway. The marine beds were deposited whenever the seaway advanced into or across the region.

The Dakota Formation and the lower part of the Tropic Shale were deposited in nonmarine and marine environments while the shoreline advanced generally westward across the region. The middle and upper parts of the Tropic Shale and the Tibbet Canyon and Smoky Hollow Members of the Straight Cliffs Formation were deposited in marine and nonmarine environments when the seaway had reached its greatest areal extent and began a gradual northeastward withdrawal. An unconformity at the top of the Smoky Hollow represents a period of erosion and possibly nondeposition before deposition of the John Henry Member of the Straight Cliffs.

The John Henry Member grades from nonmarine in the southwest to predominantly marine in the northeast, and was deposited during two relatively minor cycles of transgression and regression. The Drip Tank Member at the top of the Straight Cliffs Formation is a widespread sandstone unit deposited mainly in fluvial environments. Some of the beds in the northeastern part of the region were probably deposited in marine waters during the final incursion of the seaway into the Kaiparowits region. The overlying Wahweap Formation was deposited in nonmarine environments.

Slight but continued tectonism during Late Cretaceous time is indicated by lateral changes of facies and thickness variations that coincide at least partly with present structures. These criteria indicate that Laramide tectonism consisted of two phases. An early phase that lasted from about late Albian to late Campanian time included regional subsidence, basin downwarping, and movement on local folds and faults. A later phase that lasted from late Campanian to about late Paleocene time included regional uplift, monoclinal flexing, and probable new faulting, as well as continued basin downwarping and movement on local folds and probably on the older faults.

The principal economic resource in the Kaiparowits region is bituminous or subbituminous coal in the John Henry Member. Because basin downwarping and movement on local folds occurred during deposition, the thicker and more continuous coal beds are in the ancestral synclines and the deeper part of the structural basin. Presently indicated resources total 7.3 billion tons, but considerably larger quantities are probably present in the unexplored parts of the region. Several potential resources include ground water, titaniferous sandstone, and possibly oil and gas.

INTRODUCTION

The Kaiparowits region in south-central Utah contains coal-bearing strata of Cretaceous age that comprise a major undeveloped energy resource in the Western Interior of the United States. In the southeastern part of the region, much of the coal has been burned at the surface, and the resulting ash beds are concealed by talus or are indistinguishable from baked mudstone and sandstone except at perfect exposures in cliffs. At higher altitudes in the northeastern part of the region, soil, talus, and vegetation conceal the coal beds. Because of these factors, a detailed stratigraphic investigation was necessary in order to understand the nature of the coal deposits and to assist in a program of classifying Federal lands in the region for their mineral value.

This report describes the general stratigraphy and the depositional facies of the Dakota, Tropic, Straight Cliffs, and Wahweap Formations in the southeastern part of the Kaiparowits region. The stratigraphic relations in these formations and in younger formations in other parts of the region record sedimentation by marine and nonmarine processes and concurrent tectonism that is described here for the first time.

Geography

The Kaiparowits region is in the southwestern part of the Colorado Plateau Province in Kane and Garfield Counties, Utah (fig. 1). Most of the region has an irregular outline, but the northeast side is a nearly straight erosional escarpment named the Straight Cliffs. This escarpment is 1,000-2,000 feet high and extends 50 miles southeast from Escalante, Utah. The maximum distance across the region southwest from the Straight Cliffs is about 40 miles. The Kaiparowits region is a plateau that is prominently higher than the terrain that borders it on the northeast, southeast, and southwest. The northwestern part of the region merges with the high plateaus of central Utah.

The nearest community is Glen Canyon City, Utah, on the southwest side of Wahweap Creek canyon on U.S. Highway 89. About 6 miles south of the State line on Highway 89 is the town of Page, Ariz. No permanent habitations exist in the region, but during 1964-65, Resources Corp. maintained a camp appropriately named "Cretaceous, Utah" on Smoky Mountain about 2 miles southeast of Steamboat

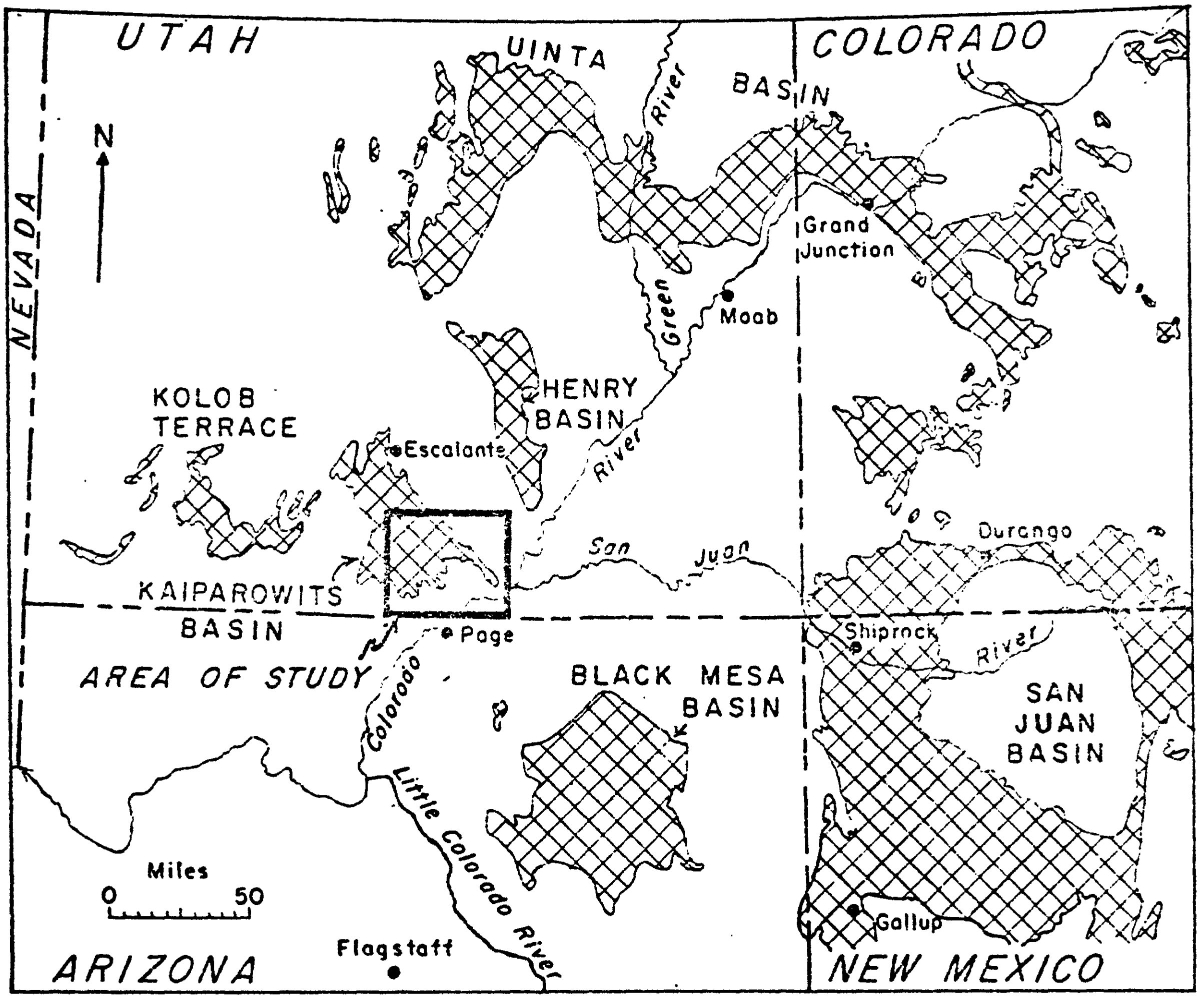


FIGURE 1.--Index map showing major Cretaceous outcrops in parts of Utah, Colorado, New Mexico, and Arizona. Modified from Fisher, Erdmann, and Reeside (1960, fig. 1).

Rock. Access is mainly by jeep, but the northeastern area between Croton Creek and the Straight Cliffs has no roads and access there is mainly by foot or horseback. Cattle grazing is the main use of the land.

Previous Work

The earliest comprehensive geologic study of the Kaiparowits region was made by H. E. Gregory and R. C. Moore during 1915-27 and was published in 1931. Earlier geologists passed through the region, but only a few observations and measured sections were published, and these are now mainly of historical interest. An excellent account of the geography and early exploration of the region is given in Gregory and Moore (1931, p. 1-35). Geologic investigations after 1931 included reconnaissance studies for uranium (Zeller, 1955) and titaniferous sandstone (Dow and Batty, 1961), coal mapping in the Tropic, Utah, area (Robison, 1966), and oil and gas exploration mainly in the northwestern part of the region (summarized in Kunkel, 1965).

Present Investigations

The present study is part of a comprehensive program by the U.S. Geological Survey of mapping, evaluating, and classifying the mineral resources in public lands in the Kaiparowits region. In the summer of 1963, H. A. Waldrop began geologic mapping of the Nipple Butte 15-minute topographic quadrangle in the southern part of the region, and during the fall of the same year the writer began a combined project of geologic mapping in the Gunsight Butte and Cummings Mesa quadrangles and determining the stratigraphic relations of coal-bearing strata throughout the southeastern part of the Kaiparowits region. H. D. Zeller, W. E. Bowers, and E. V. Stephens began mapping projects in the vicinity of Escalante, Utah, in 1964, 1965, and 1966, respectively. The mapping by Waldrop has been completed, and the results are currently being prepared for publication. A brief preliminary report on the coal-bearing Cretaceous formations in the southern part of the region was published by Peterson and Waldrop (1965), and a brief summary of the coal-bearing Straight Cliffs Formation was made by Peterson, Bowers, Waldrop, and Zeller (1966) and Peterson (1969).

Acknowledgments

The rather broad scope of the investigation in rugged and desert terrain necessitated the assistance and cooperation of many people. Personnel of the U.S. Geological Survey who have assisted in many ways are as follows. W. E. Bowers, E. V. Stephens, H. A. Waldrop, and H. D. Zeller contributed information and data from their own mapping projects in the region; discussions with them in the field and the office proved invaluable and was appreciated. During September-October 1965, a brief reconnaissance survey of the central part of the region was conducted by H. L. Cullins, D. L. Gaskill, G. A. Izett, E. M. Schell, and R. R. Trengove under the supervision of G. H. Horn, and some of their data is used in this report. L. G. Schultz aided considerably in X-ray determinations of clay minerals. W. A. Cobban identified many of the fossils and freely contributed information on broad regional relationships of Cretaceous strata in the Western Interior. The thin sections were prepared by M. E. Johnson, and most of the plates and figures were drafted by D. F. Stopp, R. R. Trengove, and May Wakabayashi. The following personnel gave capable field assistance during the summers of the years noted: C. J. Flynn and R. L. Sutton, 1964; G. W. Horton, 1964-65; B. E. Law, 1966-67; and O. L. Ligon, Jr., 1968.

Cooperation in many ways was offered by personnel of Atlantic-Richfield Co., Consolidated Coal Co., Peabody Coal Co., Resources Corp., the U.S. National Park Service--Glen Canyon National Recreation Area, and the Bureau of Reclamation--Glen Canyon Division. Horses and packing during 1968 were furnished by Walter Smallcanyon of Tonalea, Ariz., and McKay Bailey of Escalante, Utah.

The fossil collections were identified by the following: D. H. Dunkle, Nicholas Hotton 3d, and G. E. Lewis (vertebrates); J. F. Mello (foraminifers); J. E. Hazel (marine ostracodes); I. G. Sohn (fresh-water ostracodes); R. A. Scott and R. H. Tschudy (spores and pollen); R. A. Scott and J. A. Wolfe (wood, fruits, and leaves); R. E. Peck (charophytes); N. F. Sohl (gastropods). Molluscs, worm tubes, corals, and broad categories of shark teeth and decapod crustaceans were identified by W. A. Cobban and the writer.

METHODS OF STUDY

A geologic mapping program to cover the entire Kaiparowits region is still in progress, although sufficient work has already been accomplished to determine the stratigraphic relations upon which this report is based. The various formations, members, coal zones, and coal beds are mapped at the scale of 1:24,000 with plane table and alidade aided by high-altitude aerial photographs. In the stratigraphic study, significant beds or contact relations were traced throughout the region wherever exposures and access permitted. Sections of strata were measured by hand leveling or with 6- and 50-foot tapes, although a 5-foot jacob staff and Abney level were used where the beds dip more than about 5°. Approximately 330 published and unpublished sections, of which about 60 were measured by persons other than the writer, were evaluated. Nearly 190 sections are illustrated in this report, and due credit is given where the sections were measured by others. Sandstone, mudstone, and shale samples were collected from selected sections for laboratory analysis. Fossils were collected throughout the region, and a summary list is given in the description of each stratigraphic unit. Detailed information concerning each collection is given in the appendix.

Approximately 1,300 measurements of the azimuth of dipping crossbedding were made to determine the general direction of flow of fluvial and marine currents. The results are plotted as rose diagrams that include: the number of measurements in the center of the rose; the resultant, which is the vector mean of the measurements; and the consistency factor, a numerical expression for the consistency of direction of the individual measurements (Craig and others, 1955, p. 146-147). A consistency factor of 1.00 would be obtained if all the crossbedding dipped in the same direction; a consistency factor less than 0.20 indicates an insignificant trend (Stewart and others, 1959, p. 493).

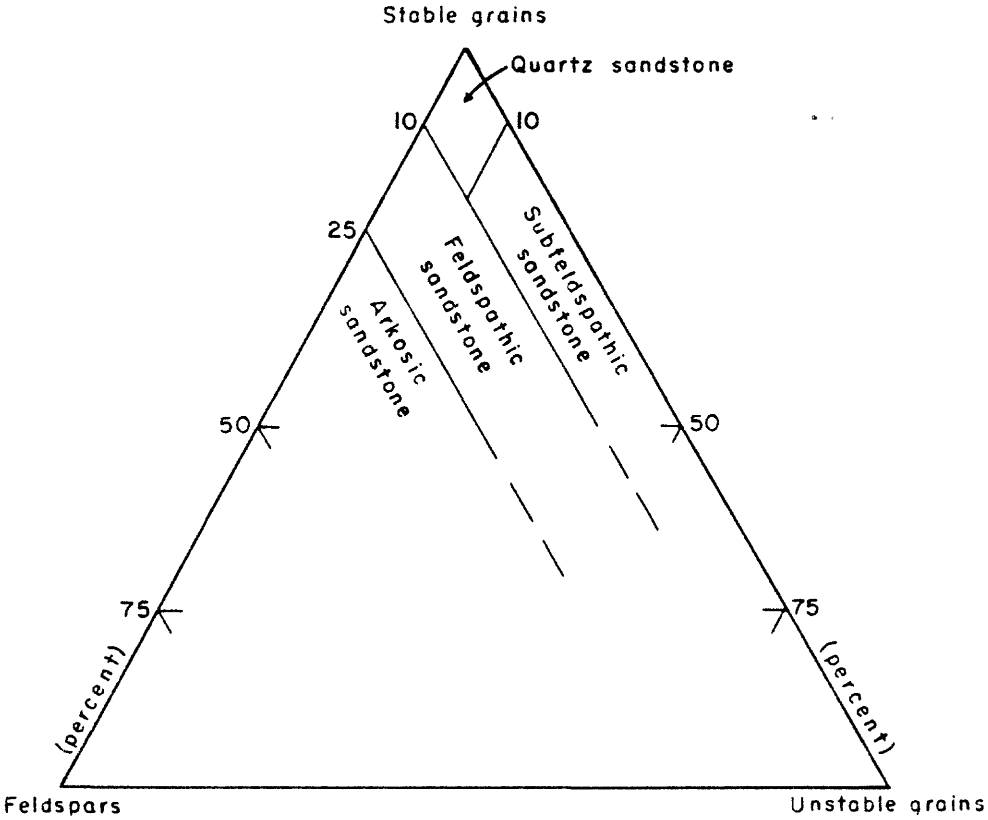
The study of depositional facies generally proceeded along with the mapping. Environments of deposition were determined first in areas where the relations were reasonably clear, such as in a regressive sequence of beds or where fossils were abundant. The distinguishing or characteristic lithologic, bedding, paleontological, or other criteria were noted and evaluated with respect to criteria in the literature. This was aided by the writer's previous experience in studying Cretaceous rocks in the San Juan Basin of New Mexico and examination during the spring of 1967 of similar modern environments of deposition in the northern Gulf of Mexico coastal region. As the field studies progressed, several categories of depositional facies were established, tested, modified when necessary, and retested until a satisfactory and reasonably consistent scheme of broad facies classification of the strata was established.

Laboratory investigations consisted of qualitative and quantitative determinations of the major lithologies in the following manner:

Thin sections of 276 sandstone samples, mainly from four measured sections of the Dakota and Straight Cliffs Formations, were stained with Högberg solution which stains calcite blue and leaves other carbonates unstained. The unstained carbonate was determined as dolomite from X-ray analyses of 12 samples. The other constituents were identified by ordinary optical methods that were aided, where possible, by the X-ray analyses. Three hundred points (excluding cement) were counted in each thin section to determine mineral percentages.

Other than quartz, many of the constituents of the nonmarine sandstones have been altered to silt- and clay-size materials, and the textural parameters obtained from these rocks would not be representative of the original sediment if the parameters were based strictly on quantitative measurements of the different sizes of materials. For this reason, median grain size and sorting were obtained partly by comparison with standardized thin sections calibrated by the methods of Friedman (1958, 1962) and partly by visual evaluation of the size distribution of the quartz grains. Although this method is somewhat subjective, the parameters thus obtained are more representative of the original sediment than a purely objective evaluation of the materials. Another textural parameter, the maximum clast diameter, was obtained by observation in the field and is the intermediate diameter of the largest grain, pebble, or cobble found at the outcrop.

The sandstone classification (fig. 2) is a simplified version of a classification proposed by Gilbert (1958, p. 292-293). If the sandstone contains 10 or more percent matrix, it is termed impure (example, impure feldspathic sandstone), but the diagram is based only on the relative proportion of stable grains, unstable grains, and feldspars.



Stable grains = quartz, chert, and quartzite.
Unstable grains = clastic dolomite and clastic calcite.

FIGURE 2.--Classification of sandstones. Percentages indicate relative proportion of stable grains, unstable grains, and feldspars. All sandstones in this study contain more than 50 percent stable grains. Matrix is not included in the diagram but if 10 or more percent matrix is present the rock is termed impure (example, impure feldspathic sandstone).

X-ray diffraction traces were run on 32 samples of shale and mudstone; identification and quantitative measurements were made by the methods of Schultz (1964) and Weaver (1958). Six traces were made of each sample; one was on the unoriented powder sample, and five were run on the following oriented aggregate samples: untreated, glycol treated, heated to 300°C, heated to 550°C, and magnesium chloride treated. These methods permit chlorite, kaolinite, illite, montmorillonite, vermiculite, biedellite, and mixed-layer clays to be distinguished.

Rock colors were noted by comparison with the G.S.A. Rock-Color Chart (Goddard, 1963), and bedding terminology follows the recommendations of McKee and Weir (1953). Grain-size terminology is listed according to the modified Wentworth Grade Scale given in Dunbar and Rodgers (1957, p. 161). Matrix in the thin-section analyses includes clastic materials finer than coarse silt size (finer than 1/32 mm). Where possible, locations are referred to the measured sections (pl. 1), which eliminates the cumbersome quarter-section-township-range nomenclature.

ORGANIZATION

The Upper Cretaceous formations are composed of widely varying lithologies with complexly interfingering relations that are best understood in terms of the environments in which they were deposited. For this reason, the remainder of the report is divided into the following four chapters: (1) Description of the lithologic character, general stratigraphic relations, and age and correlation of the stratigraphic units; (2) the depositional facies and the distribution of facies in the various formations; (3) sedimentation and tectonism, in which the conditions of deposition are interpreted from the distribution of facies and the tectonic evolution of the region is hypothesized from the lateral changes of facies and thickness variations; and (4) economic resources.

UPPER CRETACEOUS FORMATIONS

The Cretaceous rocks of the southeastern Kaiparowits region include the Dakota Formation, Tropic Shale, Straight Cliffs Formation, and Wahweap Formation (table 1). Two other Cretaceous formations present in the northwestern Kaiparowits region were not included in the investigations. These are the Kaiparowits Formation and an overlying unnamed unit of mudstone and conglomerate recently discovered by W. E. Bowers (1968). With the possible exception of the poorly dated lower beds of the Dakota Formation, no Early Cretaceous rocks are known to occur in the region.

Local conglomerate beds and lenses as much as about 80 feet thick occur at the top of the Morrison Formation (Upper Jurassic) and can be easily mistaken for basal beds of the Dakota. Lateral tracing in the field indicates that these conglomerates interfinger with other lithologies at the top of the Morrison and should not be included with other conglomerate beds that do occur at the base of the Dakota.

The geologic structure of the Cretaceous formations is fairly simple: the beds generally dip less than 3° approximately northwest toward the structurally deeper part of the Kaiparowits basin, which is several miles northwest of the area of study shown on plate 1. Dips as much as about 10° occur in the northeastern part of the region at Grand Bench monocline and Croton syncline and in a small area in the central part on the northeast flank of Smoky Mountain anticline in the vicinity of Steamboat Point (T. 40 S., R. 3 E.). The steepest dips in the southwestern part are at Echo monocline where Cretaceous strata dip as much as 13° eastward. Displacement on the faults is small; at Echo monocline the maximum noted by Waldrop and Sutton (1966a) in Cretaceous rocks is 80 feet and the maximum displacement on faults in the remainder of the region is 44 feet.

TABLE 1.--Summary of Cretaceous formations in the southeastern Kaiparowits region

SERIES	STAGE	STRATIGRAPHIC UNIT		THICKNESS (FT)		DESCRIPTION
Upper Cretaceous (part)	Campanian					Top eroded
		Wahweap Formation		1172+ - 1502+		Interbedded gray to light-brown sandstone and yellowish-green mudstone; locally fossiliferous; nonmarine
		Straight Cliffs Formation	Drip Tank Member	About 1130-1620	141-255	Light-gray to light-brown sandstone and conglomeratic sandstone; nonmarine in southwest to partly marine in northeast
	Santonian Coniacian		John Henry Member		660-1133	Interbedded white to light-brown sandstone, yellowish-green mudstone, carbonaceous mudstone, and coal; locally fossiliferous; nonmarine in southwest to marine in northeast
						Unconformity
	Turonian		Smoky Hollow Member		24-132	Interbedded white to brown sandstone, yellowish-green mudstone, carbonaceous mudstone, and coal; nonmarine
			Tibbet Canyon Member		70-185	Gray to light-brown sandstone interbedded with gray mudstone near base; fossils scarce; mainly marine
		Tropic Shale		610-705		Gray shale and calcareous shale, grades to mudstone near base and top; limestone concretions in lower 40 feet; fossiliferous; mainly marine
	Cenomanian	Dakota Formation	Upper member	14-168	0-68	Interbedded light-brown sandstone and gray mudstone; locally fossiliferous; mainly brackish-water to marine
Lower Cretaceous			Middle member		4-76	Interbedded gray to brown sandstone, yellowish-green mudstone, carbonaceous mudstone, and coal; nonmarine
			Lower member		0-66	Gray to brown conglomerate and sandstone; nonmarine
		?				

Dakota Formation

The Dakota Formation was originally termed "formation no. 1" by Meek and Hayden (1856) for a series of sandstones and clays at the base of the Cretaceous System in eastern Nebraska. Later, the same authors used the name "Dakota Group Formation No. 1" for the same beds and gave a more expanded discussion of the formation, noting that it also contained seams of impure lignite (Meek and Hayden, 1861). In the Kaiparowits region, Gregory and Moore (1931, p. 95) applied the term "Dakota(?) sandstone" to "The irregularly bedded sandstone [that] includes sandy and carbonaceous shale, poor coal, and locally conglomerate." Unfortunately, Gregory and Moore used paleontological criteria to distinguish the Dakota from the overlying Tropic Shale: "a rather arbitrary division of the lowermost Upper Cretaceous strata has been made; the sandstone, coal, and shale below the lowest marine fossil-bearing beds are classed as Dakota(?), and the beds above them, including sandstone and coal, are referred to the Tropic shale."

Lawrence (1965, p. 75-78) pointed out the inadequacy of formation contacts based on the presence or absence of certain types of fossils. He redefined the Dakota and Tropic Formations in southwestern Utah on a lithologic basis and proposed that the upper contact of the Dakota should be "above the highest ledge-forming sandstone in the basal part of Gregory and Moore's Tropic." Because the Dakota contains an abundance of rock types other than sandstone, Lawrence followed Van De Graaff's (1963, p. 67) suggestion to call it the Dakota Formation. Lawrence also suggested dropping the query after Dakota(?), a practice that has been adopted by many workers in other parts of the Colorado Plateau.

The advantage of Lawrence's redefinition is that the heterogeneous lithologies of the Dakota Formation are clearly separated from the essentially uniform lithology of the overlying Tropic Shale, and the redefined formations are easily recognized, mappable units. Accordingly, Lawrence's redefinition of the Dakota Formation and the Tropic Shale has been adopted throughout the Kaiparowits region. In the southeastern Kaiparowits region, however, it is significant to note that the contact separating the middle and upper members of the Dakota as used in this report is essentially the same contact that Gregory and Moore intended to separate their "Dakota(?) sandstone" and "Tropic shale."

The Dakota Formation ranges in thickness from 14 to 168 feet and consists mainly of mudstone, carbonaceous mudstone, sandstone, conglomerate, and coal. The formation weathers to a series of dark ledges and slopes above the light-gray cliffs of the underlying Jurassic formations and below the dark-bluish-gray slopes of the overlying Tropic Shale (figs. 3, 4, 5). The Dakota is here divided into the lower, middle, and upper members for purposes of stratigraphic discussion and synthesis.

LOWER MEMBER

The lower member of the Dakota Formation consists mainly of chert-pebble conglomerate in the southwestern part of the region near Wahweap Creek. Farther northeast, the member consists mainly of pebbly sandstone or sandstone. The member commonly forms cliffs or ledges, and where less than about 5 feet thick it is generally concealed by talus.

The conglomerate is generally yellowish gray (6Y 8/1), and the clasts are composed mainly of chert (which includes silicified limestone) with less than about 10 percent quartzite, petrified wood, and feldspathic sandstone pebbles. The estimated median diameter of the clasts is about 0.5 inch and the intermediate diameter of the largest cobbles is about 4 inches. Approximately 10-20 percent of the conglomerate is composed of sand-, silt-, and clay-size matrix, and the beds are poorly to moderately cemented by calcite. The following composition is from a count of 447 pebbles made near Wahweap Creek and is typical of the lower member.

Composition of pebbles in conglomerate in lower member of Dakota Formation (meas. sec. 12)

		Percent
Chert		91
Gray	41	
Gray, contains fossils	5	
Black	17	
White	14	
Orange	7	
Banded black and white	5	
Red	2	
Quartzite		6
Petrified wood		2
Feldspathic sandstone		1
		100

FIGURE 3.--Dakota Formation in southwestern part of region on dip slope of Echo monocline above Wahweap Creek. Formation is 117 feet thick at measured section 9 in about center of picture. Je, Entrada Sandstone (Jurassic age); Dakota Formation: Kdl, lower member, Kdm, middle member, Kdu, upper member; Kt, Tropic Shale; Ks, Straight Cliffs Formation.

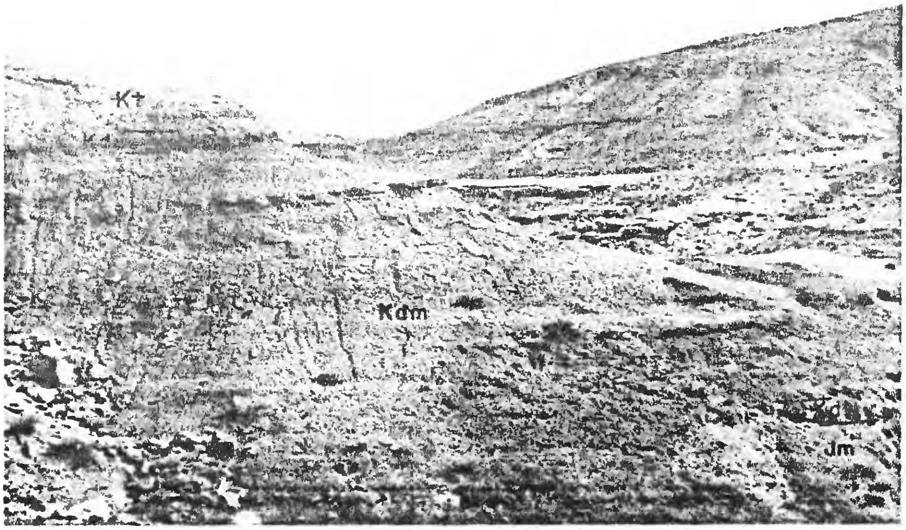


FIGURE 4.--Dakota Formation in central part of region about 1½ miles east of east end of Smoky Mountain. Formation is 40 feet thick at measured section 66 just off picture to left. Jm, Morrison Formation (Jurassic age); Dakota Formation: Kdl, lower member, Kdm, middle member, Kdu, upper member; Kt, Tropic Shale.

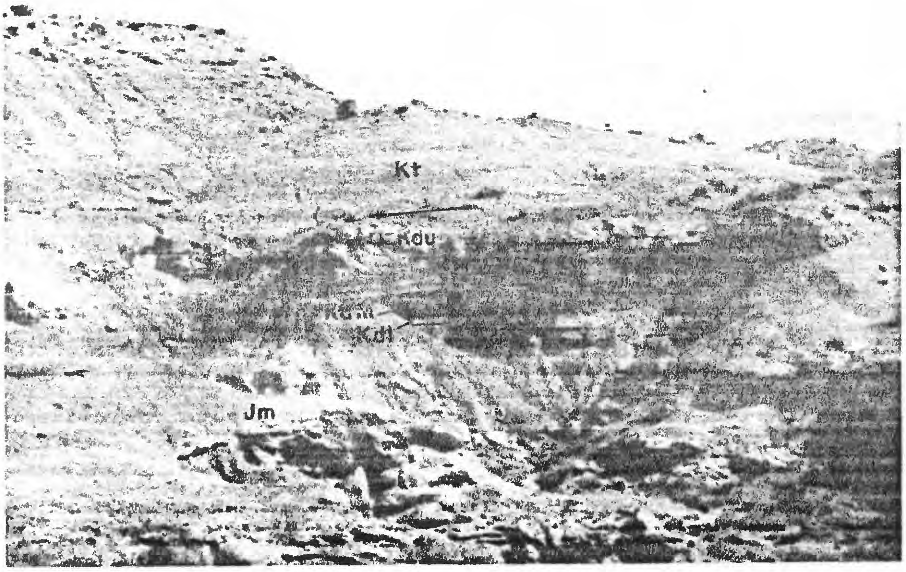


FIGURE 5.--Dakota Formation in northeastern part of region about half a mile northwest of Little Valley Canyon. Formation is 24 feet thick at measured section 98 about three-fourths mile northeast. Jm, Morrison Formation (Jurassic age); Dakota Formation: Kdl, lower member, Kdm, middle member, Kdu, upper member; Kt, Tropic Shale.

Sandstone and pebbly sandstone is interbedded with the conglomerate or is the dominant lithology in the central and northeastern parts of the region. The sandstone is generally yellowish gray (5Y 8/1) or locally light brown (5YR 5/6), fine to coarse grained, poorly to moderately sorted, and poorly to moderately cemented by calcite or rarely by silica. Black grains and flecks of carbonaceous material are locally common and help to distinguish these beds from sandstones at the top of the underlying Morrison Formation. In thin section, many of the grains are well rounded or fragmented with a few well-rounded edges still preserved. The quartz grains are strained, and inclusions in the quartz are absent or of the regular, irregular, or acicular types (Mackie, 1897, p. 152). The feldspars and accessory minerals are a small and almost insignificant part of the total mineral assemblage. Most of the clay minerals in the matrix have the optical properties of the kaolin group of clay minerals (Kerr, 1959). The following composition is an average of the modal analyses shown on plate 2. According to the classification used in this report, a rock of the following composition would be termed an impure quartz sandstone.

Average of eight modal analyses, in percent, of sandstone in lower member of Dakota Formation (cement not included)

			All constituents	Constituents (1), (2), (3)
(1)	Stable grains		87	99
	Quartz	80		
	Chert	6		
	Quartzite	1		
(2)	Feldspars		1	1
(3)	Unstable grains		0	0
(4)	Matrix		12	
(5)	Accessory minerals (biotite, muscovite, tourmaline, zircon)		≤ 1	
			100	100

Bedding is generally indistinct in the conglomerates and sandstones of the lower member. In the southwestern part of the region, the member contains small channels that are about 10-30 feet wide and 5-10 feet deep. Larger channels 1-2 miles wide are present at the base of the member and probably were small stream valleys that trended northeastward (pl. 3). The lithologies in both types of channels are not significantly different from those in the rest of the member. The bedding, where present, consists of low- to high-angle medium- to large-scale trough cross-stratification that dips down the axis of the channels.

Minor lithologies in the lower member include dark-gray (N3) carbonaceous mudstone that is slightly more silty than carbonaceous mudstone in the overlying middle member and scarce beds of light-gray (N7) to dusky-yellow (5Y 6/4) bentonitic mudstone. The mudstone occurs in lenses as much as about 5 feet thick and also as tongues of the middle member.

The lower member is 0-66 feet thick, and this variation is attributed to several factors: interfingering with the middle member, channeling at the base, erosion by streams during deposition of the middle member, or local nondeposition. Although this suggests complete randomness in thickness variations, two generalizations can be made that have significance as far as deposition is concerned. First, the lower member generally thins northeastward from Wahweap Creek to Fiftymile Point, indicating that the main source area was to the southwest. Second, the member is thicker in synclines and downthrown fault blocks and thinner in anticlines and upthrown fault blocks in several parts of the region, indicating that the folds and faults were probably growing tectonic features during deposition.

The basal contact of the lower member is a disconformity with as much as 40 feet of relief in any local area (pls. 3, 4). In a regional sense the unconformity is slightly angular, and the Dakota rests on successively older Jurassic formations from northeast to southwest (fig. 6).

The upper contact of the lower member is concealed by talus and soil in many places, but where exposures are adequate the lighter colored sandstone and conglomerate of the lower member contrast sharply with the darker mudstone and sandstone of the middle member (fig. 3).

Fossils are rare in the lower member, and only a few poorly preserved fragments were found in a conglomerate bed about 5 miles east-southeast of Glen Canyon City. These were identified by Nicholas Hotton 3d. and D. H. Dunkle as carapace fragments of a turtle that could have been a mud turtle. The lower member is probably about early Cenomanian in age on the basis of stratigraphic position beneath the middle member which is probably about early to middle Cenomanian in age, interfingering of the upper part of the

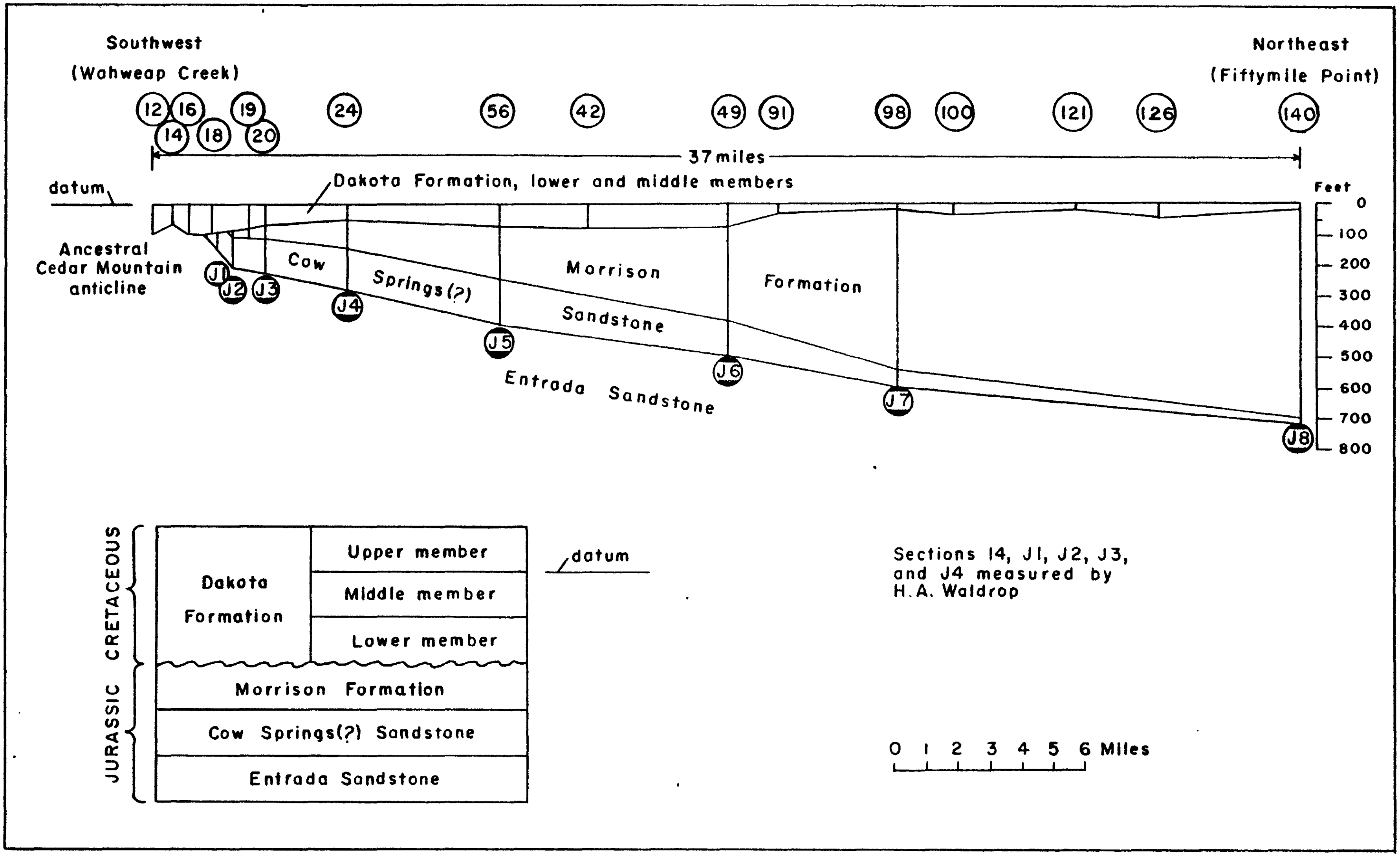


FIGURE 6.--Stratigraphic section showing southwestward regional beveling of Jurassic formations and uplift of ancestral Cedar Mountain anticline prior to deposition of the Dakota Formation.

lower member with the lower part of the middle member, and the lack of unconformities in the Dakota. Direct evidence is lacking, however, and part or all of the lower member conceivably could be of late Early Cretaceous age.

Some of the chert pebbles contain fossils that collectively indicate a source of late Paleozoic age. A list of these fossils from throughout the region follows.

Fossils in chert pebbles in the lower member
of the Dakota Formation

- Protozoa
    - Undetermined fusulinids
- Coelenterata
    - *Syringopora*? sp.
- Echinodermata
    - Undetermined pelmatozoan columnals
- Bryozoa
    - *Archimedes* sp.
- Brachiopoda
    - Undetermined articulate forms

MIDDLE MEMBER

The middle member of the Dakota Formation is a ledge- and slope-forming unit of interbedded sandstone, mudstone, carbonaceous mudstone, and coal. The rocks weather brown, yellowish green, or black and are fairly well exposed in the southwestern and central parts of the region but are poorly exposed in the northeastern part of the region (figs. 3, 4, 5).

The sandstone beds are light gray (N7) to grayish orange (10YR 7/4) and yellowish gray (5Y 7/2), very fine to fine grained, moderately sorted, and cross-stratified. Fluvial channel sandstone beds in which the crossbedding dips consistently in one direction down the axis of the channel are common in the southwestern and central parts of the region (pl. 5). Scattered quartz and chert granules or small pebbles occur locally at the base of the channels, and leaf impressions or plant fragments are scarce but occur locally at the top.

The sandstones consist mainly of subangular to subrounded slightly strained quartz grains containing all the major types of inclusions. The feldspars amount to less than 5 percent of the rock and are mainly of the plagioclase varieties (oligoclase and andesine), although scarce potassium feldspar is also present. The clastic dolomite grains are polycrystalline aggregates or monocrystalline grains. Approximately 10-20 percent of the sandstone is silt- and clay-size matrix in which most of the clay minerals have the optical properties of the kaolin group. The accessory minerals are a small and almost insignificant part of the mineral assemblage. Most of the sandstones are well cemented by calcite. The following composition is an average of the modal analyses shown on plate 2. According to the classification used in this report, a rock of the following composition would be termed an impure quartz sandstone.

Average of six modal analyses, in percent, of sandstone in the middle member of the Dakota Formation (cement not included)

		All constituents	Constituents (1), (2), (3)
(1) Stable grains		75	89
Quartz	71		
Chert	3		
Quartzite	1		
(2) Feldspars		2	3
(3) Unstable grains		7	8
Clastic dolomite	7		
(4) Matrix		15	
(5) Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		1	
		100	100

Dusky-yellow (5Y 6/4) to light-olive-gray (5Y 5/2) mudstone that weathers to a yellowish-green color is the most abundant type of mudstone in the southwestern and southern parts of the region. It is very thin to thin bedded. Sample 222 in table 2 is from an outcrop that is typical of the dusky-yellow lithology and shows a mixture of about 10-20 percent each of quartz, calcite, kaolinite, illite, and mixed-layer clays and a small amount of chlorite. Sample 221 (table 2) is from light-olive-gray mudstone and shows somewhat larger percentages of quartz, montmorillonite, and mixed-layer clays and somewhat lower percentages of chlorite, kaolinite, and illite. Montmorillonite in the mixed-layer clays causes the rock to swell slightly when moistened, thus meriting the descriptive term "bentonitic." Small blackish-red (5R 2/2) to moderate-brown (5YR 4/4) concretions composed mainly of siderite occur locally in these beds.

TABLE 2.--X-ray diffraction analyses, in percent, of mudstone and bentonite from the middle member of the Dakota Formation

	Benton-ite	Carbon-aceous mudstone	Light-olive-gray mudstone	Dusky-yellow mudstone
Sample number:	183	220	221	222
Major constituents:				
Quartz	0	14	30	20
Potassium feldspar	0	0	2	6
Plagioclase feldspar	0	0	0	2
Calcite	0	0	1	11
Dolomite	0	0	0	8
Gypsum	0	0	0	1
Clay minerals	100	86	67	52
Clay minerals:				
Chlorite	1	0	1	6
Kaolinite	11	71	11	17
Illite	0	0	7	11
Montmorillonite	17	7	16	1
Mixed-layer*	71	8	32	17
Clay minerals as proportion of clay fraction:				
Chlorite	1	0	1	11
Kaolinite	11	83	16	32
Illite	0	0	11	22
Montmorillonite	17	8	24	1
Mixed-layer*	71	9	48	34

Location of samples

183. Middle member, 9 ft above base of formation; Sit-down Bench, near meas. sec. 86; from bentonite marker bed.
220. Middle member, 21 ft above base of formation; south side of Smoky Mountain, meas. sec. 38.
221. Middle member, 34 ft above base of formation; same locality as 220.
222. Middle member, 40 ft below top of formation; south side of Nipple Bench, near meas. sec. 18.

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* = mixed-layer illite-montmorillonite clays.

Pale-brown (5YR 5/2) to black (N1) laminated to very thin bedded carbonaceous mudstone is the most common type of mudstone in the central and northeastern parts of the region. Sample 220 in table 2 is from an outcrop that is typical of this lithology and shows a composition predominantly of kaolinite. The abundance of carbonaceous materials and the association with coal beds indicate that this lithology was deposited in paludal conditions, and according to Keller (1957), kaolinite is the common end product of authigenic processes acting on clay minerals in this type of environment.

Minor, but significant, lithologies in the middle member include four coal beds and a bentonite marker bed. The coal beds are designated by numbers 1 to 4, with coal bed 1 as the oldest and coal bed 4 as the youngest. Some of the coals reach a maximum thickness of about 4 feet, but this is rare and generally they are less than about 2 feet thick. Coal bed 4 occurs at the top of the middle member and usually can be identified by lateral persistence along the outcrop and by means of fossils or key sandstone beds just above in the upper member of the formation. The bentonite marker bed occurs between coal beds 1 and 2 and is an ideal marker bed that, as a rough rule of thumb, lies about at the top of the lower third of the middle member. Exact correlation of the lower three coal beds is generally not possible where this marker bed is missing or where the coals are only a few inches thick. The bentonite bed is as much as about 2 feet thick but generally is less than 1 foot thick. An analysis of clay minerals from this bed (sample 183, table 2) indicates that it is composed mainly of mixed-layer clays and a small quantity of montmorillonite and kaolinite.

The middle member is a maximum of 76 feet thick at Wahweap Creek and irregularly thins northeastward to a minimum of 4 feet at Fiftymile Point (fig. 7; pls. 6, 7, 8). Like the lower member, the middle member thins over depositional highs that coincide with anticlines or some of the upthrown fault blocks and thickens in synclines and some of the downthrown fault blocks.

The upper contact of the middle member is the top of coal bed 4 or equivalent strata. This contact is sharp and is marked by the highest coal or carbonaceous mudstone bed in the Dakota throughout the central and northeastern parts of the region. Near Wahweap Creek a few higher thin coal beds are present, but the contact can be distinguished readily by brackish-water fossils in beds immediately overlying coal bed 4. Marine or brackish-water

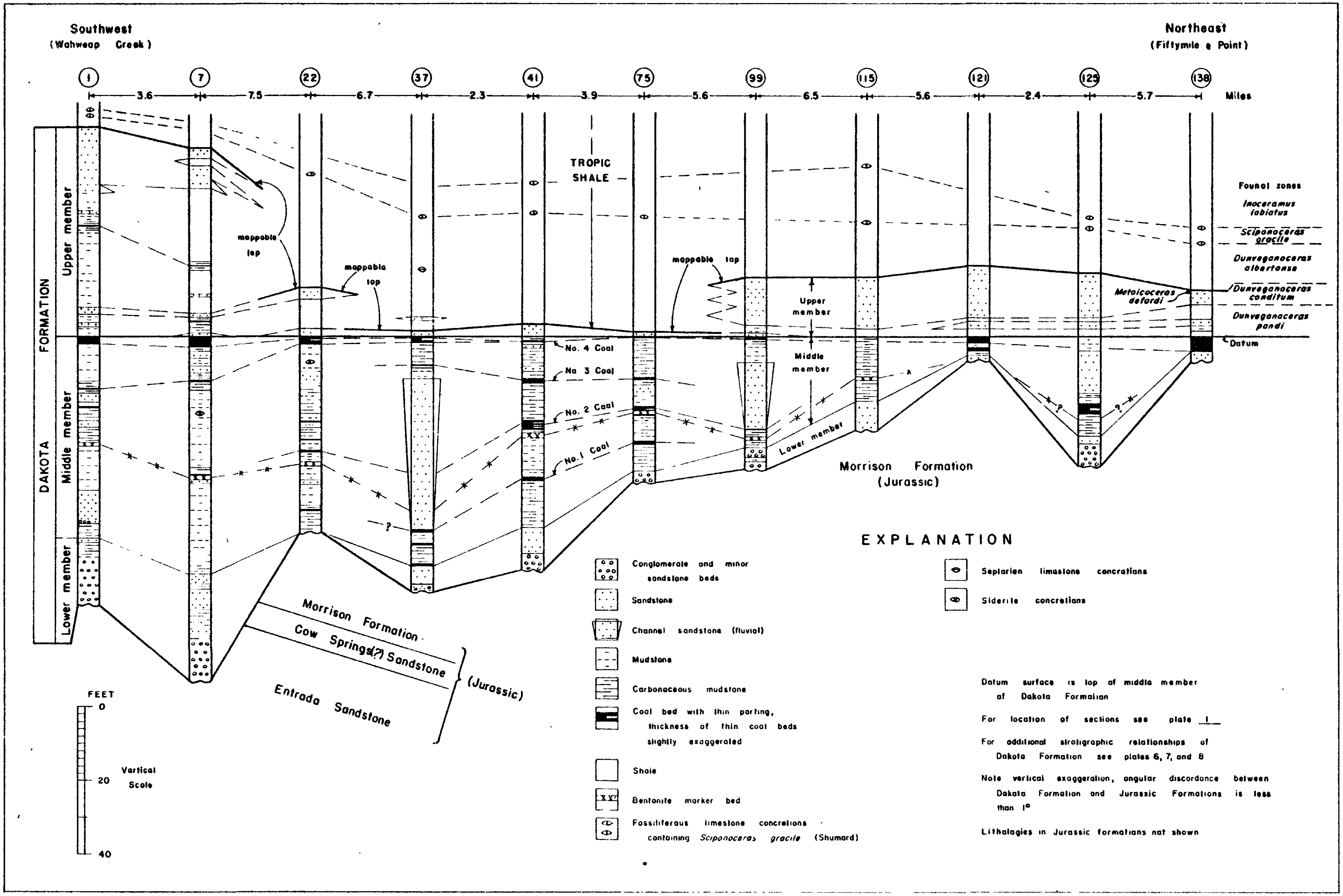

FIGURE 7.--Selected measured sections showing relations of members and informal units in the Dakota Formation.

fossils have not been found in the middle member, and apparently they are restricted to the upper member of the formation.

Megafossils are rare and are poorly preserved in the middle member. The fluvial channel sandstones locally contain a few bone fragments, but the beds are too well cemented and the fragments too small to merit collection. Fossils collected by H. A. Waldrop and the writer include a fresh-water pelecypod, *Unio* n. sp., identified by W. A. Cobban, and undetermined plant leaves. The microfossil genera listed below are from samples collected by H. A. Waldrop and the writer from strata in the middle member between the bentonite marker bed and coal bed 4; they were identified by R. A. Scott and R. H. Tschudy.

Spore and pollen genera in the middle member
of the Dakota Formation

Botryococcus
Anemia
Cicatricosisporites
Appendicisporites
Gleicheniidites
Monosulcites
Tricolpopollenites
Retitricolpites

According to R. A. Scott and R. H. Tschudy (oral commun., 1966), the tricolpate pollen indicate an age no older than Albian. The absence of angiosperm pollen other than the tricolpate type suggests an age no younger than Cenomanian, and late Cenomanian index fossils in overlying beds in the upper member of the Dakota confirm this. Another sample collected by H. A. Waldrop from strata in the middle member below the bentonite marker bed contained a florule similar to the above but it lacked tricolporate and other complex pollen grains. According to R. A. Scott (oral commun., 1966), this florule is not diagnostic but would not be inconsistent with an Early Cretaceous age.

Stratigraphic and paleontological criteria from nearby regions offer somewhat conflicting evidence for the age of the lower and middle members of the Dakota in the Kaiparowits region. About 90 miles northwest of Wahweap Creek near Cedar City, Utah, Paul Averitt collected the Early Cretaceous pelecypod *Protelliptio douglassi* (Stanton) from strata reassigned to the Dakota by Lawrence (1965, p. 80-83). The fossil came from a thin limestone bed about 400 feet below the top of the Dakota which, in that area, is about 1,075 feet thick (Averitt, 1962, p. 26). Lawrence (1965, p. 81, fig. 4) showed that the Dakota thins eastward from Cedar City to the Kaiparowits region mainly by thinning in the middle of the formation, and thus a lower undetermined part of the Dakota in the southeastern Kaiparowits region could be of Early Cretaceous age. On the other hand, palynomorphs from the Dakota Sandstone in Black Mesa basin of northeastern Arizona suggest a Cenomanian age (Agasie, 1969).

In the Kaiparowits region, the contact between the middle and upper members of the Dakota is marked by a change in environments of deposition, but the contact apparently is not an unconformity and the middle member is probably only slightly older than the upper member. The late Cenomanian cephalopod Metoicoceras defordi Young was found in the upper member, and the close relationship of the two members suggests that the middle member is probably about early to middle Cenomanian in age.

UPPER MEMBER

The upper member of the Dakota Formation is composed of sandstone, mudstone, and shale and minor amounts of carbonaceous mudstone and coal. The thicker sandstone beds crop out as prominent cliffs and ledges, but the less resistant beds form slopes that are commonly concealed by talus. The member interfingers with the lower part of the Tropic Shale, and many of the mudstone and shale beds are tongues of the Tropic that are too thin to map separately.

Sandstone beds in the upper member are grayish orange (10YR 7/4) to moderate brown (10YR 5/4) and very fine to fine grained with indistinct or irregular very thin to thin bedding or scarce low-angle medium-scale cross-bedding. The sandstones consist mainly of subangular to subrounded slightly strained quartz grains containing all the major types of inclusions. Feldspar is scarce and generally of the plagioclase varieties (oligoclase and andesine), although rare potassium feldspar is also present. The clastic dolomite grains are polycrystalline aggregates or monocrystalline grains. The matrix is composed of silt- and clay-size constituents in which the clay minerals have the optical properties of the kaolin group. Glauconite amounts to as much as 2-3 percent in some of the thin sections, although the other accessory minerals are a small and almost insignificant part of the mineral assemblage. Except for the glauconite, these sandstones have essentially the same mineralogy as those in the middle member. The following composition is an average of the modal analyses shown on plate 2. According to the classification used in this report, a rock of the following composition would be termed an impure quartz sandstone.

Average of nine modal analyses, in percent, of sandstone in upper member of Dakota Formation (cement not included)

		All constituents	Constituents (1), (2), (3)
(1) Stable minerals		78	91
Quartz	74		
Chert	3		
Quartzite	1		
(2) Feldspars		2	2
(3) Unstable minerals		6	7
Clastic dolomite	6		
(4) Matrix		13	
(5) Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		1	
		100	100

Mudstone and shale beds in the upper member are medium dark gray (N4) to dusky yellow (5Y 6/4) and laminated to thin bedded. The mineralogy is probably similar to that of the lower part of the Tropic Shale. Minor lithologies that occur in the southwestern part of the region are dark-gray (N3) to black (N1) laminated to very thin bedded carbonaceous mudstone, thin blackish-red (5R 2/2) fossiliferous beds of siderite 1-2 feet thick that occur locally at the base of the member, and thin coal seams less than 1 foot thick. Thin coquinoid mudstone or sandstone lenses that contain numerous oyster shells are generally present at or near the base of the member throughout the region.

The upper member is 37-68 feet thick in the southwestern part of the region in Wahweap Creek valley (fig. 3). A conspicuous ledge-forming sandstone bed as much as 17 feet thick and containing numerous Exogyra levis Stephenson in the upper 1-2 feet occurs at the top of the member in the southwestern area and clearly marks the upper contact. This bed pinches out eastward from Wahweap Creek, and the upper contact is, therefore, lowered to the top of the next highest underlying sandstone bed (fig. 7).

Conspicuous sandstones are absent in the central part of the region where the contact is placed at the top of a fossiliferous sandstone bed 1-3 feet thick that overlies the middle member (fig. 4). Another conspicuous ledge-forming sandstone bed as much as about 20 feet thick and also containing numerous E. levis in the upper 1-2 feet is at the top of the upper member in the northeastern part of the region (figs. 7, 5). This bed is slightly older than (and is not the same bed as) the ledge-forming sandstone bed at the top of the member in the southwestern part of the region. Thin coquinoid mudstone and sandstone beds about 0-3 feet thick that contain abundant oyster shells are common at the base of the member and aid in distinguishing the lower contact. The lowest of these beds contains scarce pebbles and rare cobbles of black chert as much as 3 inches in diameter and rare light-gray quartzite pebbles as much as 1½ inches in diameter; some of the chert pebbles and cobbles contain fusulinids, tabulate corals, and pelmatozoan columnals.

Fossils are locally abundant and moderately well preserved in the sandstone and coquinoid beds but generally are poorly preserved or preserved as external molds in the mudstone and shale beds. The following lists are of fossils collected from the upper member of the Dakota and correlative beds in the lower part of the Tropic Shale below the faunal zone of Sciponoceras gracile (Shumard). Considering the entire southeastern Kaiparowits region, these beds can be divided into a threefold vertical sequence of units that are based on the distribution of lithologies and interpretations of the age and conditions of deposition. The three units are related to Western Interior faunal zones in the following paragraphs because of the need to consider the strata in terms of time, but the boundaries of these zones may be somewhat arbitrary. From oldest to youngest, the faunal zones that are inferred or indicated for strata in the upper member of the Dakota and the lower part of the Tropic are: zone of Dunveganoceras pondi Haas, zone of Dunveganoceras conditum Haas, and zone of Dunveganoceras albertense (Warren). The fossils were collected by H. A. Waldrop and the writer, and the identifications were made by W. A. Cobban, D. H. Dunkle, Nicholas Hotton 3d, and the writer.

Fossils in the zone of Dunveganoceras pondi Haas

Pelecypoda
- Barbatia sp.
- Ostrea prudentia White
- Ostrea sp.
- Plicatula hydrotheca White
- Anomia sp.
- Brachidontes multilinigera (Meek)
- Corbicula? sp.
- Lucina sp.
- Cardium sp.
- Corbula sp.

The zone of Dunveganoceras pondi Haas is inferred for about 2-7 feet of interbedded mudstone, shale, and sandstone at the base of the upper member of the Dakota in the northeastern part of the region and for correlative strata farther southwest (fig. 7). Index fossils were not found, and the presence of the zone is suggested by (1) Ostrea prudentia which indicates a late Cenomanian age and possibly an age no older than the zone of D. pondi, according to Cobban and Reeside (1952, p. 1017); (2) the sharp change in environments of deposition at the base of the inferred zone of D. pondi in the Kaiparowits region, which may correspond to the sharp change in lithology (from shale to limestone) at the base of this zone in the Great Plains (Cobban and Reeside, 1952; Hattin, 1965, p. 44); and (3) the position beneath overlying beds that contain fossils indicating the next younger zone of D. conditum. The paleontologic evidence suggests that these beds belong in the zone of D. pondi, but the evidence is not conclusive and some or possibly all of these beds could be in the younger zone of D. conditum. The inferred presence of the zone of D. pondi in the southeastern Kaiparowits region suggests that these beds correlate approximately with the Lincoln Limestone Member of the Greenhorn Limestone (table 3) in the standard reference sequence of Cretaceous formations for the Western Interior (Cobban and Reeside, 1952).

Fossils in the zone of *Dunveganoceras conditum* Haas

Pelecypoda
- *Pinna petrina* White
- *Phelopteria* sp.
- *Ostrea* sp.
- *Exogyra levis* Stephenson
- *E. olisiponensis* Sharpe
- *Plicatula hydrotheca* White
- *Plicatula* sp.
- *Corbicula*? sp.
- *Cardium* cf. *C. pauperculum* Meek
- *Cardium* sp.
- *Callistina*? sp.
- *Corbula* sp.

Gastropoda
- *Gyrodes*? sp.

Cephalopoda
- *Metoicoceras defordi* Young
- *M.* cf. *M. whitei* Hyatt

Vertebrata--Osteichthyes (bony fish)
- Undetermined pycnodontoid tooth
- Undetermined fish scale

The zone of *Dunveganoceras conditum* includes the uppermost sandstone bed in the northeastern part of the region and correlative strata farther southwest (fig. 7). The upper 1-3 feet of the sandstone bed in the northeastern part of the region contains abundant *Exogyra levis* and a small number of *E. olisiponensis* and *Plicatula hydrotheca*. At Fiftymile Point this bed thins to 1-5 feet and the fossil fauna is more varied, containing *Callistina*? sp. (locally abundant), *Cardium* sp., *Corbula* sp., *E. levis* (locally abundant), *E. olisiponensis*, *Ostrea* sp., *Phelopteria* sp., *Pinna petrina*, *Plicatula* sp., *Gyrodes* sp., and *Metoicoceras defordi*. The mudstone and shale facies of this sandstone bed southwest of Surprise Valley contains *Cardium* cf. *C. pauperculum*, *Corbicula*? sp., *Corbula* sp., *E. levis*, *Plicatula hydrotheca*, fish scales, and a pycnodontoid fish tooth.

The boundaries of the zone of *Dunveganoceras conditum* are placed rather arbitrarily at the top and the bottom of the sandstone bed in the northeastern part of the region in which the index fossil *Metoicoceras defordi* was found. The index fossil was found in the upper sandstone bed of the Dakota at Fiftymile Point (meas. sec. 138, fig. 7). W. A. Cobban (oral commun., 1966) identified the fossil as the densely ribbed species of *Metoicoceras* found in the range zone of *D. conditum* in Montana (Cobban, 1953, p. 47) and restricted to that zone in the Western Interior. *Metoicoceras defordi* indicates that these beds are of late Cenomanian age and correlate approximately with the lower part of the Hartland Shale Member of the Greenhorn Limestone (table 3) in the standard reference sequence of Cretaceous formations for the Western Interior (Fisher and others, 1960, p. 23).

Fossils in the zone of *Dunveganoceras albertense* (Warren)

- Pelecypoda
  - *Inoceramus* aff. *I. concentricus* Parkinson
  - *Inoceramus* sp.
  - *Ostrea prudentia* White
  - *Ostrea* sp.
  - *Gryphaea newberryi* Stanton
  - *Exogyra levis* Stephenson
  - *E. olisiponensis* Sharpe
  - *Plicatula hydrotheca* White
  - *Brachidontes multilinigera* (Meek)
  - *Cymbophora*? sp.
  - *Corbula* sp.
- Cephalopoda
  - *Neocardioceras*? sp.
- Vertebrata--Chondrichthyes (sharks and skates)
  - *Scapanorhynchus subulatus* (Agassiz)

The zone of *Dunveganoceras albertense* is inferred for the 18-foot sandstone bed at the top of the Dakota in the southwestern part of the region and for correlative strata in the Tropic Shale farther northeast (fig. 7). In the northeastern part of the region, the zone includes strata from the base of the Tropic up to the base of beds containing limestone concretions with *Sciponoceras gracile* (Shumard). In the southwestern part of the region, the upper 1-3 feet of the upper sandstone bed of the Dakota contains abundant *Exogyra levis* and a small number of *E. olisiponensis*, *Ostrea prudentia*, and *Plicatula hydrotheca*. South of Wahweap Creek (meas. sec. 51, pl. 6), strata in the lower part of the zone contain several thin coquinoid beds with abundant *Ostrea* sp., and strata in the upper part contain *Corbula* sp., *Cymbophora*? sp., *Inoceramus* aff. *I. concentricus*, and *Ostrea* sp. Fossils in the mudstone and shale beds in the central and northeastern parts of the region are not common, but *Gryphaea newberryi*, *E. levis*, *Neocardioceras*? sp., and *Scapanorhynchus subulatus* were collected there.

Index fossils were not found in strata here assigned to the zone of *Dunveganoceras albertense*, but the zone is inferred by *Ostrea prudentia* which suggests an age no younger than about the zone of *D. albertense* (Cobban and Reeside, 1952, p. 1017) and by stratigraphic position between beds containing index fossils for the zones of *D. conditum* and *Sciponoceras gracile*. The inferred presence of the zone of *D. albertense* suggests approximate correlation with the upper part of the Hartland Shale Member of the Greenhorn Limestone (table 3) in the standard reference sequence of Cretaceous formations for the Western Interior (Fisher and others, 1960, p. 23).

In conclusion, the upper member of the Dakota and the lower part of the Tropic Shale are of middle to late Cenomanian age on the basis of fossil evidence. The age of the lower and middle members of the Dakota is uncertain because of lack of age-diagnostic fossils, but the lack of unconformities and the apparently continuous sequence of deposition throughout the formation suggest that the lower and middle members are probably of about early to middle Cenomanian age. On the basis of evidence cited in the preceding paragraphs, the Dakota Formation is correlated with the Dakota Sandstone of the Black Mesa and San Juan Basin regions, as shown in figures 8 and 9.

Tropic Shale

The Tropic Shale was originally named by Gregory and Moore (1931, p. 98-99) for a gray shale unit between the Dakota and Straight Cliffs Formations near the town of Tropic, Utah, about 30 miles northwest of the southeastern Kaiparowits region. Gregory and Moore also included coal and fossiliferous sandstone beds at the base with the Tropic Shale, but in the southeastern Kaiparowits region these lithologies are included in the upper member of the Dakota in accordance with Lawrence's (1965) study and recommendations. As thus restricted, the Tropic is dominantly a thick gray shale unit that weathers to broad slopes and benches or forms cliffs where overlain by resistant sandstone beds at the base of the Straight Cliffs Formation (figs. 10, 11).

Several faunal zones are either known to be present in the Tropic Shale or are inferred from indirect evidence; they are listed here as an aid in describing the lithologic and faunal variations of the formation, but they are not rock stratigraphic units. From highest to lowest these are:

zone of *Collignoniceras hyatti* (Stanton)
zone of *Collignoniceras woollgari* (Mantell)
zone of *Inoceramus labiatus* (Schlotheim)
zone of *Sciponoceras gracile* (Shumard)
zone of *Dunveganoceras albertense* (Warren)
zone of *Dunveganoceras conditum* Haas
zone of *Dunveganoceras pondi* Haas

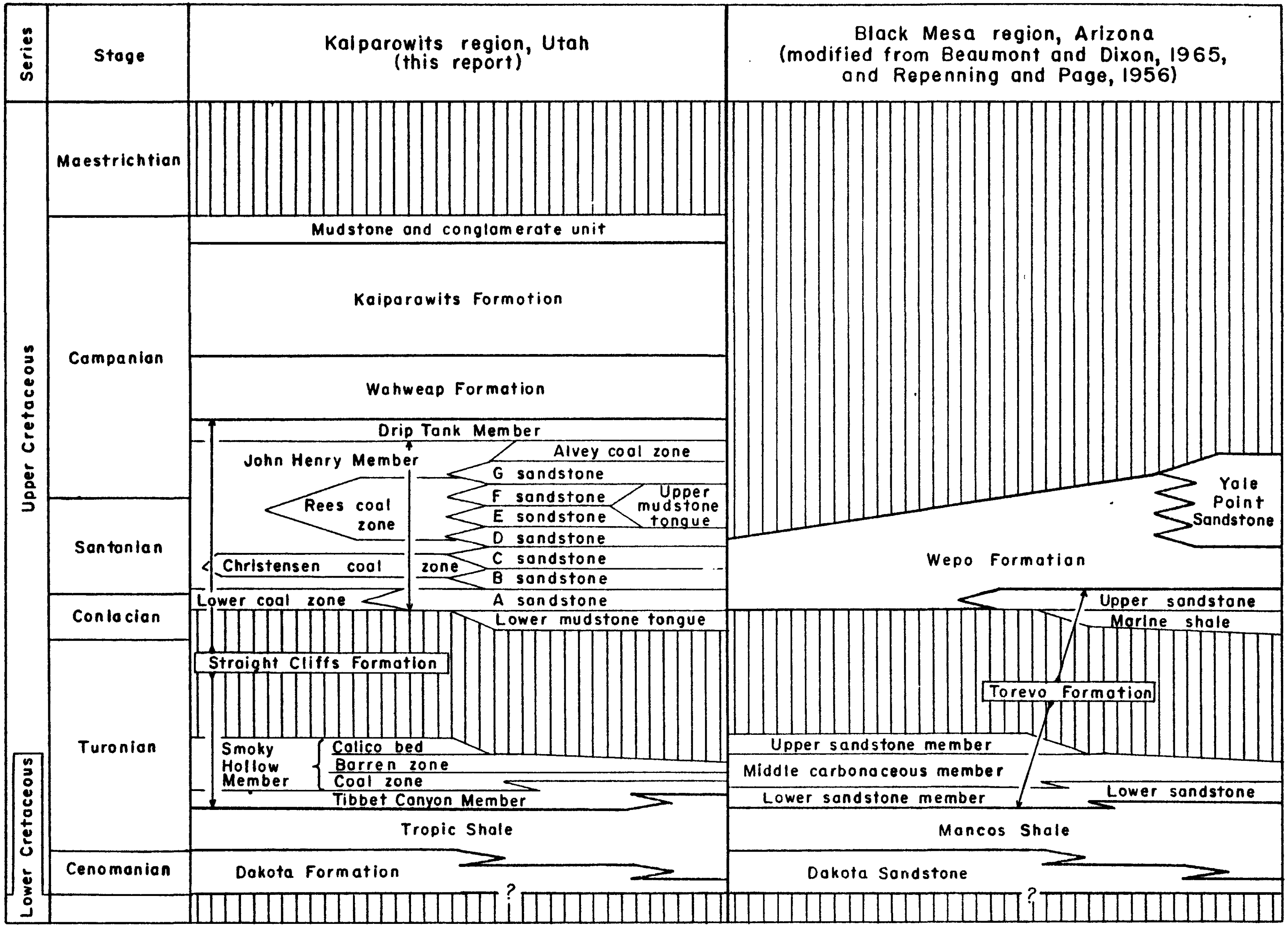

FIGURE 8.--Correlation of Cretaceous formations in Kaiparowits region, Utah, and Black Mesa region, Arizona.

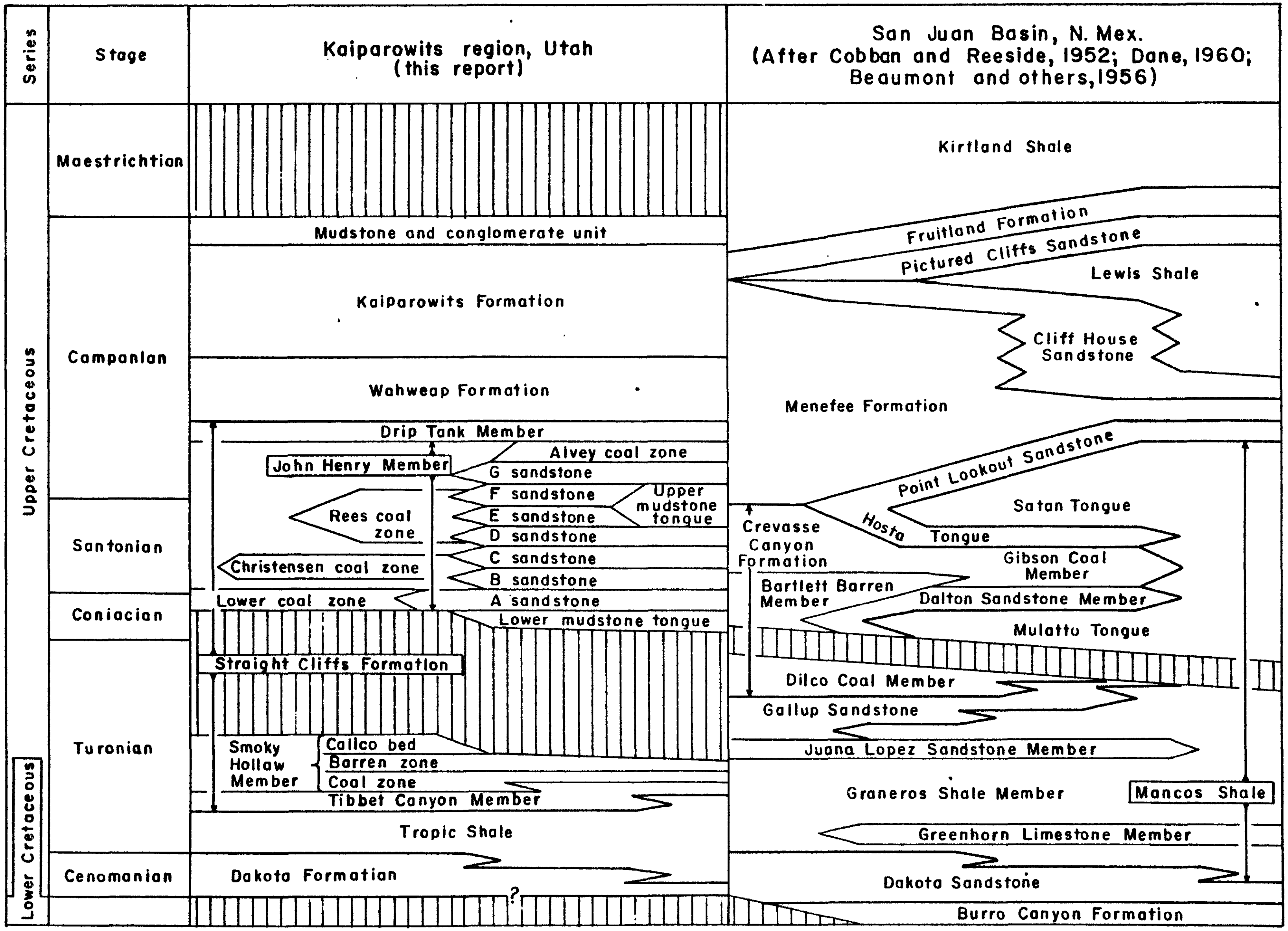

FIGURE 9.--Correlation of Cretaceous formations in Kaiparowits region, Utah, and San Juan Basin, N. Mex.

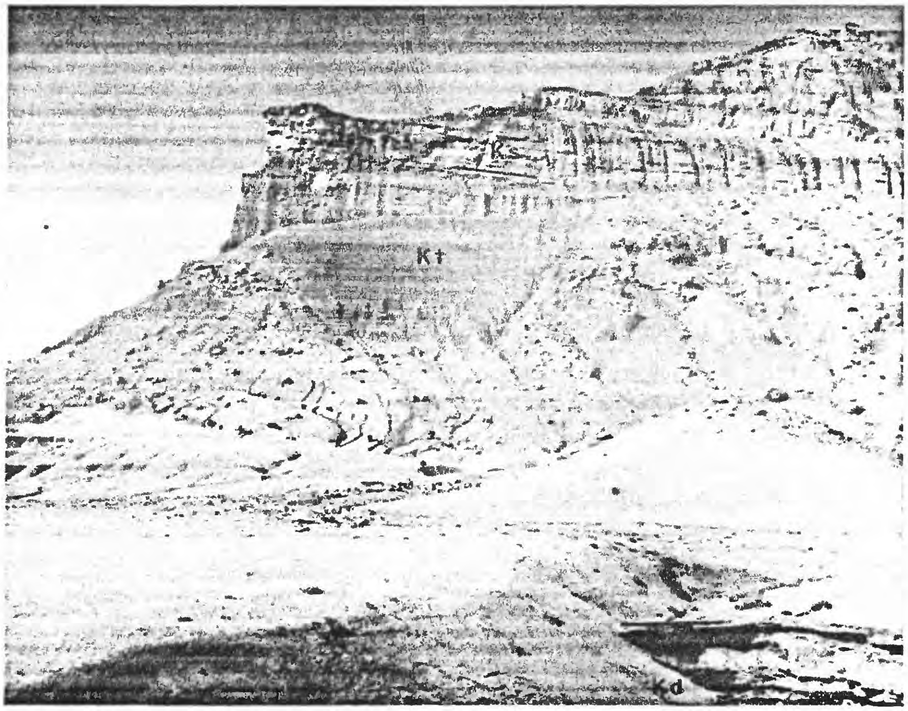

FIGURE 10.--Well-exposed Tropic Shale at measured section T2 about 1 mile west of Warm Creek at southeast end of Nipple Bench. Formation is 610 feet thick. Kd, Dakota Formation; Kt, Tropic Shale; Ks, Straight Cliffs Formation.

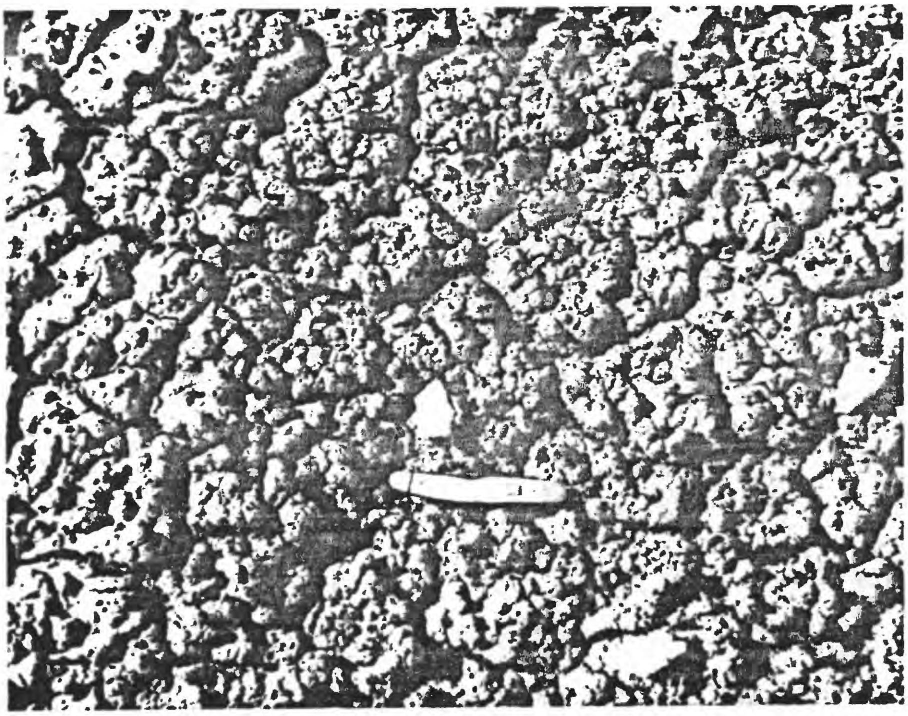

FIGURE 11.--Typical "popcorn" texture on weathered surface of Tropic Shale caused by swelling of bentonitic clays. Scattered pieces of white gypsum near knife weather out of joints and other fractures in the shale. About 1 mile west of Warm Creek at measured section T2, about 30 feet above base of formation.

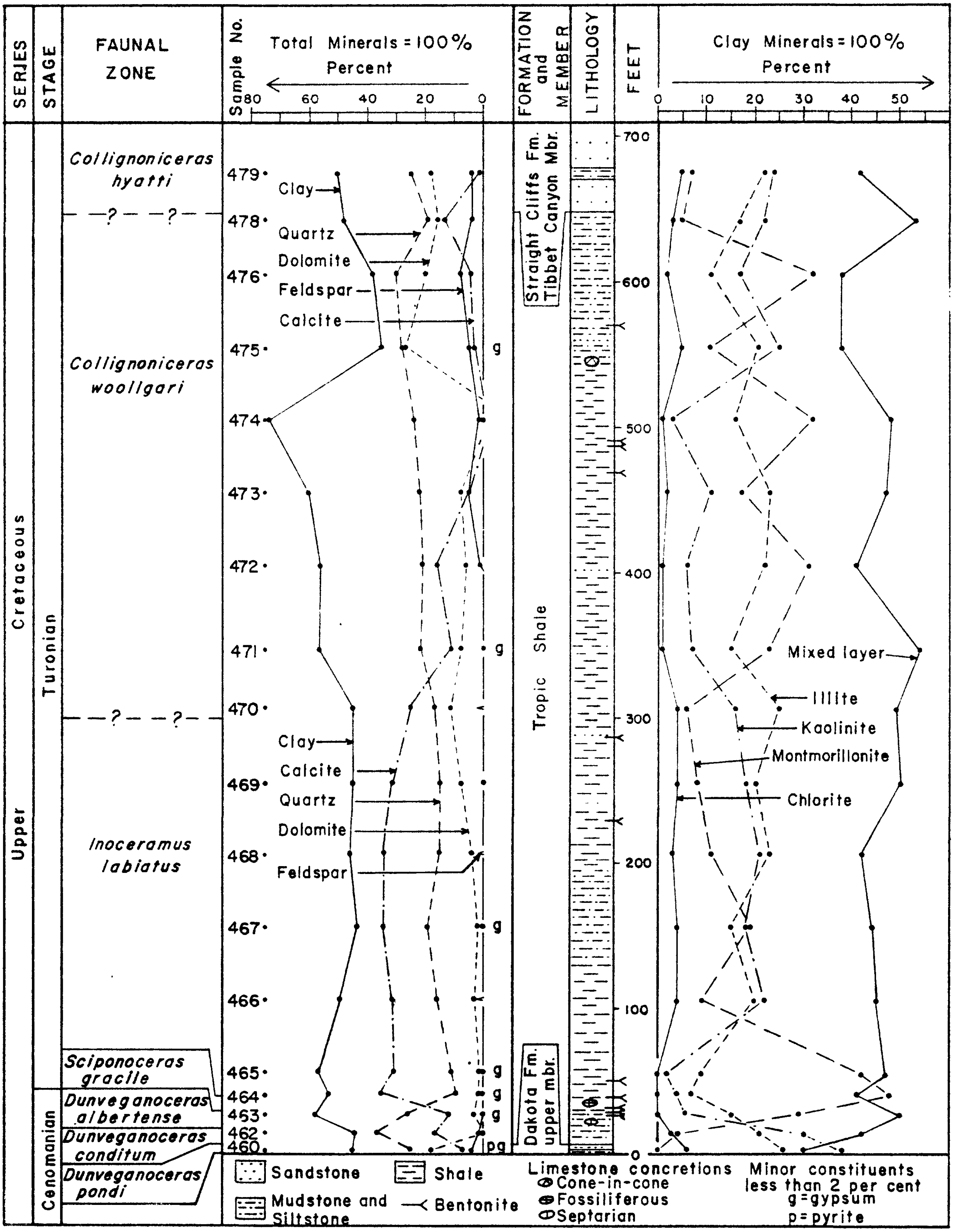

FIGURE 12.--Mineralogy of the Tropic Shale at measured section T1, about 1 mile east of Wahweap Creek.

Thin beds of mudstone, siltstone, and sandstone occur mainly in the lower and upper parts of the Tropic. Strata in the zones of Dunveganoceras pondi, D. conditum, and D. albertense contain grayish-orange (10YR 7/4) to moderate-brown (10YR 5/4) mudstone, siltstone, and very fine to fine grained poorly to moderately sorted sandstone lenses that have indistinct or irregular horizontal bedding or low-angle crossbedding (meas. sec. 37, pl. 6). A bed of grayish-orange (10YR 7/4) mudstone, about 12 feet thick, that has indistinct bedding is present in the zone of D. conditum from Smoky Mountain northeast to Surprise Valley where it grades laterally into the uppermost sandstone bed of the Dakota. The zone of Inoceramus labiatus contains several laminae of biogenic sandstone composed mainly of Inoceramus prisms and Foraminifera. Strata in the zone of Collignoniceras hyatti and the upper part of the zone of C. woollgari contain beds of grayish-orange (10YR 7/4) to moderate-yellowish-brown (10YR 5/4) mudstone, siltstone, and very fine grained poorly to moderately sorted laminated to thin-bedded sandstone. The number and the thickness of the sandstone beds generally increase upward to the contact with the lowest sandstone bed of the Straight Cliffs Formation.

Thin beds of very light gray (N8) bentonite that are generally less than 1 foot thick occur throughout the formation but are most abundant in the zone of Sciponoceras gracile and the lower part of the zone of Inoceramus labiatus. One bentonite bed in the zone of Collignoniceras woollgari locally reaches a thickness of 11 feet in the cliffs above Sit Down Bench. An analysis of a sample from this bed is given below.

X-ray diffraction analysis, in percent, of bentonite in Tropic Shale

[From measured section T5 at Sit Down Bench, 548 feet above base of Tropic Shale]

Quartz	31
Potassium feldspar	0
Plagioclase feldspar	0
Calcite	1
Dolomite	2
Gypsum	0
Montmorillonite	66

Concretions of medium-gray (N5) dense limestone about 6 inches to 3 feet in diameter and about 3 inches to 1 foot thick occur in several parts of the formation. Concretions in the zone of Dunveganoceras albertense have septarian structure and contain rare *Exogyra levis*, whereas concretions in the zone of *Sciponoceras gracile* generally lack septarian structure and contain an abundant and varied fossil fauna. Unfossiliferous limestone concretions that have cone-in-cone structure occur locally in the zone of *Collignoniceras woollgari*, but they are not common.

The Tropic ranges in thickness from 610 to 705 feet. The thickness variations are due to interfingering with the Dakota and Straight Cliffs Formations and probably to contemporaneous structural deformation (fig. 13).

The upper and lower contacts of the Tropic are gradational and interfingering. The lower contact is placed at the top of the highest thick and reasonably continuous sandstone bed at the top of the Dakota Formation (fig. 7). The upper contact is placed at the base of the lowest conspicuous ledge-forming sandstone bed, generally about 3 or more feet thick, in the lower part of the transition interval from Tropic Shale into the Straight Cliffs Formation. At several places the vertical sequence of beds at the top of the Tropic does not include a prominent sandstone bed, and the contact is arbitrarily placed where sandstone is the dominant lithology.

The Tropic contains an abundant and varied fossil fauna, but the fossils are not everywhere present and, thus, the exact boundary between the faunal zones is uncertain. Most of the fossils in the limestone concretions in the zone of *Sciponoceras gracile* are well preserved and can be collected easily where the concretions are weathered; in many of the shale and mudstone beds, however, the fossils are crushed, fragile, or preserved as internal or external molds and must be collected with care. Because the basal contact of the formation is placed at different stratigraphic positions owing to interfingering with the upper member of the Dakota Formation, the various collections and zones are referred to the time-equivalent or nearly time equivalent surface at the base of the upper member of the Dakota. The fossils were collected by H. A. Waldrop and the writer, and the identifications were made by J. F. Mello, J. E. Hazel, Nicholas Hotton 3d, D. H. Dunkle, W. A. Cobban, and the writer.

Fossils in the lower part of the Tropic in the zones of *Dunveganoceras pondi*, *D. conditum*, and *D. albertense* were included in the discussion of the upper member of the Dakota.

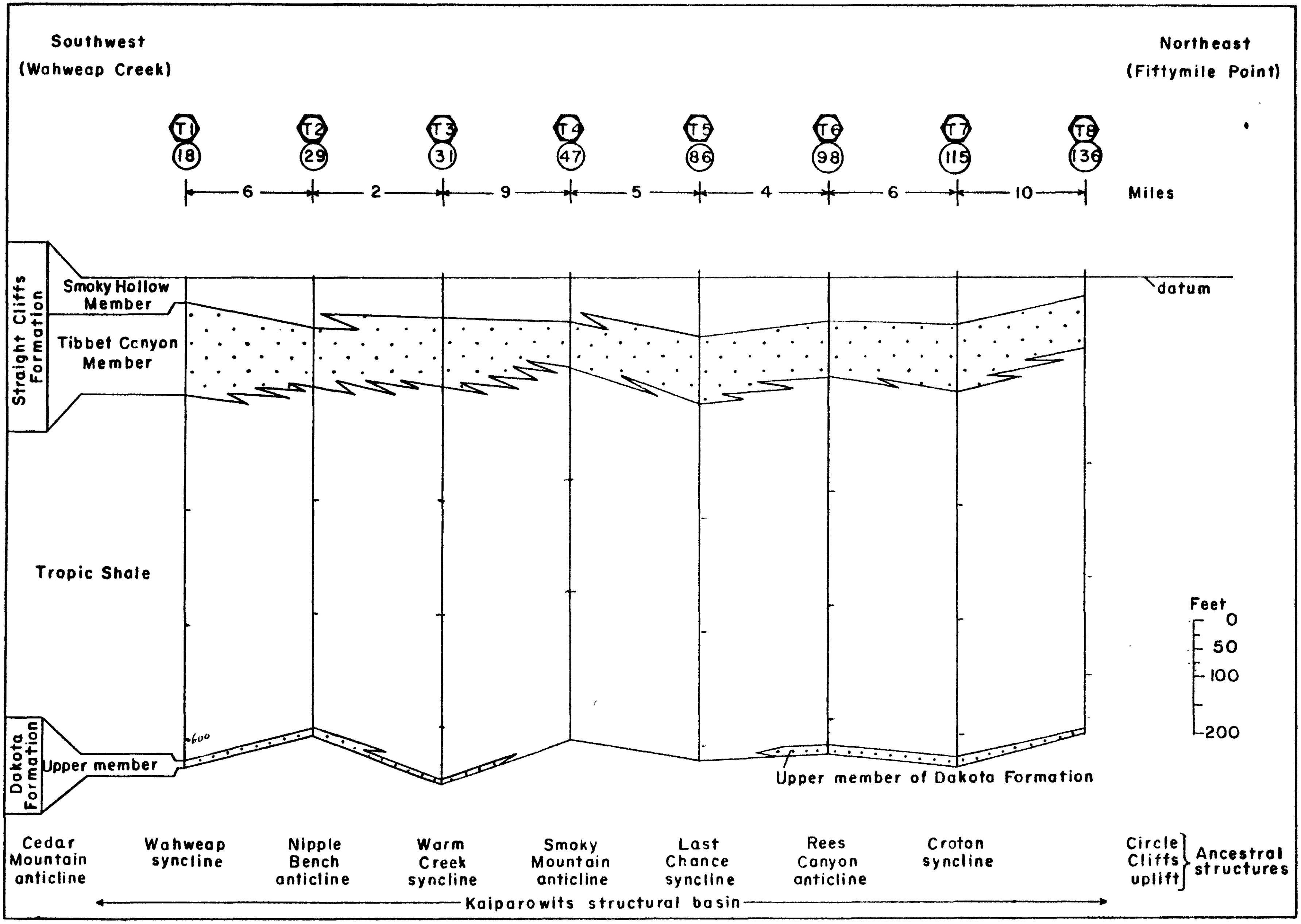

FIGURE 13.--Selected measured sections of Tropic Shale and parts of Dakota and Straight Cliffs Formations showing thickness changes over ancestral folds.

Fossils in the zone of *Sciponoceras gracile* (Shumard)

Foraminifera
- *Nodosaria* cf. *N. obscura* Reuss
- *Citharina*? sp.
- *Dentalina* sp.
- *Lagena*? sp.
- *Neobulimina canadensis* Cushman and Wickenden
- *Bulimina reussi* Morrow var. *navarroensis* Cushman and Parker
- *Guembelitria cretacea* Cushman
- *Heterohelix moremani* (Cushman)
- *Hedbergella planispira* (Tappan)
- *Hedbergella* cf. *H. delrioensis* (Carsey)
- *Planulina dakotensis* Fox
- *Virgulina tegulata* Reuss

Coelenterata
- *Trochocvathus*? sp.
- Undetermined solitary coral

Annelida
- *Serpula intrica* White

Pelecypoda
- *Solemya*? *obscura* Stanton
- *Inoceramus* cf. *I. pictus* Sowerby
- *Inoceramus* sp.
- *Ostrea* sp.
- *Gryphaea newberryi* Stanton
- *Exogyra olisiponensis* Sharpe
- *Exogyra* sp.
- *Camptonectes platessa* White
- *Lima utahensis* (Stanton)
- *Botula*? sp.
- *Psilomya meeki* (White)
- *P. concentrica* (Stanton)
- *Veniella mortoni* Hall and Meek
- *Lucina subundata* Hall and Meek
- *Lucina* sp.
- *Parmicorbula*? sp.
- *Corbula kanabensis* Stanton
- *Corbula* sp.

Gastropoda
- *Sigaretus* (*Eunaticina*?) *textilis* Stanton
- *Euspira* sp.
- *Turritella whitei* Stanton
- *Cerithium* sp.
- *Drepanochilus ruida* (White)
- *Arrhoges prolabiata* (White)
- *Mesorhytis*? *walcotti* (Stanton)

Cephalopoda
- *Sciponoceras gracile* (Shumard)
- *Allocrioceras annulatum* (Shumard)
- *Worthoceras* sp.
- *Kanabiceras septemseriatum* (Cragin)
- *Metoicoceras whitei* Hyatt
- *Actinocamax* sp.

Arthropoda
- Ostracoda
  - *Cythereis eaglefordensis* Alexander

Vertebrata
- Chondrichthyes (sharks and skates)
  - *Oxyrhina* cf. *O. angustidens* Reuss
  - Undetermined shark teeth
- Osteichthyes (bony fish)
  - Undetermined pycnodontoid tooth

The zone of *Sciponoceras gracile* includes about 10-15 feet of calcareous shale, limestone concretions, and several bentonite beds in the lower part of the Tropic Shale. The base of the zone is about 37-68 feet above the base of the upper member of the Dakota at Wahweap Creek, about 30 feet above the base of the same member throughout the central part of the region, and about 23 feet above the base of that member at Fiftymile Point.

The calcareous shale contains numerous well-preserved but small and slightly distorted *Gryphaea newberryi* associated with smaller numbers of *Exogyra levis*. Other molluscs were found in the shales but generally they were poorly preserved, and better specimens were found in the limestone concretions. The foraminifers, corals, ostracodes, and vertebrates were also found in the shales.

The limestone concretions contain an abundant and varied fossil fauna that includes all the annelids, pelecypods, gastropods, and cephalopods in the preceding list. The most common species in the concretions are *Serpula intrica*, *Gryphaea newberryi*, *Exogyra* sp., *Psilomya meeki*, *Lucina subundata*, *Corbula kanabensis*, *Euspira* sp., *Turritella whitei*, and *Sciponoceras gracile*. Foraminifers also are abundant but they are firmly embedded in the concretions and are much more difficult to extract than foraminifers in the enclosing shale. There is no apparent geographic differentiation of the fauna, and beds at Wahweap Creek contain essentially the same fossil assemblage as beds at Fiftymile Point.

Sciponoceras gracile and *Metoicoceras whitei* indicate that these beds are of early Turonian age and they also indicate correlation with the lower part of the Bridge Creek Limestone Member of the Greenhorn Limestone (table 3) in the standard reference sequence of Cretaceous formations for the Western Interior (Fisher and others, 1960, p. 23).

Fossils in the zone of *Inoceramus labiatus* (Schlotheim)

- Foraminifera
  - *Proteonina difflugiformis* (H. B. Brady)
  - *Haplophragmoides*? sp.
  - *Dentalina*? sp.
  - *Frondicularia* sp.
  - *Marginulinopsis*? sp.
  - *Bulimina* sp.
  - *Heterohelix moremani* (Cushman)
  - *Hedbergella* cf. *H. delrioensis* (Carsey)
  - ?*Ticinella aprica* Loeblich and Tappan
  - *Planulina dakotensis* Fox
- Pelecypoda
  - *Inoceramus labiatus* (Schlotheim)
  - *Inoceramus* sp.
  - *Phelopteria* cf. *P. gastrodes* (Meek)
  - *Phelopteria* sp.
  - *Ostrea* sp.
  - *Gryphaea* sp.
  - *Anomia* sp.
  - *Lucina subundata* Hall and Meek
  - *Lucina* sp.
  - *Corbula* sp.
- Gastropoda
  - *Drepanochilus ruida* (White)
  - *Rostellites*? sp.
- Cephalopoda
  - *Baculites* sp.
  - *Kanabiceras* sp.
  - *Neocardioceras* sp.
  - *Metoicoceras* sp.
  - *Watinoceras*? sp.
  - *Mammites* sp.
- Arthropoda
  - Malacostraca
    - Undetermined decapod chela
- Vertebrata
  - Chondrichthyes (sharks and skates)
    - *Oxyrhina* cf. *O. angustidens* Reuss
    - Undetermined shark teeth and vertebrae
    - *Ptychodus whipplei* Marcou
    - *Ptychodus* cf. *P. polygyrus* Agassiz
  - Osteichthyes (bony fish)
    - *Xiphactinus audax* Leidy
    - Undetermined fish scales
  - Reptilia
    - Undetermined mosasaur vertebrae

The zone of *Inoceramus labiatus* is approximately 250-300 feet thick and consists mainly of calcareous shale. The base of the zone is approximately 50-75 feet above the base of the upper member of the Dakota at Wahweap Creek and about 40-50 feet above the base of that member throughout the central and northeastern parts of the region.

The fossils are poorly to moderately well preserved, generally as external molds, and generally are more abundant in the few inches of shale beneath bentonite beds. Well-preserved and relatively large (as much as about 2 in. in height) undistorted *Gryphaea* sp. occur in about the lower 30 feet of the zone. The vertebrate bone and teeth fragments and the foraminifers are restricted to local occurrences but usually are well preserved. In general, the fossils are more abundant in the southwestern and central parts of the region and in approximately the lower half of the zone, although the foraminifers came from two samples 292 and 298 feet above the base of the upper member of the Dakota at measured section T1 (fig. 12).

Inoceramus labiatus has world-wide distribution in the Turonian Stage. In the Western Interior region this fossil is of early Turonian age and indicates correlation with the upper part of the Bridge Creek Limestone Member of the Greenhorn Limestone (table 3) in the standard reference sequence of Cretaceous formations for the Western Interior (Fisher and others, 1960, p. 23).

Fossils in the zone of *Collignoniceras woollgari* (Mantell)

Pelecypoda
- *Yoldia*? sp.
- *Inoceramus* sp.
- *Ostrea* sp.
- *Cardium* sp.

Cephalopoda
- *Baculites* sp.
- *Collignoniceras woollgari* (Mantell)

Vertebrata
- Undetermined fish scales

The zone of *Collignoniceras woollgari* is about 300-350 feet thick and may include some of the beds at the base of the Tibbet Canyon Member of the Straight Cliffs in the southwestern part of the region. The lithology grades upward from calcareous shale near the base to shale in the middle and mudstone at the top (fig. 12). The base of the zone is approximately 300 feet above the base of the upper member of the Dakota in the southwestern and central part of the region and about 350 feet above the base of that member at Fiftymile Point.

The zonal index fossil *Collignoniceras woollgari* is the best preserved fossil in these beds and is most abundant in the lower half of the zone; only small immature specimens were found in the upper part. Several poorly preserved *Inoceramus* sp. and *Ostrea* sp. were found throughout the zone, and most of the other pelecypods came from the uppermost beds.

Collignoniceras woollgari occurs in Europe and North America in the Turonian Stage. This fossil is of middle Turonian age in the Western Interior region and indicates correlation with the Fairport Chalky Shale Member of the Carlile Shale (table 3) in the standard reference sequence of Cretaceous formations for the Western Interior (Cobban and Reeside, 1952).

Fossils in the zone of *Collignoniceras hyatti* (Stanton)

Pelecypoda
- *Inoceramus* sp.
- *Ostrea* sp.
- *Corbicula*? sp.
- *Cardium* cf. *C. pauperculum* Meek
- *Cardium* sp.
- *Cymbophora*? sp.
- *Corbula* sp.

Gastropoda
- Fragments, undet.

Arthropoda?
- *Ophiomorpha* sp.

The zone of *Collignoniceras hyatti* is inferred for as much as about 130-150 feet of strata at the top of the Tropic Shale in the central and northeastern parts of the region. Zonal index fossils do not occur in these beds, and the presence of the zone is indicated by southwestward interfingering of these beds with the Tibbet Canyon Member of the Straight Cliffs which contains the index fossil *Inoceramus howelli* White. The index fossil and the interfingering relations indicate that these beds are of middle Turonian age and correlate approximately with the Blue Hill Shale Member of the Carlile Shale (table 3) in the standard reference sequence for the Western Interior (Cobban and Reeside, 1952).

The paleontological evidence indicates that the Tropic Shale ranges from middle Cenomanian to middle Turonian in age and correlates with the Greenhorn Limestone and the lower part of the Carlile Shale in the Western Interior reference sequence of formations (table 3). This age demonstrates that the Tropic was originally deposited as a westward-extending tongue of the lower part of the Mancos Shale in southwestern Colorado (Cross and Purington, 1899). Correlation with strata in nearby regions of the Colorado Plateau is shown in figure 8 (Black Mesa region, Arizona) and figure 9 (San Juan Basin, N. Mex.).

Straight Cliffs Formation

The Straight Cliffs Sandstone was named by Gregory and Moore (1931, p. 91) for exposures along the Straight Cliffs escarpment several miles south of Escalante, Utah, in the northern Kaiparowits region. In most parts of the Kaiparowits Plateau the formation contains significant amounts of rocks other than sandstone, and for this reason Peterson and Waldrop (1965, p. 62-63) applied the more general name Straight Cliffs Formation to these rocks. Recent mapping has indicated that the Straight Cliffs consists of four members that are, from oldest to youngest, the Tibbet Canyon, Smoky Hollow, John Henry, and Drip Tank Members (Peterson, 1969). The Tibbet Canyon and Drip Tank Members are generally cliff forming units composed mainly of sandstone; the Smoky Hollow and John Henry Members are cliff- and slope-forming units composed mainly of interbedded sandstone, mudstone, and coal. The Smoky Hollow and John Henry Members are divided into several informal units which are based on characteristic associations of sedimentary structures, lithologies, and fossils. An unconformity separates the Smoky Hollow and John Henry Members, and distinctive beds just above and below allow this contact to be easily recognized.

Figure 14 shows typical relations of the Straight Cliffs Formation in the southwestern part of the region at a locality that is within 3 miles of the type localities of the Tibbet Canyon, Smoky Hollow, and John Henry Members. The Drip Tank Member is not appreciably different in this area from its type locality about 11 miles north. Figure 15 shows relations in the northeastern part of the region that are similar to the type locality of the formation, which is about 47 miles northwest.

The Straight Cliffs Formation thickens irregularly northeastward across the region from about 1,130 feet at Nipple Bench to about 1,620 feet in Left Hand Collett Canyon (pls. 9, 10, 11). The formation is 1,495 feet thick in the northwestern Kaiparowits region near Tropic, Utah (Robison, 1966, p. 23).

TIBBET CANYON MEMBER

The Tibbet Canyon Member was named for exposures near the mouth of Tibbet Canyon in the N½NE¼NE¼ sec. 14, T. 42 S., R. 3 E., Kane County, Utah (Peterson, 1969). The member is commonly well exposed in cliffs above the slope-forming Tropic Shale in the southwestern and central parts of the

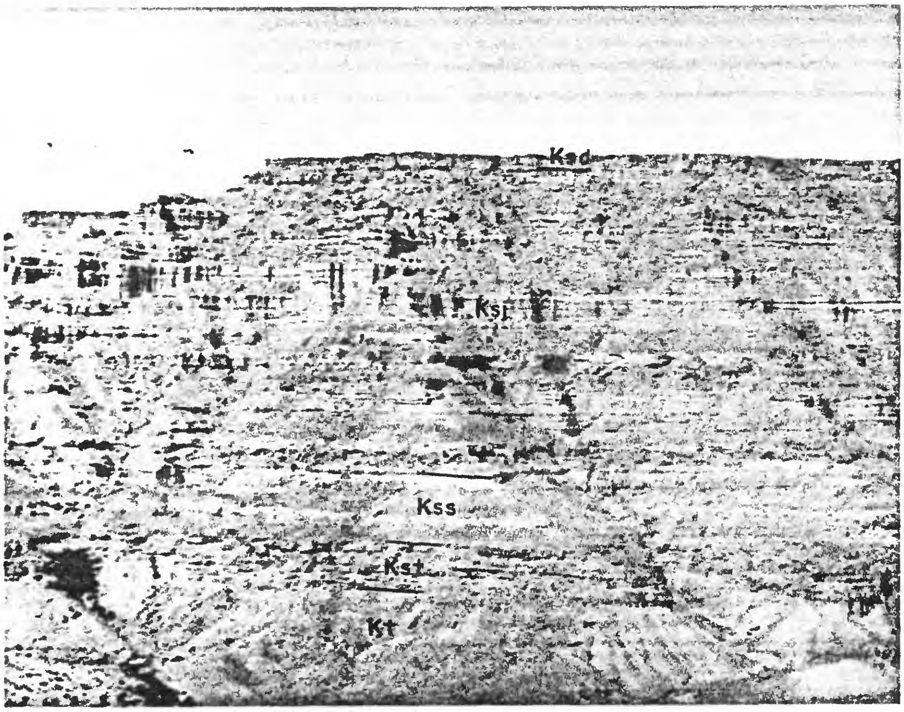

FIGURE 14.--Straight Cliffs Formation in southwestern part of region on west side of Warm Creek canyon; formation is mainly of nonmarine origin here. Numerous fluvial sandstones form small cliffs in John Henry Member. Formation is about 1,015 feet thick in measured section S14 in left-center of picture, but upper part of Drip Tank Member has been eroded. Kt, Tropic Shale; Straight Cliffs Formation: Kst, Tibbet Canyon Member, Kss, Smoky Hollow Member, Ksj, John Henry Member, Ksd, Drip Tank Member.

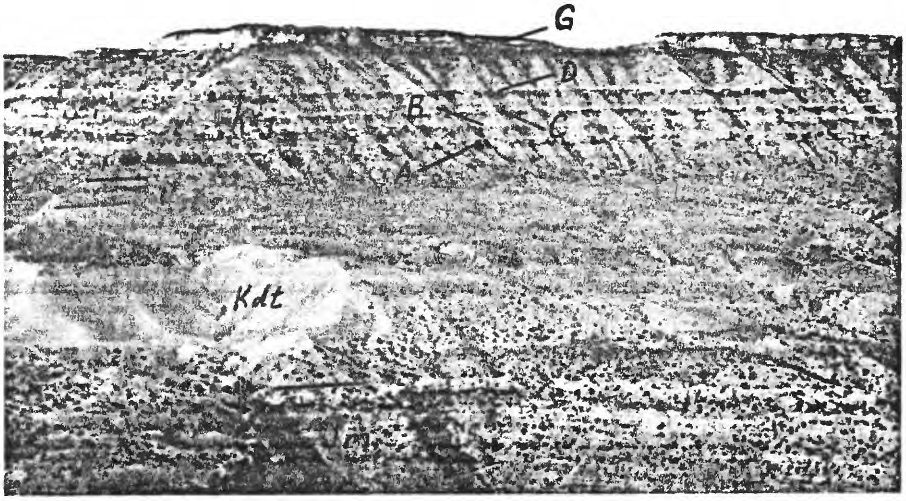

FIGURE 15.--Straight Cliffs Formation at east end of Kaiparowits Plateau above Fiftymile Point; formation is mainly of marine origin here. The A, B, C, D, and G sandstone beds (labeled) form prominent cliffs in the Straight Cliffs escarpment, which trends toward the right (northwest). Formation is 1,200 feet thick in measured section S34 along crest of sharp ridge at left, but Alvey coal zone and Drip Tank Member are missing because of erosion. Jm, Morrison Formation and other rocks of Jurassic age; Kdt, Dakota Formation (concealed) and Tropic Shale; Straight Cliffs Formation: Ksts, Tibbet Canyon and Smoky Hollow Members, Ksj, John Henry Member.

region (fig. 14), but farther northeast, and especially at the Straight Cliffs escarpment, the member is generally concealed by talus (fig. 15).

The Tibbet Canyon Member is composed of yellowish-gray (5Y 8/1), grayish-orange (10YR 7/4), and moderate-brown (10YR 5/4) sandstone that weathers to colors as dark as grayish brown (5YR 3/2). In general, the median grain size and sorting change upward from very fine grained and poorly to moderately sorted at the base to medium grained and moderately to well sorted at the top. Granules and pebbles of gray quartz, gray, brown, and black chert, and gray and red quartzite are scarce but occur in the middle and upper parts of the member. The lower part of the Tibbet Canyon is interbedded with light-olive-gray (5Y 5/2) very thin to thin bedded mudstone and siltstone beds that are southwestward- or southward-thinning tongues of the Tropic Shale too thin to map as separate units.

The sandstone consists mainly of subangular to subrounded slightly strained quartz grains containing all the major types of inclusions. The feldspars amount to about 5-25 percent of the rock and are mainly of the plagioclase varieties (oligoclase and andesine), although scarce potassium varieties (orthoclase and rare microcline) are also present. Some of these grains are moderately altered, and it is likely that part of the clay mineral fraction in the matrix originated from postdepositional alteration of the feldspars. The clastic carbonate grains are polycrystalline aggregates or monocrystalline grains and consist mainly of dolomite, although a small amount of clastic calcite can be distinguished from the calcite cement. Approximately 14 percent of the sandstone is silt- and clay-size matrix in which most of the clay minerals have the optical properties of the kaolin group. The accessory minerals are a small and almost insignificant part of the total mineral assemblage. Biotite is the most common accessory mineral. Sandstones in the lower part of the member are generally well cemented by calcite, but the middle and upper parts of the member are commonly only moderately cemented and are fairly porous. The following is an average of the modal analyses shown on plates 12 and 13. According to the classification used in this report, a rock of the following composition would be termed an impure feldspathic sandstone.

Average of 28 modal analyses, in percent, of sandstone in Tibbet Canyon Member of Straight Cliffs Formation (cement not included)

			All constituents	Constituents (1), (2), (3)
(1)	Stable grains		67	80
	Quartz	62		
	Chert	2		
	Quartzite	3		
(2)	Feldspars		12	14
(3)	Unstable grains		5	6
	Clastic dolomite	5		
	Clastic calcite	<1		
(4)	Matrix		14	
(5)	Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		2	
			100	100

Stratification near the base of the Tibbet Canyon Member is laminated to very thin bedded and ripple cross-laminated to very thinly crossbedded. The individual bedding units or sets generally range in thickness from 1 inch to about 1 foot, and maximum dip of the cross-strata is generally less than 10°. The thickness of the sets and the angle of inclination of the cross-strata generally increase upward so that the sets range in thickness from about 3 inches to 3 feet, and the maximum dip of the cross-strata is as much as about 25° in the middle and upper parts of the member. A vertical sequence of cross-stratified units that is common in sandstone beds of similar origin in the John Henry Member is rarely found in the Tibbet Canyon Member.

The lower contact of the Tibbet Canyon Member is generally placed at the base of the lowest readily traceable sandstone bed, but at several localities the vertical sequence of beds is entirely gradational and the lower contact is placed arbitrarily where sandstone is dominant. The upper contact is generally sharp and is placed where the cliff-forming sandstone of the Tibbet Canyon Member is in contact with the lowest overlying mudstone, carbonaceous mudstone, or coal bed of the Smoky Hollow Member. Because of interfingering relations shown diagrammatically in figure 16, the lower beds of the Tibbet Canyon grade northeastward into the upper part of the Tropic

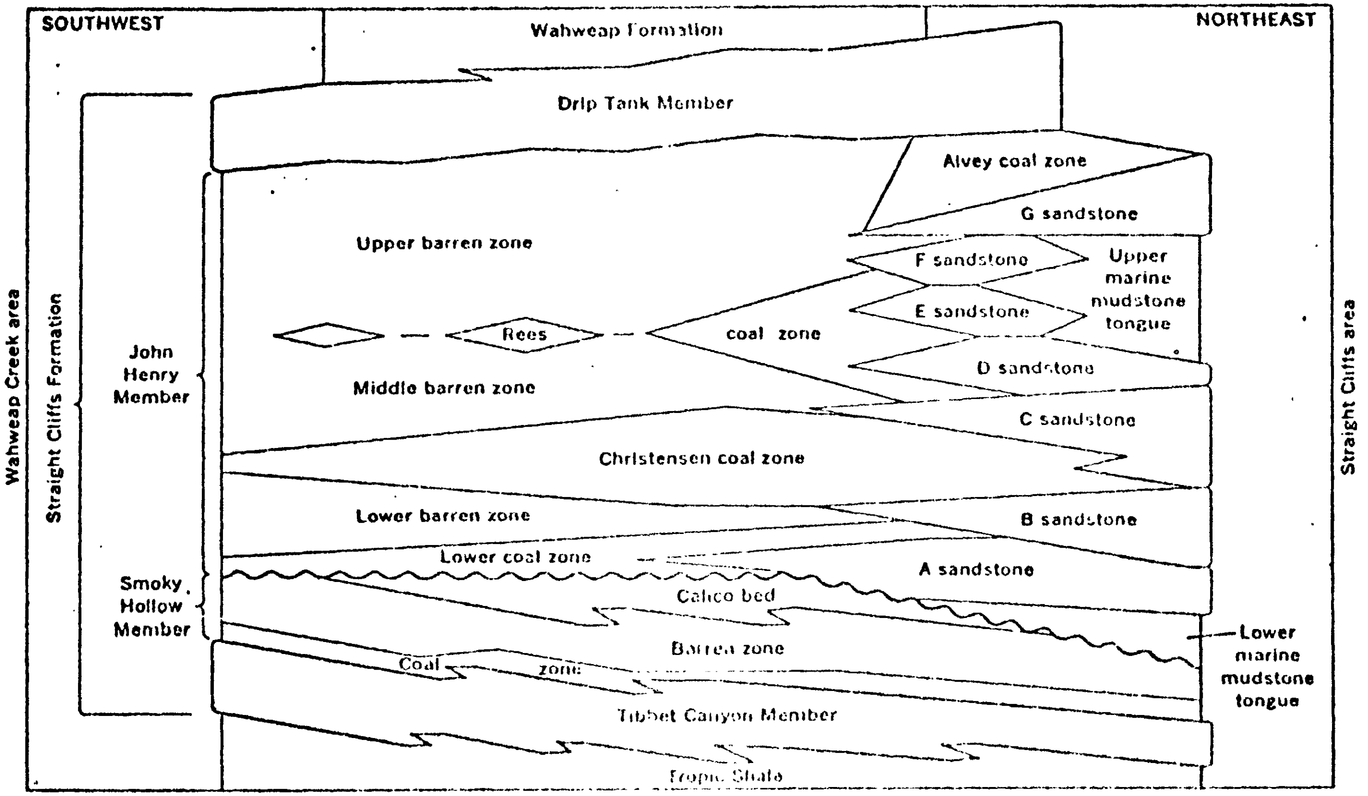

FIGURE 16.--Relations of members and informal units in the Straight Cliffs Formation, southeastern Kaiparowits region, Utah. From Peterson (1969).

Shale, and the upper beds of the Tibbet Canyon grade southwestward into the lower part of the Smoky Hollow Member.

The Tibbet Canyon Member ranges in thickness from 70 to 185 feet in the southeastern Kaiparowits region. In the northwestern Kaiparowits region, near Tropic, Utah, the lowest unit in a section that was measured by J. C. Lawrence (in Robison, 1966, p. 23) and tentatively assigned by the writer to the Tibbet Canyon Member is 84 feet thick. In the northern Kaiparowits region about 9 miles northwest of Escalante, Utah, E. V. Stephens (oral commun., 1967) measured 87 feet for the Tibbet Canyon Member.

Fossils are not common in the Tibbet Canyon Member, but several collections from localities scattered throughout the region contain sufficient numbers of species to aid in evaluating the age of the member. Most of the fossils are preserved as internal or external molds, and preservation of the original hard parts is uncommon. A summary list of the fossils is given below. The collections were made by H. A. Waldrop and the writer, and the identifications were made by W. A. Cobban, D. H. Dunkle, Nicholas Hotton 3d, and the writer.

Fossils in the Tibbet Canyon Member of the Straight Cliffs Formation

Pelecypoda
- *Inoceramus howelli* White
- *Inoceramus* sp.
- *Ostrea* sp.
- *Crassostrea soleniscus* (Meek)
- *Brachidontes*? sp.
- *Cardium* cf. *C. pauperculum* Meek
- *Legumen* cf. *L. ellipticum* Conrad
- *Cymbophora* sp.

Gastropoda
- *Gyrodes conradi* Meek
- *Gyrodes depressus* Meek
- *Cryptorhytis utahensis* (Meek)

Cephalopoda
- *Heterotissotia*? sp.

Arthropoda?
- *Ophiomorpha* sp.

Vertebrata--Chondrichthyes (sharks and skates)
- *Scapanorhynchus raphiodon* (Agassiz)

According to W. A. Cobban (oral commun., 1967), *Inoceramus howelli* is a middle Turonian index fossil that indicates the faunal zone of *Collignoniceras hyatti* in the Western Interior. This fossil indicates that the Tibbet Canyon Member and time-equivalent strata in the Tropic Shale and the Smoky Hollow Member correlate approximately with the Blue Hill Shale Member of the Carlile Shale (table 3) in the standard reference sequence for the Western

Interior (Cobban and Reeside, 1952). Although the Tibbet Canyon Member probably falls entirely within the zone of Collignoniceras hyatti in the report area, the member is somewhat younger in the northeastern part of the region because of the interfingering relations noted in preceding paragraphs.

SMOKY HOLLOW MEMBER

The Smoky Hollow Member of the Straight Cliffs Formation is a cliff- and slope-forming unit that lies above the cliff-forming Tibbet Canyon Member. The Smoky Hollow Member was named for exposures on the west side of Smoky Hollow in the NE¼NE¼SW¼ sec. 5, T. 42 S., R. 4 E. (Peterson, 1969). The member is fairly well exposed in the southwestern and central parts of the region (fig. 14) but farther northeast, and especially at the Straight Cliffs escarpment, the member is generally concealed by talus (fig. 15). The Smoky Hollow consists of three informal units: a coal zone at the base, a barren zone in the middle, and the Calico bed at the top (fig. 16).

The coal zone at the base of the Smoky Hollow Member contains medium-dark-gray (N4) to black (N1) laminated to very thin bedded carbonaceous mudstone, black (N1) coal, pale-yellowish-brown (10YR 6/2) very fine to fine grained moderately sorted laminated to very thin bedded sandstone, and minor amounts of dusky-yellow (5Y 6/4) to light-olive-gray (5Y 6/1) bentonitic mudstone. The coal zone is as much as about 30 feet thick, but it is absent over Nipple Bench and Smoky Mountain anticlines owing to lateral gradation into the barren zone or into the Tibbet Canyon Member (pls. 9, 10). Because of these relations, the coal zone consists of three parts: the lower part in Wahweap syncline is the oldest and contains one coal bed generally less than about 4 feet thick; the middle part occurs in Warm Creek syncline and contains one coal bed generally less than about 3½ feet thick; the upper part extends from Last Chance syncline northeast to the Straight Cliffs escarpment and contains several thin coal beds generally less than about 2 feet thick. For purposes of illustration, figure 16 does not show the three parts, although they can be distinguished by their steplike occurrence above the flat and noninterfingering parts of the lower contact of the zone.

The barren zone is a ledge- and slope-forming unit consisting of sandstone and mudstone that weathers light brown and yellowish green. On fresh surfaces the sandstone is generally grayish orange (10YR 7/4) to yellowish gray (5Y 7/2), although locally it is light gray. The sandstone is generally very fine to medium grained and poorly to moderately sorted and contains small- to medium-scale low- to high-angle trough-type cross-stratification or scarce horizontal stratification. Some of these beds are fluvial channel sandstones that are lens shaped in cross section, but most of the sandstones have a wider extent and persist for several miles along the outcrop. Scattered quartz, feldspar, and chert granules or small pebbles occur locally throughout the sandstone beds, and leaf impressions or plant fragments are scarce but are found at the top in a few places. Scarce thin beds of dusky-green (5G 3/2) fine- to medium-grained sandstone occur locally at the top of the other sandstones or in the mudstone beds.

Another common lithology in the barren zone is dusky-yellow (5Y 6/4) to light-olive-gray (5Y 6/1) bentonitic mudstone that weathers to a generally yellowish green color and is very thin to thick bedded. The mineral composition of this rock type is probably not significantly different from similar lithologies in the Dakota Formation or in the John Henry Member of the Straight Cliffs. Light-gray (N7) mudstone is fairly common near the top of the zone. An analysis of a sample taken 1 foot below the top of the barren zone at measured section S22 (pl. 12) in the central part of the region follows:

X-ray diffraction analysis, in percent, of light-gray mudstone in barren zone of Smoky Hollow Member of Straight Cliffs Formation

Major constituents:	
Quartz	33
Potassium feldspar	3
Plagioclase feldspar	0
Calcite	0
Dolomite	0
Gypsum	0
Clays	64
Clay minerals:	
Chlorite	0
Kaolinite	40
Illite	8
Montmorillonite	trace
Mixed-layer (illite-montmorillonite)	16

Clay minerals as proportion of clay fraction:	
Chlorite	0
Kaolinite	63
Illite	12
Montmorillonite	trace
Mixed-layer (illite-montmorillonite)	25

The barren zone ranges in thickness from 13 to 110 feet. The variation in thickness is due to interfingering with other units in the Smoky Hollow Member, interfingering with the Tibbet Canyon Member, and erosion prior to deposition of the John Henry Member.

The Calico bed is a fine- to coarse-grained poorly sorted pebbly sandstone unit at the top of the Smoky Hollow Member. The sandstone is generally white (N9) to very light gray (N8), and locally the upper 1-3 feet is stained moderate red (5R 4/6) to dark yellowish orange (10YR 6/6). The sandstone is fine to medium grained and generally poorly sorted and contains small- to medium-scale low- to high-angle trough cross-stratification. Medium-gray (N5) to dark-gray (N3) mudstone lenses or tongues from the barren zone are scarce but are found in the bed.

Conglomerate lenses and scattered pebbles are common in the Calico bed. The pebble composition of the conglomerate lenses listed below is from a count of 658 pebbles made on the northeast side of Surprise Valley in the NE¼SW¼ sec. 10, T. 41 S., R. 5 E. At this locality the quartz, quartzite, and feldspar clasts are less than 8 mm in diameter (very fine and fine pebbles) and the chert clasts are less than 16 mm in diameter (very fine to medium pebbles). This distribution of sizes by pebble composition is typical.

Pebble composition of conglomerate lenses in Calico bed at top of Smoky Hollow Member in Straight Cliffs Formation

		Percent
Quartz		42
Chert		40
Light gray	30	
Dark gray	10	
Feldspar		18
Quartzite (reddish brown)		tr
		100

tr = trace, 0.3 percent.

The Calico bed interfingers with the upper part of the barren zone, and the bed is unconformably overlain by the John Henry Member. The bed reaches a maximum thickness of 67 feet in the central part of the region (meas. sec. S21, pl. 10) but is missing in the southwestern and northeastern parts where it was removed by erosion prior to deposition of the John Henry Member. The approximate average thickness of the bed is 25 feet.

Sandstones from throughout the member consist mainly of subangular slightly strained quartz grains containing all the major types of inclusions. The feldspars are about 5-20 percent of the rock and are mainly of the plagioclase varieties (oligoclase and andesine), although scarce potassium varieties (orthoclase and rare microcline) are also present. Some of these grains are moderately altered, and probably part of the clay mineral fraction in the matrix originated from postdepositional alteration of the feldspars. The clastic dolomite grains are rare and consist of polycrystalline aggregates or monocrystalline grains. Clastic calcite, if present, could not be distinguished from the calcite cement. Approximately one-fourth of the sandstone is silt- and clay-size matrix in which most of the clay minerals have the optical properties of the kaolin group. The accessory minerals are a small and almost insignificant part of the total mineral assemblage, although biotite is the most common. Most of the sandstones are only moderately cemented by calcite and are fairly porous, but one sample was unique in that it was well cemented by barite (identified by X-ray diffraction). The following composition is an average of the modal analyses shown on plates 12 and 13. According to the classification used in this report, a rock of the following composition would be termed an impure feldspathic sandstone.

Average of 13 modal analyses, in percent, of sandstone in Smoky Hollow Member of Straight Cliffs Formation (cement not included)

		All constituents	Constituents (1), (2), (3)
(1) Stable grains		63	83
Quartz	57		
Chert	2		
Quartzite	4		
(2) Feldspars		12	16
(3) Unstable grains		1	1
Clastic dolomite	1		
(4) Matrix		23	
(5) Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		1	
		100	100

The Smoky Hollow Member is about 24-132 feet thick in the southeastern Kaiparowits region. In the northwestern Kaiparowits region, the group of beds that includes units 2-9 above the base of a section measured by J. C. Lawrence (in Robison, 1966, p. 23) and tentatively assigned by the writer to the Smoky Hollow Member is 231 feet thick. About 9 miles northwest of Escalante, Utah, the Smoky Hollow is about 331 feet thick (E. V. Stephens, oral commun., 1967).

Fossils are rare in the Smoky Hollow Member, and only a few poorly preserved and unidentifiable pelecypod molds were found in the Warm Creek area. The lower part of the Smoky Hollow in the southwestern and central parts of the region is of middle Turonian age because these beds grade northeastward or northward into the upper part of the Tibbet Canyon Member which contains the middle Turonian pelecypod Inoceramus howelli. The upper part of the Smoky Hollow is probably only slightly younger than the lower part because the member consists of a continuous sequence of beds and lacks unconformities. The interfingering relations suggest that the Smoky Hollow is about middle Turonian in age. In terms of the standard reference sequence for the Western Interior region (Cobban and Reeside, 1952), the Smoky Hollow correlates approximately with the upper part of the Blue Hill Shale Member and possibly with the lower part of the Turner Sandy Member of the Carlile Shale (table 3).

UNCONFORMITY

The unconformity that separates the Smoky Hollow Member from the overlying John Henry Member has been described by Peterson (1969). Evidence of the unconformity is briefly summarized as follows:

(1) In local areas, the unconformity is indicated by truncation of low-angle dipping stratification at the top of the Smoky Hollow and by relief of as much as 5 feet on the unconformable surface.

(2) Considering broad stratigraphic relations, the unconformity is indicated by regional truncation of at least 157 feet of strata at the top of the Smoky Hollow in the southwestern part of the report area and of at least 90 feet of strata at the top of the Smoky Hollow in the northeastern part (pls. 9, 10, 11).

(3) Paleontological data indicates that the approximate minimum time-stratigraphic interval represented by the unconformity includes the upper part of the Turonian Stage and the lower and middle parts of the Coniacian Stage. In terms of the standard reference sequence for the Western Interior region, strata correlative with the upper part of the Carlile Shale and the lower and lower middle parts of the Niobrara Formation were eroded or never deposited in the southeastern Kaiparowits region (table 3).

The unconformity at the Turonian-Coniacian boundary has been reported in other parts of the Colorado Plateau by Dane (1960) in the San Juan Basin of New Mexico (fig. 9) and by Hunt, Averitt, and Miller (1953, p. 83) in the Henry basin of south-central Utah. Reconnaissance studies by the writer indicate that the unconformity is probably present in Black Mesa basin of northeastern Arizona at the base of the marine shale tongue of the Toreva Formation (fig. 8).

JOHN HENRY MEMBER

The John Henry Member of the Straight Cliffs Formation was named for a cliff- and slope-forming unit of interbedded sandstone, mudstone, carbonaceous mudstone, and coal that lies below the cliff-forming Drip Tank Member of the Straight Cliffs (Peterson, 1969). The type locality is about 3 miles east of John Henry Canyon in a small tributary canyon on the west side of Smoky Hollow in the SE¼NW¼ and W½NW¼ sec. 32 and the N½NE¼ sec. 31, T. 41 S., R. 4 E., Kane County, Utah. The member is moderately well exposed in the southwestern part of the region, but in the central part where many of the coal beds have been burned, the member is generally concealed by talus accumulations of baked mudstone and sandstone, and exposures are best near the bottom of dry washes. In the northeastern part of the region, slope-forming units of coal and mudstone are generally concealed by talus and soil (fig. 15). The type measured section is illustrated on plate 9 (meas. sec. S17), and figure 14 shows typical relations in the member at Warm Creek canyon about 3 miles southwest of the type locality.

The John Henry Member consists mainly of nonmarine beds in the southwestern and central parts of the region and mainly of marine beds in the northeastern part. The nonmarine beds are divided into three barren zones and four coal zones on the basis of the presence or absence of coal beds 1 or more feet thick (fig. 16); the marine beds are divided into seven key sandstone beds and two mudstone tongues.

Barren zones

The barren zones consist of relatively thick cliff-forming sandstone beds and slope-forming beds of mudstone interbedded with a small amount of thin sandstone beds. The thicker sandstone beds (more than about 5 ft thick) are pale yellowish brown (10YR 5/6) to grayish orange (10YR 7/4) on fresh exposures and they weather to various shades of light brown. In general, the thick sandstones that occur with the yellowish-green bentonitic mudstones are grayish orange, fine to medium grained, and poorly sorted. They also are poorly cemented and semifriable and locally contain scattered quartz, feldspar, and chert granules or small pebbles. They contrast with sandstones that occur with dark-gray to black carbonaceous mudstones which are generally pale yellowish brown, very fine to fine grained, moderately sorted, and well cemented by calcite; they rarely contain granules or small pebbles. All these sandstones have small- to medium-scale low- to high-angle trough-type cross-stratification or rare horizontal stratification, and most of the beds grade into very fine to fine grained ripple cross-laminated sandstone in the upper 1-3 feet. Most of the thick sandstones are fairly widespread and can be traced for several miles where exposures are good, but some of the beds are channel sandstones that are lens shaped in cross section and are difficult or impossible to trace any significant distance on the outcrop. Large-scale low-angle cross-stratified units as much as about 20 feet thick and composed mainly of very fine to fine grained sandstone interbedded with minor amounts of carbonaceous mudstone commonly occur where carbonaceous mudstone beds are abundant.

The thin sandstones (less than about 5 ft thick) interbedded with the mudstones are generally pale yellowish brown (10YR 5/6), very fine to fine grained, moderately sorted, and well cemented by calcite. They commonly are ripple cross-laminated or less commonly contain small- to medium-scale low-angle trough-type cross-stratification.

The sandstones consist mainly of subangular slightly strained quartz grains containing all the major types of inclusions. The feldspars are generally about 5-15 percent of the rock and are mainly of the plagioclase varieties (oligoclase and andesine), although scarce potassium varieties (orthoclase and rare microcline) are also present. Some of these grains are moderately altered, and probably part of the clay mineral fraction in the matrix originated from postdepositional alteration of the feldspars. The clastic carbonate grains are polycrystalline aggregates or monocrystalline grains and consist mainly of dolomite, although a small amount of clastic calcite can be distinguished from the calcite cement. Approximately one-fourth of the sandstone is silt- and clay-size matrix in which most of the clay minerals have the optical properties of the kaolin group. Biotite is the most common accessory mineral, although the accessory minerals in general are a small and almost insignificant part of the total mineral assemblage. The following composition is an average of the modal analyses shown on plates 12 and 13. According to the classification used in this report, a rock of the following composition would be termed an impure feldspathic sandstone.

Average of 46 modal analyses, in percent, of sandstone in barren zones of John Henry Member of Straight Cliffs Formation (cement not included)

		All constituents	Constituents (1), (2), (3)
(1) Stable grains		54	76
Quartz	47		
Chert	4		
Quartzite	3		
(2) Feldspars		8	11
(3) Unstable grains		9	13
Clastic dolomite	7		
Clastic calcite	2		
(4) Matrix		27	
(5) Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		2	
		100	100

Very thin to thick bedded mudstone is another common rock type in the barren zones. Dusky-yellow (5Y 6/4) to light-olive-gray (5Y 6/1) bentonitic mudstone that weathers to a general yellowish-green color is abundant in the upper barren zone, common in the middle barren zone, and uncommon in the lower barren zone. Dark-gray (N3) to black (N1) carbonaceous mudstone is abundant in the lower barren zone, common in the middle barren zone, and scarce in the upper barren zone. The carbonaceous mudstone is more common in beds adjacent to the various coal zones, although thin and discontinuous beds may be found in other parts of the barren zones. All gradations exist between the two contrasting types of mudstone, and no significant difference is apparent in analyses of the six samples shown in table 4.

Minor lithologies include thin limestone lenses, siderite concretions, and thin coal beds. The limestone lenses are dense, medium gray (N5), and as much as 50 feet long and 2-3 feet thick. Bedding is generally indistinct in the smaller lenses, but the larger lenses are commonly horizontally laminated. Small blackish-red (5R 2/2) to moderate-brown (5YR 4/4) concretions that are composed mainly of siderite are scarce but occur mainly in the dusky-yellow to light-olive-gray mudstones. Thin coal beds less than 1 foot thick generally occur in the carbonaceous mudstone beds.

Other than plant fragments and impressions, megafossils are scarce in the barren zones. One collection from the middle barren zone by H. A. Waldrop and identified by W. A. Cobban consisted of the molluscs Anomia? sp., Cymbophora? sp., and Melania? sp. Several collections from the upper barren zone by G. A. Izett, H. A. Waldrop, and the writer and identified by R. A. Scott, J. A. Wolfe, and the writer included undetermined pelecypods, gastropods, bone fragments, and coniferous wood as well as one fragment of the palm leaf Geonomites? sp.

An abundant spore and pollen flora was obtained from samples collected by Robert McCurdy of the Atlantic-Richfield Co. from a drill hole on Smoky Mountain that is about 1½ miles northwest of measured section S1S (pl. 1). The samples were collected from each of the barren and coal zones through the interval about 84-552 feet above the base of the member. The microfossils were identified by R. H. Tschudy who supplied the following partial list of genera.

TABLE 4.--X-ray diffraction analyses, in percent, of mudstone from barren zones in John Henry Member of Straight Cliffs Formation

	Yellow to olive-gray mudstone		Gray mudstone			Carbonaceous mudstone
Sample number:	*369	375	264	374	382	373
Major constituents:						
Quartz	23	34	36	34	27	30
Potassium feldspar	0	1	tr	0	2	2
Plagioclase feldspar	0	0	0	0	0	0
Calcite	19	0	0	0	2	0
Dolomite	8	0	0	0	1	0
Gypsum	0	1	0	0	0	0
Clays	47	64	64	66	68	68
Clay minerals:						
Chlorite	1	1	1	0	tr	tr
Kaolinite	22	20	31	43	14	32
Illite	15	7	9	3	7	7
Montmorillonite	0	2	0	3	12	tr
Mixed-layer**	9	34	18	17	35	29
Clay minerals as proportion of clay fraction:						
Chlorite	2	1	1	0	tr	tr
Kaolinite	47	32	53	65	22	47
Illite	31	11	16	4	10	10
Montmorillonite	0	3	0	5	17	1
Mixed-layer**	20	53	30	26	51	42

Location of samples

369. Upper barren zone, 150 ft below top of member; west side of Dry Canyon, meas. sec. S3.
375. Upper barren zone, 93 ft below top of member; same locality as 369.
264. Lower barren zone, 92 ft above base of member; 3 miles east of Wahweap Creek, meas. sec. S7.
374. Upper barren zone, 96 ft below top of member; same locality as 369.
382. Upper barren zone, 3 ft below top of member; same locality as 369.
373. Upper barren zone, 101 ft below top of member; same locality as 369.

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* = 3 percent pyrite not shown.

** = mixed-layer illite-montmorillonite clays.

tr = trace, less than 1 percent.

Spore and pollen genera in the John Henry Member of the Straight
Cliffs Formation, from the lower, middle, and upper barren zones
and the lower, Christensen, and Rees coal zones

Cicatricosisporites
Appendicisporites
Lycopodiumsporites
Gleicheniidites
Verrucatosporites
Taurocusporites
Ceratosporites?
Krauselisporites
Laevigatosporites
Inaperturopollenites
Monosulcites
Classopollis
Abietineaepollenites
Rugubivesiculites
Vitreisporites
Araucariacites
Ephedra
Eucommiidites
Proteacidites
Triatriopollenites
Plicapollis
Latipollis?
Sporopollis?
Tricolpopollenites
Tricolporites
Nyssapollenites
Periporopollenites

Coal zones

The coal zones consist mainly of slope-forming units composed of interbedded carbonaceous mudstone and thick coal beds 1 or more feet thick. Small quantities of thin sandstone beds (less than about 5 ft thick) are present in the coal zones, and thick sandstone beds (more than 5 ft thick) are commonly found in the southwestern parts of the coal zones.

The thick sandstone beds are pale yellowish brown (10YR 5/6), very fine to fine grained, moderately sorted, and well cemented by calcite. They contain small- to medium-scale low- to high-angle trough-type cross-stratification or rare horizontal stratification; most of these beds grade into very fine grained ripple cross-laminated sandstone in the upper 1-3 feet. Some of the thick sandstones are fairly widespread and can be traced for several miles where exposures are good, but most of these beds are channel sandstones that are lens shaped in cross section and are difficult or impossible to trace on the outcrop. Large-scale low-angle cross-stratified units as much as about 20 feet thick and composed mainly of very fine to fine grained sandstone interbedded with minor amounts of carbonaceous mudstone also occur in the coal zones.

The thin sandstones (less than about 5 ft thick) are pale yellowish brown (10YR 5/6) to very light gray (N8), very fine to fine grained, moderately sorted, and moderately to well cemented by calcite. They are commonly ripple cross-laminated or less commonly contain small- to medium-scale low-angle trough-type cross-stratification.

The sandstones consist mainly of subangular slightly strained quartz grains containing all the major types of inclusions. The feldspars generally amount to less than 10 percent of the rock and are mainly of the plagioclase varieties (oligoclase and andesine), although scarce potassium varieties (orthoclase and rare microcline) are also present. Some of these grains are moderately altered, and probably part of the clay mineral fraction in the matrix originated from postdepositional alteration of the feldspars. The clastic carbonate grains are polycrystalline aggregates or monocrystalline grains and consist mainly of dolomite, although a small amount of clastic calcite could be distinguished from the calcite cement. Approximately one-fifth of the sandstone is silt- and clay-size matrix in which most of the clay minerals have the optical properties of the kaolin group. The accessory minerals are a small and almost insignificant part of the total mineral assemblage. Biotite is the most common accessory mineral. The following composition is an average of the modal analyses shown on plates 12 and 13. According to the classification used in this report, a rock of the following composition would be termed an impure subfeldspathic sandstone.

Average of 15 modal analyses, in percent, of sandstone in coal zones of John Henry Member of Straight Cliffs Formation (cement not included)

			All constituents	Constituents (1), (2), (3)
(1)	Stable grains		60	78
	Quartz	54		
	Chert	3		
	Quartzite	3		
(2)	Feldspar		4	5 ✓
(3)	Unstable grains		13	17
	Clastic dolomite	11		
	Clastic calcite	2		
(4)	Matrix		22	
(5)	Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		1	
			100	100

Laminated to very thin bedded dark-gray (N3) to black (N1) carbonaceous mudstone is the most common argillaceous rock in the coal zones. Dusky-yellow (5Y 6/4) to light-olive-gray (5Y 6/1) very thin to thin bedded bentonitic mudstone is scarce and, where present, is generally near a thick sandstone bed. Gray mudstones that are intermediate varieties of the two types mentioned above are also common. Medium-dark-gray (N4) laminated to very thin bedded shale and carbonaceous shale are relatively rare. X-ray diffraction analyses of some of these lithologies are listed in table 5.

Coal beds are abundant in the four coal zones of the John Henry Member. Although coal beds 1 or more feet thick are the main feature used to distinguish these zones, coal beds 4 or more feet thick are common in several parts of the region. The thickest bed found measured 29.6 feet (meas. sec. S23, pl. 10) and is in the Christensen coal zone on the northeast side of Last Chance syncline. The coal beds are generally thickest and most abundant in the synclines, and they either thin or pinch out over the anticlines. The available data also indicate that the coal thickens northwestward into the Kaiparowits structural basin. The following list indicates general areas where the coal beds are thickest and probably most continuous.

Coal zone	Area of thickest and probably most continuous coal beds
Alvey coal zone------------------	Southwest side of Croton syncline.
Rees coal zone-------------------	Last Chance syncline.
Christensen coal zone------------	Warm Creek and Last Chance synclines, southwest side of Croton syncline.
Lower coal zone------------------	Last Chance syncline.

The areas listed above are also places where coal in the Christensen, Rees, and Alvey coal zones has been extensively burned, and exposures of unburned coal in these areas are only locally present at the bottom of dry washes or on steep canyon slopes where recent erosion has been rapid. The mudstone and sandstone strata enclosing the coal have been baked to brilliant shades of red, pink, and gold where the burning has occurred. The fires were probably started by natural causes such as spontaneous combustion or lightning, and several fires still remain in Last Chance syncline. The

TABLE 5.--X-ray diffraction analyses, in percent, of mudstone and shale from coal zones in John Henry Member of Straight Cliffs Formation

	Light-olive-gray mudstone	Gray shale	Carbonaceous mudstone
Sample number:	335	477	344
Major constituents:			
Quartz	27	28	41
Potassium feldspar	tr	2	3
Plagioclase feldspar	0	0	0
Calcite	6	0	1
Dolomite	8	0	1
Gypsum	0	0	0
Clays	59	70	54
Clay minerals:			
Chlorite	1	1	tr
Kaolinite	31	51	23
Illite	9	11	15
Montmorillonite	0	0	0
Mixed-layer*	18	7	16
Clay minerals as proportion of clay fraction:			
Chlorite	1	1	1
Kaolinite	53	73	42
Illite	16	16	27
Montmorillonite	0	0	0
Mixed-layer*	30	10	30

Location of samples

335. Christensen coal zone, 170 ft above base of member; northeast side of Last Chance Creek canyon, meas. sec. S22.

477. Lower coal zone, 25 ft above base of member; above Sit Down Bench about 1,000 ft northwest of top of meas. sec. T5.

344. Christensen coal zone, 258 ft above base of member; same locality as 335.

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* = mixed-layer illite-montmorillonite clays.

tr = trace, less than 1 percent.

fires probably have been in progress, at least intermittently, for several thousand years, judging from baked mudstone and sandstone that occur in the oldest pediment and terrace gravels in the region.

Minor lithologies in the coal zones include rare limestone concretions and rare coquinoid marlstones. The limestone concretions were found in the central part of the region; they consist of medium-dark-gray (N4) dense limestone in concretions about 6 inches thick and 2 feet in diameter. The coquinoid marlstones occur in the northeastern part of the region; they consist of a poorly indurated mass of abundant broken fossil fragments in a very light gray (N8) matrix of comminuted fossil material and clay.

Fossiliferous beds are scarce in the coal zones, but where present, the fossils are commonly abundant and are dominated by one or two species. The fossils generally occur in thin gray mudstone beds 1-2 feet thick, although a few collections were obtained from thin sandstone and coquinoid marlstone strata. *Crassostrea soleniscus* (Meek) is by far the most common fossil. A summary list of fossils from the coal zones is given below. The collections were made by G. A. Izett and the writer, and the identifications were made by W. A. Cobban, N. F. Sohl, and the writer. In addition to these fossils, plant microfossils obtained from the lower, Christensen, and Rees coal zones were included in the partial list of spore and pollen genera given in the discussion of the barren zones.

Fossils from coal zones in the John Henry Member of the Straight Cliffs Formation

Christensen coal zone

Annelida
- *Serpula* cf. *S. tenuicarinata* Meek and Hayden

Bryozoa
- Undetermined genus and species

Pelecypoda
- *Inoceramus* cf. *I. mesabiensis* Berquist
- *Inoceramus* sp.
- *Crassostrea coalvillensis* (Meek)
- *Crassostrea soleniscus* (Meek)
- *Unio*? sp.
- *Anomia* sp.
- *Brachidontes* sp.
- *Corbula* sp.

Gastropoda
- *Stenomelania*? sp.
- *Pachychiloides*? sp.

Cephalopoda
- Ammonite, undet.

Rees coal zone

Crassostrea soleniscus (Meek)

Key sandstone beds

Marine strata in the northeastern part of the region include seven conspicuous cliff-forming sandstone beds and two slope-forming marine mudstone tongues composed of interbedded mudstone and sandstone.

The seven key sandstone beds, lettered A, B, C, D, E, F, and G, consist mainly of very light gray (N8) to grayish-orange (10YR 7/4) fine-grained well-sorted sandstone. In thin section, the sandstones consist mainly of subrounded slightly strained quartz grains containing all the major types of inclusions. The feldspars rarely amount to more than 10 percent of the rock, and they consist mainly of plagioclase varieties (oligoclase and andesine), although scarce potassium varieties (orthoclase and rare microcline) are also present. The feldspars are generally fresh and unaltered. The majority of unstable constituents are subrounded to sharply angular monocrystalline grains of dolomite. Many of the angular grains clearly show optically continuous overgrowths that indicate postdepositional precipitation of dolomite on the clastic grains. A small amount of clastic calcite can be distinguished from the calcite cement, but some or all of these grains could be finely divided fossil fragments. The matrix is generally less than 10 percent of the rock and consists mainly of silt-size particles of the other constituents. The accessory minerals are a small and almost insignificant part of the total mineral assemblage. The following composition is an average of the modal analyses shown on plates 12 and 13. According to the classification used in this report, a rock of the following composition would be termed a quartz sandstone.

Average of 45 modal analyses, in percent, of sandstone in the A, B, C, D, E, F, and G sandstone beds in the John Henry Member of the Straight Cliffs Formation (cement not included)

		All constituents	Constituents (1), (2), (3)
(1) Stable grains		80	87
Quartz	75		
Chert	3		
Quartzite	2		
(2) Feldspars		4	4
(3) Unstable grains		8	9
Clastic dolomite	8		
Clastic calcite	tr		
(4) Matrix		8	
(5) Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		tr	
		100	100

tr = trace, less than 0.5 percent.

Minor rock types in the sandstone beds include thin conglomerate lenses, scattered pebbles, and black sandstone lenses (fossil beach placers). Scattered conglomerate lenses as much as 2-3 feet thick occur locally in the A sandstone bed, and scattered pebbles occur locally in the A, B, C, and D sandstone beds. The pebbles are well rounded and consist of quartzite or chert. The quartzite pebbles consist of subrounded to well-rounded moderately sorted fine- to medium-grained quartz grains that contain abundant irregular inclusions or scarce acicular inclusions. Rare constituents that collectively amount to less than 1 percent include chert and feldspar. Jagged interlocking grain boundaries caused by pressure solution are common. Coarse grains and small pebbles as large as 7 mm in diameter are common and are conspicuous in the red quartzites by their light-gray color. The coarse grains and small pebbles are composed of quartzite that has a textural and mineralogical composition similar to that of the enclosing quartzite pebbles. T. E. Mullens (oral commun., 1966) examined some of the quartzite pebbles from the conglomerate lenses and stated that they appear similar to some of the Precambrian quartzites that occur in north-central Utah. The chert pebbles are light to dark gray and vuggy and commonly contain fossil fragments and fusulinids which indicate late Paleozoic age. The results of a count of 338 pebbles at measured section S24 (pl. 10) are listed below. The estimated median diameter of the pebbles at this locality is 10 mm, and the intermediate diameter of the largest pebble is 72 mm.

Pebble composition of conglomerate lenses in A sandstone bed of John Henry Member of Straight Cliffs Formation

		Percent
Quartzite		87
Light gray	73	
Red	14	
Chert		13
Light gray	8	
Dark gray	5	
		100

Several aspects of the pebbles in sandstone beds A to D are significant when compared to the scattered pebbles in the thick sandstones in the barren zones of the John Henry Member: (1) quartzite is more abundant in these beds, whereas chert is more abundant in the barren zones; (2) red quartzite is common in these beds, whereas red quartzite is rare in the barren zones; and (3) many of the pebbles are considerably larger in these beds than the pebbles in the barren zones, which seldom exceed 5 mm in diameter. Although the pebbles have not been found in strata higher than the D sandstone bed, sand-size grains of red quartzite are found as high as the G sandstone bed. The above features, and especially the red quartzite grains, are of considerable value in separating these sandstones from other sandstone beds in the barren and coal zones of the John Henry Member.

Several black sandstone lenses consisting of concentrated heavy minerals occur at the top of the B sandstone bed in Croton syncline and near the crest of Rees Canyon anticline. The beds are approximately lens shaped in cross section and trend about N. 45° W. The thickest and most concentrated deposits occur at the Long Shot claims in secs. 4, 5, 8, and 9, T. 40 S., R. 5 E., where the beds are about 200 feet wide and as much as 8 feet thick (fig. 17). Strata that include the black sandstone beds at the claims can be traced for about 1 mile in a northwest direction, although the individual black sandstone beds appear to be in lens- and wedge-shaped units that do not continue that far. Brief descriptions and analyses of the black sandstone deposits are given by Dow and Batty (1961, p. 11-14).

The black sandstone deposits at the Long Shot claims were sampled in detail by J. F. Murphy and R. S. Houston in 1967, and preliminary results of some of their work were donated to the writer for this report. The following table lists the range and average mineralogical composition of heavy minerals from five of their samples. The heavy minerals totaled 56-77 percent of the total mineral assemblage.

Mineralogical composition, in percent, of heavy minerals in black sandstone deposits, top of B sandstone bed in John Henry Member of Straight Cliffs Formation

	Range	Average
Opaque minerals	63-84	73
Zircon	15-32	22
Rutile	1- 5	2
Garnet	0- 3	2
Tourmaline	0- 1	1
Staurolite	0- 1	tr
Sphene	tr	tr
Apatite	tr	tr
		100

tr = trace, less than 0.5 percent.

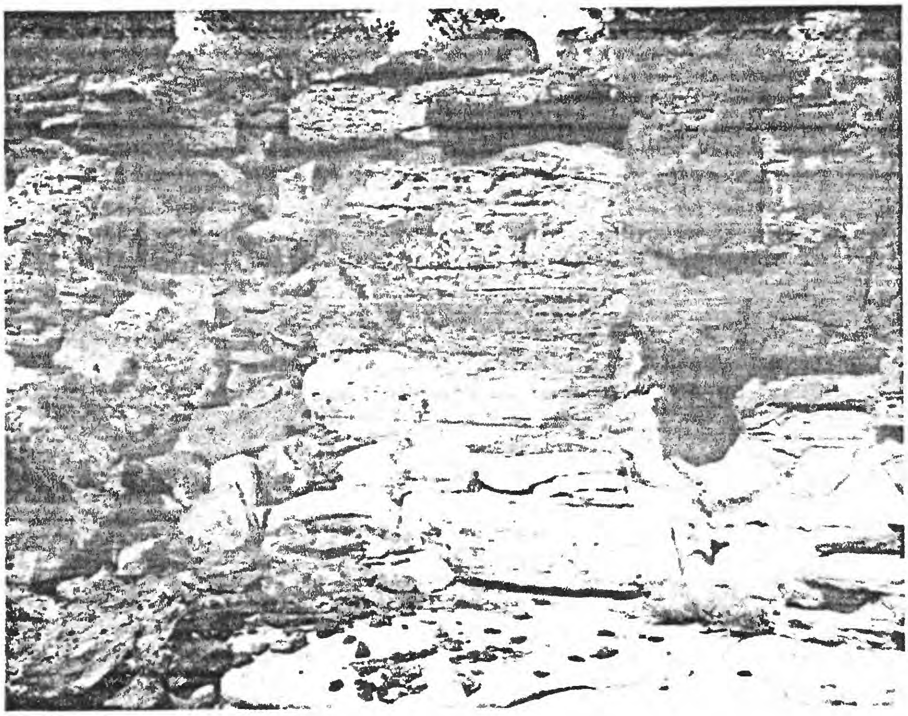


FIGURE 17.--Black sandstone bed (fossil beach placer) 8 feet thick at top of B sandstone bed in John Henry Member of Straight Cliffs Formation. The laminated to very thin bedding that dips at very low angles is typical of strata deposited in the swash zone of beach environments. In Long Shot claims, near crest of Rees Canyon anticline at measured section S24.

The sandstone beds locally contain a threefold vertical sequence of bedding structures that is not found in other sandstones in the member. The lower unit of the sequence contains horizontal stratification and low-angle medium- to large-scale trough cross-stratification, the middle unit contains low- and high-angle medium-scale trough cross-stratification, and the upper unit contains very low angle (less than about 5°) medium- to large-scale wedge-planar cross-stratification. Strata containing the lower bedding unit are grayish orange, strata containing the middle bedding unit are grayish orange to very light gray, and strata containing the upper bedding unit are very light gray to white. The black sandstone deposits are local occurrences in beds containing the upper bedding unit.

The lower bedding unit is the most common of the three types, and except in the southwesternmost part of each bed, the lower unit is always present whether or not the other types are present. The three bedding units are commonly absent in the southwesternmost parts of the beds where abundant mottles and burrows indicate that burrowing organisms have obliterated any bedding structures that might have been formed. Part or all of the vertical bedding sequence may be found locally repeated in the same bed, although this is not common. This is because the beds actually consist of several parts, and the partial or complete sequence is found in each part.

Plates 10 and 11 show that the A to G sandstone beds interfinger considerably more complexly than is suggested by the simplified relations shown in figure 16. The A, B, C, D, and G sandstones could be subdivided further but the present nomenclature is already sufficiently complex. The significance of the interfingering is that each of these beds is composed of several parts that are approximately lens shaped in a northeast-southwest direction, and for this reason the sandstone beds should not be thought of as simple tabular bodies.

The key sandstone beds are commonly 50-100 feet thick, and locally some are as much as about 200 feet thick. The A, B, C, and G sandstone beds can be traced or correlated 50 miles northwest along or within several miles southwest of the Straight Cliffs escarpment, and detailed stratigraphic studies in the many canyons northwest of Left Hand Collett Canyon would probably demonstrate that the other beds also extend that far. The E and F sandstones are about 5 miles wide in a northeast direction, and although the A, B, C, and D sandstones are eroded at the Straight Cliffs escarpment, evidence from thickness trends suggests that the B, C, and D sandstones were originally about 20 miles wide and that the A sandstone was originally about 30 miles wide. The G sandstone, or at least its lithogenetic equivalents, probably extended 50 or more miles northeast to the Henry Mountains region.

Well-preserved fossils are uncommon in the sandstone beds, but finely divided fragments of oysters and inocerams occur in many places. The A sandstone contains the most abundant and varied fossil fauna. *Inoceramus involutus*, generally ½-1 foot long, is the most conspicuous fossil in this bed because of its relatively large size. The burrow structure *Ophiomorpha* sp., probably formed by a burrowing arthropod similar to the living decapod crustacean *Callianassa major* Say (Weimer and Hoyt, 1964), is commonly found near the base of the sandstones or is locally abundant in the southwesternmost parts of several of the beds. A summary list of fossils from these beds follows. They were identified by W. A. Cobban, D. H. Dunkle, Nicholas Hotton 3d, and the writer.

Fossils from the A to G sandstone beds, John Henry Member of the Straight Cliffs Formation

A sandstone bed

Pelecypoda
- *Inoceramus* (*Volviceramus*) *involutus* Sowerby
- *I.* cf. *I. stantoni* Sokolow
- *Inoceramus* sp.
- *Ostrea congesta* Conrad
- *Ostrea* sp.
- *Crassostrea soleniscus* (Meek)
- *Cardium* cf. *C. curtum* Meek and Hayden
- *C.* cf. *C. pauperculum* Meek
- *Cymbophora*? sp.

Gastropoda
- *Gyrodes* cf. *G. depressus* Meek

Cephalopoda
- *Baculites asper* Morton
- *Placenticeras* sp.

Arthropoda? sp.
- *Ophiomorpha* sp.

Vertebrata--Chondrichthyes (sharks and skates)
- Shark teeth, undet.

Vertebrata--Reptilia
- Turtle carapace fragments, undet.

B sandstone bed

Pelecypoda
- *Inoceramus* sp.

Gastropoda
- *Gyrodes* cf. *G. conradi* Meek
- *G.* cf. *G. depressus* Meek
- *Rostellites*? sp.

Fossils from the A to G sandstone beds, John Henry Member of the Straight Cliffs Formation--continued

C sandstone bed

- Pelecypoda
  - *Inoceramus* sp.
  - *Crassostrea coalvillensis* (Meek)

D sandstone bed

- Pelecypoda
  - *Ostrea* sp.
- Cephalopoda
  - *Baculites* sp.
- Arthropoda?
  - *Ophiomorpha* sp.

E sandstone bed

- Pelecypoda
  - *Inoceramus* sp.
  - *Ostrea* sp.
- Cephalopoda
  - *Baculites* sp.
- Arthropoda?
  - *Ophiomorpha* sp.
- Vertebrata--Chondrichthyes
  - Shark teeth, undet.

G sandstone bed

- Pelecypoda
  - *Inoceramus* cf. *I.* (*Cordiceramus*) *mülleri* Petrascheck

Marine mudstone tongues

The lower and upper marine mudstone tongues consist of slope-forming units of interbedded sandstone and mudstone (fig. 15). Several other thin marine mudstone tongues occur between the A, B, C, and D sandstones and are included in the following descriptions.

The sandstone beds in the marine mudstone tongues are grayish orange (10YR 7/4) to pale yellowish brown (10YR 6/2) and consist mainly of well-sorted very fine grained sandstone. Thin-section analyses indicate that they have nearly the same mineralogical features as the A to G sandstones except that the percentage of feldspars is relatively low and the percentage of clastic dolomite grains is relatively high. Bedding is of the same types that occur in the lower bedding unit in the A to G sandstones, although ripple cross-laminated beds are also common. Most of the sandstones in the marine mudstone tongues appear to be northeastward-extending tongues of the A to G sandstones that are too thin to be traced well in the field. The following composition is an average of the modal analyses shown on plates 12 and 13. According to the classification used in this report, a rock of the following composition would be termed a subfeldspathic sandstone.

Average of 15 modal analyses, in percent, of sandstone in the marine mudstone tongues of the John Henry Member of the Straight Cliffs Formation (cement not included)

			All constituents	Constituents (1), (2), (3)
(1)	Stable grains		75	82
	Quartz	73		
	Chert	1		
	Quartzite	1		
(2)	Feldspars		2	2
(3)	Unstable grains		15	16
	Clastic dolomite	15		
	Clastic calcite	tr		
(4)	Matrix		7	
(5)	Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		1	
			100	100

tr = trace, less than 0.5 percent.

The mudstone beds are medium dark gray (N4) or, less commonly, light olive gray (5Y 6/1) and are very thin to thin bedded. The mudstone probably amounts to less than 50 percent of all the beds in the mudstone tongues.

Minor lithologies in the mudstone tongues include small limestone concretions and thin conglomerate lenses. Several small gray unfossiliferous dense limestone concretions were found in about the middle of the lower marine mudstone tongue at the Straight Cliffs escarpment. Conglomerate lenses less than 3 feet thick occur locally at the base of the lower marine mudstone tongue (fig. 18). The clasts are well rounded and range to as large as cobble size (as much as 6 in. long). They are composed mainly of red or gray quartzite (pebbles and cobbles) or less commonly of chert (pebbles), and the percentages are similar to those in the A sandstone bed.

Strata in the lower part of the lower marine mudstone tongue apparently thin and pinch out southwestward by onlap on the unconformable surface at

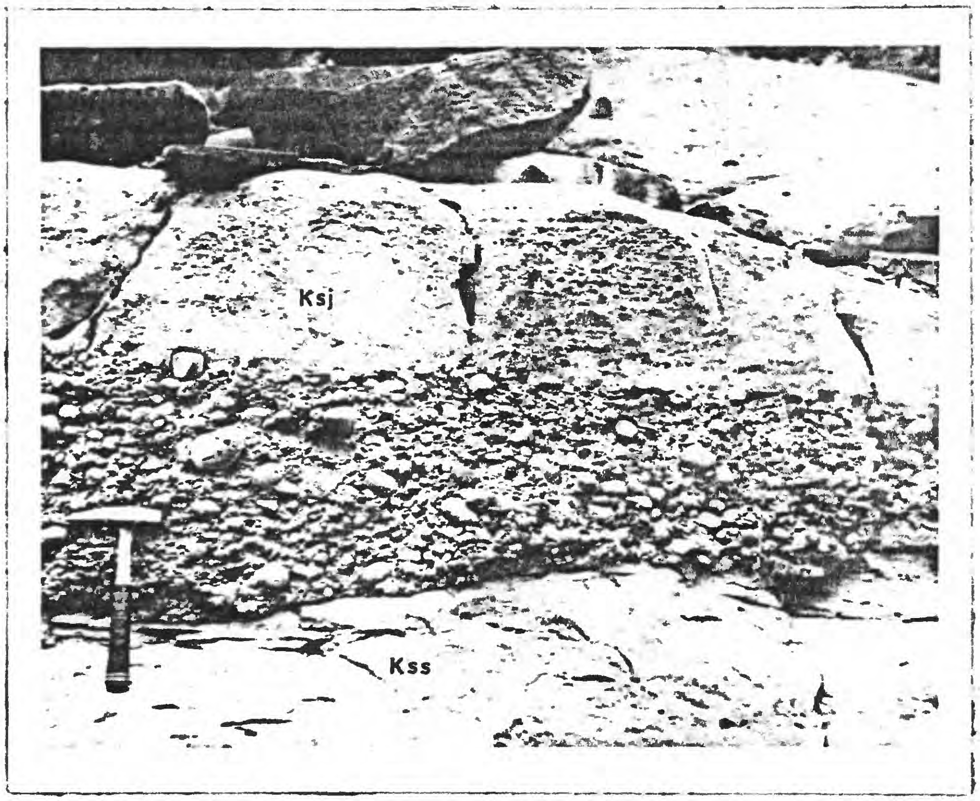


FIGURE 18.--Basal conglomerate of John Henry Member (Ksj) resting on unconformable surface at top of Smoky Hollow Member (Kss) in Straight Cliffs Formation. The pebbles and cobbles consist of red and light-gray quartzite (67 percent) and light- and dark-gray chert (33 percent). On northeast side of Main Canyon about 9 miles west of Escalante, Utah.

the base of the John Henry Member. Other beds in this tongue and strata in the other tongues grade southwestward into the A to G sandstone beds.

Well-preserved fossils are uncommon in the marine mudstone tongues, but finely divided fragments of oysters and inoceramids occur in many of the sandstones. The burrow structure *Ophiomorpha* sp. is the most abundant fossil that was found. A summary list of fossils from the lower and upper marine mudstone tongues is given below. The fossils were identified by W. A. Cobban, D. H. Dunkle, Nicholas Hotton 3d, and the writer.

Fossils from the lower and upper marine mudstone tongues, John Henry Member of Straight Cliffs Formation

Lower marine mudstone tongue

- Pelecypoda
    - *Inoceramus* cf. *I. stantoni* Sokolow
    - *Inoceramus* sp.
    - *Ostrea* sp.
    - *Anomia*? sp.
    - *Cardium* cf. *C. pauperculum* Meek
- Gastropoda
    - *Gyrodes* cf. *G. depressus* Meek
- Cephalopoda
    - *Baculites asper* Morton
    - *Baculites codyensis* Reeside
    - *Scaphites* sp.
    - *Placenticeras* sp.
    - *Protexanites shoshonensis* (Meek)
- Arthropoda?
    - *Ophiomorpha* sp.
- Vertebrata--Chondrichthyes (sharks and skates)
    - *Lamna appendiculata* Agassiz
    - *Ptychodus* sp.

Upper marine mudstone tongue

- Annelida
    - *Serpula* sp.
- Pelecypoda
    - *Inoceramus* (*Endocostea*) cf. *I. balticus* Böhm
    - *I.* (*Sphenoceramus*) sp.
    - *Inoceramus* sp., with a truncate anterior margin
    - *Ostrea* sp.
    - *Crassostrea soleniscus* (Meek)
    - *Cardium* cf. *C. pauperculum* Meek
- Arthropoda
    - *Ophiomorpha* sp.

A large sandstone block that contained abundant fossils was found at the foot of the Straight Cliffs escarpment near Fiftymile Point. The block probably came from the lower marine mudstone tongue or the A sandstone bed.

Although the shells were probably concentrated by currents, the assemblage indicates that a greater variety of animal life existed during deposition of the John Henry Member than is evident from collections at any other locality in the region. Fossils in this block were identified by W. A. Cobban and are listed below.

Pelecypoda
Nucula sp.
Inoceramus stantoni Sokolow
Oxytoma sp.
Ostrea sp.
Anomia subquadrata Stanton
Cardium sp.
Tellina sp.
Cymbophora sp.

Scaphopoda
Dentalium sp.

Gastropoda
Gyrodes aff. *G. depressus* Meek
Euspira? sp.
Xenophora sp.
Turritella sp.
Anomalofusus? sp.
Actaeon? sp.

Cephalopoda
Baculites asper Morton
Scaphites sp.
Placenticeras n. sp.
Undetermined heteromorph ammonite

General

The foregoing paragraphs have shown that the John Henry Member is composed of four different assemblages of lithologies, namely those in the barren zones, coal zones, key sandstone beds, and marine mudstone tongues. The four types of lithologic units reach their greatest thicknesses in different parts of the region, with the result that certain lateral changes in the member are fairly clear. Thus, in the southwestern part of the region, yellowish-green mudstones and fine-grained poorly to moderately sorted sandstones of the barren zones are common. In the central part from Warm Creek syncline to Last Chance syncline, carbonaceous mudstones, coal, and very fine grained moderately sorted sandstones of the coal zones are common. In the northeastern part at Rees Canyon anticline and in most of Croton syncline, the fine-grained well-sorted thick cliff-forming key sandstone beds are common. And in the northeasternmost part at the Straight Cliffs escarpment, the interbedded very fine grained well-sorted sandstones and gray mudstones of the marine mudstone tongues are common. The lateral variations in the member are especially apparent in the textural and mineralogical composition of the sandstones (pls. 12, 13). Table 6 allows comparison of the average of modal analyses from sandstones in each of the measured sections shown on plates 12 and 13 and the average of all the modal analyses that were made. The difference in quartz and matrix content is especially apparent.

TABLE 6.--Comparison of average of modal analyses, in percent, from sandstone in four measured sections, and average of all analyses

	(Southwest)			(Northeast)	
	Measured section				
	S7	S3, S22	S29	S34	All
	No. of samples				
	33	30	24	34	121
Stable grains------	52	61	78	80	67
Quartz-----------	(44)	(56)	(72)	(76)	(61)
Chert------------	(4)	(4)	(4)	(3)	(4)
Quartzite--------	(4)	(1)	(2)	(1)	(2)
Feldspars----------	9	4	5	3	5
Unstable grains----	10	10	10	10	10
Clastic dolomite-	(7)	(9)	(10)	(10)	(9)
Clastic calcite--	(3)	(1)	(0)	(tr)	(1)
Matrix-------------	27	24	7	7	17
Accessory minerals-	2	1	tr	tr	1

tr = trace, less than 0.5 percent.

The John Henry Member has a minimum thickness of about 660 feet over the Nipple Bench and Smoky Mountain anticlines. The member is thickest in Croton syncline where a restored section totaled about 1,120 feet. In the northwestern Kaiparowits region, the group of beds that includes units 10-31 above the base of a section measured by J. C. Lawrence (in Robison, 1966, p. 21-23) and tentatively assigned by the writer to the John Henry Member is 657 feet thick.

The position of the unconformity at the base of the John Henry Member is generally easy to recognize by the sharp color contrast of the carbonaceous mudstones and generally gray sandstones near the base of the member with the white to very light gray Calico bed at the top of the underlying Smoky Hollow Member. Where the Calico bed is missing, the unconformity can usually be found by the difference in character of the mudstones and sandstones above and below the contact. Red and light-gray quartzite pebbles and cobbles and chert pebbles in conglomerate lenses or as scattered clasts generally occur at the base of the lower marine mudstone tongue in the northeastern part of the region. The quartzite pebbles, and especially the red quartzite pebbles, are rare in the Smoky Hollow Member, which commonly contains small quartz, feldspar, and chert pebbles.

The upper part of the John Henry Member probably interfingers with the lower part of the Drip Tank Member, but this cannot be demonstrated conclusively because talus conceals the contact in many places. Where exposures are good, the upper contact is placed at the top of the highest mudstone bed underlying the thick cliff-forming sandstone of the Drip Tank. Where exposures are poor, the contact can be placed at the bottom of conspicuous and laterally continuous sandstone beds that occur at or near the mudstone-sandstone contact and that can be traced laterally as key beds.

Fossils that are diagnostic of age are not common in the John Henry Member, but several species indicate reasonably good age assignments and correlation. Inoceramus cf. I. stantoni and Protexanites shoshonensis in the lower marine mudstone tongue and I. cf. I. stantoni and I. (Volviceramus) involutus in the A sandstone bed indicate that the lower part of the John Henry Member is late Coniacian in age (W. A. Cobban, written commun., 1966; Scott and Cobban, 1964, p. 5). Inoceramus (Sphenoceramus) sp. and Inoceramus (Endocostea) cf. I. balticus came from the lower part of the upper marine mudstone tongue, and Inoceramus sp. which has a truncate anterior margin came from the upper part of the upper marine mudstone tongue. Inoceramus cf. I. (Cordiceramus) müIleri was found in the G sandstone bed. According to W. A. Cobban (written commun., 1966, 1968), these fossils indicate an approximately early Campanian age. Accordingly, the middle part of the John Henry Member is of Santonian age. Strata in the Alvey coal zone are probably also early Campanian in age because the Alvey coal zone interfingers with the G sandstone bed and because palynomorphs that suggest middle to late Campanian age were found in the upper part of the Kaiparowits Formation about 3,000 feet above the top of the Straight Cliffs Formation in the northwestern Kaiparowits region (R. H. Tschudy and S. D. Van Loenen, written commun., 1967; Bowers, 1968).

The paleontological evidence indicates that the John Henry Member ranges in age from about late Coniacian to early Campanian (table 3). In terms of the standard reference sequence of formations for the Western Interior region, the John Henry correlates with the middle and upper parts of the Smoky Hill Shale Member of the Niobrara Formation at Pueblo, Colo. (Scott and Cobban, 1964) and probably with the lowermost part of the Gammon Ferruginous Member of the Pierre Shale at Red Bird, Wyo. (Gill and Cobban, 1966). The lower and upper marine mudstone tongues correlate approximately with the Mulatto and Satan Tongues, respectively, of the Mancos Shale in the San Juan Basin of New Mexico (fig. 9). Correlation with rocks in Black Mesa, Ariz., is indicated in figure 8.

DRIP TANK MEMBER

The Drip Tank Member of the Straight Cliffs Formation is a cliff-forming sandstone unit that is resistant to erosion and generally supports an irregular bench or stripped structural surface at the top of the Straight Cliffs Formation (fig. 14). The lower part of the member generally forms cliffs, although talus accumulations conceal the lower contact in many places. The upper part of the member and the lower part of the overlying Wahweap Formation are generally stripped back and form a broad bench. Windblown sand on this bench and talus accumulations at the foot of bluffs that are composed of the Wahweap Formation conceal the uppermost part of the Drip Tank Member in many places. The member was named for exposures near the mouth of Drip Tank Canyon in the NE¼NE¼ sec. 24, T. 40 S., R. 3 E., Kane County, Utah (Peterson, 1969).

The Drip Tank Member consists mainly of pale-yellowish-brown (10YR 6/2) to grayish-orange (10YR 7/4) fine- to coarse-grained poorly to moderately sorted sandstone. Bedding is generally of trough-type cross-stratification and is small to medium scale and low to high angle. The sandstone consists mainly of subangular slightly strained quartz grains containing all the major types of inclusions. The feldspars generally amount to less than about 15 percent of the rock and are mainly of the plagioclase varieties (oligoclase and andesine), although scarce potassium varieties (orthoclase and rare microcline) are also present. Some of these grains are moderately altered, and probably part of the clay mineral fraction in the matrix originated from postdepositional alteration of the feldspars. The clastic dolomite grains are polycrystalline aggregates or monocrystalline grains. Approximately 15 percent of the sandstone is silt- and clay-size matrix in which the clay minerals have the optical properties of the kaolin and montmorillonite groups. The accessory minerals are a small and almost insignificant part of the mineral assemblage. The sandstone is moderately cemented by calcite and is fairly porous. The following is an average of the modal analyses shown on plates 12 and 13. According to the classification used in this report, a rock of the following composition would be termed an impure feldspathic sandstone.

Average of 13 modal analyses, in percent, of sandstone in Drip Tank Member of Straight Cliffs Formation (cement not included)

		All constituents	Constituents (1), (2), (3)
(1) Stable grains		73	87
Quartz	52		
Chert	11		
Quartzite	10		
(2) Feldspars		8	10
(3) Unstable grains		3	3
Clastic dolomite	3		
Clastic calcite	0		
(4) Matrix		15	
(5) Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		1	
		100	100

Minor lithologies in the Drip Tank Member include scattered pebbles and pebble conglomerate lenses, mudchip conglomerates, and thin mudstone tongues or lenses. The scattered pebbles and pebble conglomerate lenses occur mainly in the lower 50-80 feet of the member, and they are more abundant southwest of Smoky Mountain anticline. The pebbles are generally of chert and are less than about 16 mm in diameter, although some as large as 25 mm were found in the southwestern part of the region. Clear quartz and feldspar as coarse and very coarse sand grains, or rarely as granules, commonly occur with the chert pebbles. The pebble composition of the conglomerate lenses at measured section S1 near Nipple Butte is listed below and is based on a count of 393 pebbles. The quartz and feldspar grains at this locality were of sand size and, therefore, these minerals were not included in the count.

Pebble composition of conglomerate lenses in lower part of Drip Tank Member of Straight Cliffs Formation

	Percent
Chert:	
Light gray	83
Dark gray	16
Pink	1
	100

Scattered mudchip conglomerate lenses as much as 3 feet thick are scarce but have been found in the upper part of the member. The clasts are of dusky-yellow (5Y 6/4) to light-olive-gray (5Y 6/1) mudstone and are enclosed in a matrix of fine- to medium-grained poorly sorted poorly to moderately cemented sandstone. Scattered mudchip clasts may be found in any part of the member, but they are not common.

Dusky-yellow (5Y 6/4) to light-olive-gray (5Y 6/1) very thin to thin bedded bentonitic mudstone lenses that are as much as 20 feet thick are scarce but may be found in any part of the member. Thin beds of the same lithology commonly occur near the top of the member and are tongues of the Wahweap Formation that are too thin to map separately.

The upper part of the Drip Tank Member interfingers with the lower part of the Wahweap Formation, and where exposures are good, the upper contact is placed at the base of the lowest mudstone bed overlying the thick cliff-forming sandstone of the Drip Tank Member. Where exposures are poor, the contact can be placed at the top of prominent and laterally continuous sandstone beds that occur at or near the sandstone-mudstone contact and that can be traced laterally as key beds.

The Drip Tank Member is about 141-255 feet thick in the southeastern Kaiparowits region. In the northwestern Kaiparowits region the highest unit in a section measured by J. C. Lawrence (in Robison, 1966, p. 21) and tentatively assigned by the writer to the Drip Tank Member is 523 feet thick.

Fossils are generally poorly preserved and fragmented in the Drip Tank Member. Petrified logs and fragments of petrified wood and vertebrate bones were found throughout the member but are more abundant in about the lower half. D. H. Dunkle and Nicholas Hotton 3d identified some of the collected material as Trionyx? sp. (soft-shelled turtle). E. V. Stephens (oral commun., 1967) found shark teeth in the member about 9 miles northwest of Escalante, Utah, in the northern Kaiparowits region. These are long-ranging fossils and are not diagnostic of age.

The Drip Tank Member is probably early Campanian in age on the basis of indirect evidence from fossils in older and younger beds. Early Campanian fossils occur about 150 feet below the Drip Tank in the G sandstone bed of the John Henry Member. Strata in these members apparently represent continuous deposition, and the members are not separated by an unconformity. Palynomorphs that suggest middle to late Campanian age occur about 3,000 feet above the Drip Tank in the upper part of the Kaiparowits Formation in the northwestern Kaiparowits region (R. H. Tschudy and S. D. Van Loenen, written commun., 1967; Bowers, 1968). From this evidence it is clear that the Drip Tank is Campanian in age, and proximity to early Campanian beds suggests that the Drip Tank Member is of early Campanian age (table 3). This age assignment suggests that the Drip Tank correlates approximately with the lower part of the Gammon Ferruginous Member of the Pierre Shale at Red Bird, Wyo. (Gill and Cobban, 1966) or possibly with the uppermost part of the Smoky Hill Shale Member of the Niobrara Formation at Pueblo, Colo. (Scott and Cobban, 1964). Correlation with rocks in the San Juan Basin of New Mexico is shown in figure 9.

Wahweap Formation

The Wahweap Sandstone was named by Gregory and Moore (1931, p. 91, 104-106) for exposures on upper Wahweap Creek about 15 miles northwest of Glen Canyon City, Utah. The formation consists mainly of interbedded mudstone and sandstone, and for this reason Peterson and Waldrop (1965, p. 65-66) applied the more general name Wahweap Formation to these beds. Because mudstone is the dominant lithology near the base and sandstone is the dominant lithology near the top, the lower part of the formation weathers easily to smooth and rounded slopes that commonly are concealed by talus and windblown sand and silt; the upper part of the formation is resistant to erosion, weathers to cliffs, and forms a broad bench or stripped structural surface (fig. 19). The Wahweap was not studied in great detail, but the following description gives an understanding of the general lithology of the formation and furnishes the background for conclusions regarding deposition and structural movements in the region.

Sandstone is the dominant lithology in the upper part of the Wahweap (fig. 20), and the top of the formation is capped by a prominent cliff-forming sandstone unit that is commonly 250-350 feet thick (fig. 19). The sandstone is generally grayish yellow (5Y 8/4) to dark yellowish orange (10YR 6/6), fine to medium grained, and poorly to moderately sorted.

Thin sections were made only of sandstones near the base of the formation, but in these the rock consists mainly of subangular slightly strained quartz grains containing all the major types of inclusions. The feldspars generally amount to about 15 percent of the rock and are mainly of the plagioclase varieties (oligoclase and andesine), although scarce potassium varieties (orthoclase and rare microcline) are also present. Some of these grains are moderately altered, and probably part of the clay mineral fraction in the matrix originated from postdepositional alteration of the feldspars. The clastic carbonate grains are rare and consist mainly of polycrystalline aggregates of dolomite or calcite. Approximately one-fourth of the sandstone is silt- and clay-size matrix in which the clay minerals have the optical properties of the kaolin or montmorillonite groups. The accessory minerals are a small and almost insignificant part of the mineral assemblage. The rock is moderately cemented by calcite, but except for the beds at the

FIGURE 19.--Wahweap Formation on northeast side of Drip Tank Canyon. Numerous discontinuous fluvial sandstones form light-colored cliffs and alternate with slope-forming units of yellowish-green mudstone. Upper sandstone unit about 250 feet thick caps ridge and Reynolds Point at right. Measured section W4, up other side of Reynolds Point, totaled 1,360 feet. Drip Tank Member of Straight Cliffs Formation forms tree-covered bench in foreground.

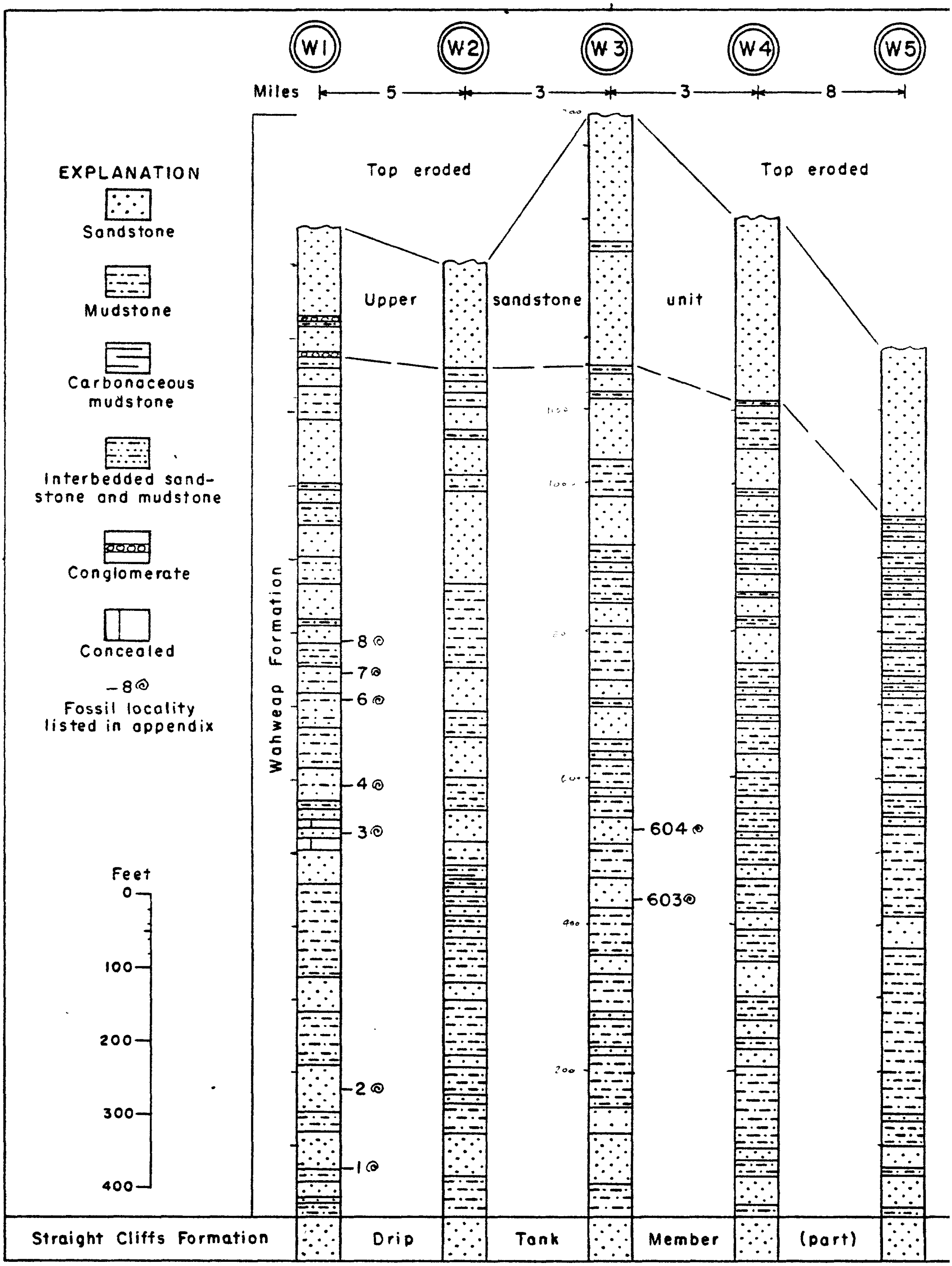


FIGURE 20.--Measured sections of the Wahweap Formation.

top of the formation, the sandstone is not very porous because of the high matrix content. The following is an average of the modal analyses shown on plate 12. The analyses were made on samples from the base of the formation and may not be representative of sandstones in the rest of the formation, although significant differences cannot be noted with a hand lens. According to the classification used in this report, a rock of the following composition would be termed an impure feldspathic sandstone.

Average of seven modal analyses, in percent, of sandstone near base of Wahweap Formation (cement not included)

			All constituents	Constituents (1), (2), (3)
(1)	Stable grains		55	76
	Quartz	45		
	Chert	7		
	Quartzite	3		
(2)	Feldspars		15	21
(3)	Unstable grains		2	3
	Clastic dolomite	1		
	Clastic calcite	1		
(4)	Matrix		27	
(5)	Accessory minerals (biotite, garnet, glauconite, muscovite, tourmaline, zircon)		1	
			100	100

The thicker sandstones (more than about 5 ft thick) generally contain small- to medium-scale low- to high-angle trough cross-stratification and rare horizontal stratification. Commonly, the beds grade upward into very fine grained ripple cross-laminated sandstone in the upper 1-3 feet. Thinner sandstone beds (less than about 5 ft) commonly have small-scale low-angle cross-stratification or ripple cross-lamination.

Mudstone that weathers to a general yellowish-green color is the common lithology in about the lower 500 feet of the formation. The mudstone is dusky yellow (5Y 6/4) to light olive gray (5Y 6/1) at fresh exposures, very thin to thick bedded, and bentonitic. Thin sandstone beds are commonly interbedded with the mudstone.

Minor lithologies include carbonaceous mudstone lenses, scattered pebbles or pebble conglomerate lenses, and mudchip conglomerate lenses. Medium-gray (N5) carbonaceous mudstone is rare but occurs in lenses generally less than 3 feet thick in the other mudstones. Some of the sandstones also contain thin laminae of carbonaceous mudstone. Scattered pebbles occur in many of the thicker sandstone beds, and thin pebble conglomerate lenses that are generally less than 2 feet in maximum thickness occur in the upper part of the formation (fig. 20). The clasts are composed mainly of light- and dark-gray chert pebbles less than about 16 mm in diameter. Clear quartz and feldspar pebbles less than about 8 mm in diameter are also common, and red chert pebbles less than about 8 mm in diameter are rare. Scattered mudchip conglomerate lenses generally less than 8 feet thick occur in the lowermost beds of the formation (fig. 21). The clasts are of dusky-yellow to light-olive-gray mudstone and are enclosed in a matrix composed of fine- to medium-grained poorly sorted poorly to moderately cemented sandstone.

The upper contact of the Wahweap Formation could not be determined because it occurs on a broad bench that is covered by windblown sand and silt. In other parts of the Kaiparowits region, however, the contact occurs where the light-colored cliff-forming sandstone at the top of the Wahweap grades into dark-colored slope-forming sandstone and mudstone at the base of the overlying Kaiparowits Formation. Judging from this, it is likely that the contact is within about 50-100 feet of the top of measured sections W3, W4, and W5 shown in figure 20.

The Wahweap totals 1,172 and 1,502 feet, respectively, at incomplete measured sections W5 and W3 shown in figure 20. Because it is believed that the upper contact is within 50-100 feet of the top of the formation at these localities, the thicknesses given above seem to be a reasonable minimum approximation of the true thickness of the formation. The Wahweap is 900-1,364 feet thick in the northwestern Kaiparowits region (Robison, 1966, p. 25-26; Bowers, 1968), and Gregory and Moore (1931, p. 105) found that the formation averages about 1,250 feet thick throughout the Kaiparowits Plateau.

Fossils are generally scarce in the Wahweap Formation, although they are surprisingly common at measured section W1 (fig. 20) in the southwestern part of the region. Vertebrate bone fragments are common in some of the sandstone beds but generally they are not adequately preserved to merit collection, and

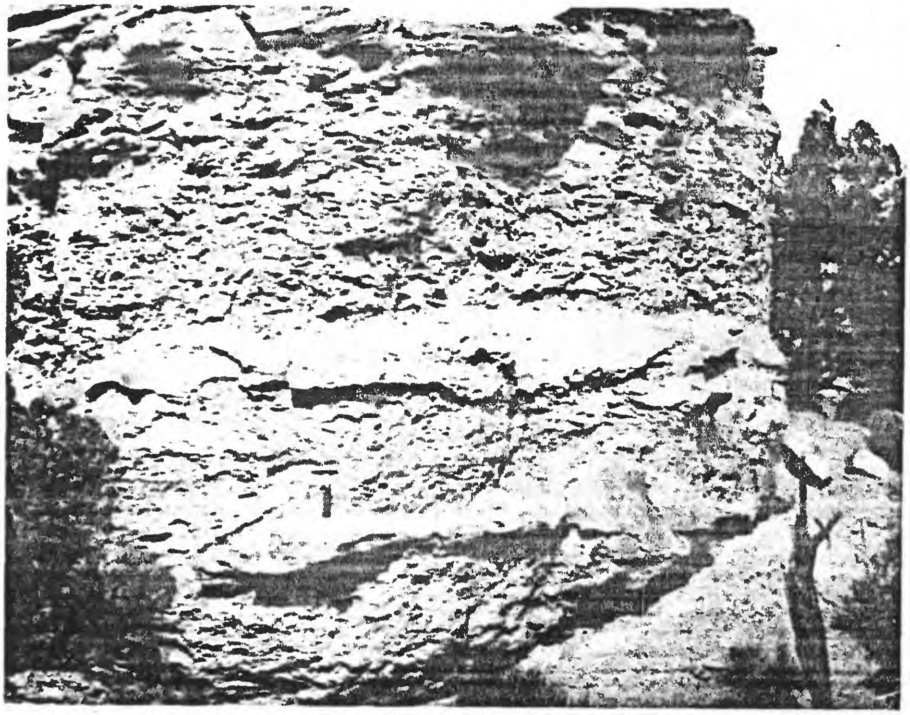


FIGURE 21.--Mudchip conglomerate about 50 feet above base of Wahweap Formation. The clasts are as much as about 1 foot long and are embedded in a poorly sorted medium-grained sandstone matrix. In measured section S4 about 3 miles northeast of Last Chance Creek.

those that are well preserved are too firmly embedded in the rock to be extracted. The following summary list of fossils is from several collections made by G. A. Izett, G. W. Horton, R. L. Sutton, H. A. Waldrop, and the writer; they were identified by W. A. Cobban, G. E. Lewis, R. E. Peck, R. A. Scott, I. G. Sohn, and the writer.

Fossils in the Wahweap Formation

- Pelecypoda
  - *Plesielliptio* sp.
  - *Proparreysia* aff. *P. baueri* (Stanton)
  - *Proparreysia P. gardneri* (Stanton)
  - *Proparreysia* sp.
- Gastropoda
  - *Viviparus* sp.
  - *Campeloma* cf. *C. nebrascensis* (Meek and Hayden)
  - *Campeloma* sp.
  - *Tulotomops* aff. *T. laevibasalis* Yen
  - *Tulotomops* sp.
  - *Physa* sp.
- Ostracoda
  - *Cypridea* spp.
  - Undetermined ostracodes
- Vertebrata
  - Osteichthyes (bony fish)
    - *Lepidosteus* sp. (garpike)
  - Reptilia
    - Undetermined turtle
    - Undetermined crocodile
    - Undetermined hadrosaurian ornithischian dinosaur
- Plants
  - *Chara* n. sp.
  - *Mesochara* n. sp.
  - Undetermined coniferous wood
  - *Cercidiphyllum*? sp.; (fruit)

The fossils indicate a Late Cretaceous age for the Wahweap Formation, but the underlying John Henry Member of the Straight Cliffs Formation contains fossils that indicate an early Campanian age, and the upper part of the overlying Kaiparowits Formation contains palynomorphs that suggest middle to late Campanian age (R. H. Tschudy and S. D. Van Loenen, written commun., 1967; Bowers, 1968). The fossils in these formations indicate that the Wahweap Formation is probably early and middle Campanian in age and that the formation correlates approximately with the lower and middle parts of the Pierre Shale at Red Bird, Wyo. (Gill and Cobban, 1966, p. 35). The thick upper sandstone unit of the Wahweap is similar to the Castlegate Sandstone of the Book Cliffs region in that both of these units are widespread fluvial sandstones. According to W. A. Cobban (oral commun., 1969), the best estimate of the age of the Castlegate is that it correlates with a middle Campanian faunal zone that is characterized by an unnamed smooth species of *Baculites* that occurs between the zones of *B. perplexus* and *B. asperiformis* in the sequence of Western Interior ammonite zones suggested by Gill and Cobban (1966, p. 35). This long distance correlation with the Castlegate, although tenuous, is in agreement with an early and middle Campanian age assignment for the Wahweap. This age suggests that the lower and middle parts of the Wahweap Formation are the same approximate age as the Mesaverde Formation and the Masuk Member of the Mancos Shale in the Henry Mountains region (Hunt and others, 1953). Correlation of the Wahweap with rocks in the San Juan Basin of New Mexico is shown in figure 9.

Formations in northwestern Kaiparowits region

Two Upper Cretaceous formations that are younger than the Wahweap Formation occur in the northwestern part of the Kaiparowits region. The Kaiparowits Formation consists of slope-forming bluish-gray sandstone and minor mudstone (Robison, 1966, p. 27-28) and is as much as 2,756 feet thick (Lohrengel, 1968). The Kaiparowits conformably overlies the Wahweap, and apparently these formations represent a continuous sequence of deposition. Contrary to the opinions expressed by Van De Graaff (1963, p. 68) and Lessentine (1965, p. 2017), there is no evidence that an unconformity separates these formations. On the basis of palynomorphs, the upper part of the Kaiparowits is about middle to late Campanian in age, according to R. H. Tschudy and S. D. Van Loenen (written commun., 1967) and Bowers (1968).

A newly discovered Upper Cretaceous formation about 0-900 feet thick that consists mainly of red to gray mudstone and conglomerate overlies the Kaiparowits Formation. According to W. E. Bowers (oral commun., 1969), local erosion of the Kaiparowits Formation occurred prior to deposition of the mudstone and conglomerate unit, but it has not yet been determined whether this is strictly a local phenomenon in an otherwise continuous sequence of beds or if an unconformity separates these two formations. The lower part of the mudstone and conglomerate unit contains late Campanian palynomorphs (R. H. Tschudy and S. D. Van Loenen, written commun., 1967; Bowers, 1968), and the unit is probably entirely of late Campanian age. The approximate correlation of the Kaiparowits Formation and the mudstone and conglomerate unit with rocks in the San Juan Basin of New Mexico is shown in figure 9.

The concept of facies as applied to sedimentary rocks was first proposed by Armand Gressly (1836, 1838, 1840, 1841), who used the term to describe local lithologic or paleontological differences in Jurassic formations of northwestern Switzerland.

> "I was thus able to recognize in the horizontal dimension of each formation various well-marked lateral changes that had constant peculiarities not only in the petrographic make-up but also in the palaeontological character (or aspect) of the assemblage of fossils * * *" (Gressly, 1838, p. 10-11; translation by Schenck, 1961, p. 8).

Gressly also recognized that the local differences in the formations were at least partly the result of deposition in different environments.

> "I think that the changes, whether petrographic or palaeontologic that one sees in a formation in its horizontal extent are caused by the different environments and other circumstances that up to the present day influence so decidedly the different genera and species of organisms populating the modern seas" (Gressly, 1838, p. 11; translation by Schenck, 1961, p. 8).

Gressly did not use a precise scheme in applying names to the facies; instead, he named them according to the particular sediment type, fossils, or environment that seemed to characterize each. Thus, in his various reports, he wrote of mud facies with hydrozoans, coralline facies, littoral mud facies, pelagic facies, and open marine facies.

The term facies is used in this report in essentially the same context as that used by Gressly. The Cretaceous formations in the southeastern Kaiparowits region are composed of several different types of rock units or facies in which the lithologic and paleontological aspects are consistently different. These differences were largely caused by contemporaneous deposition in geographically separated environments--each of which had its own characteristic physical, chemical, and biological processes. The lithologic and tectonic character of the source area was also important in governing the type and the quantity of detritus carried into the region, and the tectonic framework of the depositional region was important in governing the distribution and the occurrence of depositional environments. Thus, the Cretaceous formations are best understood in terms of the different facies of which they are composed, or, to put it another way, the formations are best understood in terms of the environments in which their lithologic subdivisions were deposited.

Unfortunately, the lithologic and paleontological characters that serve to distinguish the various environments of deposition are not everywhere present or apparent. Some beds could have been deposited in any one of several environments, and other beds lack diagnostic features on the outcrop that would aid in determining the conditions of deposition. Lithologies that fall under these categories must be interpreted on the basis of their association with other nearby beds or on the basis of the general horizontal and vertical depositional framework of the stratigraphic units.

Five broad categories of sedimentary facies are recognized in the region, and, for continuity of thought, two others from nearby regions are discussed. The facies are established on the basis of evidence from fossils, lithologies, bedding structures, geometry of beds, and lateral gradations. Stratigraphic position and comparison with modern depositional environments have also been considered. All the facies interfinger to some extent, but the lateral boundary between several of the facies is marked by considerable interfingering and lateral gradation; in these cases, the boundary must be placed somewhat arbitrarily where strata of one facies dominate over the other. The interfingering, however, is a common geological phenomenon found in Cretaceous rocks of the Western Interior (Sears and others, 1941; Hollenshead and Pritchard, 1961). The seven depositional facies that are recognized in this report are listed in table 7. They are arranged in order with strata at the top of the list having been deposited in or near the source area and strata at the bottom of the list having been deposited farthest from the source area. The succeeding discussion shows that the list is somewhat idealized, and exceptions do occur.

Piedmont Facies

Principal features.--Rocks of the piedmont facies do not occur in the southeastern Kaiparowits region, but the unnamed mudstone and conglomerate unit in the northwestern part is probably fairly representative. Spieker (1949, p. 60) briefly described the facies in central Utah as consisting of conglomerate, red beds, and fresh-water limestone. The Indianola Group,

TABLE 7.--Summary description of facies in or near the southeastern Kaiparowits region

Facies	Dominant or characteristic lithologies	Environments of deposition
Piedmont*	Conglomerate, conglomeratic sandstone, red beds, minor limestone.	Piedmont alluvial fans, local ponds or small lakes.
Alluvial plain		Alluvial coastal plain.
Subdiv. A	Conglomeratic and pebbly sandstone in thick and widespread units.	Braided streams.
Subdiv. B	Fine- to medium-grained poorly to moderately sorted poorly cemented sandstone in beds of moderate lateral extent; yellowish-green mudstone; minor limestone and carbonaceous mudstone lenses.	Braided streams, overbank flood plain, local ponds or small lakes at higher elevations, local backswamps at lower elevations.
Subdiv. C	Very fine to fine grained moderately sorted well-cemented channel sandstones; carbonaceous mudstone; minor coal.	Meandering streams, backswamps.
Deltaic plain	Very fine to fine grained moderately sorted well-cemented foreset, channel and large-scale crossbedded sandstones; carbonaceous mudstone; coal.	Deltas, distributaries, crevasse splays, interdistributary troughs including swamps, marshes, and lagoons.
Lagoonal-paludal	Carbonaceous mudstone, coquinoid marlstone lenses, coal.	Brackish-water lagoons, estuaries, or embayments; swamps and marshes.
Barrier sandstone	Fine-grained well-sorted moderately cemented fossiliferous sandstone.	Beach, shallow-water nearshore lagoon and marine, associated with barrier islands.
Offshore marine	Gray mudstone or shale, lesser amounts of very fine grained well-sorted fossiliferous sandstone.	Open marine waters, approximately 5-10 to as much as several hundred miles offshore, depending on currents and tectonism.
Distant marine*	Limestone.	Open marine waters, approximately 50-100 to as much as several hundred miles offshore, depending on currents, tectonism, and biogenic sedimentation.

* Not present in report area.

also in central Utah, was included in the piedmont facies by Spieker. According to Hardy and Zeller (1953, p. 1266-1267), the Indianola on the Gunnison Plateau consists mainly of cobble and boulder conglomerate and contains relatively small quantities of interbedded red, light-gray, and light-brown sandstone and shale.

Interpretation.--The pebbles, cobbles, and boulders indicate bedload transportation in the upper flow regime in streams having relatively high current velocities and probably having steep gradients (Simons and Richardson, 1961; Fahnestock and Haushild, 1962; Harms and Fahnestock, 1965, p. 106-108). The red color in some beds indicates oxidizing conditions or at least conditions in which red sediments could be preserved without reduction. Precipitation of the calcium carbonate that formed the fresh-water limestones probably occurred during temporarily dry periods that might have been seasonal.

The lithologies of the piedmont facies in central Utah are associated with thrusts and angular unconformities, and the relations suggest deposition in or near a highland region in an active orogenic belt (Spieker, 1949, p. 70-76; Armstrong, 1968). The Cretaceous Willow Tank, Baseline, and Overton Formations of southern Nevada (Longwell, 1949; Armstrong, 1968) consist of conglomerate and sandstone and were deposited in an active orogenic region that was probably one of the principal source areas for many of the beds in the report area. The southern Nevada formations, thus, constitute a piedmont facies of some of the Cretaceous formations in the southeastern Kaiparowits region.

Alluvial Plain Facies

SUBDIVISION A

Principal features.--Subdivision A of the alluvial plain facies consists almost entirely of sandstone and occurs in relatively thick and widespread beds. These beds contain scattered pebbles and conglomerate lenses that generally increase in abundance toward the southwest. Most of the pebbles are composed of chert, and the pebbles are generally less than about 16 mm in diameter, although sparse pebbles as large as about 25-35 mm have been found in the southwestern and central parts of the region. The sandstone is generally poorly to moderately sorted, fine to coarse grained, and moderately cemented. Relative to other sandstones in the region, the beds contain fairly large quantities of matrix, feldspar, chert, and quartzite grains and little clastic dolomite. Most of the beds would be termed impure feldspathic sandstones, although some contain considerable amounts of feldspar and are impure arkosic sandstones. Petrified logs and fragments of petrified wood and vertebrate bones are scarce but occur in some beds.

The amount of silt and clay matrix in fluvial sandstones in each of the three subdivisions of the alluvial plain facies is considerably greater than in modern fluvial sands. Some of this material was undoubtedly a part of the original sediment, but most of the matrix probably was formed by post-depositional alteration of unstable constituents of the sediment. Corroded and partly kaolinized feldspar grains indicate that some of the matrix was formed by alteration of this mineral. In addition, some of the matrix was probably formed by alteration of volcanic ash that was present in abundance, judging from the abundance of bentonite in most of the mudstones in the region. The alteration was apparently caused by slightly acid intrastratal solutions which are commonly present in continental sandstones (Weaver, 1959, p. 173). Exposure in outcrops augments the process (Glass, 1958, p. 231), and all the samples collected for this study were taken from outcrops.

Crossbedding is generally of the low- and high-angle medium-scale planar or trough types (McKee and Weir, 1953) in sets that are about 1-3 feet thick. Less common bedding forms include horizontal stratification and low-angle small-scale trough types. Ripple cross-lamination is rare. Cut-and-fill structures, channel forms, and crude terraces also occur in these beds, although they are relatively scarce. The base of these sandstones is commonly an erosional or locally channeled surface.

Subdivision A of the alluvial plain facies occurs mainly as three stratigraphic units: the Drip Tank Member and the Calico bed of the Smoky Hollow Member, both in the Straight Cliffs Formation, and the thick upper sandstone unit of the Wahweap Formation. The Drip Tank Member and the upper unit of the Wahweap Formation are about 140-350 feet thick. The Calico bed was eroded after deposition, but judging from the thickness of a unit in the northwestern Kaiparowits region (Robison, 1966, p. 20) that is interpreted by the writer as the Calico bed, the bed originally was as much as about

360 feet thick and possibly more. The Drip Tank Member and the upper unit of the Wahweap Formation presently occur throughout the Kaiparowits region and probably were originally deposited over a far larger part of northern Arizona and southern Utah. The Calico bed is missing in the southern and eastern parts of the region, but this is because of erosion prior to deposition of the overlying beds and not because of nondeposition. Thus, it is highly probable that the Calico bed originally had approximately the same broad lateral extent as the other units.

Interpretation.--Judging by the character of the fossils and the lithologic and bedding features, the beds included in subdivision A probably were deposited in nonmarine conditions by braided streams. A local exception is the northeasternmost part of the Drip Tank Member where lithologic and bedding features suggest a transition into nearshore marine beds. Although fossils are rare, those that were found in the report area were all nonmarine forms. The shark teeth found in the Drip Tank Member in the northern Kaiparowits region by E. V. Stephens (oral commun., 1967) support the interpretation that this unit grades northeastward into nearshore marine beds.

Deposition of these beds by braided streams is suggested by comparison of the lithologies and bedding structures with sediments and bedding structures of modern braided streams and with the results of flume experiments. Doeglas (1962) and Ore (1964, p. 7) found that modern braided stream deposits consist of two different but intergrading types. The one type is poorly sorted, consists of gravel with sand matrix, and is commonly found on the upstream ends of longitudinal bars. The other type is better sorted, consists of sand, and is generally deposited in transverse bars or on the downstream ends of longitudinal bars. This compares well with the scattered pebbles and conglomerate lenses found in the sandstones of the Kaiparowits region.

Fisk (1952, p. 680-681) noted that alluvial deposits of the Mississippi River west of Cairo, Ill., were deposited when that river was once braided and are characterized by the absence of silt and clay and the presence of gravels. Scarcity of mudstone beds and presence of conglomerate lenses and scattered pebbles in the sandstones of the Kaiparowits region suggest a similar origin. The Kosi River of northeastern India provides an example of the processes that remove mud and clay beds from these deposits. Leopold, Wolman, and Miller (1964, p. 291) and Leopold and Wolman (1957, p. 62) noted that after it leaves the Himalaya Mountains, the Kosi has a braided character as it flows 130 miles down a broad alluvial cone. During the past 200 years, this river has shifted its course 70 miles westward by means of sporadic movements as much as 12 miles in 1 year. The relatively rapid lateral migration of this stream suggests that braided streams which deposited the beds in the alluvial plain facies under similar circumstances continuously migrated across their alluvial plains and removed most of the fine overbank materials that may have been previously deposited.

The abundance of medium-scale low- and high-angle trough and planar crossbedding suggests bedload movement primarily by dunes and bars in the lower flow regime, although rare occurrences of chert pebbles as large as 25-35 mm and horizontal stratification with current lineations suggest sediment movement sometimes occurred by plane-bed transportation in the lower part of the upper flow regime (Simons and Richardson, 1961, 1962; Fahnestock and Haushild, 1962; Harms and Fahnestock, 1965, p. 105-108). Horizontal stratification suggesting the upper flow regime was found by Ore (1964, p. 11) in Pliocene braided stream deposits near Farthing, Wyo. It should be noted that bedding structures formed in the upper flow regime can easily be destroyed by the passage of troughs and dunes of the lower flow regime as would be expected to occur when the discharge of a stream is reduced. Absence of upper flow regime bedding structures cannot be considered as proof that the upper flow regime was never attained.

Channel forms, cut-and-fill structures, and terracelike structures in these beds reflect the rapid lateral migration and local scouring of the many anabranches of the braided streams (Doeglas, 1962; Ore, 1964, p. 5; Allen, 1965c, p. 144-145, 163). The erosional and locally channeled lower surface of many of these beds is a common feature of fluvial deposits (Allen, 1965a, p. 242), but similar features also occur at the base of some nearshore marine and beach sandstone beds deposited during a phase of marine transgression and, therefore, cannot be considered diagnostic.

Braided streams generally flow on relatively steeper slopes than meandering streams having the same discharge (Leopold and Wolman, 1957, p. 59-62; Leopold and others, 1964, p. 293). Fisk (1952, p. 680-681, 687-688) attributed the past braided character of the Mississippi River to its steeper gradient when sea level was considerably lower than at present. The Kosi River of India, cited previously, is braided where it flows on the relatively steep slopes of its alluvial cone, whereas the river changes to meandering at the foot of the alluvial cone where it flows across the comparatively flat plain of the Ganges River (Leopold and Wolman, 1957, p. 62).

In conclusion, the various features of the widespread and thick sandstone units of subdivision A of the alluvial plain facies suggest deposition primarily from the bedload of braided streams that had moderately steep gradients. Bedload transportation was largely in the lower flow regime as sediment was deposited, but was at least occasionally and perhaps commonly in the lower part of the upper flow regime as well. Most of the fine overbank deposits were removed by the streams as they migrated laterally across the plain on their way to the sea, although scarce mudstone lenses in these beds indicate that the reworking process was not entirely complete. The conditions of deposition indicated for these beds is similar to Facies A of the Upper Old Red Sandstone (Upper Devonian) described by Allen (1965b) and the Shinarump and Moss Back Members of the Chinle Formation (Upper Triassic) described by Stewart, Williams, Albee, and Raup (1959) and Stewart (1961).

SUBDIVISION B

Principal features.--This subdivision of the alluvial plain facies consists mainly of two contrasting types of lithologies--relatively thick sandstone beds having moderate lateral continuity and thick yellowish-green mudstone beds. Other significant lithologies include relatively thin sandstone beds, thin limestone lenses, and thin carbonaceous mudstone or coal lenses.

The sandstone beds are generally about 5-60 feet thick and consist of impure sandstone that locally contains scattered small quartz, feldspar, and chert pebbles. Compared to other sandstones in the region, these beds contain the largest amounts of matrix; they also contain relatively large quantities of feldspar. Fragments of petrified wood and vertebrate bones and external molds of logs and branches are also present. Some of the beds occur as lens-shaped channel deposits, but most of the beds have irregularly parallel tops and bottoms and can be traced for as much as several miles on the outcrop (fig. 14).

Many of these beds consist of two parts that suggest a cycle of deposition (Allen, 1965a). The lower part of the cycle includes nearly the entire thickness of the bed and is composed of fine- to medium-grained poorly to moderately cemented sandstone that contains low- to high-angle medium-scale trough and planar cross-stratification in sets about 1-3 feet thick. Horizontal stratification with primary current lineation (Stokes, 1947) is scarce. Cut-and-fill structures, channel forms, and crude terracelike structures are also scarce. The base of a bed, and thus the base of a cycle, is generally an erosional or locally channeled surface. The upper part of the cycle is about 1-3 feet thick and is composed of very fine to fine grained well-cemented sandstone that has ripple cross-lamination or ripple-drift cross-lamination (climbing-ripple structure of McKee, 1966).

Another common lithology is very thin to thin bedded bentonitic mudstone that weathers yellowish green. Interbedded with the mudstone are relatively small quantities of thin sandstone beds that are generally less than 5 feet thick. The sandstone is very fine to fine grained and generally well cemented and contains ripple cross-lamination and ripple-drift lamination.

Minor lithologies include thin lenses of laminated to very thin bedded carbonaceous mudstone and thin lenses of coal less than 1 foot thick. Thin dense gray limestone lenses commonly occur in the John Henry Member of the Straight Cliffs, and siderite concretions (clay ironstones) occur in the middle member of the Dakota Formation and in the Smoky Hollow Member of the Straight Cliffs.

Megafossils are generally scarce and usually amount to poorly preserved unidentifiable molds of pelecypods and gastropods, vertebrate bone fragments, carbonized impressions of leaves and other plant fragments, and coalified small logs, branches, tree trunks, and root systems. Section W1 of the Wahweap Formation contains a surprisingly large amount of fossils in beds that are included in this facies. The fossils include pelecypods, gastropods, ostracodes, fish, reptiles, and plants. A rich and varied assemblage of plant microfossils that was dominated by fern spores and pollen grains was obtained from strata in the John Henry Member of the Straight Cliffs that included subdivision B of the alluvial plain facies as well as the deltaic plain facies and the lagoonal-paludal facies.

Subdivision B includes beds in the lower part of the Wahweap Formation below the thick upper sandstone unit. In the Straight Cliffs Formation the subdivision includes the barren zone of the Smoky Hollow Member and parts of the lower, middle, and upper barren zones of the John Henry Member. The middle member of the Dakota contains yellowish-green mudstone beds that apparently represent a transition into subdivision B.

Interpretation.--The paleontological evidence indicates nonmarine environments of deposition. Among the fossils in the collections from the Wahweap Formation that are most characteristic of nonmarine environments are the charophytes, Unionidae, and all the gastropods, which include the genera *Viviparus*, *Campeloma*, *Tulotomops*, and *Physa* (Peck, 1957; Fisher and others, 1960, p. 37).

The assemblage of plant microfossils from the John Henry Member also indicates nonmarine deposition. The microfossils came from strata in subdivision B of the alluvial plain facies as well as from strata of the deltaic plain and lagoonal-paludal facies. The following comments on the paleoecology of the region as interpreted from these fossils were furnished by R. H. Tschudy (written commun., 1968) who made the identifications.

> "Comparatively few paleoecological inferences can be derived from a palynomorph assemblage as old as that obtained from the Straight Cliffs Formation. Most of the plant microfossils found are now extinct or their similarity to modern relatives has not been recognized.
>
> "The Straight Cliffs assemblage was dominated by fern spores and pollen grains. The lack of marine palynomorphs and the paucity of bisaccate conifer pollen suggests deposition isolated from highlands and from the sea. The lack of genera such as *Azolla* that would indicate the presence of more or less permanent fresh-water ponds or lakes such as were present during the time that the Eagle, Judith River, and Hell Creek Formations were deposited, suggests that the coals were deposited under paludal rather than lacustrine conditions. The presence of *Araucariacites*, *Gleicheniidites*, *Cicatricosisporites*, and *Vitreisporites* suggests a subtropical climate.
>
> "The available evidence suggests that deposition took place in a wet or swampy subtropical lowland site at some distance from highlands and under conditions that prevented even occasional marine inundations."

Although any of the fossils could have been transported out of their normal environments by streams, none of the genera that are more commonly found in brackish-water or marine deposits are present; it is concluded from this that subdivision B was deposited in nonmarine and probably fresh-water conditions.

Most of the lithologies and bedding structures of the thicker sandstone beds are essentially the same as those of the sandstones in subdivision A, and by this analogy these beds were probably deposited primarily from the bedload of braided streams. The sandstones in subdivision B contain scattered pebbles and granules but only rarely contain conglomerate lenses, suggesting that deposition was farther from the source area and (or) by streams having more reduced gradients and flow velocities than the streams that deposited the conglomeratic sandstones of subdivision A.

The cyclic nature of the thicker sandstone beds suggests the fining-upward cycles that commonly are associated with stream deposits (Allen, 1965a; see also Beerbower, 1964; McCave, 1968, p. 87-89). The erosion surface at the base of many of the beds indicates fairly strong water currents associated with the initial stages of deposition from the bedload of the streams. The trough and planar crossbedding and scarce horizontal stratification of the lower part of the cycles indicate that bedload transportation in the streams was mainly in the lower flow regime and at least occasionally in the lower part of the upper flow regime (Simons and Richardson, 1961; Allen, 1963, 1965c; Harms and Fahnestock, 1965). Channel forms, cut-and-fill structures, and terracelike structures suggest the rapid lateral migration and local scouring of the numerous channels of braided streams (Doeglas, 1962; Ore, 1964, p. 5; Allen, 1965c, p. 144-145, 163). Net deposition of the bedload probably was caused by a slight general reduction in the transporting capacity of the streams (Colby, 1963, p. 32), best explained by a general decrease in the gradient.

The thin upper parts of the cycles that contain ripple and ripple-drift cross-lamination were deposited under flow conditions in the lower part of the lower flow regime (Simons and others, 1965). The relative abundance of clay, silt, and very fine sand-size constituents indicates that the sediment was derived from both the bed and the suspended load, although deposition from the bedload predominated.

Although the fluvial sandstones cannot be traced for more than several miles on the outcrop, even this much lateral persistence indicates that they were probably deposited in a fairly wide zone or belt that marked the general course of the stream toward the sea. Lateral gradation into mudstone beds indicates that the braided streams did not migrate continuously over the entire alluvial plain as they did during deposition of the sandstone beds in subdivision A. Instead, the braided stream belts remained fairly stabilized, in a geographic sense, between the relatively brief periods when flooding or alluviation caused the stream to shift to an entirely different course. Leopold, Wolman, and Miller (1964, p. 294-295) concluded that braiding appears to represent an adjustment of a stream possessing unstable banks and a bedload too large to be carried in a single channel. Although the braided pattern need not imply aggradation, the abundance of these deposits in the Kaiparowits region implies that the streams indeed were aggrading and overloaded.

The yellowish-green bentonitic mudstone beds that occur between and adjacent to the thick fluvial sandstones represent vertical accretion by deposition of silt- and clay-size sediments from the suspended load of streams during overbank stages. The color, texture, bedding characteristics, abundant plant debris, and the remains of tree trunks and root systems in the original growth positions all have their counterparts in Late Pleistocene overbank deposits of the Brazos River in Texas (Bernard and others, 1962, p. 189-190) and in modern overbank deposits in the Connecticut Valley of Massachusetts (Jahns, 1947, p. 84-126) and the Ohio River valley (Mansfield, 1938, p. 701-703). Ripple-drift cross-lamination occurs in the thin very fine to fine grained sandstone beds that are interbedded with the mudstones, and it is a common bedding structure formed in modern overbank deposits where sandy sediment is abundant and current flow is gentle (McKee, 1966). This bedding structure indicates that bedload transportation in the lower part of the lower flow regime has taken place.

The minor lithologies represent locally different conditions of deposition, but these conditions are not inconsistent with the general hypothesis of deposition on an alluvial plain. The scarce carbonaceous mudstones and thin coal lenses intercalated with the yellowish-green mudstones indicate the accumulation of abundant vegetative debris in local swamps, bogs, or marshes in the overbank part of the alluvial plain and in areas where the rate of clastic sedimentation was low. The carbonaceous beds generally occur near strata of subdivision C of the alluvial plain facies or near strata of the deltaic plain facies, both of which contain abundant carbonaceous mudstone deposits. Proximity to these beds suggests that the thin carbonaceous mudstones and coal lenses of subdivision B represent part of a progressive downslope transition into environments in which the accumulation and preservation of abundant organic debris was favorable.

The thin limestone lenses in the John Henry Member suggest another type of local depositional conditions. Some of the wider limestone lenses, about 50-100 or more feet wide, were probably precipitated in local ponds or small lakes, because they contain gastropods, pelecypods, carbonized impressions of leaves and other plant debris and the bedding is laminated. Although these lenses commonly occur in the yellowish-green mudstones, some have been found at the top of the thick fluvial sandstones, suggesting deposition in local depressions in abandoned stream courses. The limestone lenses containing fossils and bedding structures generally do not occur near beds that contain carbonaceous mudstone or coal, suggesting that the ponds or small lakes existed at elevations that were probably slightly higher and farther inland on the alluvial plain than the localities where the carbonaceous mudstone and thin coal lenses were deposited. Precipitation of the calcium carbonate probably occurred during temporary, possibly seasonal dry periods. The role of plants in the precipitation processes is unknown, but no traces of plants (other than the ubiquitous carbonized debris) could be found in thin sections. The smaller limestone lenses that lack fossils and bedding structures are apparently of concretionary origin (Müller, 1967, p. 154) and are somewhat similar to calcareous nodules found in overbank deposits of the Brazos River in Texas (Bernard and others, 1962, p. 189-190; Bernard and Major, 1963). Siderite concretions in mudstones of the Dakota Formation and the Smoky Hollow Member of the Straight Cliffs were probably formed by precipitation from neutral or basic ground-water solutions in which the oxygen was exhausted (Krauskopf, 1967, p. 83, 252-253).

The cyclic sedimentation represented by the thicker sandstone beds indicates relatively rapid flow conditions during deposition of the thicker, lower part of the bed and gradual reduction in current velocity during the final stages of deposition. The sediment was derived primarily from the bedload but included increasing quantities of the suspended load in the final stages. The mudstones that overlie the thicker sandstone beds compose an additional part of the cycle. The mudstones indicate deposition primarily from the suspended load under gentle flow rates that are less than those required to produce ripples (Harms and Fahnestock, 1965, p. 108).

In summary, the sandstones and mudstones that compose subdivision B were deposited in fresh-water environments by braided streams that had moderate gradients. The thicker sandstone beds were formed by net deposition of the bedload during transportation in the lower flow regime and occasionally in the lower part of the upper flow regime. The streams migrated continuously across a narrow zone or belt several miles wide on their way to the seaway, but lateral migration of the braided stream belt was discontinuous and occurred during relatively brief time periods. The yellowish-green mudstones and interbedded thin sandstones were deposited in overbank flood-plain areas between the major stream belts. Deposition was primarily from the suspended load and occurred in gentle flow conditions. Thin carbonaceous mudstone and coal lenses in the Straight Cliffs Formation indicate local swamps, bogs, or marshes on the alluvial plain. They generally occur near the thick carbonaceous mudstone beds of the deltaic plain facies and apparently represent a transitional area between the two environments of deposition. Some of the thin limestone lenses in the John Henry Member of the Straight Cliffs contain fossils and bedding structures that suggest precipitation of limy muds in small ponds situated at slightly higher elevations and farther inland on the alluvial plain than the depressions where the carbonaceous mudstone and coal lenses were deposited.

Fluvial channel sandstones, more common in rocks of the deltaic plain facies or subdivision C of the alluvial plain facies, are uncommon but do occur in rocks of subdivision B. Their presence suggests local differences from the predominantly braided stream conditions that are indicated by the thicker and more widespread fluvial sandstones. The local variations, as well as the minor lithologies mentioned previously, are significant because they indicate that the general braided stream belt and overbank flood-plain conditions represented by subdivision B were part of a gradational series of depositional environments on the alluvial plain from subdivision A to subdivision C or the deltaic plain facies.

SUBDIVISION C

Principal features.--Subdivision C consists mainly of two different litholgies: channel sandstones and carbonaceous mudstones. Scarce, thin coal beds, generally less than 1 foot thick, also occur in the mudstones.

The channel sandstones are approximately lens shaped in cross section (fig. 22) and generally are less than about 40 feet in maximum thickness. A fining-upwards cycle (Allen, 1965a) can be distinguished in most of the beds and is similar in most aspects to the fining-upwards cycles represented by the thicker sandstones in subdivision B. The lower part of the cycle includes nearly all the bed and consists of very fine to fine grained moderately sorted well-cemented sandstone that locally contains sparse scattered small chert pebbles and quartz granules near the base. Crossbedding dips consistently in one direction down the axis of a channel (fig. 23) and is in medium-scale low- and high-angle trough and planar sets about ½-2 feet thick. Horizontal stratification with parting lineation has not been found in these beds. The upper part of the cycle includes the upper 0-3 feet of the channel sandstones and is composed of very fine to fine grained moderately sorted well-cemented sandstone that locally is interbedded with thin partings of mudstone (fig. 24). Crossbedding in this part of the cycle includes ripple cross-lamination or ripple-drift cross-lamination (climbing-ripple structure of McKee, 1966).

The other common lithology is laminated to very thin bedded carbonaceous mudstone containing abundant carbonized plant fragments. Most of this mudstone is dark gray, but brown is also common. Thin seams and lenses of coal generally less than 1 foot thick are uncommon. Other lithologies include yellowish-green bentonitic mudstone and light-gray mudstone that is gradational between the other types.

Fossils, other than the plant fragments in the carbonaceous mudstone, are scarce. Vertebrate bone fragments and leaf impressions occur in some of the channel sandstones, and the pelecypod Unio n. sp. was found in carbonaceous mudstone. A small amount of spores and pollen was obtained from strata in the Dakota Formation that are included in this facies.

The middle member of the Dakota is considered most typical of subdivision C.

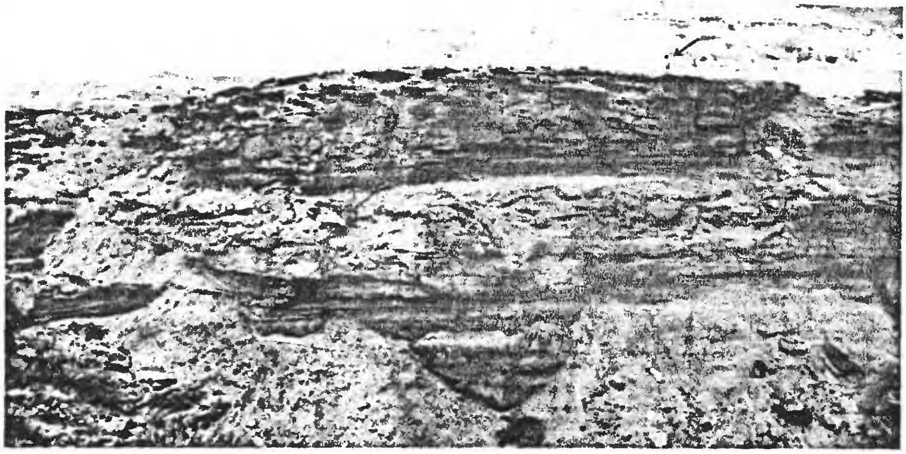


FIGURE 22.--Cross section of two fluvial channel sandstone beds commonly found in subdivision C of alluvial plain facies. Scale given by man on top right side of upper bed (arrow). About one-fourth mile northeast of Wahweap Creek and 500 feet southwest of measured section 13, in middle member of Dakota Formation.

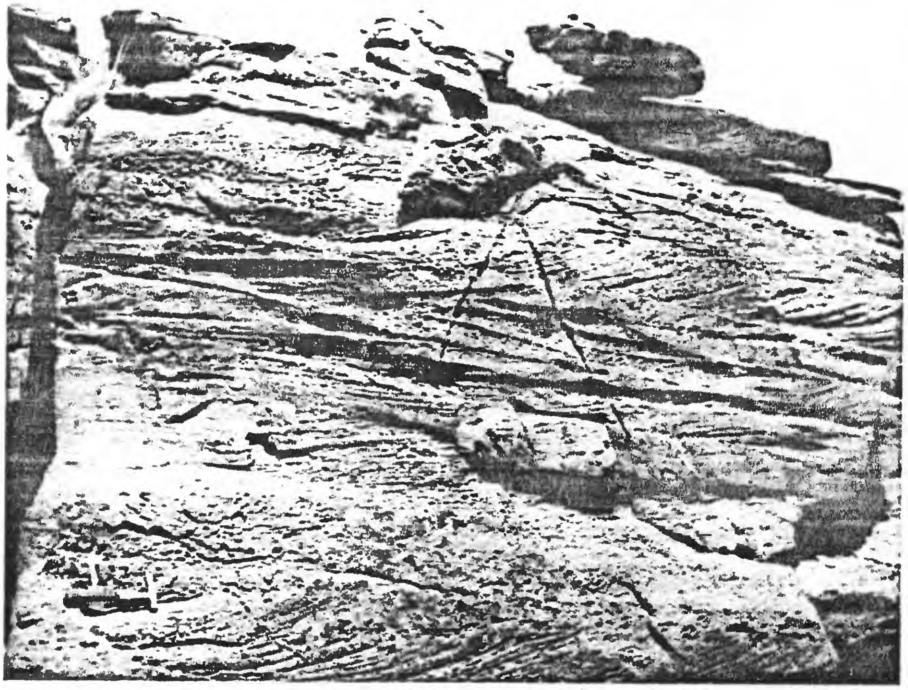


FIGURE 23.--Low- and high-angle medium-scale trough-type cross-stratification in fluvial channel sandstone bed. Cliff face trends parallel to long axis of channel, and unidirectional dip of cross-bedding indicates deposition by a stream that flowed from right to left. About half a mile southwest of Last Chance Creek in middle member of Dakota Formation at measured section 78.

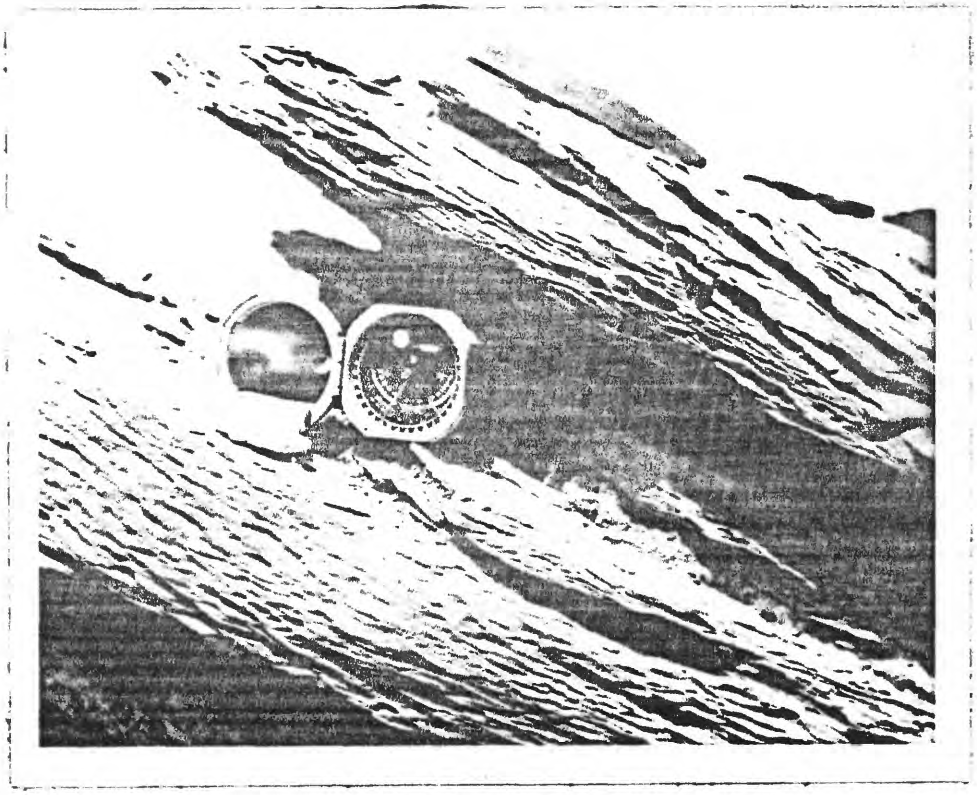


FIGURE 24.--Ripple-drift cross-lamination (climbing-ripple lamination) at top of fluvial channel sandstone bed, indicating current flow from right to left. Brunton compass is set at level and is approximately parallel to attitude of the channel sandstone bed. Larger scale crossbedding suggested by beds dipping to right is false crossbedding and does not indicate current flow. About one-fourth mile northeast of Wahweap Creek at top of upper fluvial channel sandstone bed in figure 22.

Interpretation.--The scant paleontological evidence suggests deposition in nonmarine conditions. The pelecypod family Unionidae, to which the genus Unio belongs, includes inhabitants of fresh-water environments today (Ward and Whipple, 1918, p. 1000; LaRoque, 1967) and is considered to have been restricted to similar environments in the past (Shimer and Shrock, 1944, p. 399; Fisher and others, 1960, p. 37).

The cyclic aspect of the channel sandstones suggests fluvial sedimentation (Allen, 1965a, c) in conditions that differed only moderately from conditions that prevailed during deposition of the thick braided-belt sandstones in subdivision B. The lens-shaped cross section of the channel sandstones indicates that the streams flowed in one or a few distinct channels rather than in the numerous anastomosing and constantly shifting channels hypothesized for streams that deposited the thick braided-belt sandstones of subdivision B.

Crossbedding throughout most of the channel sandstones differs little in type from crossbedding in the braided-belt sandstones, except that it dips more consistently in one direction (fig. 23), whereas crossbedding in the braided-belt sandstones generally has more variable dip directions. The low- and high-angle medium-scale trough and planar crossbedding indicates that bedload transportation by dunes and bars occurred mainly in the lower flow regime. Lack of horizontal stratification in very fine and fine grained sandstones suggests that the upper flow regime was not a significant part of the general flow conditions or that bedding structures formed in the upper flow regime were obliterated by the passage of dunes and troughs of the lower flow regime. An analogous situation was found in flume experiments cited by Simons, Richardson, and Albertson (1961, p. 36) in which it was not possible to stop the flow and drain the flume without appreciably altering bed forms produced during upper flow regime conditions. Net deposition of the bedload was probably caused by a slight general reduction in transporting ability of the streams (Colby, 1963, p. 32) best explained by a general decrease in the gradient.

The upper 1-3 feet of the channel sandstones contains ripple cross-lamination which indicates transportation in the lower part of the lower flow regime. Relatively large amounts of clay, silt, and very fine sand-size constituents indicate that the sediment was derived from both the bed and the suspended load, although deposition from the bedload was probably predominant.

The fluvial channel sandstones in the Dakota Formation are fairly well exposed in the southwestern and central parts of the region where some of them can be traced for as much as about 3 miles (pl. 5). Their sinuous trend suggests meandering streams (Allen, 1965c, p. 164-166). Point bar accretionary topography consisting of concentric ridges and swales is still preserved where some of the channels curve broadly and where recent erosion has stripped off the overlying soft shales and mudstones. The crossbedding preserved in these deposits is essentially the same as that described in preceding paragraphs and is comparable to crossbedding in modern point bar deposits in Louisiana described by Frazier and Ozanik (1961) and Harms, MacKenzie, and McCubbin (1963).

The relatively high organic content of the carbonaceous mudstones suggests deposition of overbank silts and clays in paludal conditions. Deposition in backswamps (flood basin lowlands) is indicated because the beds occur between and adjacent to the fluvial channel sandstones that apparently were deposited by meandering streams, and they are similar to modern backswamp deposits in the Mississippi River valley which also consist of organic-rich clays and silts. Brown colors, found in some of these beds, occur in modern backswamp deposits and are the product of local desiccation between floods (Fisk, 1947, p. 57; Kolb and Shockley, 1957, p. 5-6). Local oxidizing conditions caused by intermittent desiccation of the backswamps probably account for the poorly preserved palynomorphs or lack of palynomorphs in many of the samples that were collected from these beds. Similar poor recovery of palynomorphs was found in modern well-drained swamp deposits in Louisiana by Coleman (1968, p. 165). Thin sandstone beds interbedded with the carbonaceous mudstone contain ripple and ripple-drift cross-lamination, a bedding structure commonly found in modern overbank flood-plain deposits (McKee, 1966).

In summary, the evidence indicates that the strata in subdivision C were deposited on an alluvial plain of low gradient from the bed and the suspended load of meandering rivers and streams. The channel sandstones were formed by net deposition of the bedload during transportation predominantly, if not entirely, in the lower flow regime. Deposition of the carbonaceous mudstone beds occurred in backswamps where vegetative debris from growing plants was added to silt and clay brought in during floods. Yellowish-green bentonitic mudstones, especially common in the southwestern and southern parts of the region, suggest a gradual transition into lithologies more characteristic of subdivision B.

Deltaic Plain Facies

Principal features.--The deltaic plain facies, recognized only in the John Henry Member of the Straight Cliffs, generally occurs between subdivision B of the alluvial plain facies and the lagoonal-paludal facies. Locally, however, the deltaic plain and lagoonal-paludal facies are absent and the alluvial plain facies grades directly into the barrier sandstone facies. The deltaic plain facies consists mainly of sandstone and carbonaceous mudstone and includes comparatively small amounts of coal. The sandstone units are grouped into the following four types for purposes of discussion: (1) thick deltaic sandstones, (2) thick-bedded large-scale crossbedded sandstones interbedded with thin beds of carbonaceous mudstone, (3) fluvial channel sandstones, and (4) relatively thin sandstones.

(1) The deltaic sandstone units are as much as about 50 feet thick and are composed of very fine to fine grained moderately sorted impure subfeldspathic sandstone. Biotite is a common accessory mineral in these beds as contrasted with relatively scarce biotite in the sandstones of the alluvial plain facies. Thin beds of carbonaceous mudstone generally less than 1 foot thick are also present and, by their relatively faster rates of weathering, tend to emphasize the foreset bedding that is characteristic of these beds. The deltaic foreset beds consist of several sandstone beds, each approximately 2-15 feet thick, that dip about 2°-7° consistently in one direction in any local area. The dipping sandstone beds are considered as foreset beds if they occur throughout an approximate minimum straight-line distance of about a quarter of a mile. Even this short distance may not be sufficient to distinguish between deltaic foreset beds and low-angle dipping beds that might have been deposited under other circumstances, but a quarter of a mile is a reasonable minimum distance considering talus cover, access, and sinuous outcrop patterns. The maximum straight-line distance

that any deltaic foreset sandstone unit could be traced in the field was approximately 1½ miles for the unit shown in figure 25. The base of the deltaic units is locally erosional, but more commonly it is nonerosional.

(2) Thick-bedded large-scale low-angle crossbedded units approximately 5-15 feet thick are common in the deltaic plain facies, but each set generally extends for only about 50-200 feet along the outcrop. These units consist mainly of sandstone and are interbedded with about 10-20 percent carbonaceous mudstone. Burrow structures (but not Ophiomorpha sp.) are common in some of these beds. Some units, such as those in figure 26, occur in channels and have erosional bases; others, such as those in figure 27, occur as complexly interbedded and interfingering cosets and have erosional or nonerosional basal contacts.

Bedding in the individual sandstone beds that comprise the thick deltaic sandstones and the thick-bedded large-scale crossbedded sandstones is generally small- to medium-scale low- and high-angle trough and planar types of crossbedding. Many of these beds are ripple cross-laminated or ripple-drift cross-laminated. Bedding features are commonly shown clearly by concentrations of biotite along bedding surfaces. The fining-upwards cycle of deposition (Allen, 1965a) is uncommon.

(3) Channel sandstones also occur in the deltaic plain facies (fig. 25). These have the same general size, shape, bedding structures, and composition as the fluvial channel sandstones that were described in subdivision C of the alluvial plain facies.

(4) Thin sandstone beds approximately 1-5 feet thick containing horizontal stratification or small- and medium-scale low-angle trough and planar crossbedding or ripple and ripple-drift crossbedding are also common in the deltaic plain facies. They occur interbedded with coal beds or laminated to very thin bedded gray mudstone and carbonaceous mudstone.

The median size of the various deltaic and fluvial sandstones in the deltaic plain facies is generally very fine to fine grained, whereas the median size of the various sandstones in the alluvial plain facies is fine to medium grained. Maximum grain sizes larger than medium sand are rare in sandstones of the deltaic plain facies but are common in sandstones of the alluvial plain facies. Bernard, LeBlanc, and Major (1962, p. 181) found that a similar change in grain size occurs between the fine sand

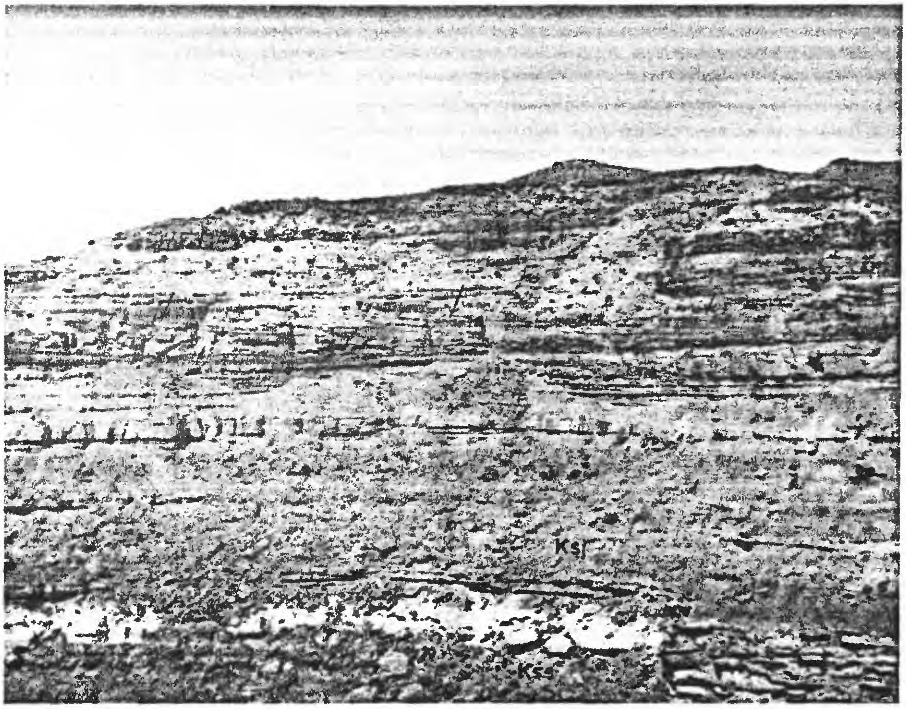


FIGURE 25.--Deltaic foreset beds (arrows) in deltaic plain facies. Unit is about 30 feet thick. The edge of a fluvial channel sandstone bed is present on the right just below the foreset beds. On northeast side of Smoky Hollow about 1½ miles northeast of measured section S16, at top of lower barren zone in John Henry Member of Straight Cliffs Formation. Kss, Smoky Hollow Member; Ksj, John Henry Member.

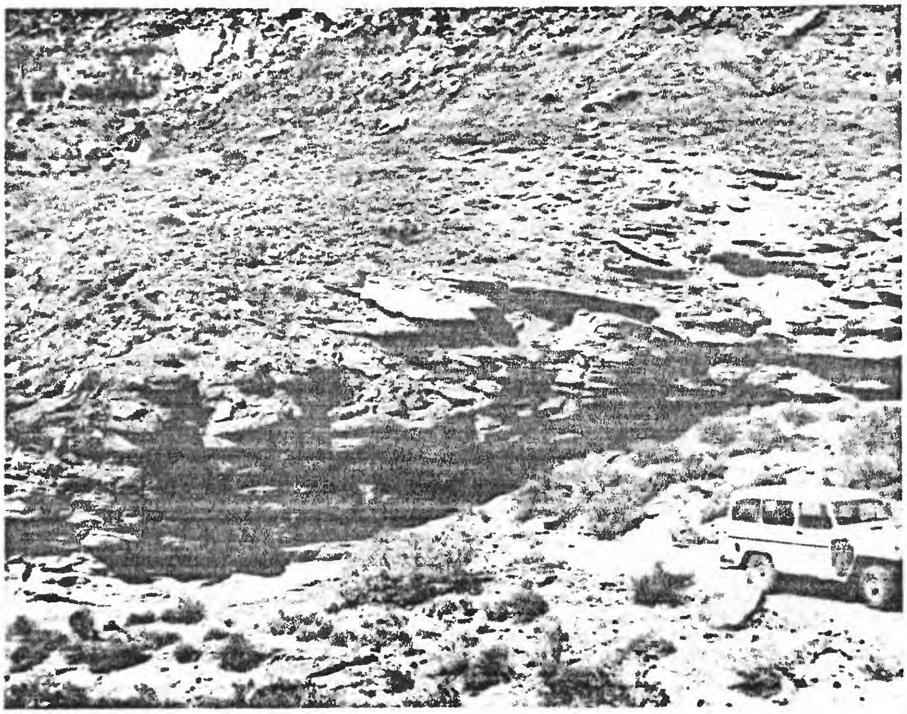


FIGURE 26.--Two sets of large-scale cross-stratified units of sandstone with minor amounts of mudstone. Strata in the lower left set dip about 5° toward the viewer and completely fill a channel, evidently marking the course of a stream channel in which sand and mud were deposited alternately. On southwest side of Smoky Mountain about 1½ miles northwest of measured section S17, in upper part of lower barren zone of John Henry Member, Straight Cliffs Formation.

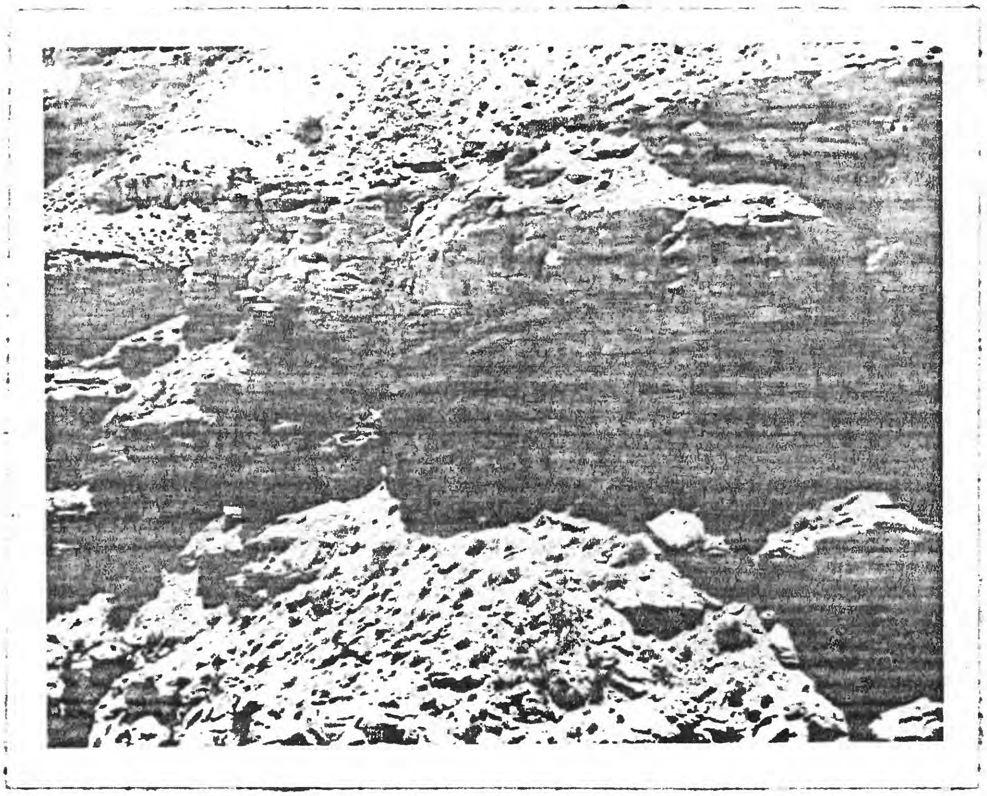


FIGURE 27.--Cosets of large-scale irregularly cross-stratified units of sandstone and carbonaceous mudstone in the deltaic plain facies. Thickness of strata along right edge of picture is about 80 feet. Approximately 2½ miles northeast of Last Chance Creek and 1,000 feet northwest of top of measured section T5, in lower part of lower barren zone in John Henry Member of Straight Cliffs Formation.

bedload of distributaries on the deltaic plain and the coarser bedload of streams on the alluvial plain in the northern Gulf of Mexico coastal region. Most of the fluvial sandstones in the deltaic plain facies are well cemented by calcite, whereas most of the fluvial sandstones in the alluvial plain facies, especially subdivisions A and B, are moderately to poorly cemented and, thus, are semifriable to friable.

Other lithologies in the deltaic plain facies include carbonaceous mudstone, coal, and scarce coquinoid marlstone lenses. The carbonaceous mudstone is dark gray and very thin bedded and contains abundant carbonized plant fragments. Thin coal beds less than 1 foot thick are common near strata of the alluvial plain facies, and thicker coal beds are common near strata of the lagoonal-paludal facies. Thin coquinoid marlstone lenses containing abundant _Crassostrea soleniscus_ are scarce but are associated with strata containing the thicker coal beds.

The deltaic plain facies is only recognized in the John Henry Member of the Straight Cliffs. Thick-bedded large-scale crossbedded sandstones are locally present in the lower part of the Smoky Hollow Member of the Straight Cliffs but are scarce and, therefore, are included in the lagoonal-paludal facies.

Interpretation.--The sparse paleontological evidence suggests deposition in nonmarine conditions. _Crassostrea soleniscus_, locally abundant in thin beds or lenses in gray mudstone beds, is more commonly found in brackish-water deposits of the lagoonal-paludal facies. The beds containing this fossil probably represent incursions of lagoons into areas usually occupied by deltas. Even in modern situations where deltas are prograding into lagoons, it is difficult to separate the two environments in many places. Fresh-water conditions are inferred from the various fluvial deposits, but fossils characteristic of fresh-water environments were not found.

(1) The thick deltaic sandstone units were probably deposited in gentle flow conditions. The trough and planar crossbedding indicates net deposition from the bedload during transportation by dunes and bars in the lower flow regime. Horizontal stratification in these beds lacks primary current lineation and; therefore, is inferred to have formed primarily by deposition of the finer grained constituents from the suspended load. Net deposition throughout the area of the deltaic plain was probably caused by

the reduction in transporting ability of the streams because of the low gradients on the deltaic plain. By comparison, during low-water stages in 1936 the surface of the Mississippi River had a gradient of approximately 2-3 feet in about 130 miles on its deltaic plain between Donaldsonville, La., and Head of Passes (Fisk, 1947, pl. 1).

(2) The thick-bedded large-scale crossbedded units containing interbedded mudstone were apparently formed as abandoned channel fillings and crevasse splays or possibly as bars at the mouths of distributaries. The units that occur in channels having erosional bases were probably deposited in abandoned distributary or crevasse channels. Apparently, sand-size detritus was carried into the abandoned channels during high-water stages and the thin interbeds of carbonaceous mudstone were formed during low-water stages when organic detritus was added to the bottom materials. The large-scale crossbedding in this case does not necessarily indicate primary current flow; instead, it may indicate an originally sloping surface of deposition. Some of the gently dipping beds of alternating sandstone and mudstone may be natural levee deposits, but generally this cannot be demonstrated conclusively in the field.

Crossbedding structures in the individual thick sandstone beds associated with mudstone interbeds include low-angle medium-scale planar-type cross-stratification, scarce low- and high-angle medium-scale trough-type cross-stratification, and ripple or ripple-drift cross-lamination. These structures suggest net deposition from the bedload during transportation by bars (or, rarely, dunes) in the lower flow regime (Simons and others, 1965). Horizontally stratified very fine grained sandstone beds that lack indications of primary current flow were probably deposited mainly from the suspended load, as was the silt and mud fraction that is present in the carbonaceous mudstones.

Strata in modern deltaic environments that are comparable to the large-scale crossbedded cosets of interbedded sandstone and carbonaceous mudstone have not been well described in the literature. Some of the subunits or sets have erosional bases, indicating that current velocities locally were sufficiently high to erode the substrata. Crossbedding in the individual sandstone beds is mainly of the low-angle medium-scale planar type or the ripple or ripple-drift types of cross-lamination, all of which indicate bedload transportation primarily in the lower flow regime. Horizontal stratification, also found in these beds, lacks features that might indicate current flow and, therefore, was probably formed by deposition from the suspended load. The silt- and clay-size clastic constituents of the interbedded mudstones were also derived from the suspended load, and deposition probably occurred mainly during floods.

It seems likely that the alternating lithologies and inferred variations in current velocities represent deposition under highly variable conditions such as occur at crevasses or breaches in natural levees. Similar alternating lithologies in the Upper Old Red Sandstone (Devonian) in Great Britain were attributed to deposition on crevasse-splays by Allen (1965b, p. 185), and modern flood-plain splays that are somewhat similar were illustrated and briefly described by Happ, Rittenhouse, and Dobson (1940, p. 24). The large-scale coset units also may have formed at the mouths of minor distributaries where bars built up and were modified quickly because of rapid changes in the velocity and direction of flow of the streams as they entered relatively quiet waters of lagoons. Russell (1954, p. 363-365) noted somewhat similar rapid bar building, bifurcation, and erosional modification at the mouths of distributaries of the Sakarya River in northwestern Turkey, although the distributary-mouth deposits in this example differ somewhat because the Sakarya carries a large sand load and discharges directly into the sea where the deposits are modified further by sea waves and currents.

(3) Channel sandstones that have the same bedding features as the meander-belt channel sandstones described in subdivision C of the alluvial plain facies also occur in the deltaic plain facies. Their association with other beds in the deltaic plain facies suggests that the channel sandstones represent fillings in distributary channels or possibly bar-finger sands (Fisk, 1961), but at present there is no clear way to distinguish channel sandstones that were deposited in the two environments.

(4) The thin sandstone beds associated with the coal and mudstone beds apparently were deposited in relatively quiet waters of interdistributary troughs. The horizontal stratification that lacks primary current lineation and the small-scale crossbedding indicate deposition from the suspended load or bedload transportation in the lower part of the lower flow regime.

Other strata that were deposited in interdistributary troughs include carbonaceous mudstone, coal, and coquinoid marlstone lenses. The silt- and clay-size constituents of the carbonaceous mudstone were carried into the interdistributary troughs in suspension. The abundant organic debris and lack of brown colors indicate that vegetation was abundant and that the sediments were not oxidized before burial and lithification. The coal indicates deposition of abundant plant debris in paludal conditions in areas well removed from places near the distributaries where clastic sedimentation occurred. Scarce thin coquinoid marlstone lenses contain abundant Crassostrea soleniscus, which apparently was restricted to brackish-water environments.

There is no appreciable difference between the interdistributary deposits and backswamp deposits associated with meander-belt channel sandstones in subdivision C of the alluvial plain facies. The principal distinguishing features of the interdistributary trough deposits in the deltaic plain facies are lack of oxidized brown carbonaceous mudstone, thin beds or lenses containing abundant oysters, and greater abundance of coal. The thin sandstones, carbonaceous mudstones, coal beds, and oysters are all features that occur in greater abundance in the lagoonal-paludal facies. Their presence in the deltaic plain facies emphasizes, once again, that the lateral boundaries of the various sedimentary facies are gradational and interfingering.

In summary, the evidence indicates that the beds of the deltaic plain facies were deposited by rivers and distributaries in fresh- and brackish-water environments on or at the periphery of coalescing deltas. Crossbedding in the sandstones indicates that bedload transportation was mainly, or possibly entirely, in the lower flow regime, and horizontal stratification in some of the finer grained sandstones suggests deposition from the suspended load. Abundant biotite in the sandstone appears to be characteristic of deltaic deposits (Shepard, 1960, p. 80). Silt- and clay-size constituents in the carbonaceous mudstones were also deposited from the suspended load, but mainly in interdistributary or interdeltaic troughs, bays, or inlets where abundant vegetation grew and added considerable quantities of organic debris to the bottom sediments. The coal beds represent deposits of organic debris that were not contaminated appreciably by sedimentation of detrital materials. The areas with thicker and more abundant coal beds were probably in interdistributary or interdeltaic areas where paludal conditions were dominant. Strata consisting mainly of carbonaceous mudstone and coal and containing thin oyster-shell lenses are more characteristic of the lagoonal-paludal facies, but their presence in the deltaic plain facies indicates the gradational nature of the lateral boundary between these units. The gradation is not surprising, however, as in many places it is difficult to separate deltas from lagoons and swamps in modern situations.

Lagoonal-Paludal Facies

Principal features.--The lagoonal-paludal facies is characterized by an abundance of carbonaceous mudstone and coal and by the absence of thick sandstone beds (fig. 28). The facies also includes thin beds of sandstone, black shale, and coquinoid marlstone. The sandstones are generally very fine to fine grained, moderately sorted, and either structureless, mottled, and burrowed or contain small-scale low-angle trough and planar cross-laminations. Ripple marks with well-rounded or fairly sharp crests are common at the tops of the sandstones. Coalified plant fragments are common in the mudstones and shales, and invertebrate fossils, mainly one species of oyster, are locally common to abundant in the mudstones and coquinoid marlstones. Typical exposures of the facies are shown in figures 28 and 29.

The lagoonal-paludal facies occurs in parts of the Dakota, Tropic, and Straight Cliffs Formations. The facies is subdivided into lagoonal and paludal components in the middle and upper members of the Dakota Formation and in the lower part of the Tropic Shale where the distinction can be made on the basis of relations to other facies. In the Straight Cliffs Formation, however, strata deposited in lagoonal and paludal conditions are interbedded, and a clear distinction between the two types of environmental deposits cannot be made.

Interpretation.--The relatively large quantities of organic deposits and fine detrital materials in these beds are common constituents of deposits formed in coastal lagoons and swamps where the rate of detrital sedimentation is low and conditions are suitable for the growth of abundant vegetation.

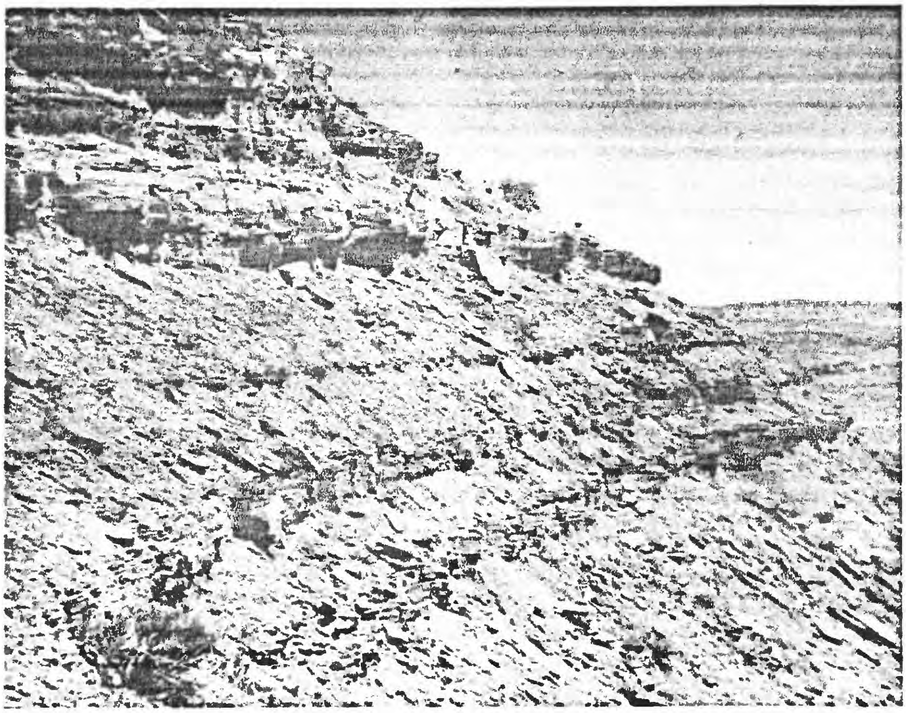


FIGURE 28.--Alternating beds of sandstone, carbonaceous mudstone, and coal in the lagoonal-paludal facies. The brackish-water oyster Crassostrea soleniscus was found in several of the mudstone beds. On southwest side of Surprise Valley at measured section S22, in Christensen coal zone of John Henry Member of Straight Cliffs Formation.

FIGURE 29.--Interbedded strata consisting of laminated to very thin bedded sandstone and carbonaceous mudstone in the lagoonal-paludal facies. Some of the sandstone beds have rounded ripple crests that may be the result of deposition in tidal-flat environments. At bottom of Rees Canyon about 4 miles northwest of measured section S21, in Christensen coal zone of John Henry Member of Straight Cliffs Formation.

The thick coal beds indicate deposition and partial decomposition of abundant plant debris in swamps or marshes (fig. 30). The thin beds that contain numerous fossil oyster shells are comparable to modern oyster-shell reefs that commonly occur in brackish-water lagoons, estuaries, and embayments along the northern part of the Gulf of Mexico and the southeastern Atlantic coastal states (Parker, 1956, 1960; Hoyt and others, 1966, p. 24). Crassostrea soleniscus, common in the Straight Cliffs Formation, apparently preferred a brackish-water habitat, judging from faunal and lithologic relations in the central part of the Western Interior region (Kauffman, 1967). In the Kaiparowits region, C. soleniscus is considerably more abundant in strata assigned to the lagoonal-paludal facies, whereas another oyster, C. coalvillensis, is more abundant in strata that were deposited in normal marine waters. The two fossils only rarely occur together, and the difference in the occurrences of the two closely related species is apparently the result of different environmental preferences.

The thin sandstone beds were probably formed in several different ways. Mottles and burrow structures including Ophiomorpha sp. in some of these beds indicate reworking of the sands by bottom-dwelling organisms (Moore and Scruton, 1957). The burrow structure Ophiomorpha sp. was probably formed by an animal similar to the living decapod crustacean Callianassa major Say (Weimer and Hoyt, 1964; Waage, 1967, p. 250), but the presence of these structures in the lagoonal-paludal facies and in the lagoonal parts of barrier sandstones suggests that the animal lived in brackish-water environments as well as in the normal marine nearshore environments that were indicated by Hoyt and Weimer (1963) and Weimer and Hoyt (1964). The structureless sandstones may have been completely reworked by burrowing organisms or they may have been deposited rapidly and under uniform conditions (Moore and Scruton, 1957).

Small-scale low-angle crossbedding in some of the sandstones indicates sediment movement under lower flow-regime conditions. Ripple axes that have varying trends and crossbedding that dips in various directions (fig. 31) are common in these beds and, according to Masters (1967), are a common feature in tidal-flat environments where the direction of water currents changes rapidly. Rounded ripple crests may be the result of fluctuations in water depth as suggested by Masters (1967, p. 2042) or by gentler

FIGURE 30.--Two thick coal beds indicating paludal environments of deposition in the lagoonal-paludal facies. The coal beds are at the top of the Christensen coal zone in the John Henry Member of the Straight Cliffs Formation and are overlain by a fluvial sandstone bed in the middle barren zone. About 2½ miles northeast of Last Chance Creek at measured section S21. Thicknesses shown do not include partings.

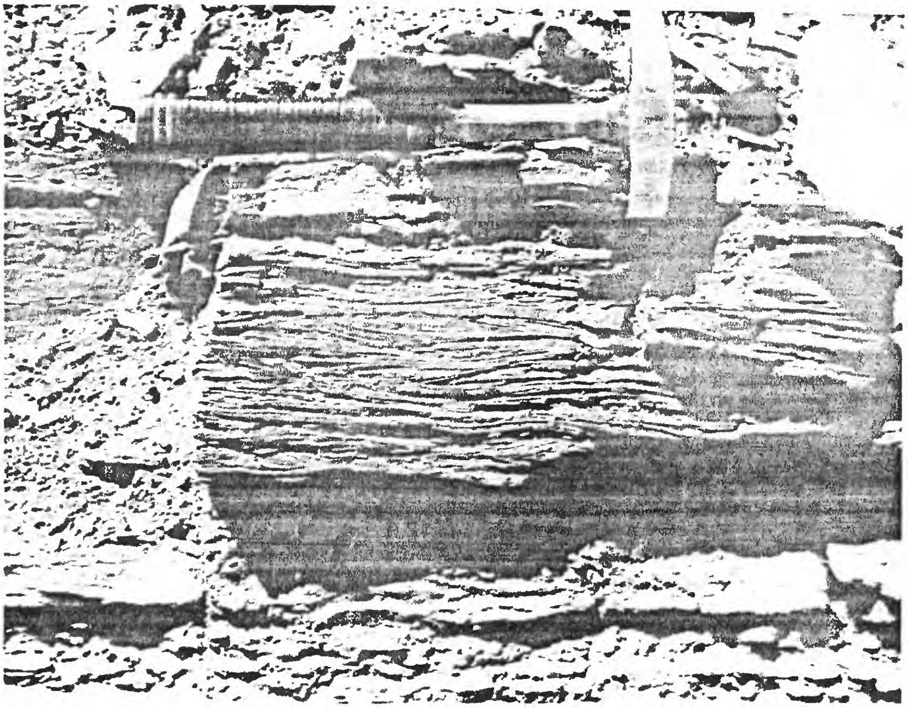


FIGURE 31.--Small-scale crossbedding in thin sandstone bed of lagoonal-paludal facies. Cross-laminae with variable dip directions are common in sandstones of this facies. On southwest side of Surprise Valley at measured section S22, in Christensen coal zone of John Henry Member of Straight Cliffs Formation.

agitation subsequent to initial formation as postulated by Gilbert (1899, p. 136), but flume experiments by Simons, Richardson, and Haushild (1963, p. 30) demonstrate that rounded ripple crests can also form where the water contains more clay than can be kept in suspension by turbulence and bedload transportation is in the lower flow regime.

In the John Henry Member of the Straight Cliffs, the gray moderately sorted sandstones that contain abundant biotite are similar to sandstones in the deltaic plain facies, and were probably deposited from sediment that was carried into the lagoonal and paludal areas by rivers and their distributaries. Other very light gray well-sorted sandstones, which are similar to lithologies in the barrier sandstone facies, contain very little biotite and were probably deposited by currents that carried the sediment over or around barrier islands that separated the lagoonal and paludal areas from the seaway. These beds probably represent deposits on washover fans or at the inner mouths of tidal inlet channels.

Thin beds of black shale in the Straight Cliffs Formation are locally present throughout the lagoonal-paludal facies. The excellent fissility in this lithology is probably the result of slow deposition of clay-size suspension-held particles in areas that were sheltered from currents. Although carbonaceous mudstone cannot be used to distinguish between paludal and lagoonal environments of deposition, an abundance of this lithology is considered fairly diagnostic of either or both environments, especially where supported by other evidence.

Masters (1967, p. 2041) found that slump structures were common in lagoonal deposits of Cretaceous rocks in northwestern Colorado. In the Kaiparowits region, however, slump structures are rare in strata of the lagoonal-paludal facies and are more common in beds in the alluvial plain, deltaic plain, and barrier sandstone facies. This simply indicates that slump structures can be formed in many different environments.

In summary, the lithologies, bedding structures, fossils, and stratigraphic relations of the lagoonal-paludal facies indicate deposition in coastal swamps and lagoons. Deposition of organic materials was rapid and deposition of detrital sediments was slow compared to rates of deposition of beds in most of the other facies in the report area. Detrital clay, silt, and very fine to fine grained sand were carried into the lagoons and swamps as suspended or bedload materials in relatively gentle flow conditions. The presence of thick coal beds interbedded with carbonaceous mudstone and the absence of oxidized brown mudstones suggest that the paludal environments were similar to those of modern poorly drained swamps (Coleman, 1968). The thin sandstones, coquinoid marlstones, and black shales interbedded with carbonaceous mudstone are similar to Upper Cretaceous estuarine and lagoonal strata in the North and South Carolina coastal plain (Swift and Heron, 1967) and are somewhat similar to Middle Devonian tidal-flat deposits in New York (McCave, 1968, p. 89-90).

Barrier Sandstone Facies

Principal features.--The barrier sandstone facies consists almost entirely of grayish-orange to very light gray very fine to fine grained moderately to well-sorted sandstone in beds or units 0-200 feet thick. The beds or units are generally continuous parallel to the shoreline, and several in the John Henry Member of the Straight Cliffs can be traced 60 or more miles along the Straight Cliffs escarpment (fig. 15). Other lithologies locally present in minor quantities include black sandstone beds or fossil beach placers and scattered pebbles, cobbles, or conglomerate lenses.

Fossils are whole or fragmented and occur scattered throughout many of the beds or concentrated in thin lenses or beds. The most common forms are the inocerams, oysters, and the burrow structure Ophiomorpha sp. The forms most diagnostic of environments of deposition are the inocerams and the ammonites.

The barrier sandstone facies is present in the upper member of the Dakota and in the Tibbet Canyon and John Henry Members of the Straight Cliffs. In addition, the northeasternmost part of the Drip Tank Member of the Straight Cliffs contains features that are suggestive of this facies. There are significant differences in the barrier sandstone facies in each of these members. In the upper member of the Dakota, current-formed bedding is generally absent, but mottles are present and fossils dominated by one species are more abundant. In the Tibbet Canyon Member of the Straight Cliffs, current-formed bedding is present but not in well-defined units and fossils are scarce. In the John Henry Member of the Straight Cliffs, current-formed bedding occurs in three well-defined bedding units, and fossil fragments are common, although whole fossils are scarce.

The barrier sandstone beds in the John Henry Member of the Straight Cliffs contain a threefold vertical sequence of units of current-formed bedding structures. The lower unit of the sequence occurs in grayish-orange sandstone and consists of horizontal stratification and low-angle medium- to large-scale trough and planar cross-stratification (fig. 32). The middle unit of the sequence occurs in grayish-orange to very light gray sandstone and consists of low- and high-angle medium-scale trough cross-stratification (fig. 33). The upper unit of the sequence occurs in very light gray to white sandstone and consists of very low angle (less than about 5°) medium- to large-scale wedge-planar cross-stratification (fig. 34). Black sandstone deposits occur locally as irregular lens-shaped bodies in the upper unit (fig. 17). Fossils and pebbles or conglomerate lenses occur mainly in the lower unit and less commonly in the middle unit.

Interpretation.--Various authors have reached somewhat conflicting conclusions about the paleoenvironmental adaptations of the fossils that occur in the barrier sandstone facies, particularly the ammonites, but they agree that the inocerams and ammonites lived predominantly in, and probably were restricted to, marine habitats (Scott, 1940; Arkell and others, 1957; Bergquist and Cobban, 1957; Hattin, 1962, 1965; Kauffman, 1967). Most other fossils found in these beds indicate that deposition was mainly in normal marine environments.

Some of the lithologic and faunal relations suggest local deposition in brackish-water lagoonal environments. The southwesternmost parts of several of the barrier sandstone beds in the John Henry Member of the Straight Cliffs lack current-formed bedding structures and contain abundant Ophiomorpha sp. and other burrows. Because these beds interfinger southwestward with brackish-water strata of the lagoonal-paludal facies and because Ophiomorpha sp. is found in both marine and brackish-water beds in the report area, it is concluded that the southwesternmost parts of the barrier sandstone beds were deposited in brackish-water conditions. Similarly, the brackish-water fossil Crassostrea soleniscus occurs locally in the southwesternmost parts of tongues of the Tibbet Canyon Member of

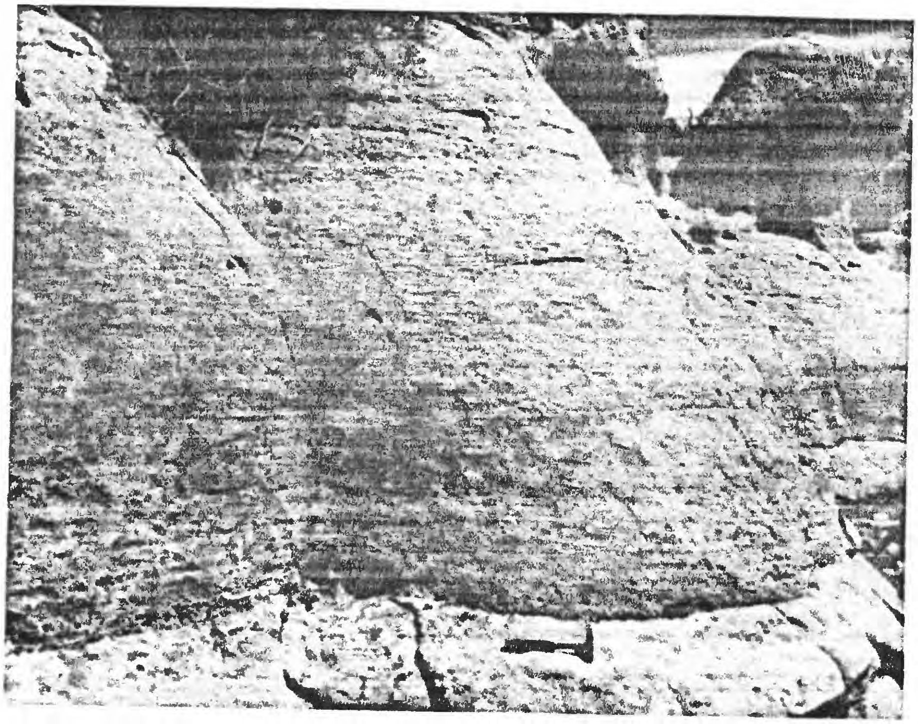


FIGURE 32.--Lower bedding unit of barrier sandstone facies; unit contains marine fossils (inocerams, shark teeth) and consists of well-sorted very fine to fine grained sandstone with horizontal stratification and medium- to large-scale low-angle trough-type cross-stratification. Probably formed in shallow marine waters by coastal currents. About half a mile southwest of Straight Cliffs escarpment and 2 miles east of top of measured section S6, about in middle of G sandstone bed in John Henry Member of Straight Cliffs Formation.

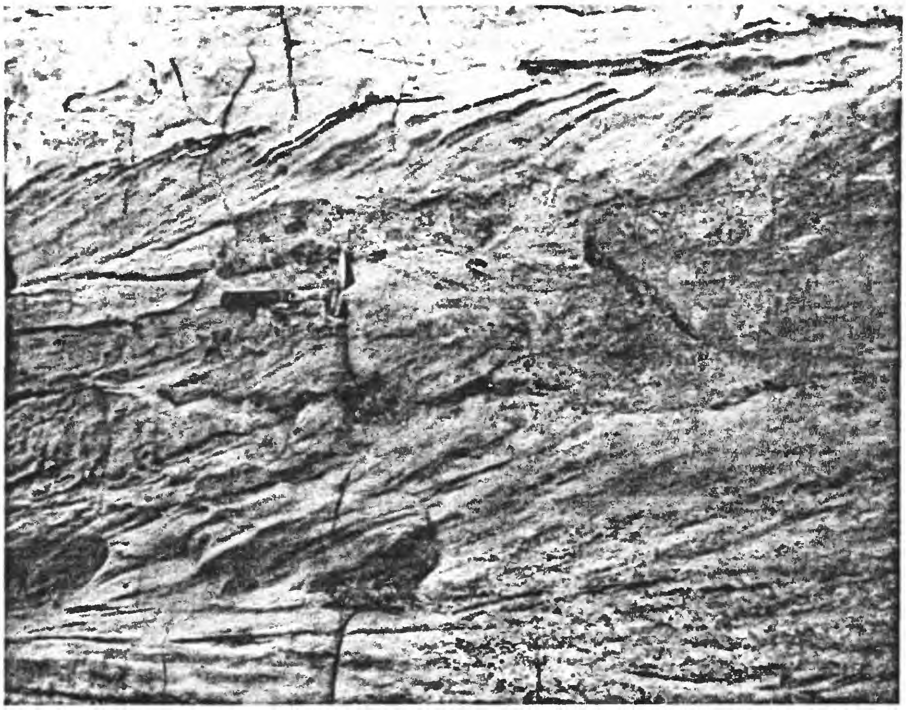


FIGURE 33.--Middle bedding unit of barrier sandstone facies. Unit consists of well-sorted fine-grained sandstone with medium-scale low- and high-angle trough-type cross-stratification. Cross-laminae dip southeast, parallel to the Cretaceous shoreline, and probably were formed in shallow marine waters by longshore currents. About 2½ miles southeast of Left Hand Collet Canyon in cliffs of Straight Cliffs escarpment, 20-30 feet below top of G sandstone bed in John Henry Member of Straight Cliffs Formation.

FIGURE 34.--Upper bedding unit of barrier sandstone facies above level of man's knee. Unit consists of well-sorted fine-grained sandstone with large-scale very low angle wedge-planar cross-stratification. Similar stratification is commonly found in strata deposited in the swash zone or upper foreshore of modern beaches. In Trail Canyon tributary to Left Hand Collet Canyon, top of D sandstone in John Henry Member of Straight Cliffs Formation, at measured section S5.

the Straight Cliffs that interfinger with lagoonal-paludal beds of the Smoky Hollow Member of the Straight Cliffs. C. soleniscus is also found in parts of the barrier sandstone beds with normal marine fossils including inocerams and ammonites, but in most of these occurrences the shells of C. soleniscus are fragmented and abraided and probably were eroded from preexisting beds and transported by waves and currents into the normal marine areas.

The upper and middle units of the threefold vertical sequence of current-formed bedding structures in the John Henry Member of the Straight Cliffs are similar to bedding structures that occur in modern beach deposits. Very low angle seaward-dipping wedge-planar crossbedding like that in the upper bedding unit is common in the upper foreshore of modern beaches (Thompson, 1937; McKee, 1957). High-angle trough and planar crossbedding like that in the middle bedding unit is common in the lower foreshore (Thompson, 1937; Hoyt, 1962), although Hoyt found that the high-angle crossbedding also occurs in the upper foreshore under certain conditions. The distribution of fossils within the threefold sequence is also significant. No fossils were found in the upper bedding unit, only fossil fragments were found in the middle bedding unit, but whole fossils as well as fragments occur in the lower bedding unit. This distribution of fossils is apparently a function of the different energy levels in the beach and shallow-water nearshore marine environment.

The upper bedding unit probably represents intermittent flow conditions in the upper flow regime where the abundant very low angle seaward-dipping laminae are comparable to plane bed forms. Upcurrent migrating antidune waves that clearly indicate upper flow regime conditions are common features in the swash zone or upper foreshore of modern beaches, although bedding structures formed by these waves are usually destroyed as the water current diminishes. Lack of fossils in the upper bedding unit was apparently caused by winnowing and attrition by these relatively high velocity currents of high turbulence, and the white to very light gray color of these beds reflects the general scarcity of heavy minerals whose lack is the result of winnowing by these currents.

The middle bedding unit was probably formed slightly farther toward the sea in the lower foreshore and in the inshore area which extends out to the breaker zone. In this area, sediment grains are placed in motion by waves, and the grains are then moved by relatively strong longshore currents (Ingle, 1966, p. 53-54). The crossbedding indicates lower flow-regime conditions, but chert or quartzite pebbles and cobbles larger than 1 inch in some of these beds indicate that upper flow-regime conditions were at least intermittently present (Fahnestock and Haushild, 1962). The highly turbulent currents and the back-and-forth surges probably destroyed any upper flow-regime structures that may have been formed and were probably responsible for fragmenting any shells of organisms that may have been carried into this zone.

The lower bedding unit was probably formed in offshore areas that were farther seaward than the breaker zone. Articulated, whole, and nonabraded fossils in these beds suggest gentler currents, and the crossbedding indicates lower flow-regime conditions. Horizontal stratification may indicate local upper flow-regime conditions near rip currents and (or) intermittent upper flow-regime conditions that accompanied strong currents generated during storms. It may also have been formed by deposition of sand grains that were placed in suspension in the highly turbulent conditions of the breaker zone and subsequently carried offshore to be deposited directly from suspension.

The threefold separation of bedding structures is not clearly indicated in other beach and nearshore marine sandstones in the Tibbet Canyon Member of the Straight Cliffs or in the upper member of the Dakota Formation, and observations by the writer in Cretaceous marine sandstones of the southern part of the Colorado Plateau indicate that, in general, the sequence of bedding structures is not a common phenomenon. Perhaps special circumstances, suggested mainly by the local black sandstone deposits, are necessary to explain the sequence. On the basis of comparison of modern black sand deposits in Florida, Oregon, and eastern Australia, Houston and Murphy (1962, p. 70-74) concluded that Cretaceous black sandstone deposits in Wyoming were formed by concentration of the heavy minerals during severe storms. The black sandstone beds in the Kaiparowits region occur in stratigraphic sequences that are similar to those in Wyoming, and a similar origin by concentration of heavy minerals during storms is likewise inferred. Jacka (1965, p. 88-89, fig. 6, zone 2) also concluded that trough crossbedding in the Almond Formation (Upper Cretaceous) in Wyoming similar to that of the middle bedding unit was formed by strong longshore currents that were generated during storms. Although none of the evidence can be considered conclusive, the relations and comparisons suggest that the lower, middle, and upper bedding units, respectively, were formed by coastal, longshore, and swash currents and that the bedding structures and sequences as well as the black sandstones may have been formed primarily by strong currents that were generated during storms.

Current-formed bedding structures are generally not well preserved on the lagoonal, or landward, side of the barrier sandstone beds in the John Henry Member. The lagoonal parts of some of these beds contain abundant Ophiomorpha sp. or mottles which suggest that any current-formed bedding structures that may have been formed were obliterated by bottom-dwelling organisms.

The barrier sandstone beds are locally overlain by very fine to fine grained moderately to well-sorted very thin bedded sandstone that is generally less than about 10 feet thick. These beds were probably formed from sand that was reworked from the subaerial part of the barrier island during a landward or seaward shift of the shoreline. No beds that contain features suggesting deposition in subaerial environments have thus far been found at the top of the various barrier-island sandstone beds, and it is concluded that the subaerial deposits were removed or reworked by water currents so that their original character cannot now be determined.

Bedding structures in the Tibbet Canyon Member of the Straight Cliffs are mixed, and a threefold separation of the structures is generally not apparent. Locally, the Tibbet Canyon grades landward into fluvial sandstones of the alluvial-plain facies, indicating that streams, at least locally, discharged directly into the sea rather than into the lagoons and swamps behind the barrier islands as more commonly occurred during deposition of the barrier sandstone beds in the John Henry Member. This suggests that the three types of bedding structures were formed where there was little or no disruption of the various nearshore marine currents by fluvial currents.

The upper member of the Dakota Formation contains three sandstone beds that are linear or gently curved in plan view and approximately lens shaped in cross section. These beds are generally devoid of current-formed bedding structures, but they are mottled or contain burrow structures including Ophiomorpha sp., which suggests that bottom-dwelling organisms destroyed any bedding that may have been present. Numerous Exogyra levis are present in the upper 1-3 feet of two of these sandstones. There is no evidence in the report area that these beds were ever built up as islands above sea level, and they may have been formed as submarine offshore bars or shoals.

In summary, barrier sandstone beds in the Straight Cliffs Formation were deposited as barrier islands that separated the open marine waters of the Western Interior seaway from lagoonal and paludal areas in the coastal lowlands. The only remnants of the subaerially exposed parts of the islands that are still preserved are the relatively thin strata that contain the upper bedding unit and possibly some of the middle bedding unit. The larger part of each of the barrier sandstone beds was deposited in shallow nearshore marine waters, although a small part was deposited in brackish-water lagoonal conditions.

The seaward parts of the barrier sandstone beds in the John Henry Member were probably deposited under the action of coastal, longshore, and swash currents. The distribution of fossils and fossil fragments, black sandstone deposits, and current-formed bedding structures suggests strong currents that probably occurred intermittently and were generated during storms. The landward parts of the barrier sandstone beds were deposited under gentle current conditions in brackish waters of lagoons and swamps. The Tibbet Canyon Member was deposited under similar conditions except that streams which discharged directly into the seaway probably disrupted the continuous flow of nearshore currents. The sandstone beds in the upper member of the Dakota Formation were probably deposited under more gentle current conditions in shallow marine to brackish waters. Deposition of most of these beds was probably near the shoreline, but beach deposits are not present in the report area and the shoreline was probably a short distance to the southwest or northwest.

Offshore Marine Facies

Principal features.--The offshore marine facies is characterized by an abundance of fossiliferous mudstone and shale. Other lithologies that are locally common are very fine grained sandstone, siltstone, calcareous shale, and limestone concretions (fig. 35). The sandstone and siltstone beds, generally less than 2 feet thick, are horizontally stratified or ripple cross-laminated and occur near strata of the barrier sandstone facies. The calcareous shales, including those that contain fossiliferous limestone concretions, generally occur at moderate distances away from time-equivalent strata of the barrier sandstone facies. The fossil fauna, in general, is rich and varied and includes species of foraminifers, coelenterates, annelids, pelecypods, gastropods, cephalopods, arthropods, and vertebrates.

The Tropic Shale and thin tongues of the Tropic that extend into the upper member of the Dakota Formation and into the lower part of the Tibbet Canyon Member of the Straight Cliffs compose the stratigraphic unit that is most typical of the offshore marine facies in the report area. The lower and upper marine mudstone tongues of the John Henry Member of the Straight Cliffs are also included in the offshore marine facies.

Interpretation.--The abundant and varied benthonic, nektonic, and planktonic fossil fauna clearly indicates deposition in waters of normal marine salinities. The balanced numbers of planktonic and benthonic foraminifers, especially in the zone of Sciponoceras gracile, suggest water depths comparable to those over modern continental shelves, that is, approximately 200-400 feet (J. F. Mello, written commun., 1965). Living pelecypods of the genera Ostrea, Anomia, Lima, and Corbula suggest approximate maximum depths of 120-250 feet (Keen, 1958, 1963). The whole assemblage suggests water depths of about 200-250 feet in the zone of S. gracile, and the relation to underlying transgressive and overlying regressive deposits suggests somewhat shallower depths in the other beds of the offshore marine facies. This can be considered only a rough approximation because little is known about the environmental adaptations of these organisms so far back in geologic time. Water temperatures are equally difficult to estimate, but comparison of living gastropods and pelecypods

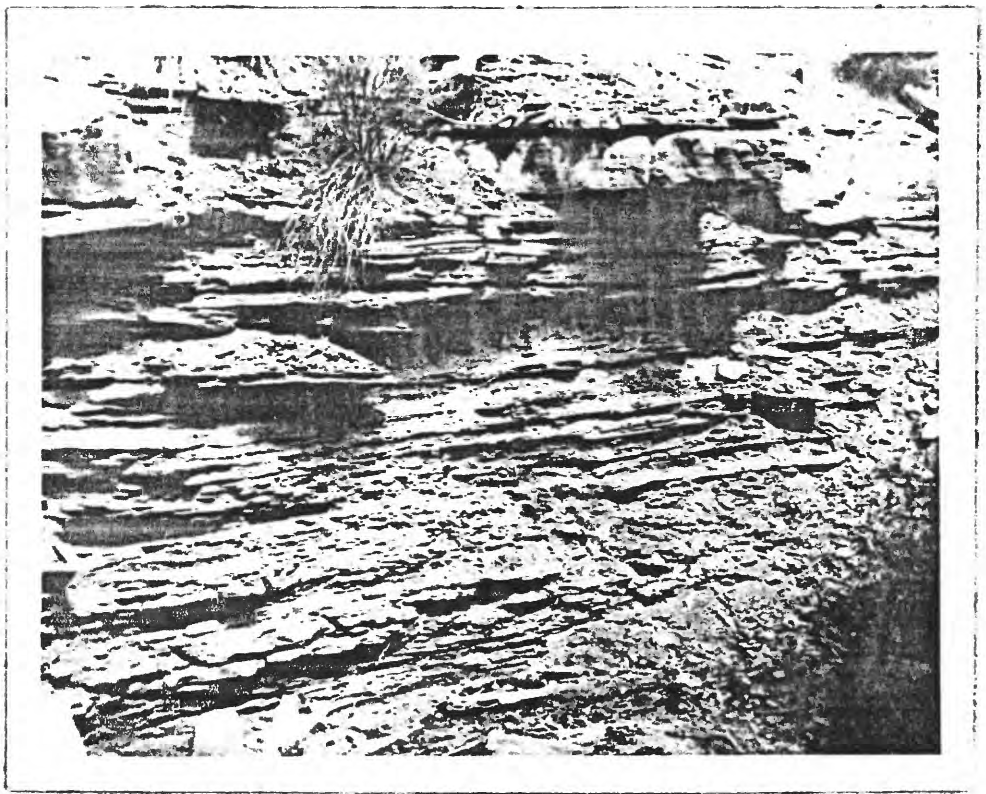


FIGURE 35.--Interbedded sandstone and mudstone of the offshore marine facies. Inoceramus sp. and Ophiomorpha sp. were found in these beds. Upper sandstone bed is about 2 feet thick. About half a mile southwest of Straight Cliffs escarpment and 1½ miles east of top of measured section S6, near top of upper marine mudstone tongue of John Henry Member of Straight Cliffs Formation.

with the same fossil genera that occur in the offshore marine facies suggests warm to temperate waters. Foraminiferal evidence in northwestern Colorado led Kent (1968) to conclusions that suggest water temperatures were 20°C (68°F) or more in southern Utah.

The vertical sequence of lithologies in the middle and upper parts of the Tropic Shale demonstrates the lateral gradations that occurred during deposition of the offshore marine facies. Interbedded sandstone, siltstone, and mudstone at the top of the Tropic were deposited nearer the shoreline, noncalcareous and calcareous shale farther down in the Tropic were deposited farther offshore, and calcareous shale containing fossiliferous limestone concretions in the faunal zone of Sciponoceras gracile were deposited at even greater distances offshore. Ripple cross-lamination in the sandstone and siltstone beds that were deposited nearer the shoreline indicates seaward diminishing of bottom current velocities which were of greatest intensity at the shoreline.

Thin quartz sandstones and bioclastic sandstones (calcarenites) that are present in minor amounts throughout the offshore marine facies also contain ripple cross-lamination which indicates that gentle bottom currents were at least intermittently active. The calcareous shales containing fossiliferous limestone concretions are transitional beds that mark a lateral gradation into limestone beds of the distant marine facies which is not present in the report area. The transitional beds occur in areas where deposition of limy muds, probably caused by biogenic processes, was approximately equal to or exceeded deposition of detrital sediment that was ultimately derived from land areas. Because hydrodynamic conditions and contemporaneous crustal disturbances also governed the distribution of detrital sediment that was carried into the seaway from land, limestone could have been deposited nearer the shoreline at one time than shales and mudstones were deposited at another time.

In summary, the offshore marine facies was deposited in normal salinity, open marine environments in the Western Interior seaway. Maximum water depths were probably about 200-250 feet, and the water temperatures were comparable to modern warm or temperate seas. Stratigraphic relations indicate that deposition occurred approximately 5-10 miles to several hundred miles offshore, but the type of deposits was determined by several factors including rate of detrital sediment carried into the seaway from land, hydrodynamic conditions, and biogenic sedimentation. Ripple cross-laminated thin sandstones indicate that gentle bottom currents were at least intermittently active, and the abundant fossil fauna present in most of the beds indicates that oxygenated water was circulated freely.

Distant Marine Facies

Principal features.--The distant marine facies is not present in the report area, but the Greenhorn Limestone of central Kansas is considered typical of the facies. Hattin (1962, p. 17; 1965, p. 11-12) described the Greenhorn in Kansas as consisting of olive- to medium-gray chalky shale and limestone in thin to medium beds, some of which are crossbedded or emit a petroliferous odor when freshly broken. The formation contains abundant fossils that mainly include inocerams, but oysters, ammonites, and cirripeds are also present. The nearest beds of the distant marine facies are the Greenhorn Limestone Member of the Mancos Shale in the San Juan Basin of New Mexico, about 120 miles east-southeast of the Kaiparowits region.

Interpretation.--The abundance of benthonic and nektonic fossils in the Greenhorn Limestone indicates deposition in well-oxygenated, normal marine waters. Comparison with time-equivalent barrier sandstone strata indicates that the facies was deposited approximately 50-100 miles to several hundred miles offshore in areas where the rate of detrital sedimentation was exceeded by the rate of deposition of calcareous materials that probably were derived largely from biogenic processes. The calcareous shales and fossiliferous limestone concretions in the zone of Sciponoceras gracile in the Tropic Shale are transitional between the offshore marine facies and the distant marine facies. They are included in the offshore marine facies because of the lack of limestone beds and because the zone is composed predominantly of calcareous shale.

DAKOTA FORMATION

Lower member.--The oldest Cretaceous deposits in the region are the fluvial and residual strata in the lower member of the Dakota Formation. These beds do not fit well into any of the facies categories used in this report, but they are included in subdivision A of the alluvial plain facies, mainly for convenience but also on the basis of fluvial origin of some of the beds and relative coarseness of materials. However, the fluvial deposits are not as widespread as more typical strata in subdivision A that occur in younger formations. Carbonaceous mudstone that is more typical of subdivision C of the alluvial plain facies occurs as lenses and tongues in the lower member and indicates the gradational nature of the transition into the middle member which contains abundant carbonaceous mudstone. The general relations of facies in the lower member are shown diagrammatically in figure 36.

Middle member.--The middle member of the Dakota consists mainly of fluvial channel sandstones and backswamp deposits of subdivision C of the alluvial plain facies (fig. 36). The member contains yellowish-green mudstone beds in the southwestern and southeastern parts of the region that are more typical of subdivision B (pls. 14, 15, 16). These beds contain fluvial channel sandstones instead of the more widespread fluvial braided-belt sandstones that are more typical of subdivision B and, for this reason, the yellowish-green mudstones in the middle member are somewhat transitional between the two subdivisions.

The four coal beds in the middle member compose a paludal facies and indicate times when swamps were well established in the region (fig. 36). Plate 16 shows the total thickness and extent of coal bed No. 4, whereas plates 14 and 15 show the total thickness of all other coal beds or lenses that are below or above the bentonite marker bed, respectively. Thus, plate 14 shows mainly the thickness and distribution of coal bed No. 1 but also includes scattered lenses and approximately contemporaneous coal beds in the northeastern part of the region that could not be correlated reliably with coal bed No. 1. Similarly, plate 15 mainly shows the thickness and distribution of coal in coal beds 2 and 3 that also cannot be correlated reliably in the northeastern part of the region.

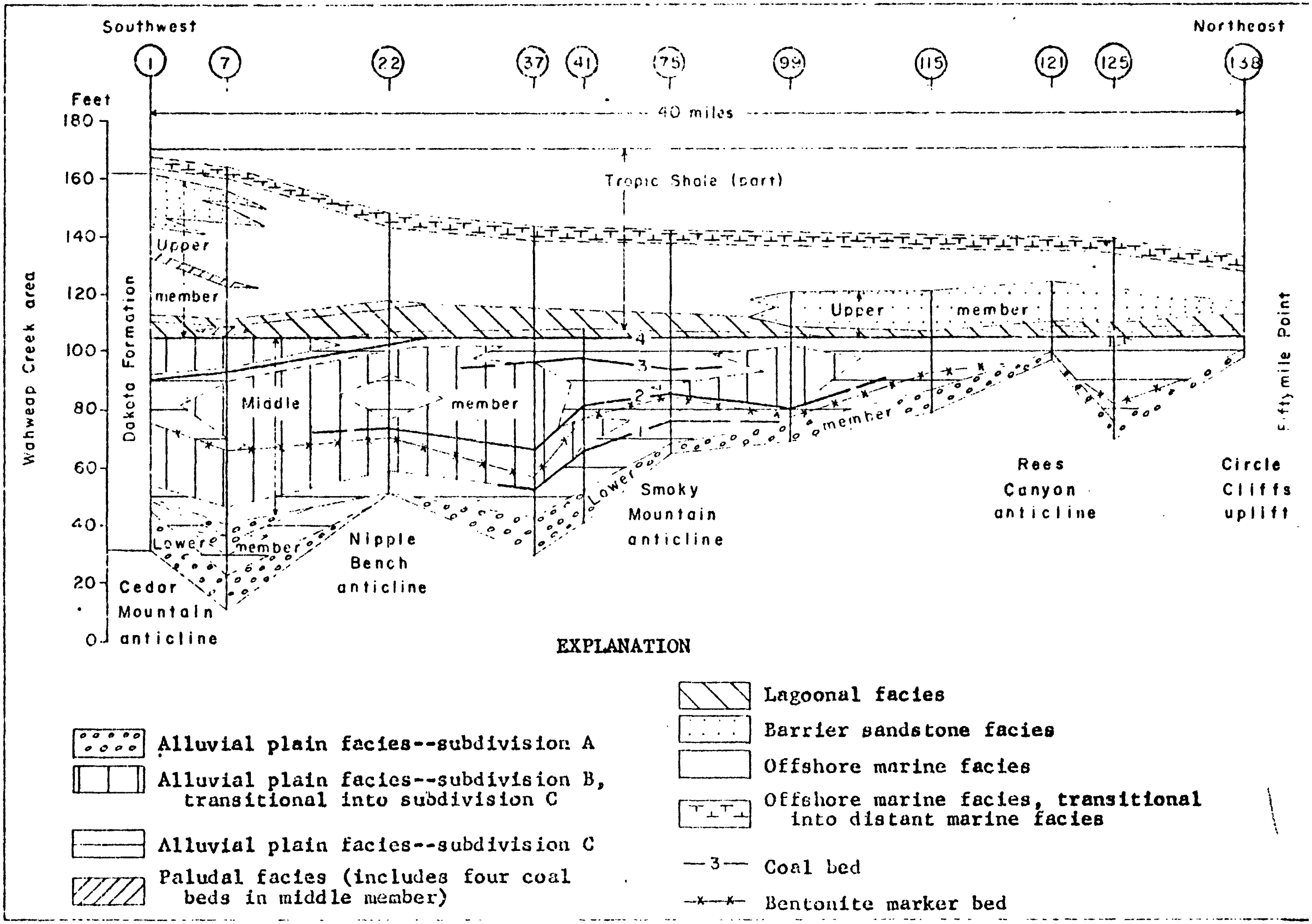


FIGURE 36.--Diagrammatic section of Dakota Formation and lower part of Tropic Shale showing facies relations and ancestral folds in southeastern Kaiparowits region.

Although paludal and lagoonal strata are interbedded in the Straight Cliffs Formation, no faunal evidence was found that would indicate the presence of lagoonal strata in the middle member of the Dakota Formation.

Upper member.--The upper member of the Dakota includes strata of the lagoonal, paludal, barrier sandstone, and offshore marine facies (fig. 36). The lagoonal facies is characterized by thin beds or lenses of sandstone, mudstone, or coquinoid marlstone that contain abundant oyster shells and that probably represent oyster reefs and deposition in brackish-water environments. A thin coal bed 0-6 inches thick occurs in the southwestern part of the region and indicates a local area of paludal deposition. Two relatively thick sandstone beds that are included in the barrier sandstone facies occur at the top of the member in the southwestern and northeastern parts of the region (fig. 36). Although these beds are of slightly different age (fig. 7), they are similar in composition (pl. 2) and contain abundant Exogyra levis in the upper part. The sandstone bed in the faunal zone of Dunveganoceras conditum in the northeastern part of the region extends about as far southwest as Surprise Valley (pl. 1) where the bed grades into mudstone in the lower part of the Tropic Shale. The sandstone bed in the faunal zone of D. albertense in the southwestern part of the region is only present in Wahweap Creek canyon, and this bed grades northeastward into mudstone in the lower part of the Tropic Shale. Marine mudstone and shale below this bed compose an offshore marine facies (fig. 36).

TROPIC SHALE

The Tropic Shale consists almost entirely of the offshore marine facies except for the lowest beds in the zone of Dunveganoceras pondi (figs. 7, 36) that contain thin coquinoid marlstone lenses of abundant oyster shells. These fossils suggest deposition in brackish-water environments, and their presence is the reason for placing these beds in the lagoonal facies. The limestone lenses and calcareous shales in the thin zone of Sciponoceras gracile suggest a transition into the distant marine facies, but these beds are included in the offshore marine facies because calcareous shale predominates and the limestone is not in beds.

STRAIGHT CLIFFS FORMATION

Tibbet Canyon Member.--The Tibbet Canyon Member is a thick sandstone unit at the base of the Straight Cliffs Formation and is considered typical of the barrier sandstone facies. The member grades southwestward into lagoonal, paludal, and alluvial plain strata in the lower part of the Smoky Hollow Member and grades northeastward into offshore marine strata in the upper part of the Tropic Shale (fig. 37). Some of the southwestward-extending tongues of the Tibbet Canyon contain abundant well-preserved *Crassostrea soleniscus* which suggest local deposition in lagoonal environments. The intertonguing relations, shown in detail on plates 9 and 10, indicate that the member was formed by deposition of sandstone bodies, which are lens shaped in northeast-southwest cross section, and that these lenses overlap each other like shingles on a roof, giving a general imbricate structure to the member.

Smoky Hollow Member.--The Smoky Hollow Member consists mainly of the alluvial plain facies, although three large irregularly lens shaped bodies of the lagoonal-paludal facies are present at the base (fig. 37). Two of the irregular lenses in the southwestern part of the region are outlined by the included coal beds as shown on plate 17. The third, or northeasternmost, body of lagoonal-paludal strata is somewhat more irregular in outline and occurs in an area where the coal beds could not be correlated in detail because of talus and soil cover. Deltaic strata are not common in the member, and this accounts for the lack of a deltaic plain facies in figure 37. The reason for the general absence of this facies is that the streams generally discharged directly into the seaway instead of at the landward side of the lagoonal-paludal areas. Most of the strata in the remainder of the member consist of yellowish-green mudstone and fluvial braided-belt sandstones that are typical of subdivision B of the alluvial plain facies. The pebbly sandstone of the Calico bed at the top of the Smoky Hollow is typical of subdivision A of the alluvial plain facies.

John Henry Member.--Strata in the John Henry Member grade from nonmarine in the southwestern part of the region to predominantly marine in the northeastern part. Progressing from southwest to northeast, the lateral sequence of facies in the member generally is: the alluvial plain facies (subdivision B), the deltaic plain facies, the lagoonal-paludal facies, the barrier sandstone facies, and the offshore marine facies. The lagoonal-paludal facies was not deposited continuously in the area, although it may have been deposited continuously farther northwest. The distribution of facies is illustrated in figure 38, which shows a somewhat irregular

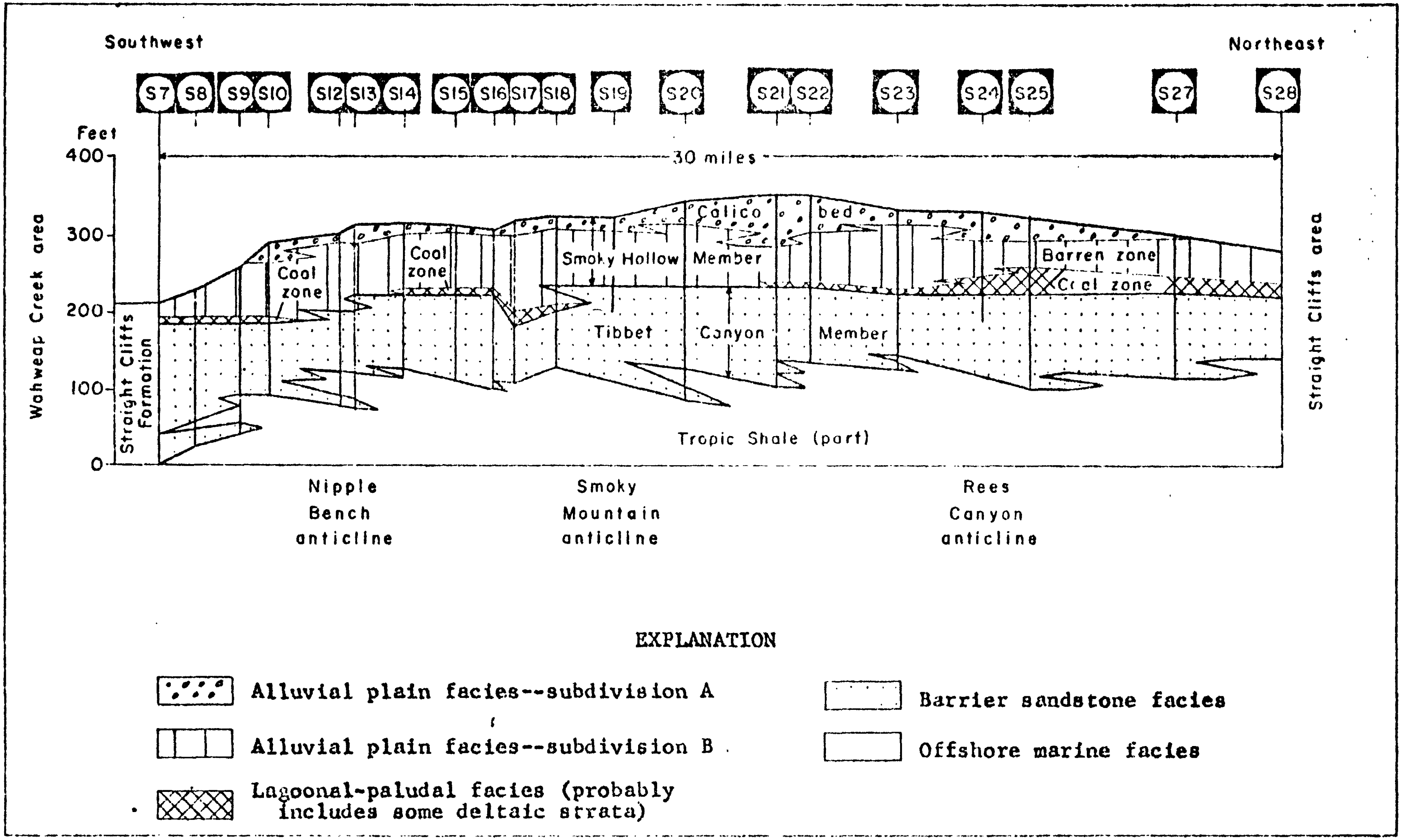


FIGURE 37.--Diagrammatic section of upper part of Tropic Shale and lower members of Straight Cliffs Formation showing facies relations and ancestral folds in southeastern Kaiparowits region. Measured sections are projected onto a line that is normal to the Cretaceous shorelines. Interfingering at top of Tropic Shale greatly simplified.

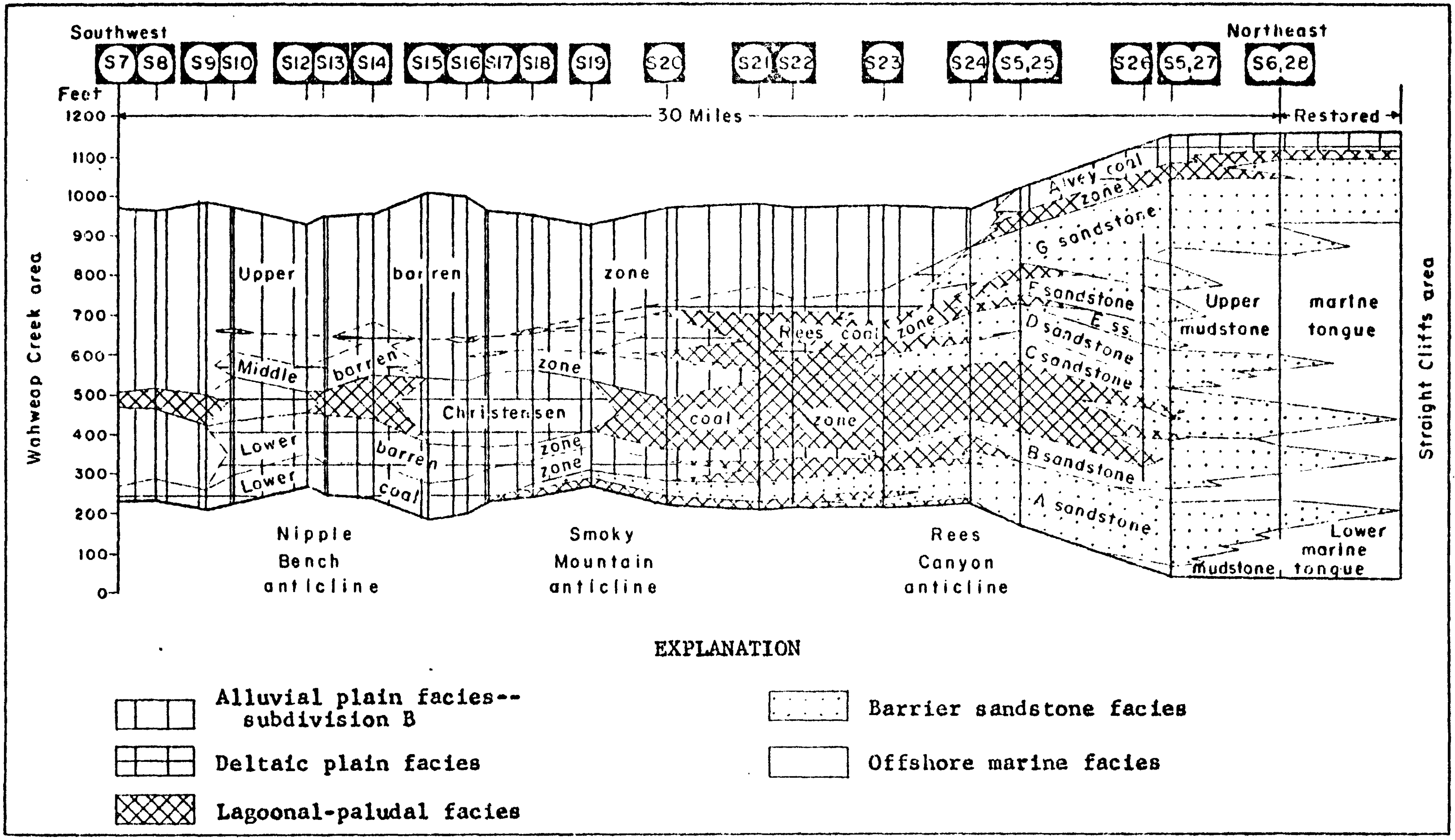


FIGURE 38.--Diagrammatic section of John Henry Member of Straight Cliffs Formation showing facies relations and ancestral folds in southeastern Kaiparowits region. Measured sections are projected onto a line that is normal to the Cretaceous shorelines.

distribution of the deltaic plain facies because the line of section cuts across several lobes of this facies that extend into the region from the southeast. Lagoonal and paludal strata in the member are included in one facies because they are complexly interbedded and cannot be readily separated.

The deltaic plain facies occurs in both the coal and barren zones, which are distinguished primarily on the presence or absence of coal in beds 1 or more feet thick. However, the deltaic plain facies is recognized primarily on the type and distribution of the sandstone beds. Ideally, strata of subdivision C of the alluvial plain facies should occur between strata of subdivision B and strata of the deltaic plain facies. It was not practical, however, to separate these beds owing to the difficulty of distinguishing fluvial channel sandstones deposited by meandering streams from fluvial channel sandstones deposited by delta distributaries.

The horizontal distribution of coal during deposition of the lower, Christensen, and Rees coal zones is shown on plates 18, 19, and 20. In general, the deltaic plain facies occurs along the southeast and southwest edges of the coal areas shown on these plates and in figure 38. The Alvey coal zone has been eroded from most of the area, but the stratigraphic relations shown in figure 38 indicate that the deltaic and lagoonal-paludal facies as applied to this coal zone are restricted to the area northeast of the Rees Canyon anticline.

Drip Tank Member.--The Drip Tank Member is a widespread, thick predominantly fluvial sandstone unit that is mainly included in subdivision A of the alluvial plain facies. Some of the bedding structures in the northeastern part of the region suggest northeastward gradation into the barrier sandstone facies; this gradation is also suggested by shark teeth that were found in the member in the northern part of the Kaiparowits region by E. V. Stephens (oral commun., 1967). Correlation with the Emery Sandstone Member of the Mancos Shale in the Henry Mountains region (fig. 39) indicates that the area where most of the facies changes occurred was northeast of the Kaiparowits region.

WAHWEAP FORMATION

The Wahweap Formation consists mainly of interbedded fluvial braided-belt sandstones and yellowish-green mudstones that are typical of

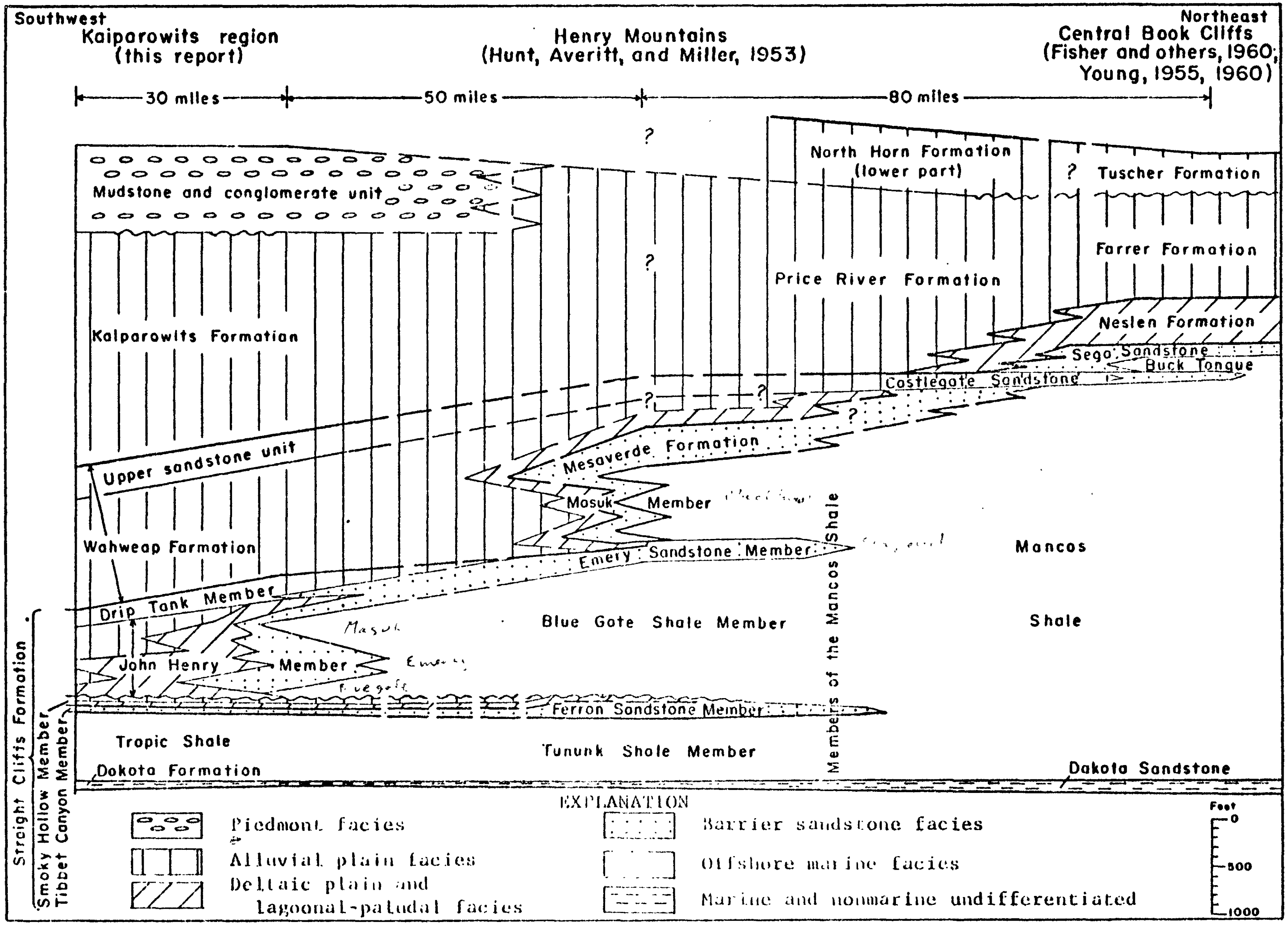


FIGURE 39.--Diagrammatic restored section showing relations of facies from Kaiparowits region to Book Cliffs region in northeastern Utah.

subdivision B of the alluvial plain facies (fig. 39). The lower part of the formation contains large quantities of mudstone (fig. 20), some of which might have been deposited in local lacustrine environments. Large-scale crossbedded units similar to those found in the deltaic plain facies but interbedded with yellowish-green mudstone instead of carbonaceous mudstone are scarce but occur in this part of the formation and suggest local deltas on the periphery of the lakes. Palynomorphs can be helpful in distinguishing lacustrine environments, but the samples collected from this formation were barren. The thick and widespread fluvial sandstone unit at the top of the formation is typical of subdivision A of the alluvial plain facies. There is no evidence that any part of the Wahweap was deposited in marine environments as indicated by Van De Graaff (1963) and Lessentine (1965, p. 2017).

FORMATIONS IN NORTHWESTERN KAIPAROWITS REGION

The two younger Cretaceous formations in the northwestern part of the Kaiparowits region were not studied in detail for this report. The descriptions given by Robison (1966, p. 27-28) and Lohrengel (1968) suggest that the Kaiparowits Formation consists of alluvial plain and possibly deltaic plain facies. The conglomerate and mudstone unit that lies on the Kaiparowits Formation is similar to strata that are considered typical of the piedmont facies of Spieker (1949).

SEDIMENTATION AND TECTONISM

Cretaceous sedimentation in the region occurred while slight, but nevertheless significant, structural deformation was in progress. The growing structures partly governed the distribution of sediments in such a manner that movement on the ancestral structures can be distinguished by facies changes and thickness variations that approximately coincide with at least parts of the present structures. The evidence for contemporaneous structural deformation during any given time interval is commonly subtle and could be explained for any single case as only coincidence. However, when the evidence for several time intervals is considered, the close relations of facies and thicknesses to the present structures are repeated too often to be explained by chance, and growth of the structures during sedimentation is the only reasonable interpretation.

Movement on local folds and faults must be considered in relation to large-scale structural movements. For example, thinning of beds over an anticline suggests that the anticline grew during deposition of the beds, but if regional subsidence was occurring at the same time and no local unconformities are present, the anticline was merely subsiding at a slower rate than the adjacent synclines. The tectonic movements, both local and regional, were continuous when considered throughout the broad scale of geologic time, but it could not be determined whether the movements were continuous or intermittent at the scale of time represented by several feet of strata.

General Setting

The Kaiparowits region is a relatively small structural basin in the southwestern part of the Colorado Plateau Province of Utah, Colorado, New Mexico, and Arizona. The province was part of the stable shelf, or platform, region that lay east of the Cordilleran geosyncline from Precambrian to about Jurassic time. With the probable exception of the Ordovician and Silurian, each of the other systems belonging to this long time interval was deposited on the shelf area but in considerably thinner sequences than equivalent rocks in the geosyncline. During the Nevadan orogeny of Late

Jurassic to Early Cretaceous time, the Cordilleran geosyncline was uplifted to form a long, narrow highland or possibly a mountainous region that extended from Mexico north into Canada, and an arm or bulge in this uplifted area extended southeastward through central Arizona and into New Mexico. Uplift in the Cordillera and adjacent regions caused the seas to recede, and the Colorado Plateau region became the site of erosion and local continental deposition during Early Cretaceous time.

The Cordillera was continuously uplifted during Late Cretaceous time while the region to the east, from Texas northward into Canada, gradually subsided and allowed marine waters from the Gulf of Mexico and the Arctic Ocean to invade the Western Interior. Between the Cordillera and the seaway, an alluvial coastal plain was formed by aggrading streams that flowed generally eastward or northeastward from the Cordillera. South-central Utah at that time was between the Cordillera and the main part of the seaway and was situated about where the coastal plain bordered the seaway.

A series of barrier sand islands generally extended along the shoreline of the seaway and separated the open marine waters from deltaic, swamp, and lagoonal areas on the lower part of the coastal plain. The type and the distribution of the various depositional environments were governed partly by landward or seaward migration of the strandline and partly by growing structures.

Late Jurassic Time

Jurassic sedimentation in south-central Utah ended with deposition of fluvial sandstone and conglomerate beds of the Morrison Formation. Studies by Craig and others (1955) and Cadigan (1967) have shown that the formation was deposited on a broad northeastward- to eastward-sloping alluvial plain in a climate that was semiarid but gradually changed to more humid conditions during deposition of the upper Morrison strata. Jurassic formations older than the Morrison consist of eolian and marginal marine strata comprised mainly of very fine grained sandstones, siltstones, mudstones, and shales. The relatively coarser grained sandstone and pebbly sandstone beds throughout the Morrison and local occurrences of conglomerate beds as much as 80 feet thick at the top of the Morrison suggest gradually increased tectonism in the source regions. The source regions probably were more than 100 miles west and southwest in highlands on the Cordilleran geanticline and in an extension of the geanticline that stretched southeastward across central Arizona and into southern New Mexico (Imlay, 1956, figs. 7, 8; Eardley, 1962, pl. 10). These regions consisted mainly of sedimentary rocks (Craig and others, 1955, p. 150). Some of the thickness and facies variations in Upper Jurassic strata suggest slight local tectonic activity in the southeastern Kaiparowits region, but at present the investigations are too preliminary to be conclusive.

Early Cretaceous Time

Little is known about conditions in the Kaiparowits region during most of Early Cretaceous time because rocks of this age are not known to be present. Craig and others (1955, p. 145) and Imlay (1956, fig. 9) indicate that the region consisted of low to high plains that sloped gently northeastward or eastward during latest Jurassic time. Indications that the region had a hilly topography and that the land surface continued to slope generally eastward during Early Cretaceous time are suggested by the slight northeastward regional tilting that occurred before deposition of the Dakota Formation (fig. 6), by northeastward-, eastward-, and southeastward-trending paleostream patterns in the lower and middle members of the Dakota (pl. 5), and by remnants of the hilly topography preserved beneath the Dakota (pl. 3). Several lenses and tongues of carbonaceous mudstone in the lower member of the Dakota and abundant coal and carbonaceous mudstone in the middle member suggest moderate amounts of rainfall which probably persisted through the Early Cretaceous from latest Jurassic time.

Imlay (1956, text for fig. 9) noted that much of the erosion of the Morrison Formation occurred during Neocomian time, suggesting that this may have been a time of broad regional uplift. That regional subsidence occurred during the later part of Early Cretaceous time is suggested by gradual inundation of the Western Interior region by marine waters beginning in about late middle Albian time (Reeside, 1957, p. 513) and by continued inundation that reached the Kaiparowits region by middle Cenomanian time. It should be noted that the role of eustatic sea-level changes during Cretaceous time is unknown at present, but this mechanism cannot explain the presence of nearshore marine and beach strata in approximately 2,300 feet of strata in the Kaiparowits region and in considerably greater thicknesses of strata in other parts of the Western Interior. It would appear, then, that eustatic sea-level changes were minor compared to the large-scale structural movements. Local tectonic activity during at least the latest part of Early Cretaceous time is suggested by thickness variations in the lower and middle members of the Dakota that coincide approximately with present fold axes or fault blocks (pl. 3) and by abrupt truncation of Upper Jurassic rocks in the southwestern part of the region (fig. 6). A summary of the active tectonic features in the region during at least the latest part of Early Cretaceous time is shown in figure 40.

Cenomanian Time

Cenomanian strata include the Dakota Formation and the lower part of the Tropic Shale (table 3). These beds record deposition in continental, transitional, and marine environments during regional subsidence and a transgressive phase in which marine waters of the Western Interior seaway gradually inundated the region. In addition, the nature and distribution of the various facies were partly governed by growing structures.

The oldest strata in the region are the fluvial and residual deposits in the lower member of the Dakota. Fluvial conglomerates are abundant in the southwestern part of the region in Wahweap syncline where crossbedding measurements indicate that the streams flowed into the region from the southwest (pl. 5). The abundance of pebbles at Wahweap syncline was probably caused by a change in stream gradients. Thus, streams flowing across upland areas of the ancestral Cedar Mountain anticline and regions farther southwest had relatively steep gradients, and the coarser fraction of the bedload was deposited at the change to relatively gentle gradients in the southwestern part of the ancestral Kaiparowits structural basin. Relative uplift of the ancestral Cedar Mountain anticline occurred before deposition of the lower member of the Dakota (fig. 6), and the presence of the conglomerates suggests that the anticline continued to grow during deposition of the lower member.

Northeast from Wahweap syncline in the central and northeastern parts of the region, the lower member consists of fluvial sandstones and residual

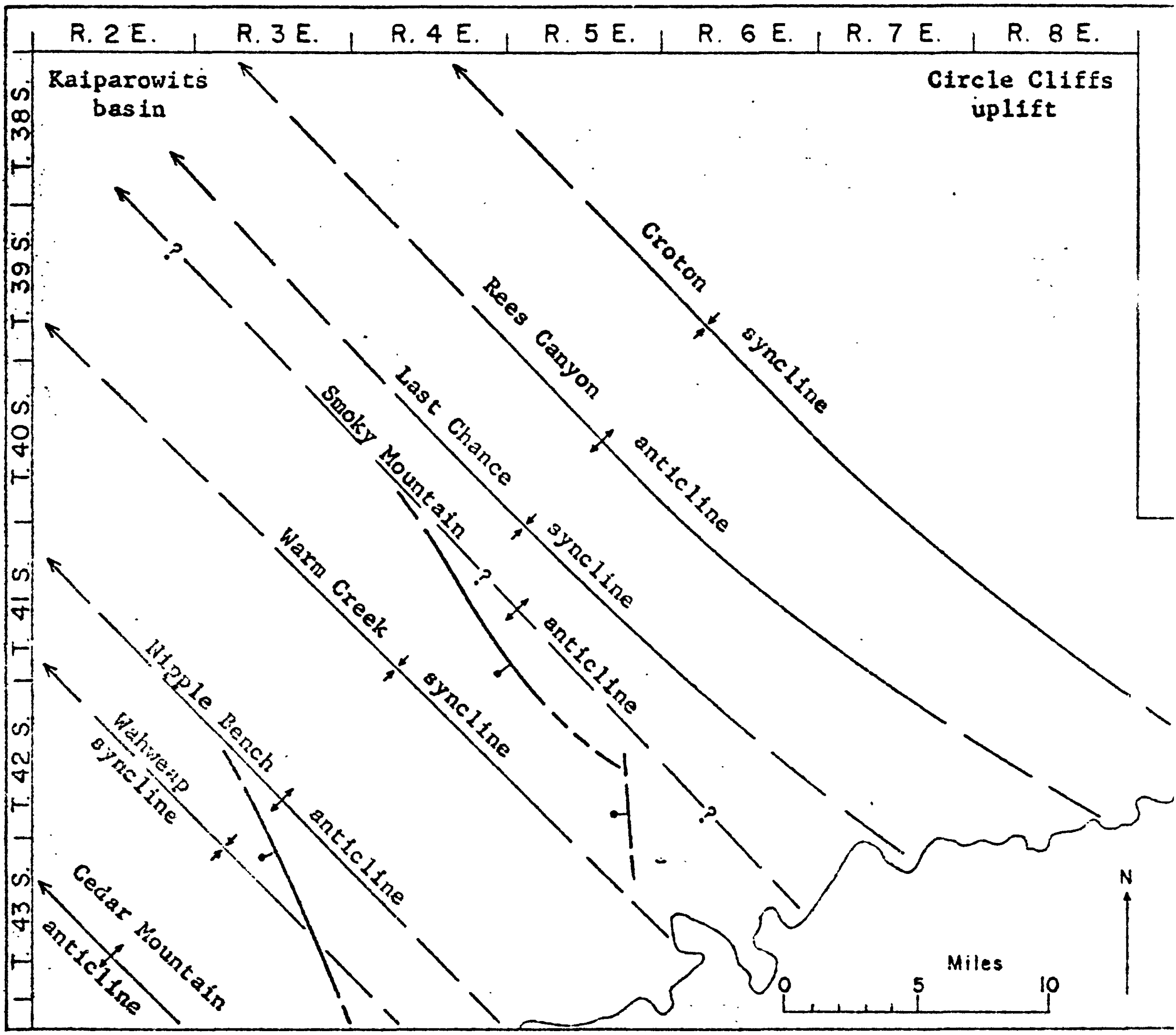


FIGURE 40.--Ancestral structures that were activated during Albian and Cenomanian time. Movement on the fault in Wahweap syncline probably did not occur after Albian time, and movement on the faults at Smoky Mountain anticline probably did not occur after early middle Cenomanian time.

deposits of sandstone, pebbly sandstone, and local conglomerate. The residual deposits are recognized by their poor sorting, presence of broken sand- or pebble-size clasts, carbonaceous material, lack of current-formed bedding structures, and light-gray color similar to that of the sandstones and conglomerates of the underlying Morrison Formation. The residual deposits are especially common on the depositional highs of the ancestral Rees Canyon anticline and the northeast flank of the structural basin near Fiftymile Point. Apparently, these were areas of deep weathering that were completely buried by younger Dakota sediments before erosional processes stripped off all the surficial weathered materials.

The lithologies indicate a source primarily from older sedimentary rocks. Chert pebbles in the member contain late Paleozoic fossils that could have been reworked from Morrison beds, but the general southwestward truncation of Upper Jurassic strata shown in figure 6 suggests that the Morrison was not present farther southwest at that time. None of the older Jurassic or Triassic formations southwest of the region, including the Shinarump Member of the Chinle Formation (Phoenix, 1963, p. 18), contain such an abundance of chert pebbles, and the evidence suggests that most of the chert came directly from late Paleozoic formations which probably were exposed more than 100 miles southwest in the Cordilleran geanticline. Late Paleozoic rocks that contain fossiliferous chert nodules and that are presently preserved in northwestern Arizona and southern Nevada include limestones and dolomites, and presumably these lithologies were the source of the chert pebbles in the Kaiparowits region. The relatively high quartz content, the presence of well-rounded grains and fragments of well-rounded grains, and the scarce pebbles and cobbles and rare boulders of sandstone indicate an origin from quartz sandstones that probably included nearby Jurassic and Triassic quartzose eolian sandstones as well as sandstones in the Cordillera.

The middle member of the Dakota Formation consists mainly of fluvial and overbank deposits of the alluvial plain facies (fig. 36). Statistical studies of paleostream channels in the member (pl. 5) demonstrate that streams entered the region southwest of the Rees Canyon anticline from highland areas to the southwest, west, and northwest and generally left the region by flowing southeastward. The presence of a low topographic ridge at the ancestral Rees Canyon anticline is indicated by isopachs of the lower and middle members (pl. 3) and isopachs of coal in the middle member (pls. 14, 15, 16). This ridge prevented the streams from flowing farther northeast. Other streams that entered the northeastern part of the region were probably deflected southeast by the same topographic ridge or possibly flowed across low places in the ridge and into the central part of the region.

The detrital materials in the middle member were derived primarily from older sedimentary rocks in areas near the Kaiparowits region and also in the highlands of the Cordillera. Scattered chert pebbles that contain late Paleozoic fossils are scarce but occur at or near the base of some of the fluvial channel sandstones in the southwestern part of the region. Like those in the lower member, the pebbles probably came directly from late Paleozoic carbonate rocks in the Cordillera far to the southwest. The high quartz content and the quartz, quartzite, and dolomite grains in the sandstones indicate an origin mainly from preexisting quartz sandstones, quartzites, and dolomite beds in the Cordillera or from nearby quartzose eolian sandstones of Jurassic and Triassic age. The presence of only one bentonite bed in the report area suggests that most of the bentonitic materials in the mudstones came from preexisting bentonitic rocks and (or) from ash falls outside the area, with subsequent reworking and stream transportation. It would seem that conditions should have been suitable for at least local preservation of other bentonite beds if other ash falls had occurred directly in the region. The coal beds originated in the sedimentary basin and indicate areas in which little or no detrital sedimentation occurred and conditions were suitable for the preservation of abundant plant debris.

Downwarping of the region as a structural basin is indicated by the distribution of coal in the member (pls. 14, 15, 16). The cyclic alternation of the coal beds and the alluvial plain deposits was the result of differences in the rate of sediment influx--the coal beds indicating times when the rate of detrital sedimentation was slow and the alluvial plain deposits indicating times when the rate of detrital sedimentation was relatively rapid. Southeastward-trending paleostream directions in the central part of the region indicate that a southeastward-sloping alluvial plain was formed between the periods in which coal swamps occupied the basin. Regional subsidence in relation to sea level probably continued from Albian time because the middle member is overlain by brackish-water strata that record the first stages of invasion by the Western Interior seaway.

Movement on many of the folds and some of the faults before and during deposition of the Dakota Formation is suggested by thickness variations in an isopach interval consisting of the lower and middle members (pl. 3). The upper contact of the isopach interval is the top of coal bed No. 4, which is a time-equivalent or nearly time equivalent surface and probably was horizontal or nearly horizontal at the time of deposition. Thinning of units within the isopach interval generally is proportional except at the fluvial channel sandstones where differential compaction occurred (fig. 7). The isopach map, therefore, indicates that (1) the surface on which the Dakota was deposited had a mature topography consisting of low ridges and broad valleys; (2) many of the present structures in the region are closely related to the ridges and valleys, indicating that the structures shown on plate 3 had begun moving before deposition of the Dakota; (3) the inferred trends of the ancestral folds cut across the present trends of Grand Bench and Echo monoclines, indicating that the monoclines were formed later, presumably at the end of the Cretaceous Period; and (4) continued growth of these structures occurred during deposition of the lower and middle members. A small but undetermined amount of erosion that must have occurred on the ridges before they were completely covered by the uppermost beds of the middle member is also reflected in the isopachs. Uplift on the ancestral Smoky Mountain anticline is not clearly indicated because of downfaulting at the crest of the fold. Judging from the thinning northeast of the faults, however, a small amount of uplift probably occurred.

The coal isopach maps (pls. 14, 15, 16) also support the hypothesis that many of the folds and some of the faults were actively moving structures during deposition of the middle member. The ancestral fault in Wahweap syncline, shown on plate 3, cuts across the coal isopachs and probably was not active at that time.

A summary of the various structures that were active during deposition of the member are shown in figure 40. The position of the fold axes in this figure was determined by the best fit of data in figure 6 and on plates 3, 5, 14, 15, and 16. Lack of precise correspondence of some of the fold axes to isopach minimums or maximums is attributed to erosional irregularities caused by the greater abundance of streams in the central part of the region (pl. 5) and to relatively greater sedimentation at the change in stream gradients in the southwestern part.

The general ecological conditions during deposition of the nonmarine part of the Dakota Formation in southern Utah were probably similar to those of the approximately time equivalent Dakota Sandstone in Black Mesa basin, which is only about 70 miles southeast of the Kaiparowits region in northeastern Arizona. J. M. Agasie obtained an abundant assemblage of palynomorphs from the Dakota in Black Mesa basin and concluded (Agasie, 1969, p. 16-17) that,

> "The area during deposition of the Dakota Sandstone probably consisted of a low-lying coastal plain, covered with ferns and angiosperm trees and shrubs, with conifers occupying well-drained, low upland sites. * * * Although the ecological requirements might have been somewhat different in the geologic past, the flora of the Dakota Sandstone, when compared with analogous modern floras, suggests very wet, subtropical to tropical climatic conditions in the lowlands with diminishing warmth at higher elevations."

The stratigraphic relations of the Dakota in the Kaiparowits region indicate that the lower and middle members were deposited in the topographic low areas of a broad plain that stretched from the highlands of the Cordillera to the west and southwest to the Western Interior seaway that lay farther east or southeast. Although marine beds are not present in or near the Kaiparowits region, approximately correlative nearshore marine beds are present in northwestern New Mexico, indicating that the shoreline of the seaway probably was in southeastern Utah. Southeastward thinning of the coal beds and gradation into strata of the alluvial plain facies suggest that the coal was not formed in coastal swamps that were separated from the seaway by a narrow zone of barrier sand islands as occurred during deposition of the Straight Cliffs Formation. Instead, the evidence suggests that the coal swamps were farther inland on the alluvial plain in a slight topographic basin that was formed by relatively greater subsidence of the ancestral Kaiparowits structural basin. The paleogeography of the region as inferred from the distribution of facies and their relation to contemporaneous structures is shown in figures 41, 42, and 43.

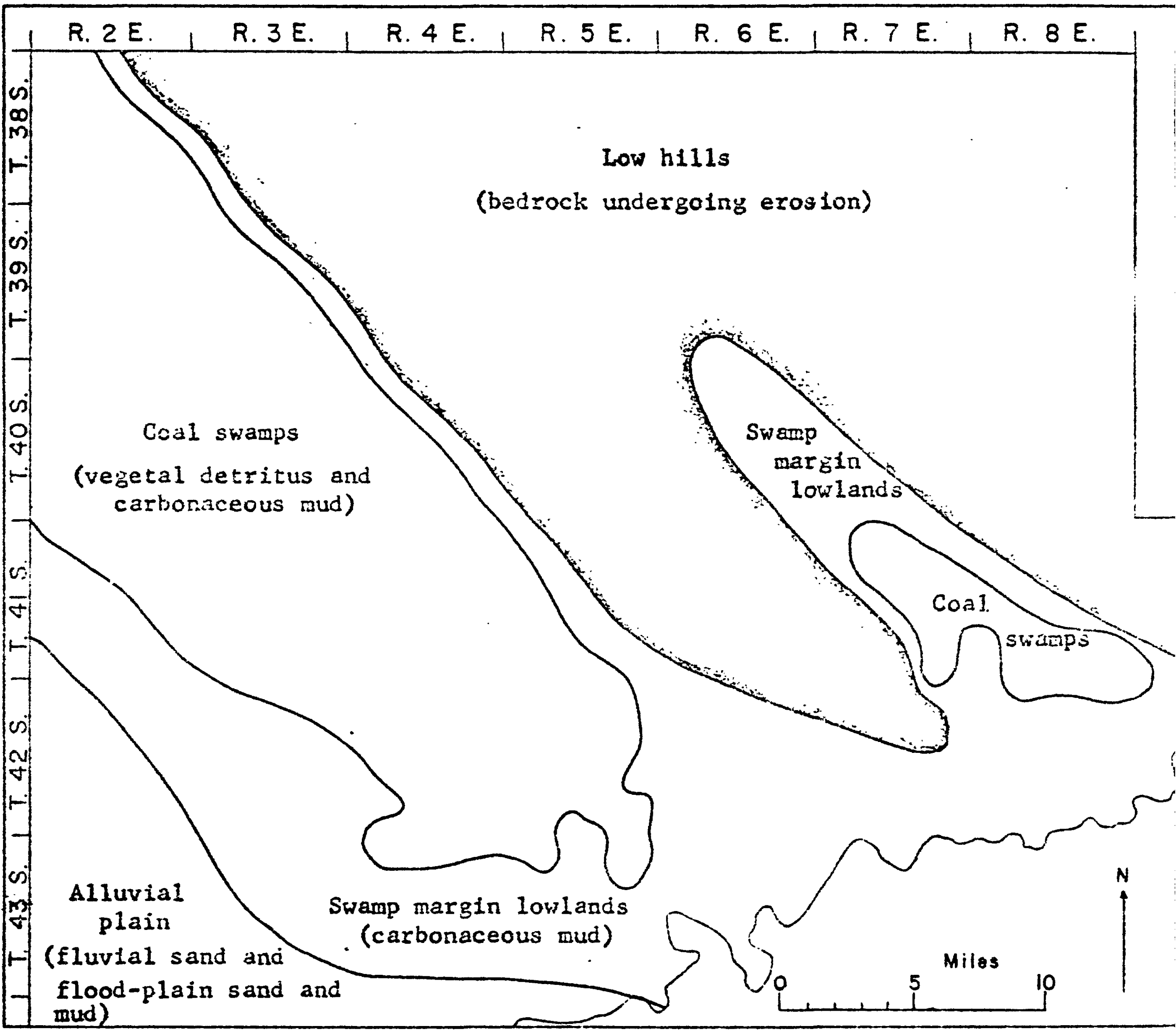


FIGURE 41.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of coal bed No. 1 in the middle member of the Dakota Formation.

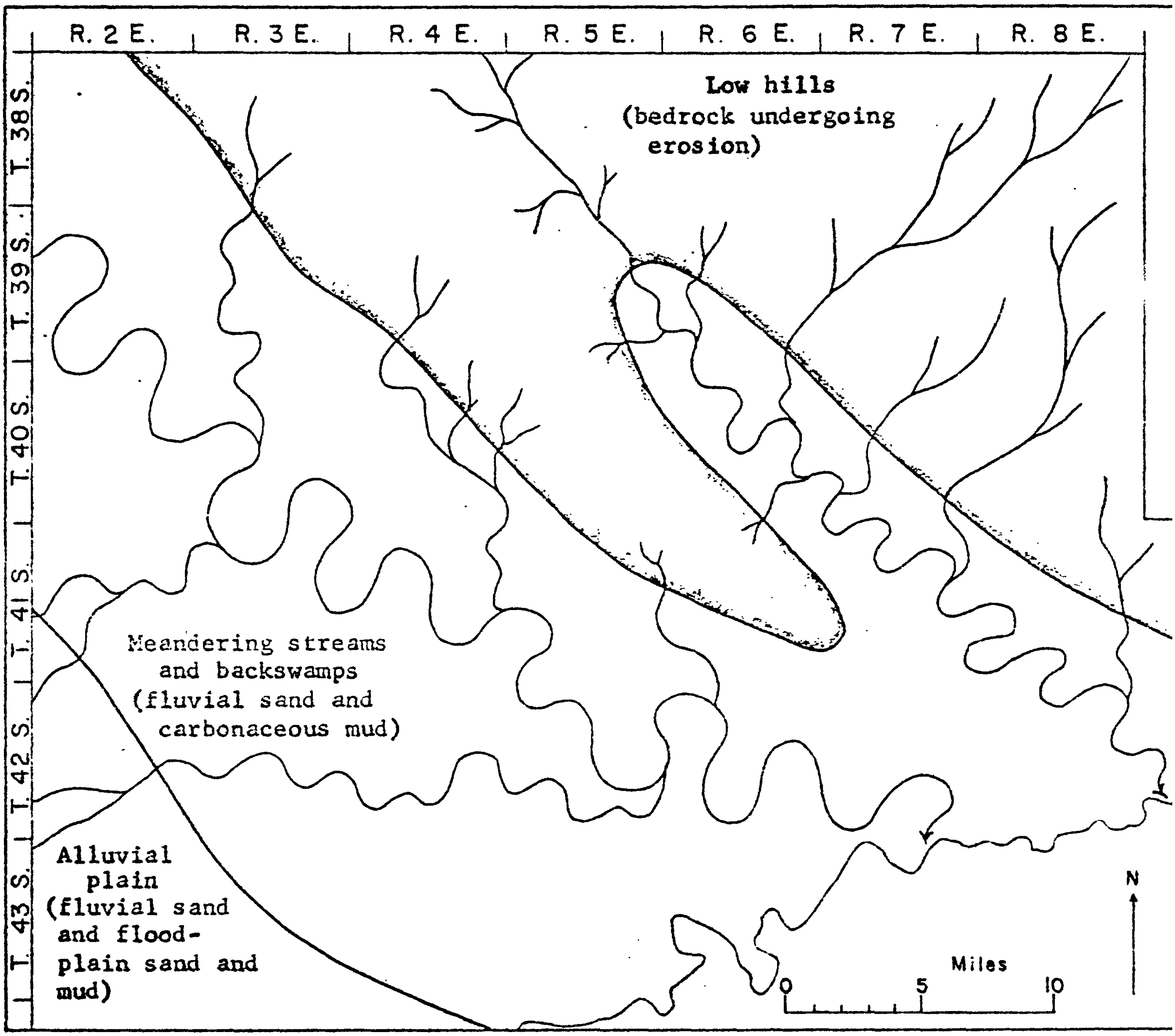


FIGURE 42.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the middle part of the middle member of the Dakota Formation.

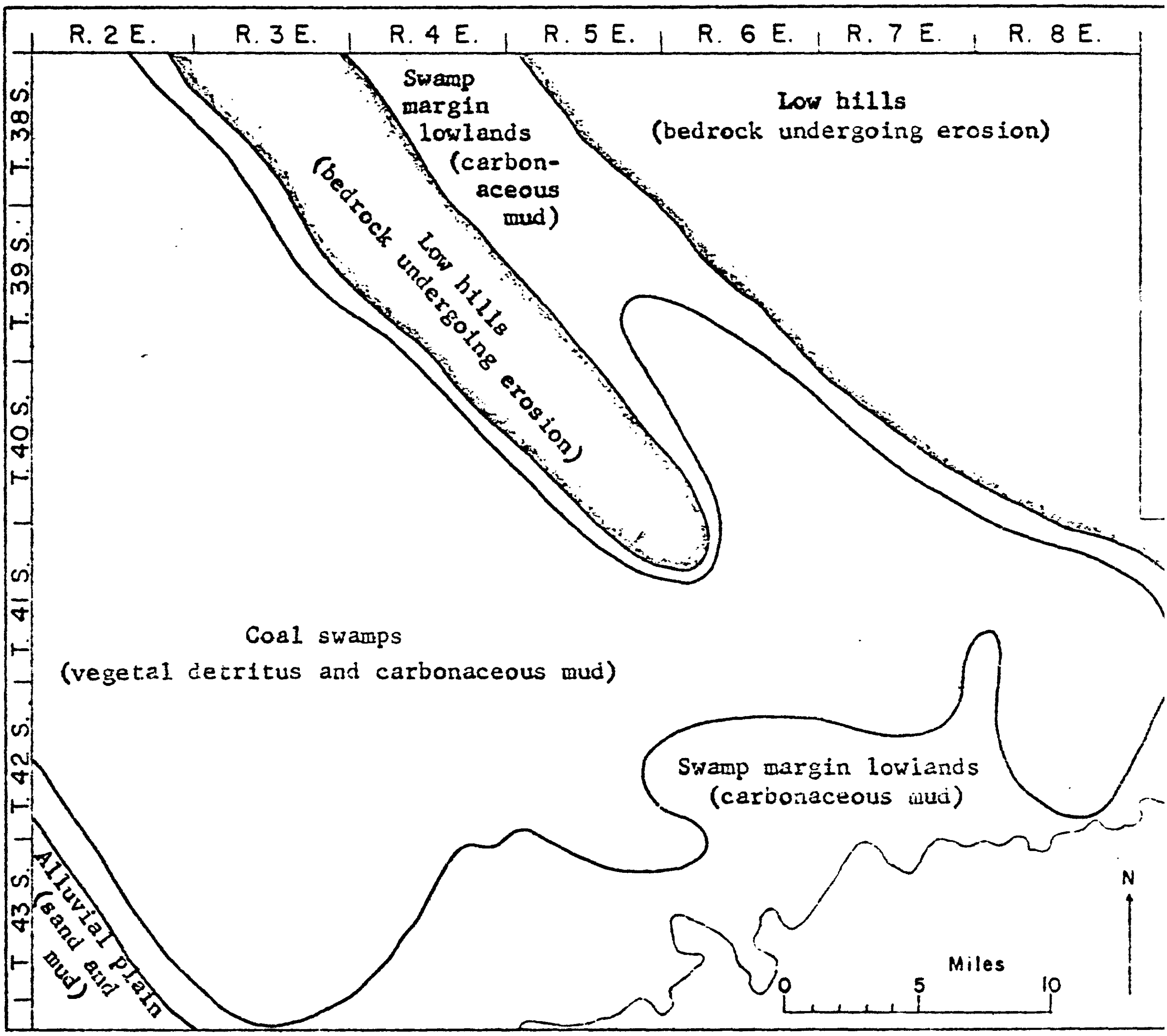


FIGURE 43.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of coal bed No. 4 in the middle member of the Dakota Formation.

The upper member of the Dakota Formation and the lower part of the Tropic Shale mainly include strata of the lagoonal, barrier sandstone, and offshore marine facies (fig. 36). These beds were deposited in brackish to marine waters during late middle and late Cenomanian time, and they record progressive submergence during a phase of marine transgression in which waters of the Western Interior seaway gradually inundated the region. The detrital materials in these beds probably came from the same general rock types and source regions as those in the middle member of the Dakota Formation, that is, from nearby Jurassic and Triassic sedimentary rocks and from Paleozoic strata in the Cordillera.

The oldest strata overlying the middle member of the Dakota consist of brackish-water sandstone and mudstone beds and thin coquinoid marlstone lenses in the faunal zone of Dunveganoceras pondi (figs. 7, 36). Sandstone beds in the southwestern part of the region extend into the region about as far as Nipple Bench anticline, suggesting that slight relative uplift on this fold prevented the sands from being distributed farther northeast. A thin sandstone bed about 0-8 feet thick that is present in the northeastern part of the region has a sinuous southeast trend and lies mainly on or near the crest of the ancestral Rees Canyon anticline. Relatively slower subsidence on this fold evidently resulted in a shallow area where shoaling occurred and shallow-water currents winnowed out the finer particles.

The presence of a low land area northeast of the region is suggested by northeastward thinning in the underlying middle member of the Dakota Formation and in the overlying thick sandstone bed which is in the next younger zone of Dunveganoceras conditum. The source of the sand in the northeastern part of the region is unknown, but it probably came from land areas farther northwest or north. Mudstone and shale beds with coquinoid marlstone lenses of abundant oyster shells that probably were originally formed as oyster reefs occur in the middle of the region and suggest relatively greater distances from land than the sandstone beds farther southwest and northeast. They also indicate that the middle of the region was probably the middle of a shallow brackish-water embayment that connected southeastward with open marine waters of the Western Interior seaway. Downwarping of the ancestral Kaiparowits structural basin is indicated by the coincidence of the embayment with the present structural basin and lateral gradation into shallower water deposits on the flanks of the basin. The hypothesized distribution of environments during deposition of these beds is shown in figure 44, and the growing structures are shown in figure 40.

Most of the region was covered by normal salinity marine waters during deposition of the zone of Dunveganoceras conditum (fig. 36). In the southwestern part of the region, some of the beds on the northeast flank of Cedar Mountain anticline contain sandstone, mudstone, carbonaceous mudstone, or thin coal, indicating that deposition probably occurred in shallow nearshore waters or paludal conditions on the southwestern flank of the ancestral Kaiparowits structural basin. Strata in about the middle of the basin from Cedar Mountain anticline to Rees Canyon anticline consist mainly of marine mudstone and shale that indicate relatively greater distances offshore and also suggest that this was the lower part of the structural basin.

A moderately thick sandstone bed containing Metoicoceras defordi and abundant Exogyra levis extends from the ancestral Rees Canyon anticline to the flank of the Circle Cliffs uplift. Northeastward thinning of this bed toward the flank of the present structural basin suggests that relatively slower subsidence in this area and especially in the Circle Cliffs region farther north formed depositional high areas on the sea floor where shoaling occurred. This bed correlates with the upper sandstone member of the Dakota Sandstone in Black Mesa basin of northeastern Arizona and the Twowells Sandstone Member of the Dakota Sandstone in the southern San Juan Basin of northwestern New Mexico, indicating that the bed was probably deposited over a large part of the southern Colorado Plateau Province (Repenning and Page, 1956, p. 259-263; Marvin, 1967, p. 172; W. A. Cobban, oral commun., 1968). The hypothetical paleogeography of the region during deposition of these beds is shown in figure 45 and the growing structures are shown in figure 40.

Subsidence continued and nearshore or offshore marine waters covered the entire region during deposition of the zone of Dunveganoceras albertense. The presence of a relatively thick sandstone bed on the flank of Cedar Mountain anticline in the southwestern part of the region (figs. 7, 36) suggests shoaling conditions and, therefore, that this fold subsided less rapidly than the basin farther northeast. Several thin lenses of coquinoid marlstone containing abundant oyster shells occur in the southernmost

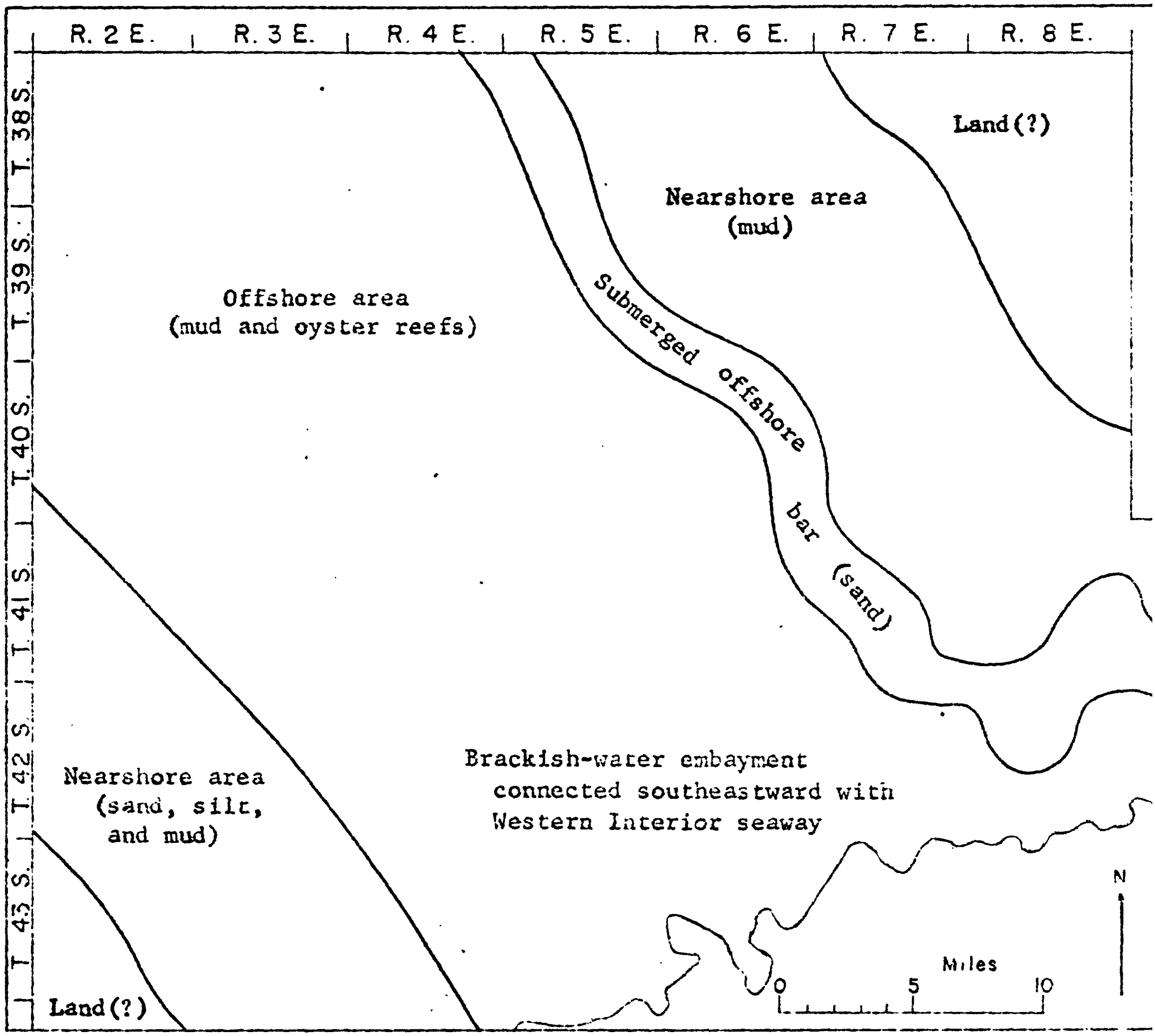


FIGURE 44.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the lower part of the upper member of the Dakota Formation (zone of Dunveganoceras pondi).

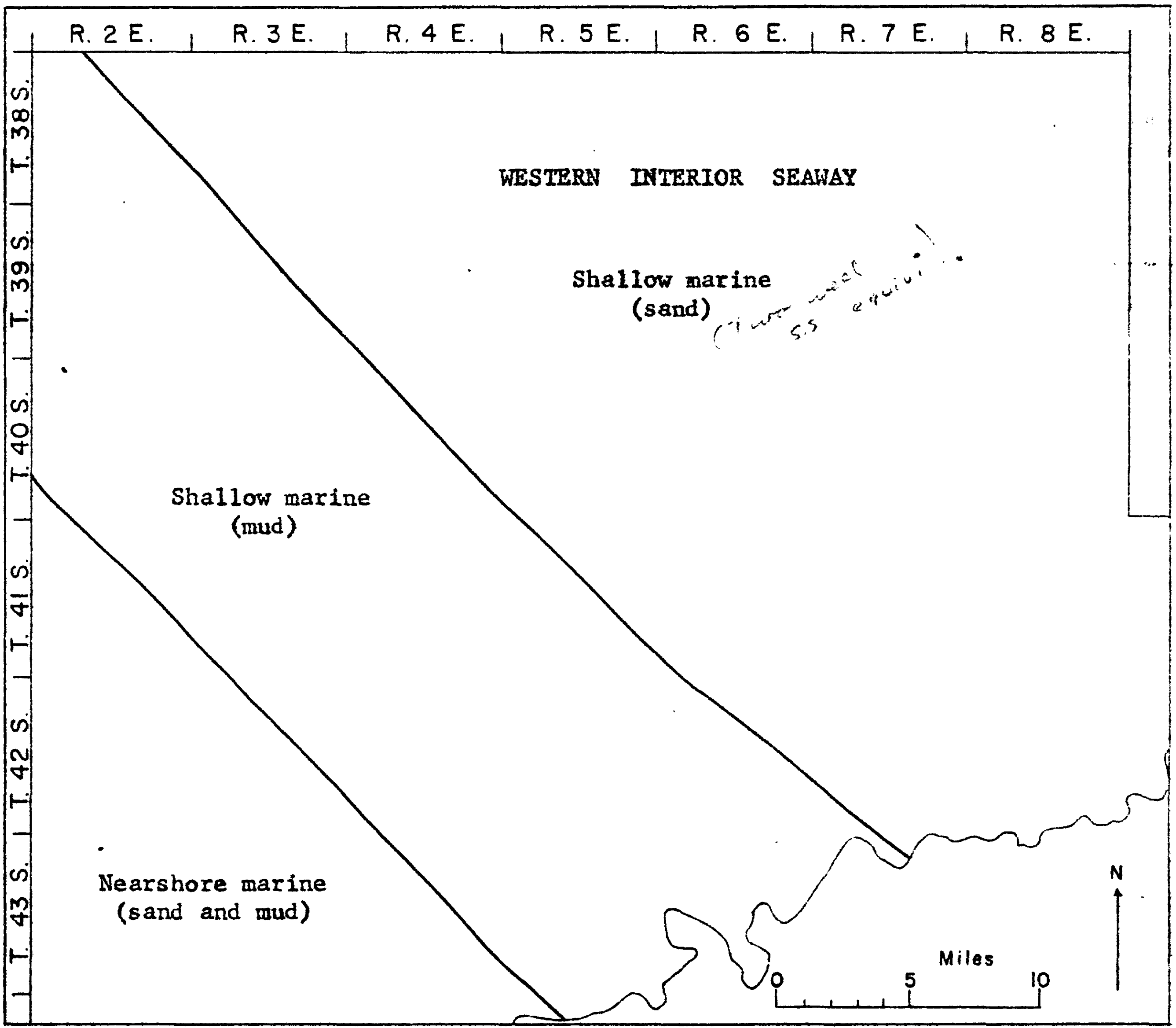


FIGURE 45.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the middle part of the upper member of the Dakota Formation (zone of <u>Dunveganoceras conditum</u>).

exposures on the Arizona-Utah State line and indicate that shallow brackish-water conditions were present on that side of the basin. An approximately correlative sandstone bed occurs in the northern part of the region at Left Hand Collett Canyon, but exposures are too poor in this area to determine the general areal extent of the bed. The hypothesized distribution of environments during deposition of these beds is shown in figure 46, and a summary of the active structures is shown in figure 40.

The relations indicate that the upper member of the Dakota and the lower part of the Tropic Shale were deposited during a period of marine transgression. Waters of the Western Interior seaway first advanced northwestward into the region, following the lowest part of the ancestral Kaiparowits structural basin and forming a shallow brackish-water embayment. As regional subsidence continued, the land area to the northeast on the ancestral Circle Cliffs uplift was gradually inundated and the northeastern shoreline of the embayment probably shifted to a more northerly trend. The position and the configuration of the shoreline in nearby regions are uncertain because the stratigraphic relations in the Dakota have not been adequately studied in adjacent parts of the Colorado Plateau Province.

Early and Middle Turonian Time

The lower part of the Tropic Shale, described in preceding paragraphs, was deposited in Cenomanian time when the Western Interior seaway slowly advanced across the region. The remainder of the Tropic was deposited in early and middle Turonian time (table 3) when the seaway had reached its greatest extent and then began a long intermittent process of retreating from the region. The formation consists mainly of an offshore marine facies, although the thin zone of Sciponoceras gracile represents a transition into the distant marine facies.

Analyses of lithologies in the formation indicate that it consists of a fairly broad mineral assemblage that includes mainly quartz, calcite, dolomite, kaolinite, illite, montmorillonite, and mixed-layer illite-montmorillonite. Most of the calcite, especially that in the middle of the formation, is probably of biogenic origin. The dolomite and a small amount of the calcite probably came from carbonate rocks in the Cordillera because

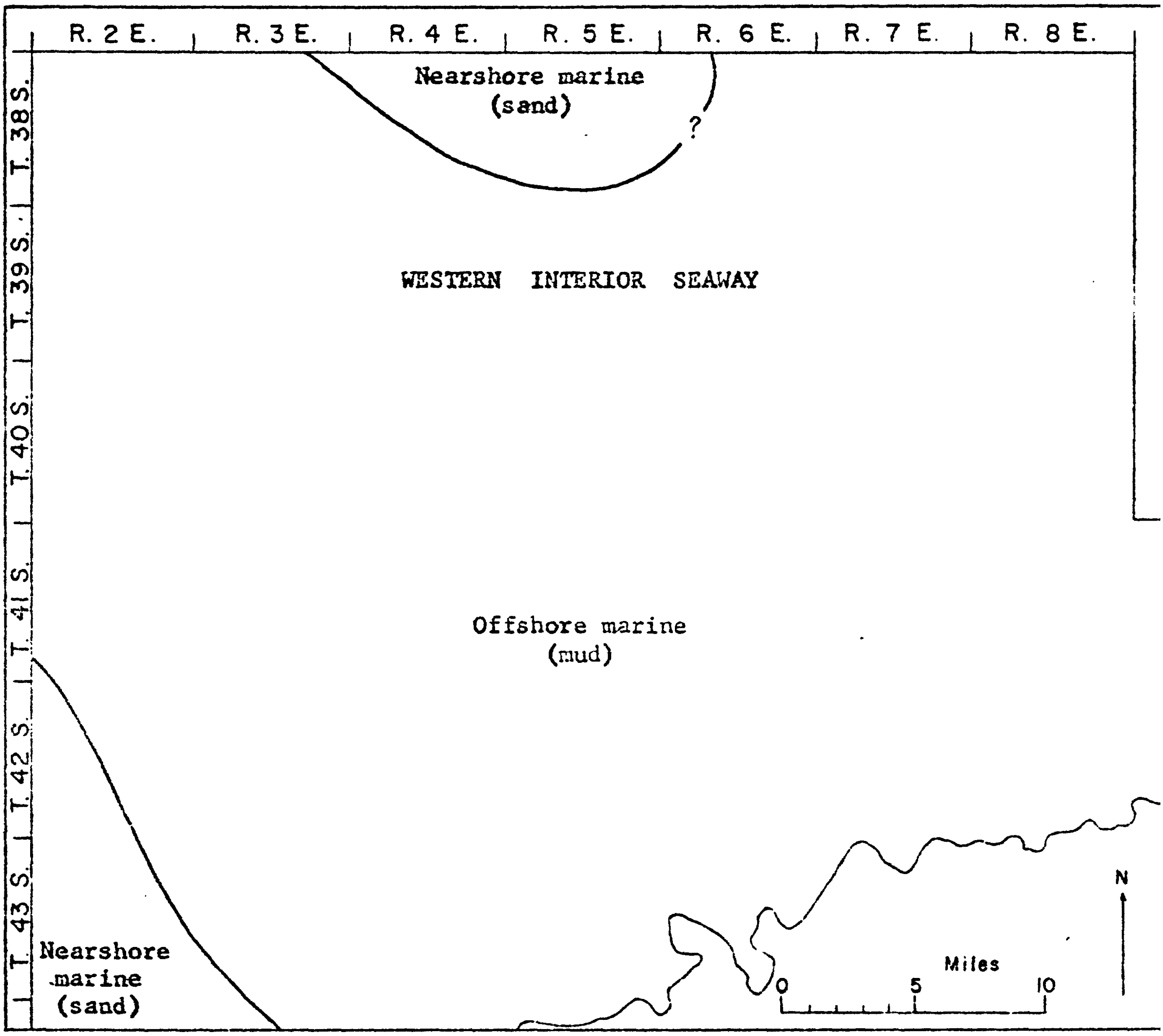


FIGURE 46.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the upper part of the upper member of the Dakota Formation (zone of Dunveganoceras albertense).

these minerals are found as detrital constituents in sandstone beds of alluvial plain strata in other formations in the region. The variety of clay minerals probably reflects the variety of lithologies from which they were obtained, as well as additions of bentonitic materials which were the product of explosive volcanism, probably in the Cordillera to the west. Contrary to the interpretation of Lawrence (1965, p. 89), a slightly acidic environment need not be postulated to account for the kaolinite. The amount of this mineral is not excessive (8 percent average), and it probably indicates nothing more than the presence of kaolinitic rocks in the regions from which any of the other detrital materials originated.

By about the beginning of Turonian time and deposition of the zone of Sciponoceras gracile, the seaway had reached its greatest extent and the shoreline had moved about 70 miles west to the vicinity of Cedar City, Utah (Lawrence, 1965, fig. 4). The shoreline was probably about the same distance southwest of the Kaiparowits region, but Cretaceous strata are no longer present farther southwest and the exact position cannot now be determined. The abundant and varied benthonic, nektonic, and planktonic fossil assemblage in the calcareous shales and limestone concretions of this zone indicates deposition in normal marine waters of moderate depths that are comparable to depths over modern continental shelves. Regional subsidence probably continued during deposition of these beds, and movement on the ancestral Smoky Mountain anticline and other folds farther southwest is suggested by general thinning of the Tropic Shale over the anticlines (fig. 13).

The zone of Inoceramus labiatus apparently marks the beginning of the regressive phase in the transgressive-regressive cycle represented by the Tropic Shale. Calcareous mud was deposited during that time, and the abundant and varied fossil fauna indicates deposition in normal marine waters. General subsidence continued, and contemporaneous movement on the ancestral Smoky Mountain anticline and other folds farther southwest is suggested by local slump structures and general thinning of the Tropic Shale over the anticlines (fig. 13).

Thin beds of bentonite are common near the base of this zone and in the underlying zone of Sciponoceras gracile. Inasmuch as the beds represent explosive volcanism in the Cordillera, their presence at the time of maximum advance of the seas suggests that they marked the beginning of tectonic activity and uplift in the Cordillera that resulted in an increased supply of sediment to the Kaiparowits region and the general regression of the sea.

Regression continued during middle Turonian time and deposition of the zone of *Collignoniceras woollgari* in the upper part of the Tropic Shale. The lower beds in this zone consist of shale and commonly contain *C. woollgari* as well as other molluscs and fish remains that indicate deposition in normal marine waters. The upper beds of the zone contain mudstone, siltstone, and very fine grained sandstone and indicate deposition nearer the shoreline than the underlying beds. The relatively large amount of silt suggests moderately turbid waters, which probably accounts for the scarce and diminutive fossils in these beds. Pyrite is present inside some of the fossils but in quantities no greater than in fossils in the zone of *Sciponoceras gracile*, and a widespread reducing environment with restricted circulation is not necessarily indicated (Lawrence, 1965, p. 89). Regional subsidence continued during deposition of the zone, and contemporaneous movement on the ancestral Smoky Mountain anticline and other folds farther southwest is suggested by local slump structures (fig. 47) and general thinning of the Tropic Shale over the anticlines (fig. 13).

Strata in the zone of *Collignoniceras hyatti* include several facies that are the record of contemporaneous deposition in different environments in different areas. Progressing from southwest to northeast, the sequence generally includes the alluvial plain and lagoonal-paludal facies in the Smoky Hollow Member of the Straight Cliffs Formation, the barrier sandstone facies in the Tibbet Canyon Member of the same formation, and the offshore marine facies in the uppermost beds of the Tropic Shale. In several places, the lagoonal and paludal strata are not present, and alluvial plain strata grade directly into the barrier sandstone beds of the Tibbet Canyon Member. The various facies were deposited during a regressive phase in which the shoreline retreated northeastward across the region. The relations of the different facies and stratigraphic units are shown diagrammatically in figure 37, which illustrates that by that time the shoreline trended northwestward.

The offshore marine facies consists mainly of mudstone, siltstone, and very fine grained sandstone that contains scarce small fossils. Like the

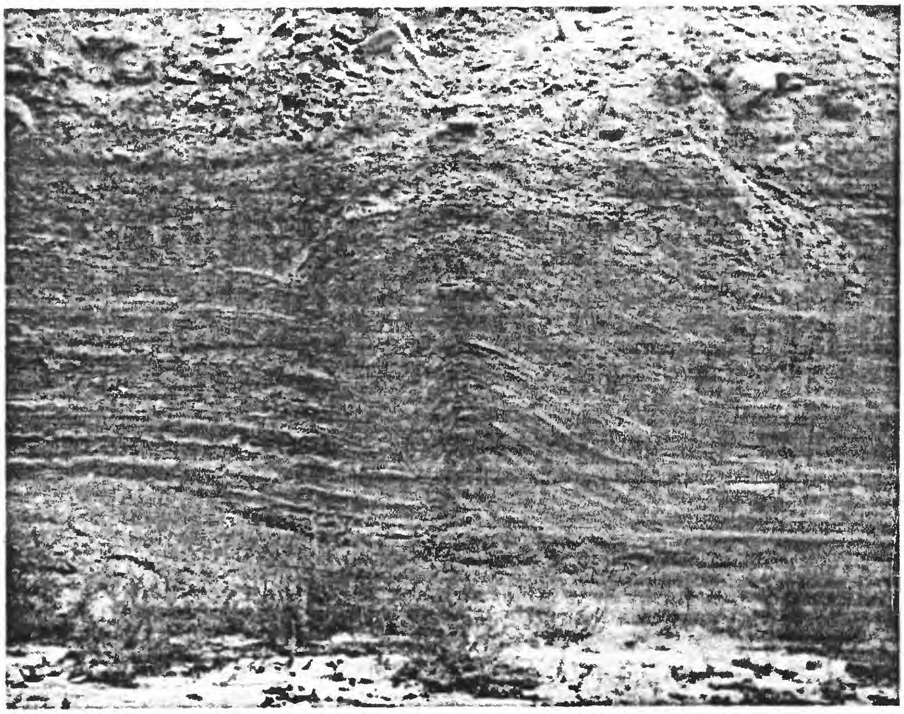


FIGURE 47.--Asymmetric to overturned fold in the Tropic Shale (zone of Collignoniceras woollgari) caused by slumping or settling during deposition. Ultimate cause probably was movement on growing structures in the region. Near bottom of Warm Creek canyon about one-fourth mile north of base of measured section S14. Handle of geologist's pick on left side of fold is approximately 1 foot long.

underlying beds in the upper part of the zone of *Collignoniceras woollgari*, these beds were probably deposited in waters that were moderately turbid. Sandstone strata in the barrier sandstone facies were deposited in nearshore marine, beach, and lagoonal environments on or near barrier sand islands at the edge of the seaway. The coal zone at the base of the Smoky Hollow Member was deposited in lagoonal and paludal environments in coastal lowland areas that were landward from the barrier islands, and strata in the barren zone of the same member were deposited mainly in braided-stream and overbank flood-plain conditions on an alluvial plain that was southwest of the coastal lagoons and swamps. Streams coming from highlands in the Cordillera farther southwest usually emptied into the landward side of the lagoonal and paludal areas, but at times the streams cut across the coastal lowlands and emptied directly into the seaway, and at other times the coastal lowlands were filled with sediment and the alluvial plain extended directly to the shoreline. Palynomorphs were not obtained from samples of these beds, but the general ecological conditions were probably similar to the wet or swampy subtropical to tropical conditions that prevailed during deposition of the Dakota Formation and the John Henry Member of the Straight Cliffs Formation. The distribution of environments and the intermittent northeastward retreat of the shoreline is shown diagrammatically in figures 48, 49, and 50.

Crossbedding studies indicate that streams flowed into the region from the southwest (fig. 51), and stratigraphic relationships shown on plate 17 and in figure 37 indicate that the streams sometimes discharged directly into the sea. Crossbedding in the Tibbet Canyon Member (fig. 51) indicates that sediment brought to the sea by streams was redistributed by nearshore currents that had a net eastward or southeastward movement. The lack of a threefold vertical distribution of bedding types that is common in the barrier sandstone facies of the John Henry Member of the Straight Cliffs was probably the result of the complex interaction of fluvial and nearshore currents. Red quartzite pebbles are scarce in the Tibbet Canyon Member, but because they do not occur in the alluvial plain facies of the Smoky Hollow Member, they probably were transported into the region from the northwest by nearshore currents, as occurred during deposition of the overlying John Henry Member. Undoubtedly, the nearshore currents carried significant quantities of sand into the region, but at present, there is no way of estimating the relative percentages carried in by nearshore currents from the northwest and by streams from the southwest.

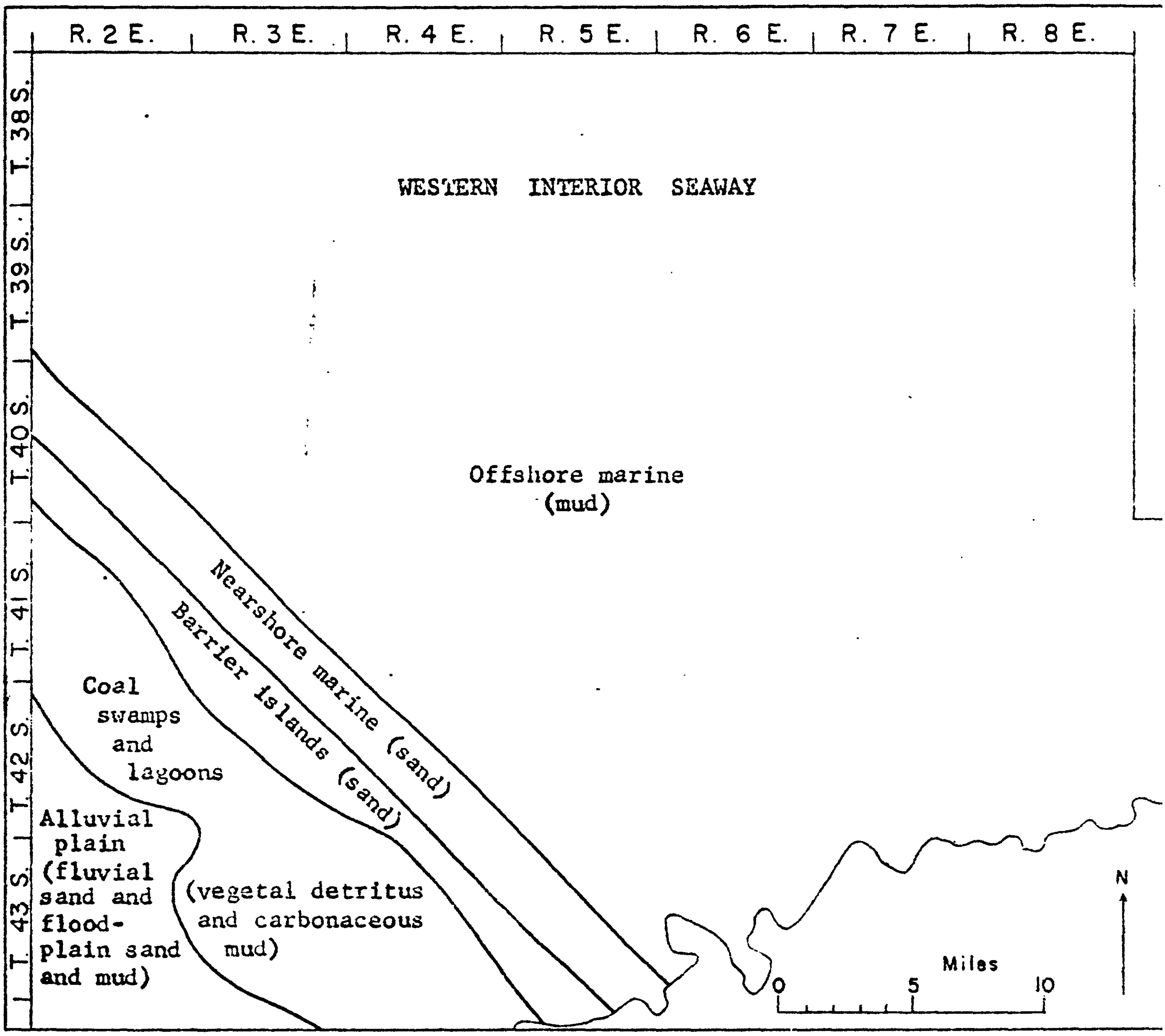


FIGURE 48.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the coal bed in the lower part of the coal zone in the Smoky Hollow Member of the Straight Cliffs Formation.

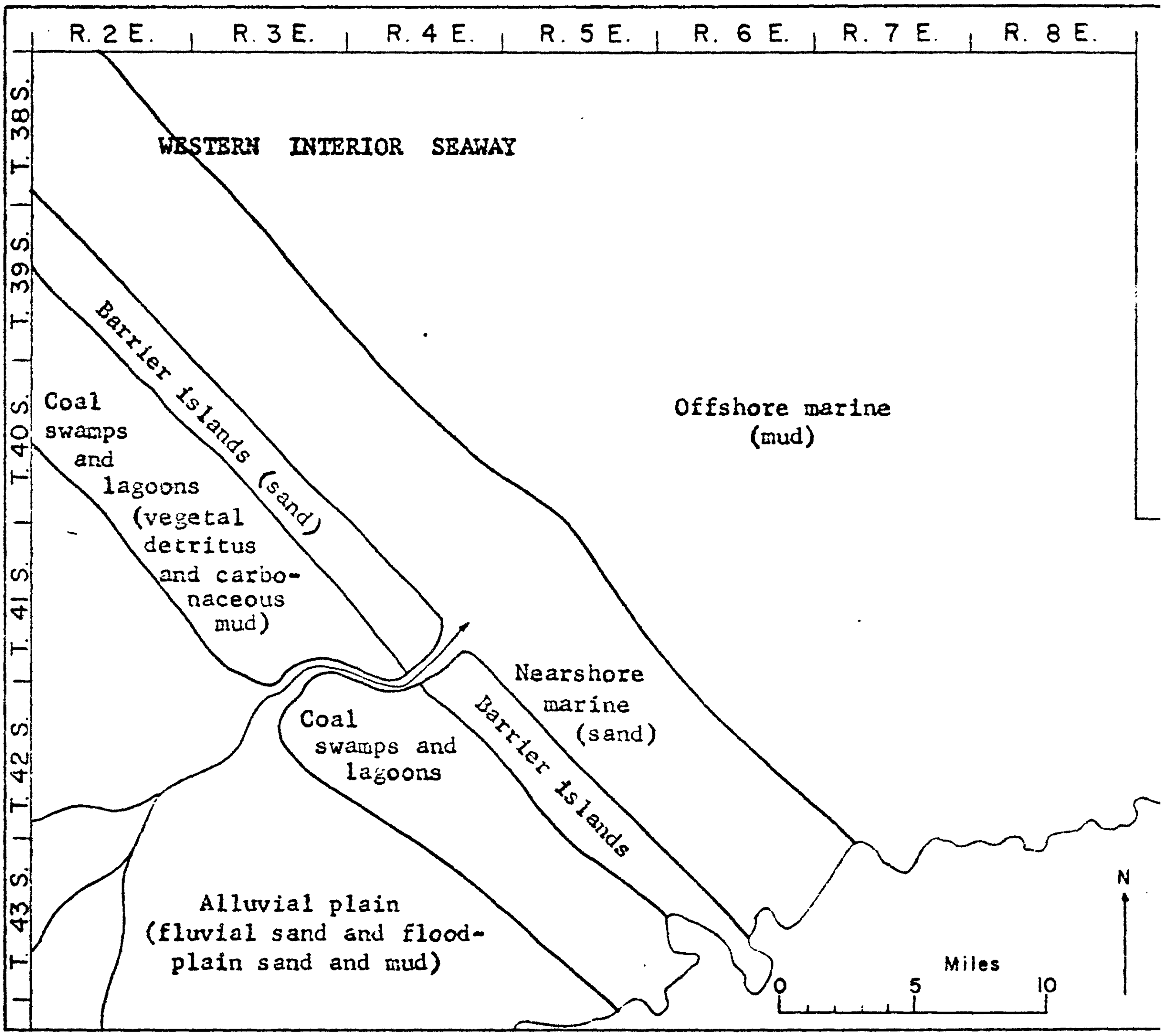


FIGURE 49.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the coal bed in the middle part of the coal zone in the Smoky Hollow Member of the Straight Cliffs Formation.

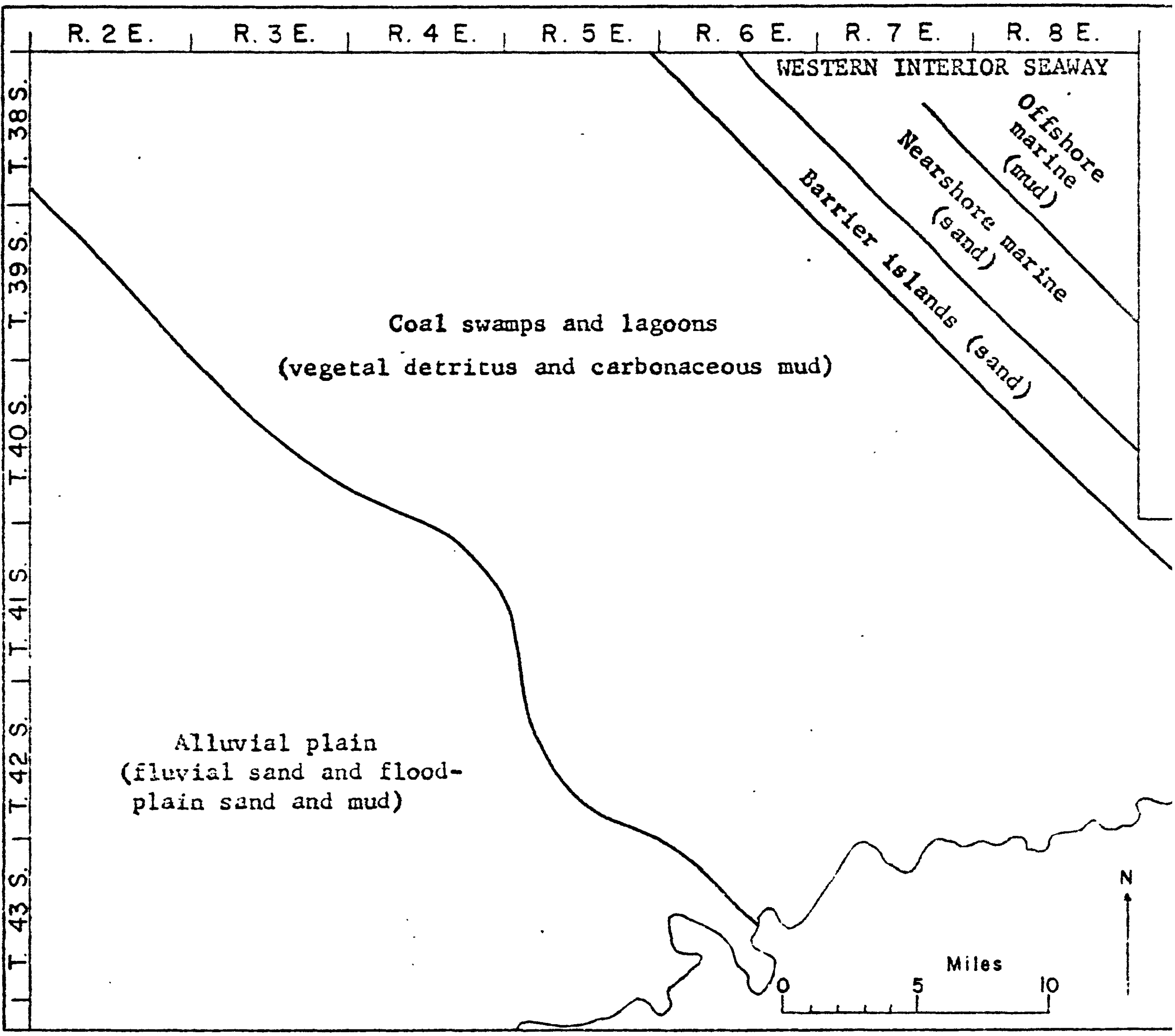


FIGURE 50.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the upper part of the coal zone in the Smoky Hollow Member of the Straight Cliffs Formation.

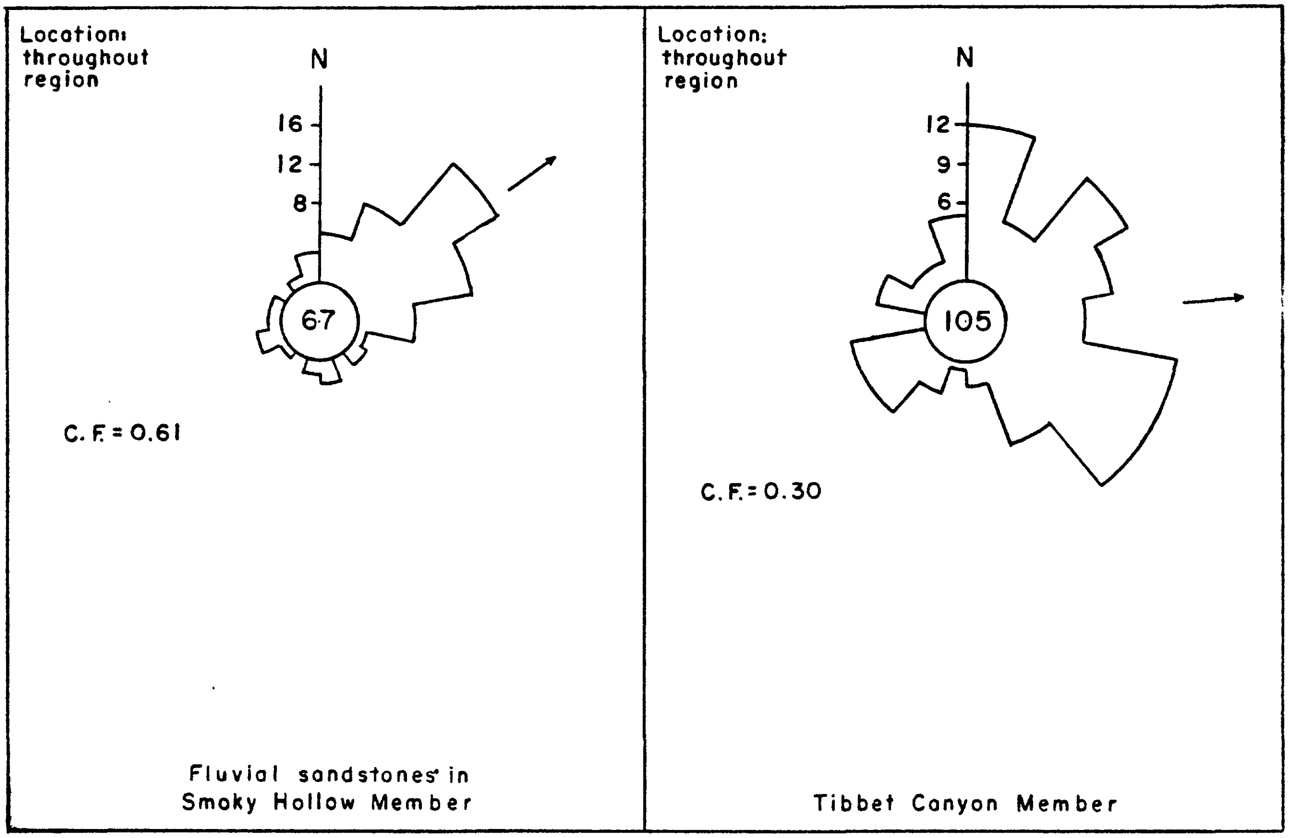


FIGURE 51.--Rose diagrams showing cross-stratification azimuths for sandstones in Smoky Hollow and Tibbet Canyon Members of Straight Cliffs Formation. Number of measurements in center; resultant shown by arrow; C.F. = consistency factor.

The relative abundance of feldspar in sandstones in the alluvial plain and barrier sandstone facies suggests that continued uplift and erosion resulted in exposure of feldspathic igneous and (or) metamorphic basement rocks in the Cordillera. Very fine to fine quartz pebbles suggest a similar origin. Chert pebbles containing late Paleozoic fossils indicate that rocks of that age in the Cordillera also were a source of detritus to the Kaiparowits region. Although the amount of clastic carbonate minerals is small in rocks of the alluvial plain facies (1 percent), it is in agreement with the hypothesis that the chert pebbles came from Paleozoic limestones and dolomites. The bentonitic materials in the alluvial plain mudstones probably came from ash falls outside the report area that were subsequently reworked and transported by streams. On the basis of the abundance of feldspar, the abundance of coarse angular quartz grains, the absence of well-rounded quartz grains that would have been derived from eolian sandstones, and the progressively greater burial of the region as indicated by the greater thickness of Cretaceous rocks at that time compared to thicknesses at the time of deposition of the Dakota Formation, it is thought that rocks of Jurassic and Triassic age had ceased to be a significant source of detritus by the time of deposition of the zone of Collignoniceras hyatti.

Contemporaneous tectonism in the region is indicated by slump structures and the thickness and distribution of beds. Movement on the ancestral Smoky Mountain anticline and other folds farther southwest is indicated by variations in thickness of the Tibbet Canyon Member (fig. 13) and by coal beds that are restricted to the synclines (pl. 17). Figure 13 also shows thickness variations in the Tropic Shale that are in agreement with the hypothesis that these folds were actively growing during deposition of that formation, but the amount of growth that occurred during deposition of each of the zonal subdivisions could not be determined. Possible movement on the ancestral Rees Canyon anticline is suggested by structures on the southwest side of Rees Canyon anticline in Last Chance Creek canyon that indicate southwestward slumping. A summary of the structures that were active at this time is shown in figure 52. Comparison with figure 40 indicates that some of the fold axes shifted slightly after Cenomanian time.

The conglomeratic sandstone of the Calico bed at the top of the Smoky Hollow Member is typical of subdivision A of the alluvial plain facies,

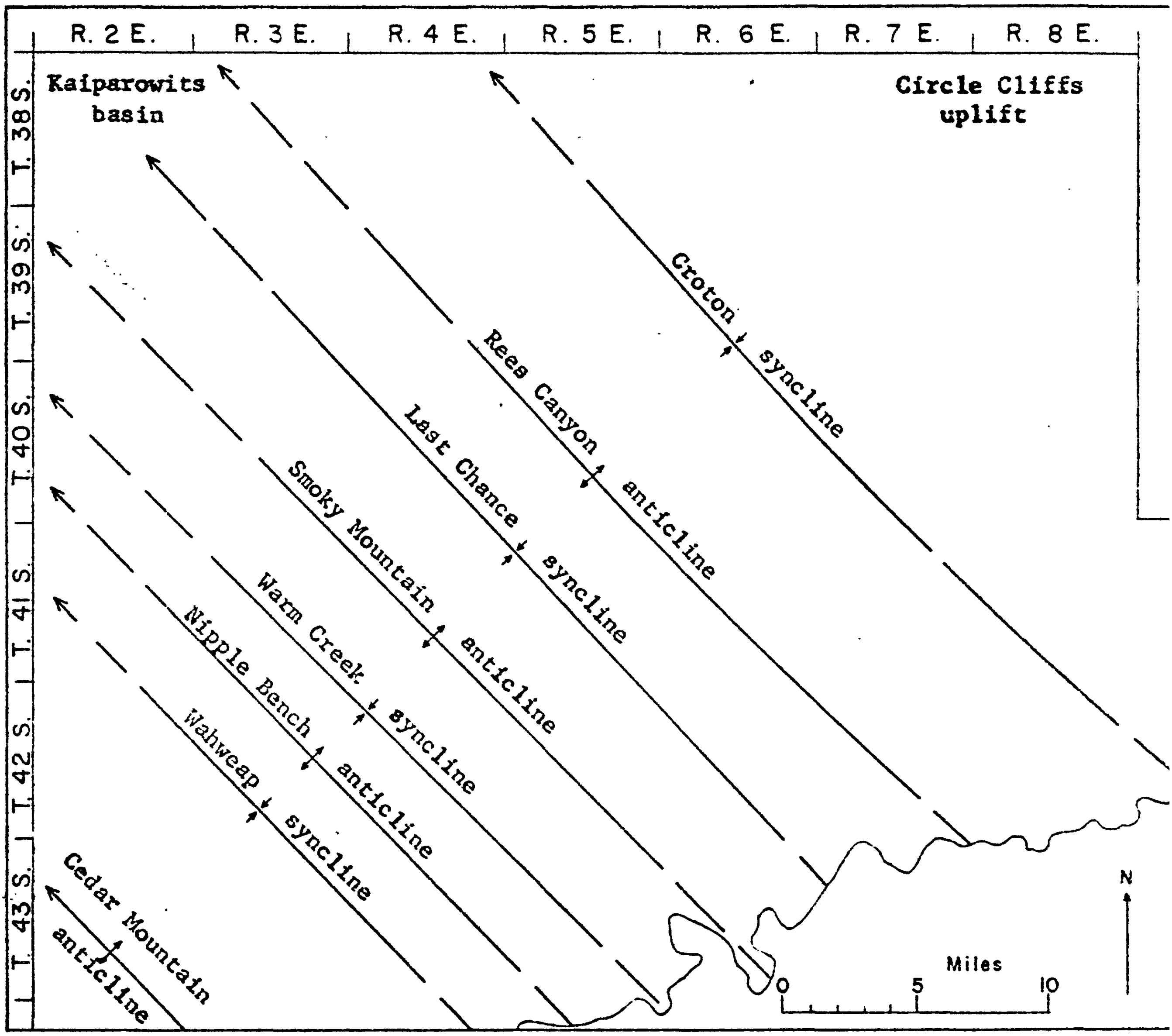


FIGURE 52.--Ancestral structures that were activated during Turonian to middle Coniacian time. Basin downwarping occurred by the end of this time interval but could not be detected in rocks of early and middle Turonian age.

and it indicates a time of relatively rapid deposition by braided streams that migrated laterally over a broad area. The bed was deposited during or possibly just after the culmination of a phase of steadily increasing tectonic activity and uplift in the Cordillera that began during deposition of the zone of Sciponoceras gracile. This is indicated by the general upward increase in size of detrital materials, shown best on plate 12 (meas. sec. S22), and by the increasing rate of regression of the shoreline which remained in southwestern Utah during early Turonian time (Lawrence, 1965, p. 81) and then moved relatively rapidly into east-central Utah during middle Turonian time (fig. 39).

The distribution of facies and the variations in thicknesses of units described in the preceding paragraphs demonstrate that tectonic movements during early and middle Turonian time were slight but, nevertheless, of sufficient magnitude and extent to have influenced the type and distribution of sediments. Subsidence continued from Cenomanian time, and growth continued on most of the folds. Evidence of movement on the ancestral Rees Canyon anticline is poor, and movement on this fold might not have occurred. There is no indication of movement on the older faults, and there is no indication that basin downwarping occurred.

Late Turonian to Middle Coniacian Time

Little is known about conditions in the region during late Turonian to middle Coniacian time because rocks of this age are not present (table 3). Approximately 350-600 feet of interfingering marine and nonmarine strata of late Turonian age are present in the San Juan Basin of northwestern New Mexico (Dane, 1960), and similar thicknesses of marine and nonmarine rocks may have been deposited in the Kaiparowits region.

Regional erosion had removed the upper part of the Smoky Hollow Member by the end of middle Coniacian time, and the unconformity that now separates the Smoky Hollow from the overlying John Henry Member of the Straight Cliffs Formation was formed. Regional subsidence during at least the later part of this time is indicated by shallow marine and beach strata in the lower part of the John Henry Member. Basin downwarping is indicated by erosional thinning of the Smoky Hollow Member in the southwestern and northeastern parts of the region (figs. 13, 37, 53) and by northwestward thickening of the Smoky Hollow to 231 feet near Tropic, Utah (units 2-9 above the base of a section in Robison, 1966, p. 23, and tentatively assigned by the writer to the Smoky Hollow Member), and northward thickening of the Smoky Hollow to 331 feet about 9 miles northwest of Escalante, Utah (E. V. Stephens, oral commun., 1967). Movement on the ancestral folds by about the end of middle Coniacian time is suggested by the southwest pinch-out onto the ancestral Smoky Mountain and Rees Canyon anticlines by the A sandstone bed and the lower marine mudstone tongue, respectively, of the John Henry Member and by the distribution of coal at or near the base of this member (pl. 18).

The general processes that formed the unconformity are not understood. The widespread erosion surface suggests regional uplift, but this is inconsistent with regional subsidence that otherwise continued without a break from middle Albian to about late Campanian time, and subsidence must have occurred during at least the later part of the time interval represented by the unconformity because shallow marine and beach strata lie on the unconformable surface. The available evidence is inconclusive, however, and the unconformity could have been the result of regional uplift, eustatic lowering of sea level, and (or) abrupt cessation of tectonism in the Cordillera. Hunt, Averitt, and Miller (1953, p. 83) found the unconformity in the Henry Mountains (fig. 39) but they did not attach much significance to it. W. A. Cobban (oral commun., 1969) found several unconformities in rocks of middle Turonian to early Coniacian age in the Western Interior. Thus, tectonism and sedimentation at this time may have been considerably more complex in the Kaiparowits region than is suggested by the preceding paragraphs.

Late Coniacian to Earliest Campanian Time

The John Henry Member of the Straight Cliffs Formation was deposited in marine and nonmarine environments along the southwest side of the Western Interior seaway during late Coniacian, Santonian, and earliest Campanian time (table 3). During most of this time interval, the rates of sedimentation and subsidence were nearly balanced and the shoreline generally remained in the northeastern part of the region. On a small scale, two cycles of transgression and regression are defined by the landward, or

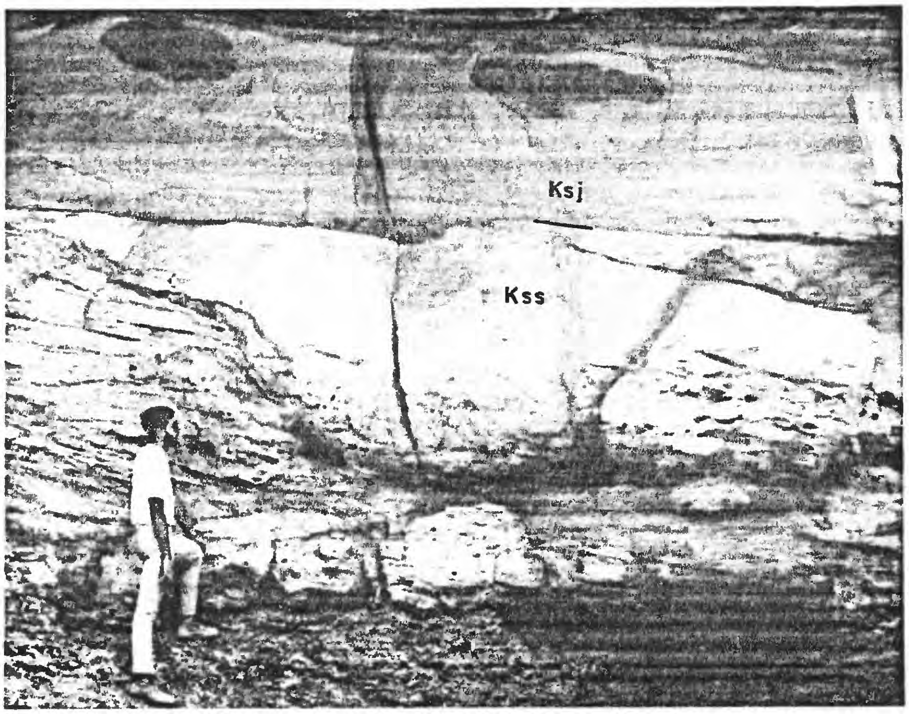


FIGURE 53.--Probable angular unconformity between Smoky Hollow Member (Kss) and John Henry Member (Ksj) in Straight Cliffs Formation. View is toward southeast on northeast side of Kaiparowits structural basin. Low-angle dip to right of beds beneath the unconformity apparently reflects uplift on northeast flank of basin before deposition of John Henry Member. Near bottom of Left Hand Collet Canyon about half a mile northeast of base of measured section S5.

southwestward, pinch-out of the two marine mudstone tongues in the member (fig. 38), and several subcycles of transgression and regression are apparent when the strata are examined in detail. As shown in figure 38, the member grades from southwest to northeast through the following somewhat generalized sequence of depositional facies: alluvial plain-subdivision B, deltaic plain, lagoonal-paludal, barrier sandstone, and offshore marine.

Northeastward-dipping crossbedding and reduction in size and quantity of pebbles in the fluvial beds of the alluvial plain and deltaic plain facies indicate that streams originating in the Cordillera generally flowed into the region from the southwest, whereas crossbedding in the barrier sandstone facies indicates southeastward-moving shoreline currents (figs. 54, 55). That the streams generally discharged into the lagoonal and paludal lowland areas southwest of the shoreline instead of directly into the seaway is indicated by the abundance of lagoonal and paludal strata southwest of the barrier sandstone facies (fig. 38; pls. 18, 19, 20) and by the significant differences of size, composition, and relative percentages of pebbles in the barrier sandstone facies and in the alluvial plain facies. Thus, the evidence indicates that a large part of the materials in the barrier sandstone and offshore marine facies was carried into the region from the northwest by shoreline currents. The strong influence of swash, longshore, and coastal currents was also responsible for the threefold separation of bedding types in the barrier sandstones previously described.

The relative abundance of feldspar in sandstones of the alluvial plain facies suggests an origin in feldspathic igneous and (or) metamorphic rocks in the southwestern source area in the Cordillera. Scattered very fine to fine pebbles of quartz also suggest a similar origin. Fossils in the chert pebbles are of late Paleozoic age and indicate that rocks of that age were also present in the source area. Detrital grains of dolomite and calcite are common in the sandstones and probably came from Paleozoic dolomite and limestone beds including those that contained the chert pebbles. The bentonitic materials in the alluvial plain mudstones suggest ash falls outside the report area that were subsequently reworked and transported by streams.

The nature of rocks in the northwestern source area is uncertain because the pebbles in the marine beds of the John Henry Member could have come from Cretaceous conglomerates or from Paleozoic and older formations.

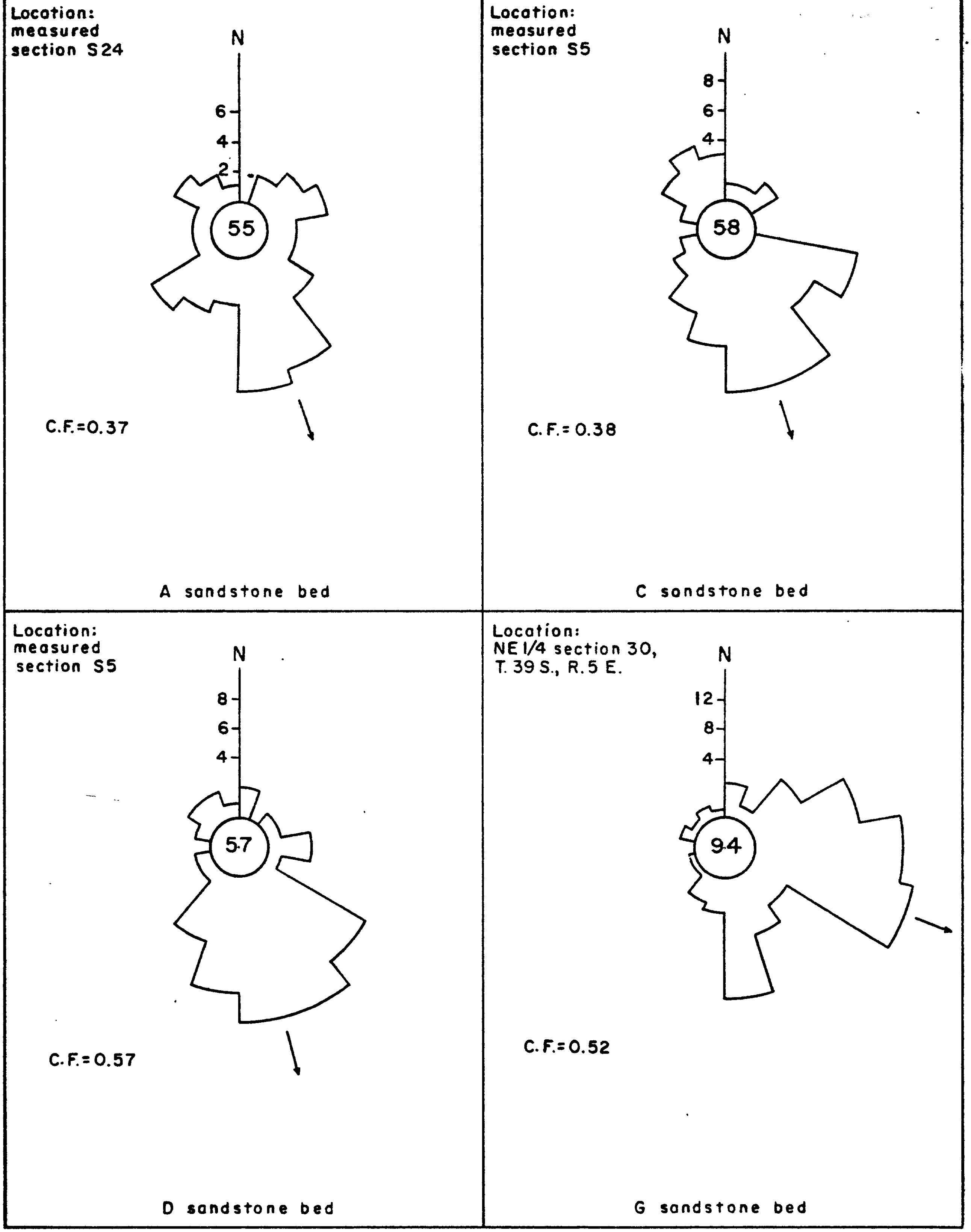
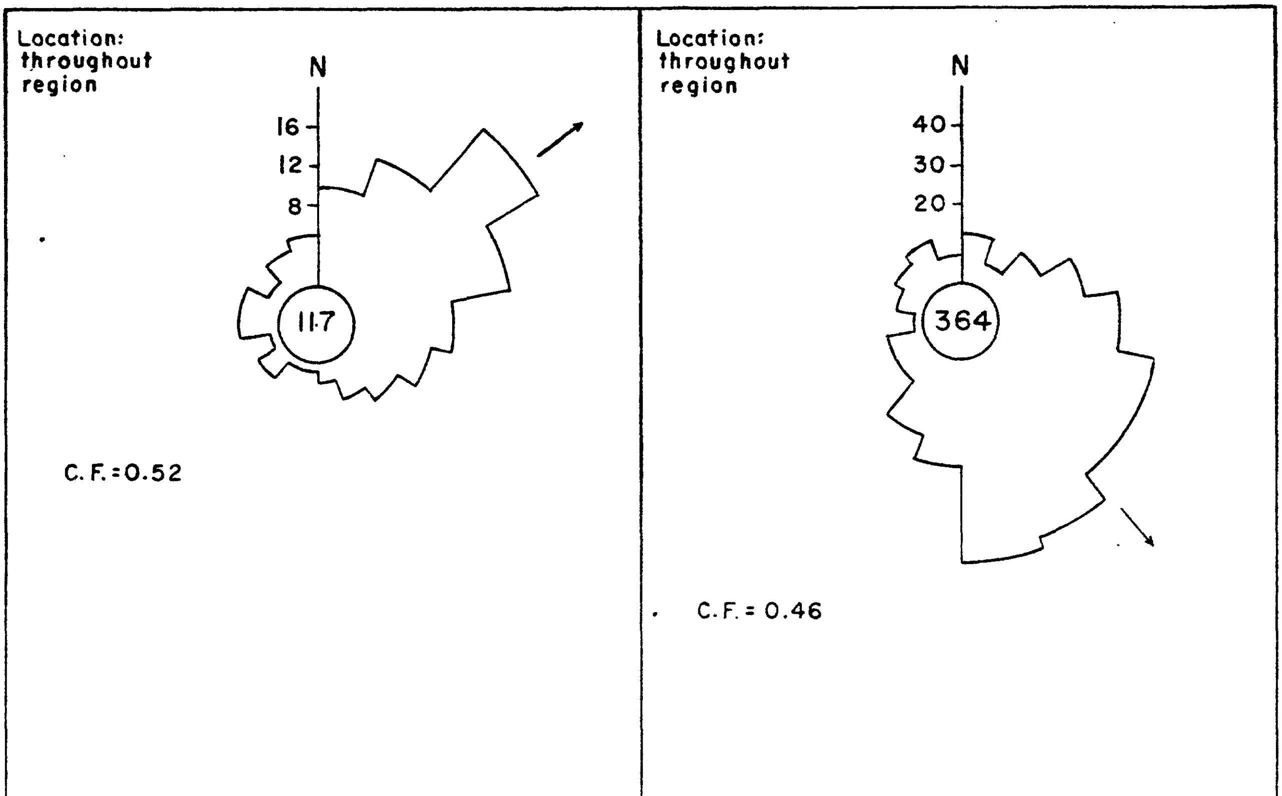
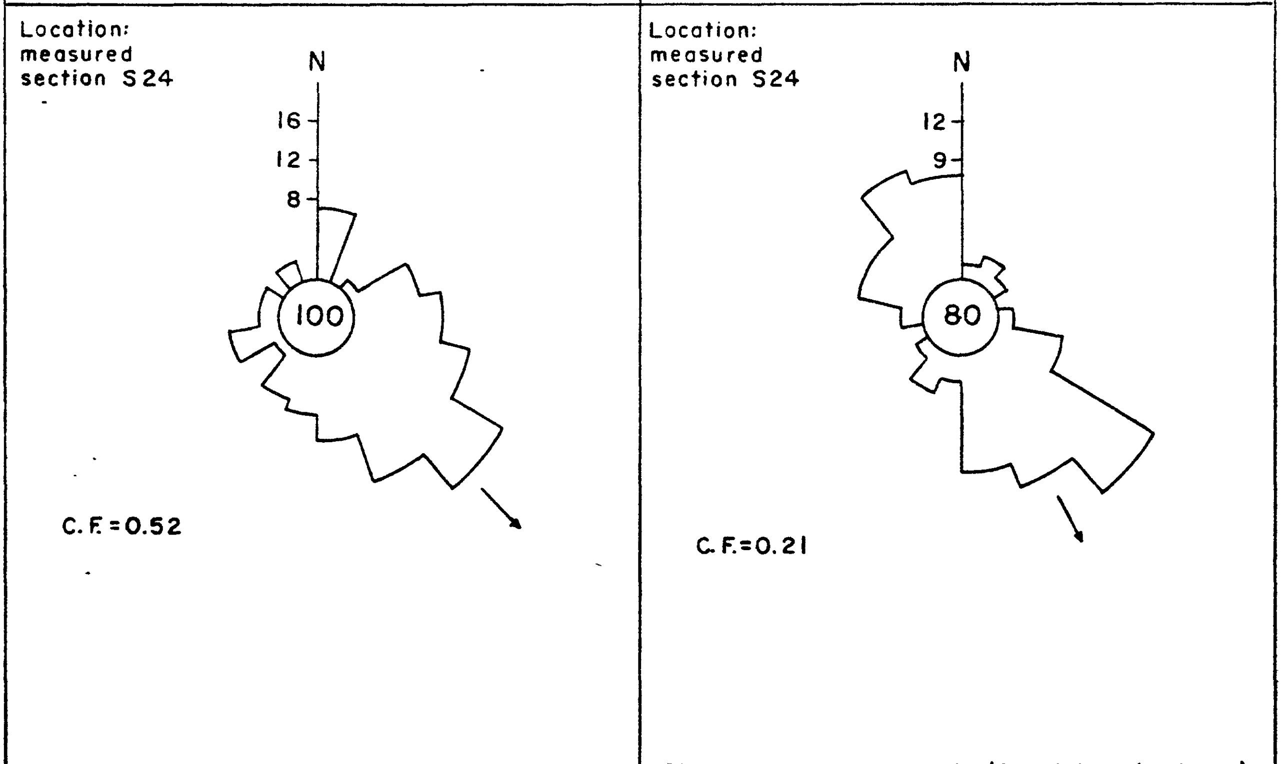


FIGURE 54.--Rose diagrams showing cross-stratification azimuths for key sandstone beds in John Henry Member of Straight Cliffs Formation. Number of measurements in center; resultant shown by arrow; C.F. = consistency factor.



Fluvial sandstones

Marine sandstones



B sandstone bed

Black sandstone deposit (fossil beach placer)
Top of B sandstone bed

FIGURE 55.--Rose diagrams showing cross-stratification azimuths for sandstones in John Henry Member of Straight Cliffs Formation. Number of measurements in center; resultant shown by arrow; C.F. = consistency factor.

The chert pebbles contain late Paleozoic fossils which indicate an original source in rocks of that age, and detrital dolomite grains suggest a source in Paleozoic carbonate rocks. As previously noted, the quartzite pebbles may have come from Precambrian formations.

Contemporaneous structural deformation in the region is shown by the thickness and distribution of lithologies in the member. Regional subsidence is indicated by the presence of shallow marine and beach deposits in the barrier sandstone beds, and northeastward tilting is suggested by northeastward thickening of the John Henry Member and correlative rocks in the Henry Mountains region (fig. 39). Downwarping of the region as a structural basin is indicated by the basinward increase in thickness and number of coal beds in the lower, Christensen, and Rees coal zones (pls. 18, 19, 20) and by the predominance of lagoonal and paludal strata in the middle of the basin (fig. 38). The northeastern flank of the basin was the ancestral Rees Canyon anticline or possibly the ancestral Circle Cliffs uplift, but the data are inadequate to determine whether the Circle Cliffs region was structurally active at that time.

Relatively slower subsidence of anticlines in the ancestral Kaiparowits structural basin is clearly shown by thinning of the John Henry Member over these structures (pl. 21) and by thinning or pinching out of coal seams and coal beds in the lower, Christensen, Rees, and Alvey coal zones over the ancestral Cedar Mountain, Nipple Bench, Smoky Mountain, and Rees Canyon anticlines (fig. 38; pls. 18, 19, 20). All the barrier sandstone beds pinch out on or near the crests of the ancestral Smoky Mountain or Rees Canyon anticlines and indicate that relatively slow subsidence on these folds formed slight depositional highs that prevented the sea from migrating farther inland. Uplift in relation to sea level probably did not occur on these anticlines because local unconformities have not been found on the crests of these folds. Relatively slower subsidence on the anticlines divided the ancestral Kaiparowits structural basin into several subbasins, and the anticlines acted as sediment barriers that allowed coal swamps to thrive in the subbasins when fluvial sedimentation was not excessive. Movement on several faults during deposition of the lower coal zone is shown on plate 18. Slump structures, such as shown in figure 56, are locally common in the lower coal zone and probably were formed by tremors caused by contemporaneous

FIGURE 56.--Slump structures in the lower coal zone of John Henry Member of Straight Cliffs Formation; probably caused by tremors associated with growing folds or faults in the region. On southwest side of Smoky Mountain about 800 feet south of measured section S18. The middle coal bed is about 1 foot thick at the left side of the photo.

movement on the various structures in the region. A summary of the structures that were active at that time is shown in figures 57 and 58.

The relations described above give a fairly accurate picture of the paleogeography of the region during deposition of the John Henry Member. Figure 59 illustrates the broad distribution of environments in the southwestern part of the Colorado Plateau region and adjacent parts of the Cordillera during deposition of the member. The source of most of the sediment that was carried into the Kaiparowits region was in the Sevier Highlands to the west (Harris, 1959; Armstrong, 1968) and in the Mogollon Highlands to the south (Harshbarger and others, 1957, p. 44). The shoreline of the Western Interior seaway remained in the northeastern part of the Kaiparowits region during all but the latest part of that time, when it migrated an unknown but presumably short distance farther northeast.

The paleoecological conditions during deposition of the nonmarine part of the member are inferred mainly from the palynomorphs which suggest deposition in a wet or swampy subtropical lowland site at some distance from highlands (R. H. Tschudy, written commun., 1968). Evaluation of the distribution of planktonic foraminifers in approximately time equivalent strata in the Western Interior led Kent (1968, p. 2110) to conclusions that suggest that the marine part of the member was deposited in tropical or subtropical seas.

Two cycles of transgression and regression are recorded in the member. The first cycle occurred during about middle Coniacian to middle Santonian time when the shoreline advanced southwest to the ancestral Smoky Mountain anticline and then retreated northeast to the general area of the ancestral Rees Canyon anticline and Croton syncline (fig. 60). During middle Santonian time, relatively rapid rates of sedimentation by longshore and coastal currents approximately balanced the rate of regional subsidence, and the shoreline remained in the ancestral Croton syncline (fig. 61). At the same time, the rate of sedimentation by streams was comparatively low, and a broad area of swamps and lagoons was formed in coastal lowlands behind the shoreline.

The second transgressive-regressive cycle lasted from about middle Santonian to earliest Campanian time when the shoreline advanced southwestward onto the crest of the ancestral Rees Canyon anticline (figs. 62, 63)

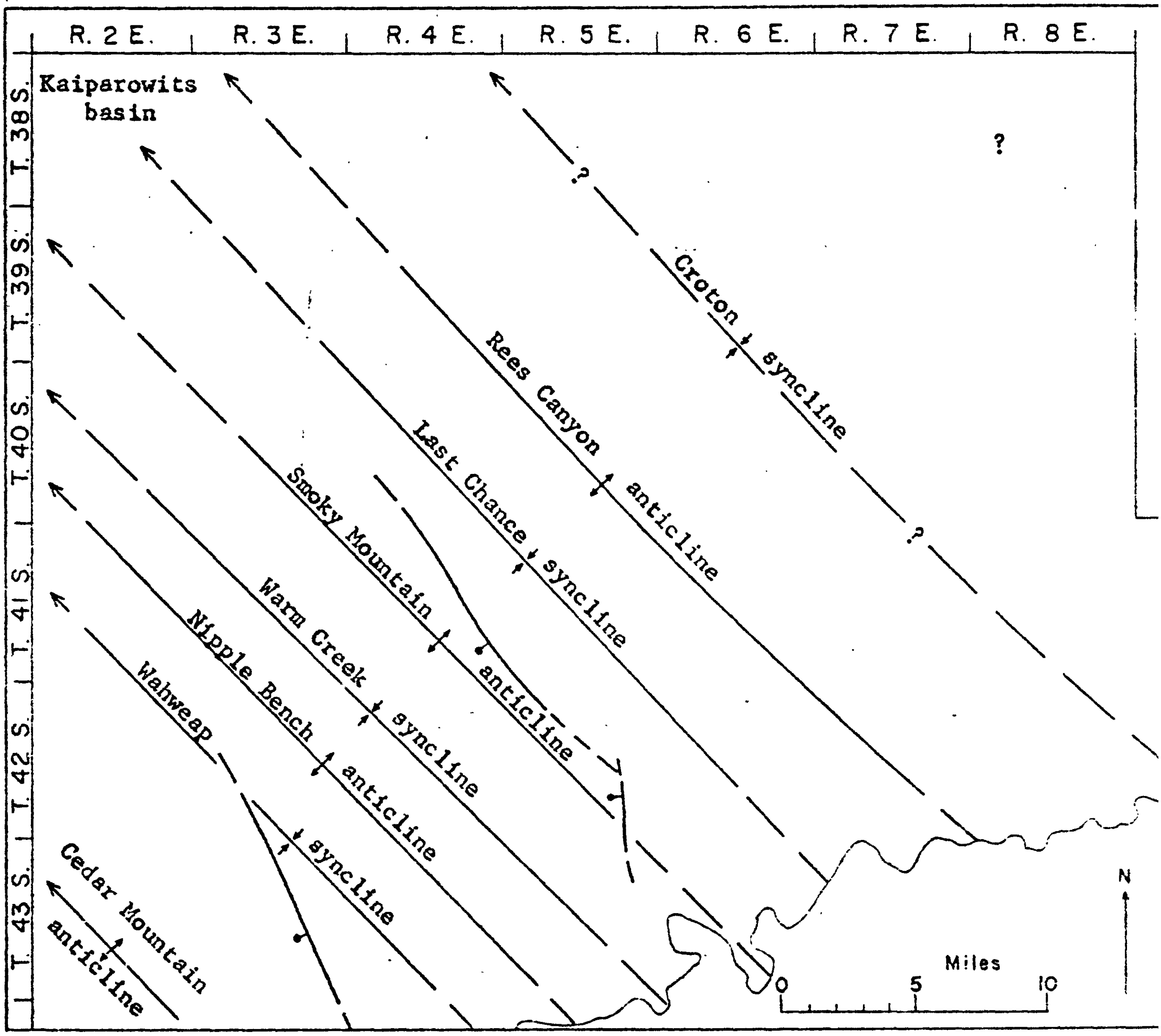


FIGURE 57.--Ancestral structures that were activated during late Coniacian time (during deposition of the lower coal zone in the John Henry Member of the Straight Cliffs Formation).

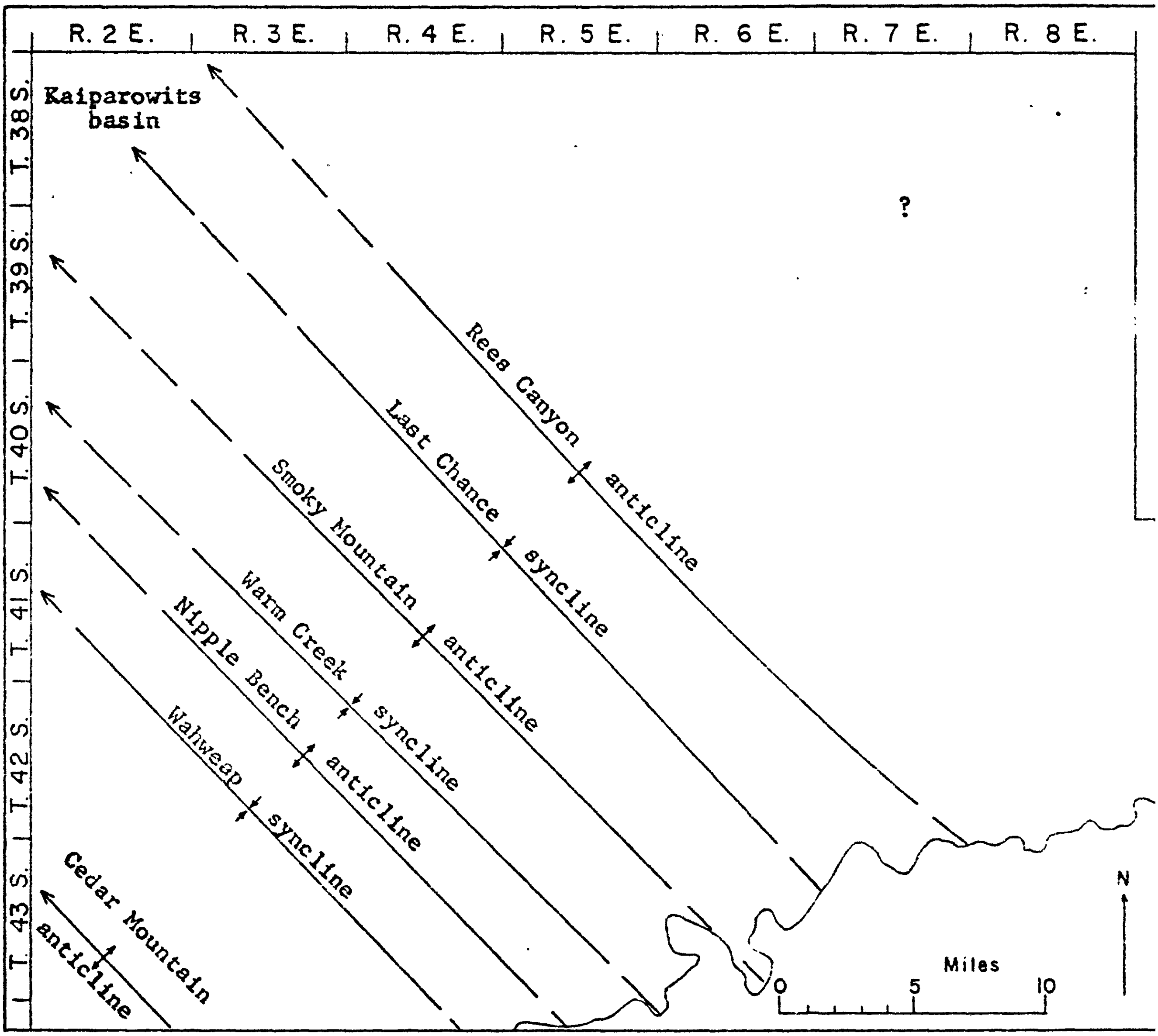


FIGURE 58.--Ancestral structures that were activated during Santonian and earliest Campanian time.

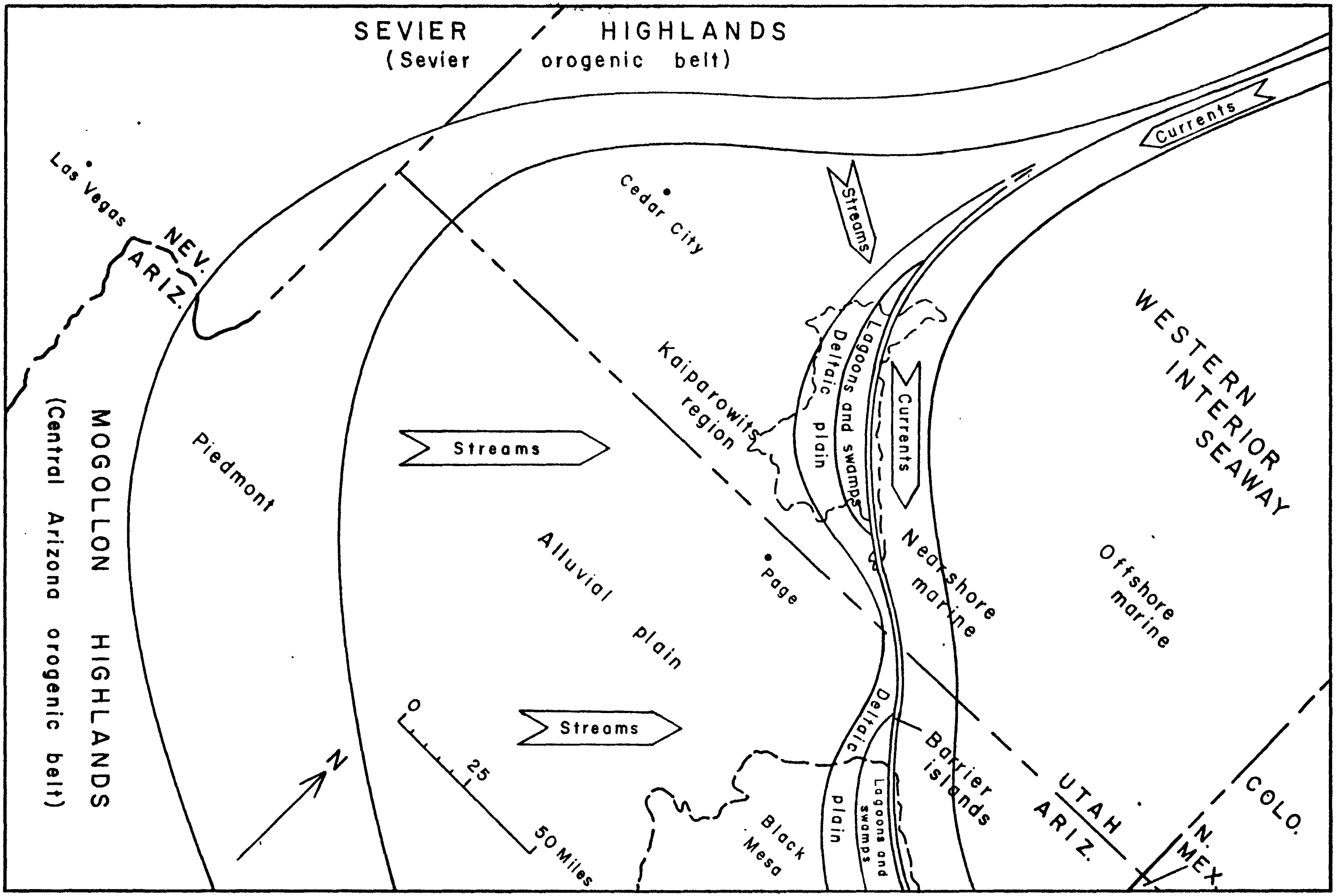


FIGURE 59.--Hypothetical paleogeography of southwestern Colorado Plateau and adjacent regions during deposition of the John Henry Member of the Straight Cliffs Formation.

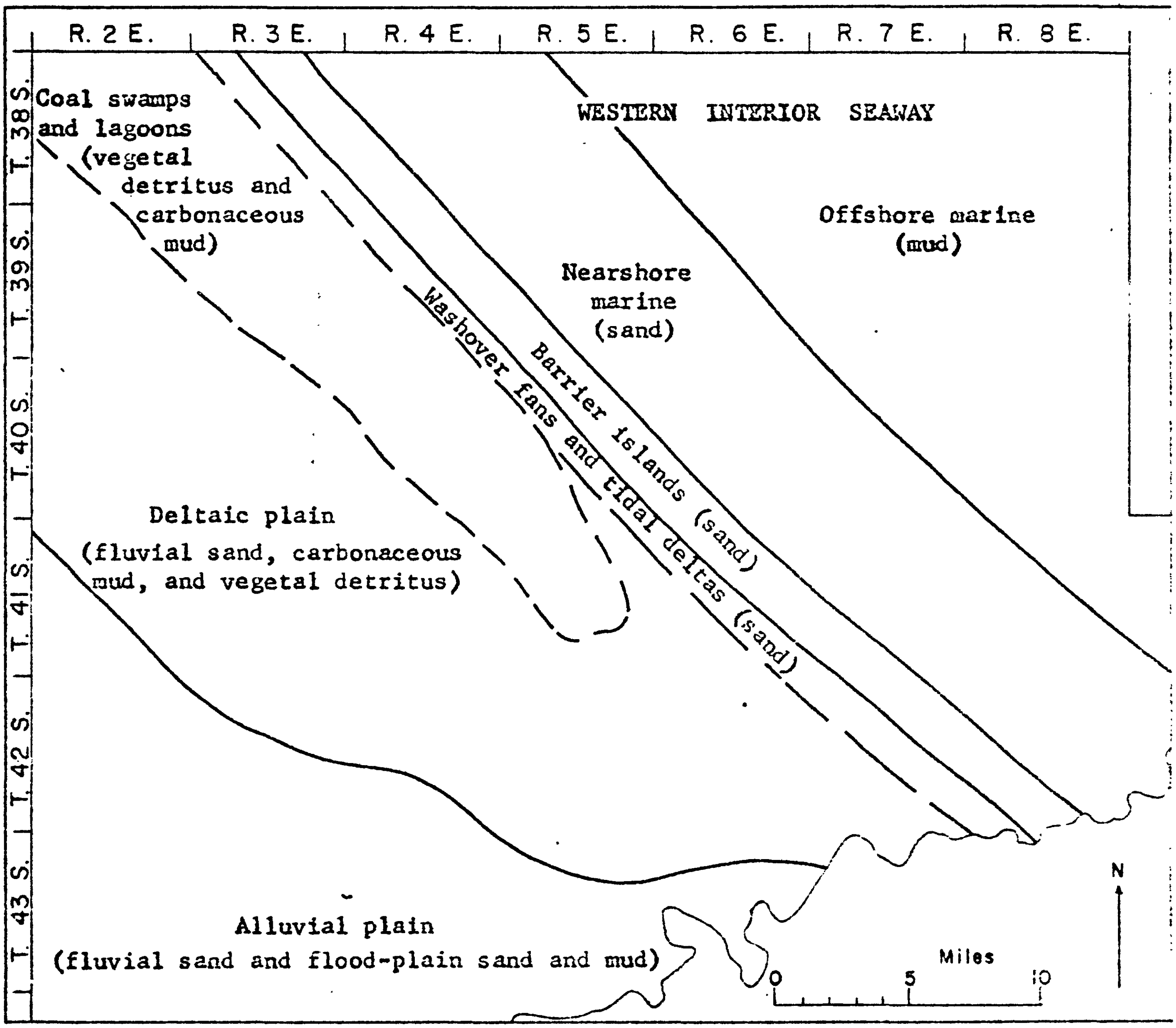


FIGURE 60.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the upper part of the lower coal zone and the A sandstone bed in the John Henry Member of the Straight Cliffs Formation.

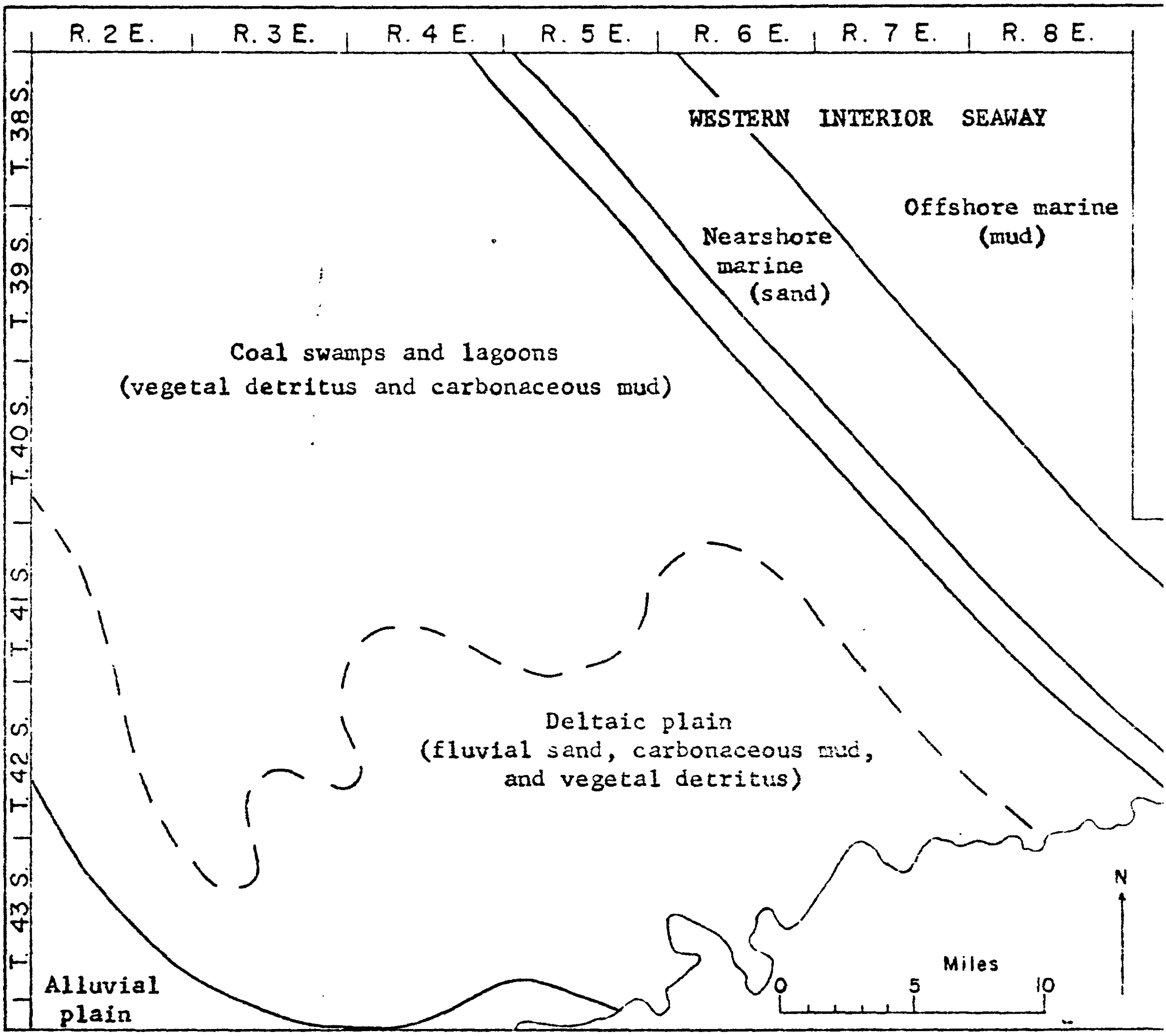


FIGURE 61.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the Christensen coal zone and B sandstone bed in the John Henry Member of the Straight Cliffs Formation.

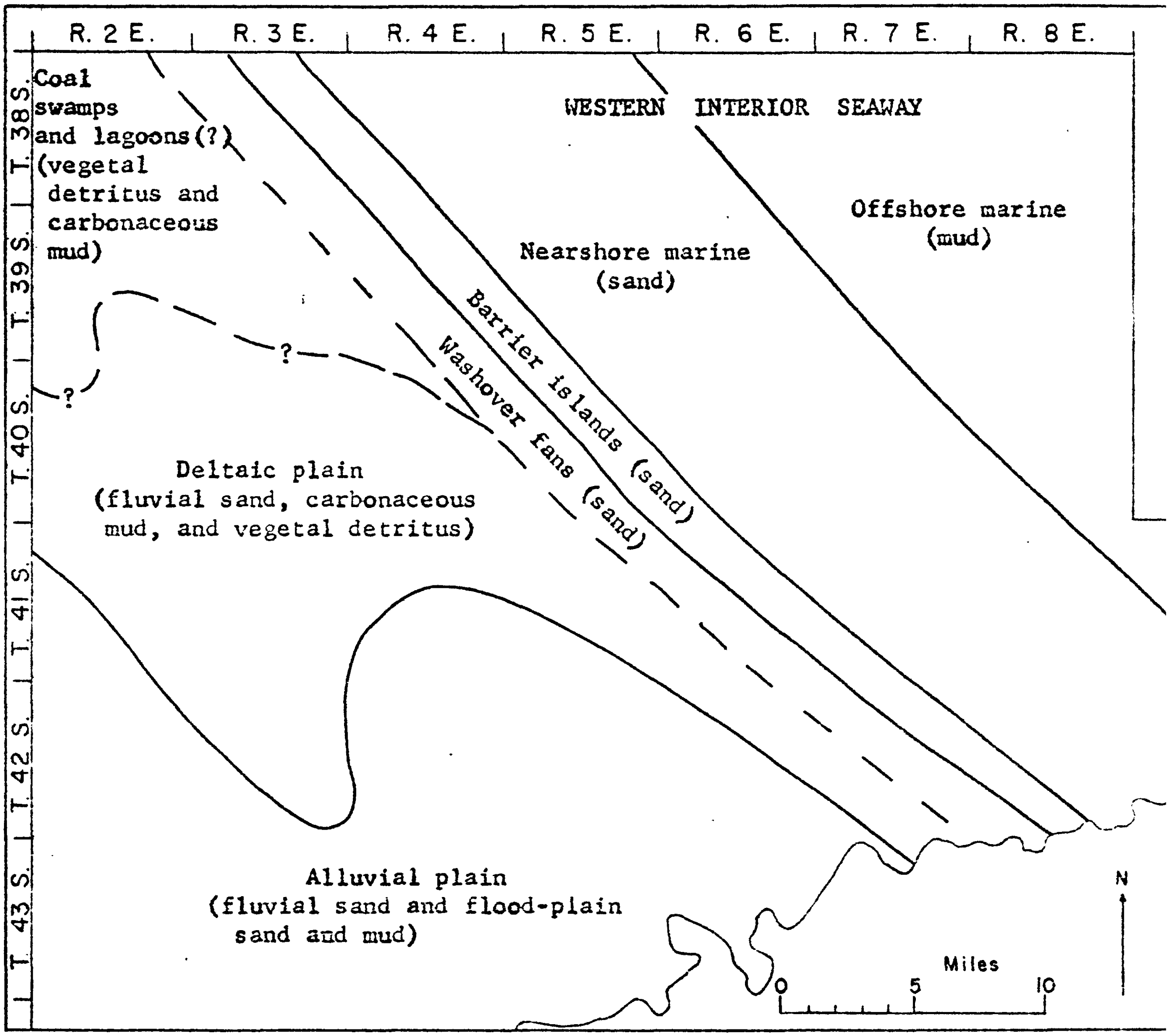


FIGURE 62.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the middle barren zone and C sandstone bed in the John Henry Member of the Straight Cliffs Formation.

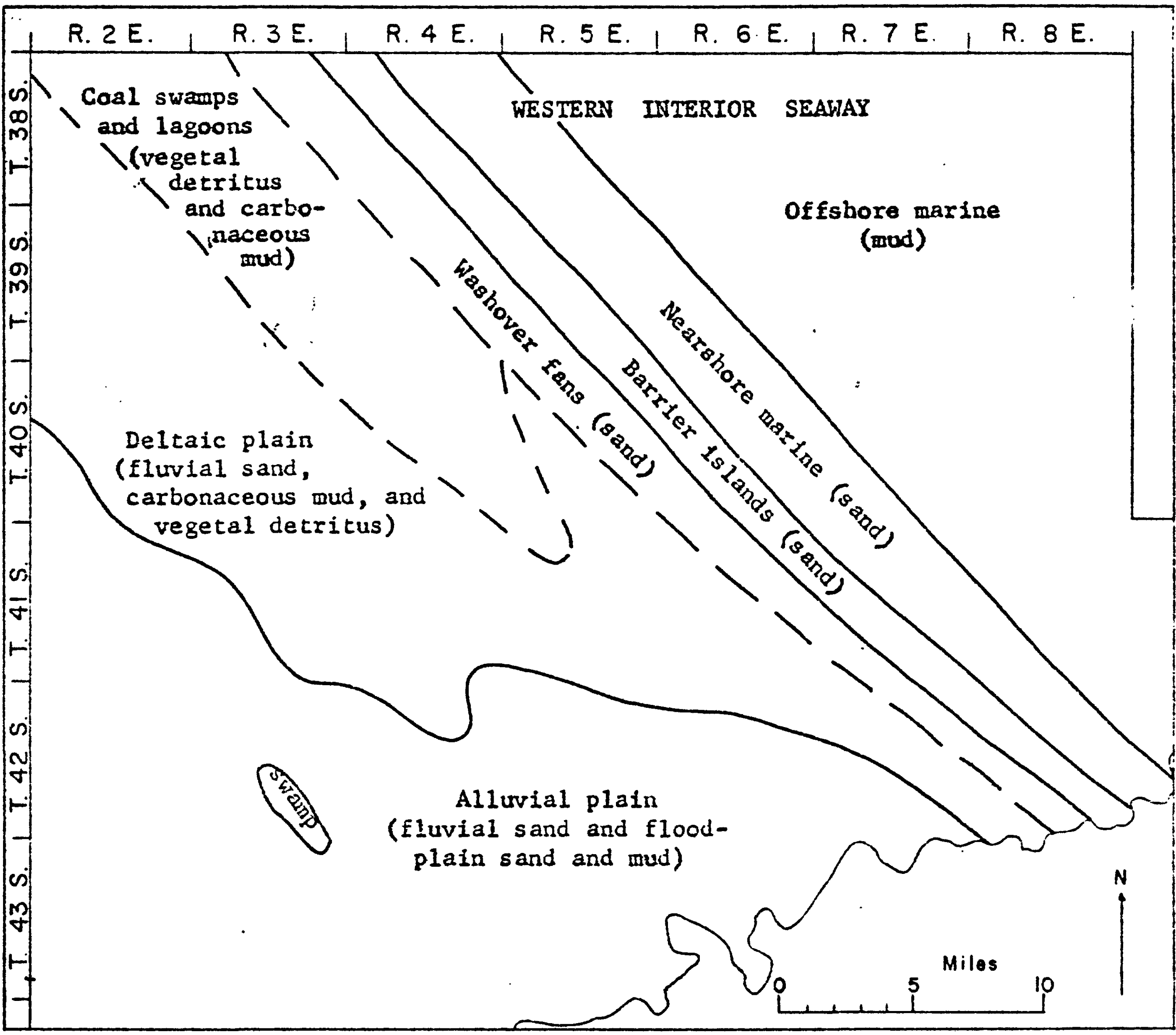


FIGURE 63.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the Rees coal zone and F sandstone bed in the John Henry Member of the Straight Cliffs Formation.

and then retreated northeastward out of the region (fig. 64). Figure 62 also illustrates the hypothesis that the coastal swamps and lagoons were present in the deeper part of the structural basin during deposition of the barren zones.

Sediment transport by shoreline currents generally has not been considered significant, judging from the literature on Cretaceous rocks in the Western Interior. The abundance of coal in the middle of the region indicates low rates of influx of detrital sediment and suggests that strata in the John Henry Member would have been deposited during a single transgressive-regressive cycle if shoreline sediment transportation had been insignificant. In this case, the shoreline probably would have reached a maximum southwestward extent during about middle Santonian time, which is almost the opposite of what actually occurred. This indicates that shoreline currents in the geologic past may have had considerable influence on the movement of sediment, the formation of barrier islands, and the timing of transgressive-regressive cycles.

Campanian Time

Strata of this age include the upper part of the John Henry Member, which was discussed in the preceding section, the Drip Tank Member of the Straight Cliffs Formation, the Wahweap and Kaiparowits Formations, and the unnamed unit of mudstone and conglomerate at the top of the Cretaceous section in the northwestern Kaiparowits region.

Throughout most of the region the Drip Tank Member consists of conglomeratic sandstone that is typical of subdivision A of the alluvial plain facies. That at least part of the member grades northeastward into nearshore marine beds of the barrier sandstone facies is suggested by well-sorted light-gray sandstone beds in Croton syncline that contain southeastward-dipping crossbedding (fig. 65) and by shark teeth that were found in the northern Kaiparowits region by E. V. Stephens (oral commun., 1967). Northeastward-dipping crossbedding (fig. 65) and reduction in size and quantity of pebbles in the alluvial plain facies indicate a sediment source in the Cordillera to the southwest. Moderate quantities of feldspar and dolomite grains and quartz and fossiliferous chert pebbles suggest

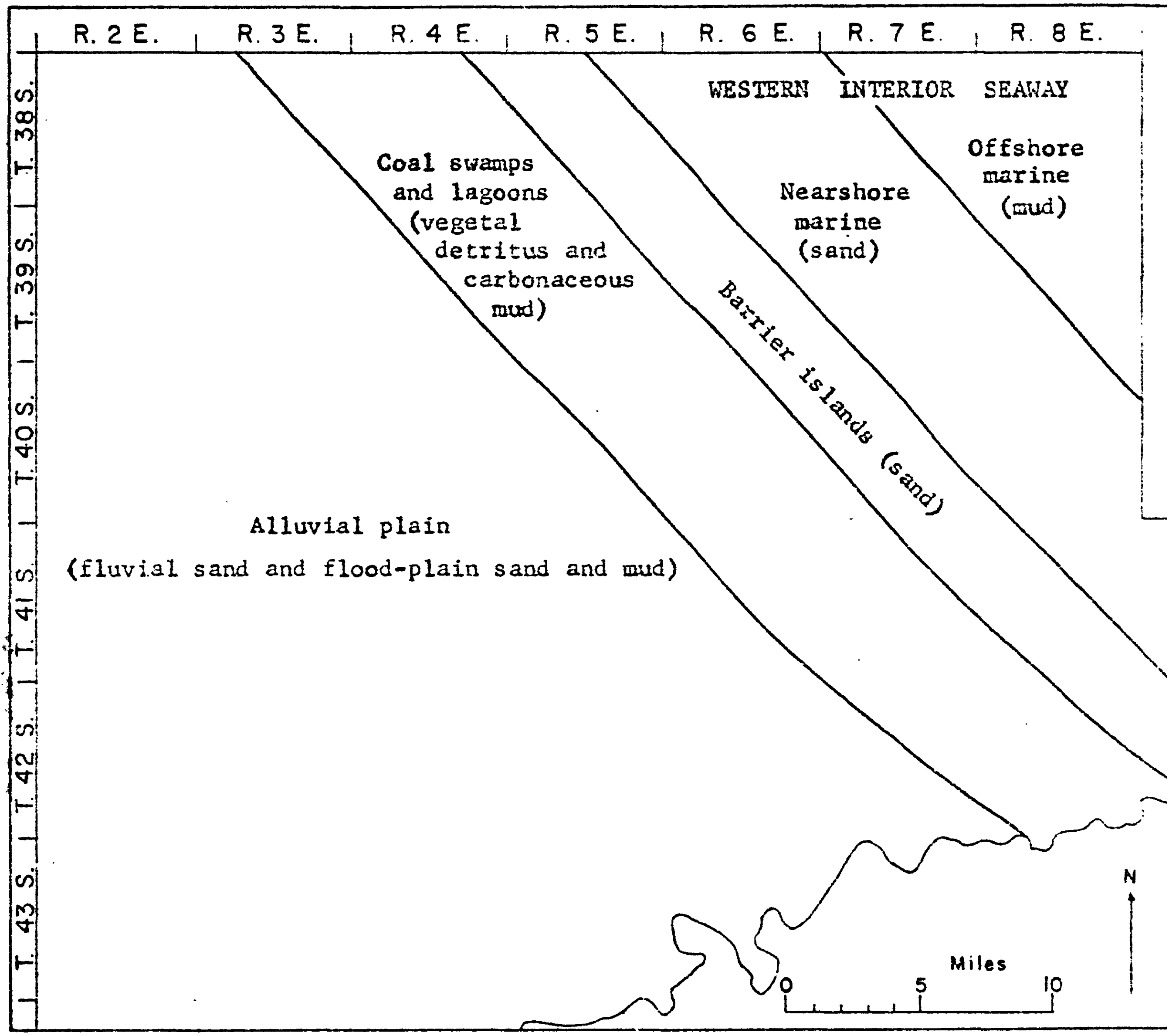


FIGURE 64.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the lower part of the Alvey coal zone in the John Henry Member of the Straight Cliffs Formation.

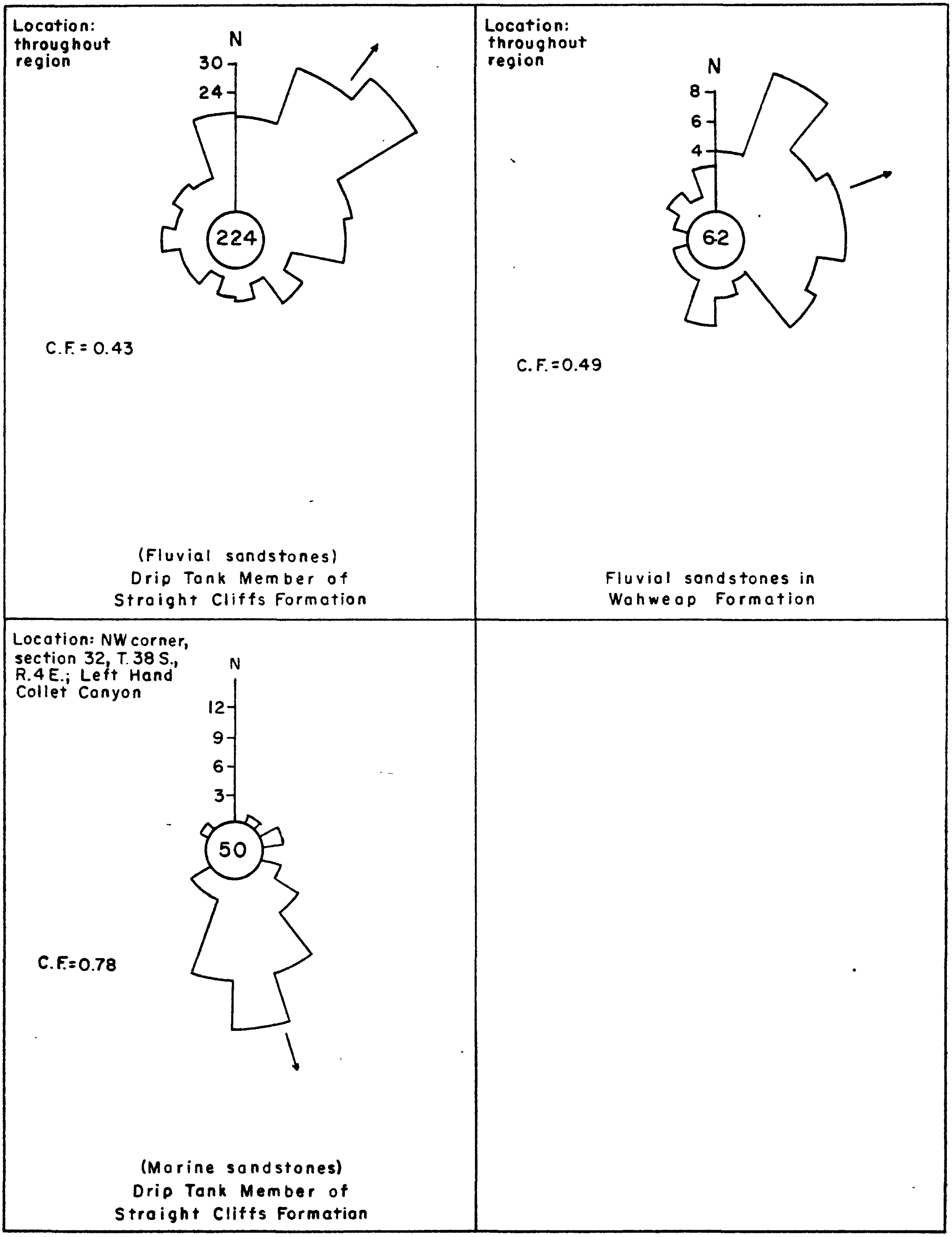


FIGURE 65.--Rose diagrams showing cross-stratification azimuths for sandstones in Drip Tank Member of Straight Cliffs Formation and in Wahweap Formation. Number of measurements in center; resultant shown by arrow; C.F. = consistency factor.

Paleozoic carbonates and igneous and (or) metamorphic rocks of unknown age in the source region. The southeastward-dipping crossbedding in some of the beds in the northeastern part of the region suggests another source area to the northwest that probably was similar to the northwesterly source area of the barrier sandstone deposits in the John Henry Member.

Continued regional subsidence is suggested by the presence of nearshore marine beds in the northeastern part of the region, and relatively slower subsidence on the ancestral Rees Canyon anticline is suggested because the marine beds do not extend southwest of this fold (figs. 66, 67). Basin downwarping is suggested by northwestward thickening of the member to 523 feet near Tropic, Utah (highest unit of section in Robison, 1966, p. 21, and tentatively assigned by the writer to the Drip Tank Member), although some of this thickening may be due to interfingering with the John Henry Member and the Wahweap Formation. Movement on other structures may have occurred but could not be determined. The wide extent and relatively coarse composition of materials in the member suggest that deposition was rapid and essentially completed before significant structural changes could have occurred.

The Drip Tank Member was deposited during (or possibly just after) the culmination of a phase of steadily increasing tectonic activity and uplift in the southwestern source area that began during deposition of the Christensen coal zone in the John Henry Member. This is indicated by the general upward increase in coarseness of materials (shown best on pl. 12, meas. secs. S3 and S22) and by the increasing rate of regression of the shoreline which remained in the northeastern part of the region during middle and late Santonian time and then moved rapidly into east-central Utah during earliest Campanian time (fig. 39). As noted before, if local uplift in the northwestern source area had not occurred, the shoreline probably would have been farther southwest during deposition of the Christensen coal zone, and the steadily increasing rate of regression of the shoreline would have been more apparent.

The Wahweap Formation consists mainly of strata that were deposited in alluvial plain environments during early and middle Campanian time (figs. 8, 9). Most of the formation was deposited in braided-stream channels or in overbank flood-plain areas, although the lower part of the formation locally contains large quantities of mudstone and scarce large-scale

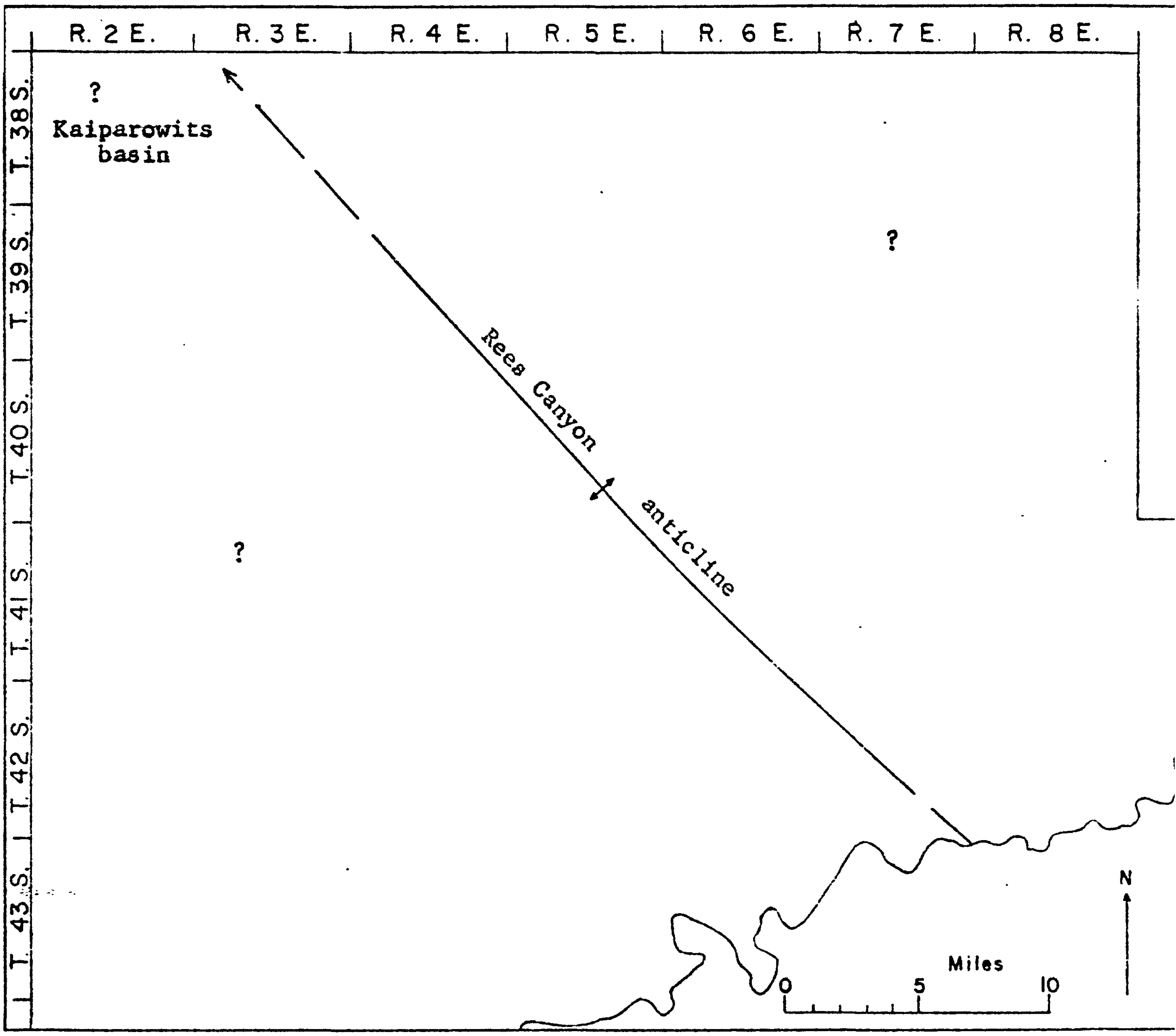


FIGURE 66.--Ancestral structures that probably were activated during early and middle Campanian time (during deposition of the Drip Tank Member of the Straight Cliffs Formation and the Wahweap Formation). Basin downwarping may have occurred during deposition of the Drip Tank Member. Movement of other structures may have occurred but could not be determined.

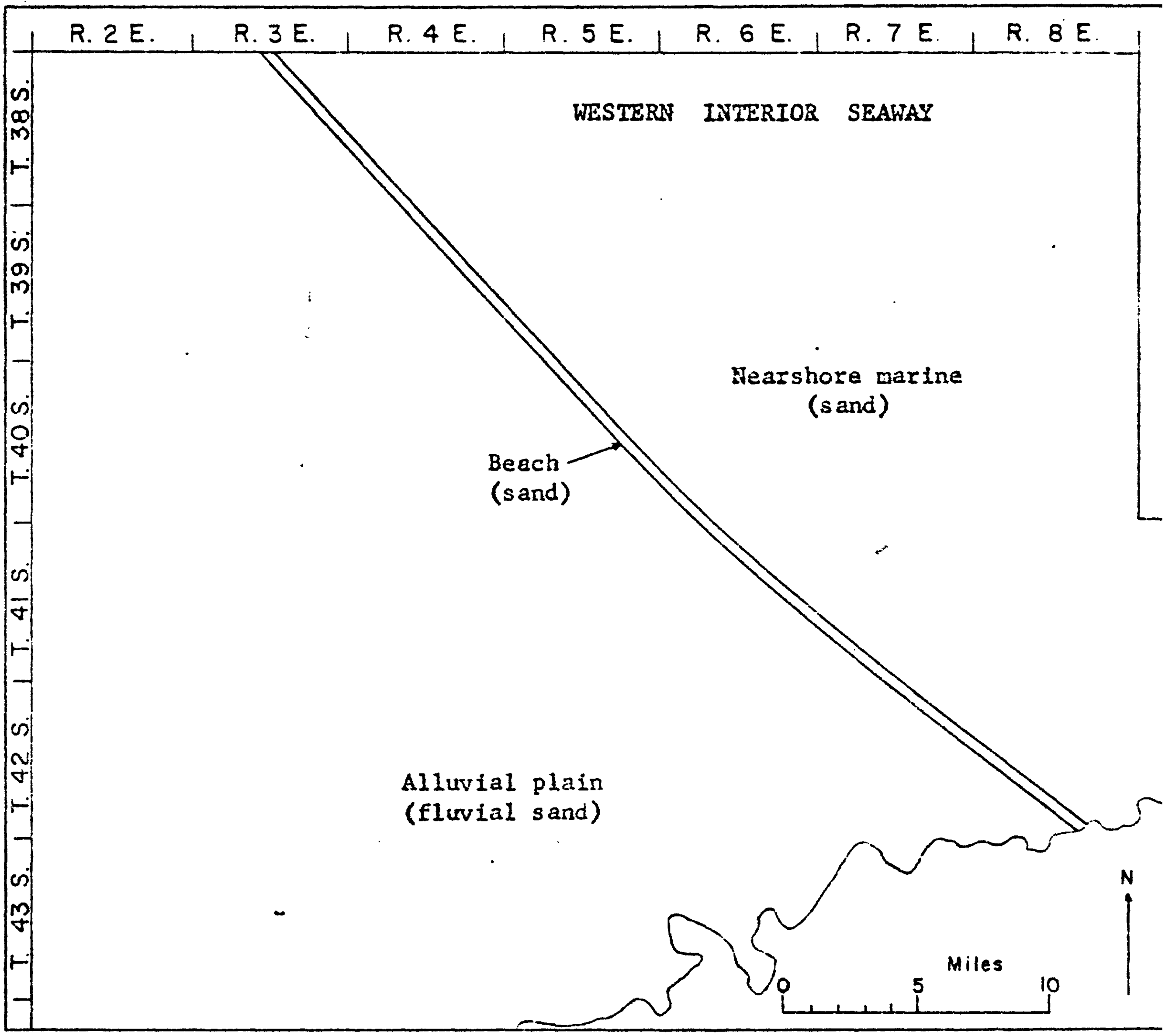


FIGURE 67.--Hypothetical paleogeography of the southeastern Kaiparowits region during deposition of the middle part of the Drip Tank Member of the Straight Cliffs Formation.

crossbedded units that suggest local deposition in lacustrine and lacustrine-delta environments. The thick and widespread upper sandstone unit is typical of subdivision A of the alluvial plain facies and was deposited mainly by braided streams.

Crossbedding studies suggest that the streams that deposited the Wahweap flowed generally northeastward, but the results are so varied that the streams could have come from highlands to the northwest, west, and southwest (fig. 65). The rocks are similar in composition to those in the alluvial plain facies of the John Henry Member of the Straight Cliffs, and they likewise suggest a source in Paleozoic carbonates, igneous and (or) metamorphic rocks of unknown age, and reworked volcanic ash deposits. Red chert granules and small pebbles are rare but their presence suggests additions from a different source to the west or from newly exposed rocks in the southwestern source region.

Little is known about the structural history of the region during deposition of the Wahweap Formation. Regional subsidence is suggested by correlation with the Masuk Member of the Mancos Shale (fig. 39). The Masuk is partly marine in origin and was deposited when the shoreline migrated back and forth across the present Henry Mountains region (Hunt and others, 1953, p. 85), indicating that the Wahweap Formation was deposited from 25 to 50 or more miles inland from the seaway. Although the altitude of the land surface during deposition of the Wahweap cannot be determined, the land surface of a comparable modern region 50 miles inland in the Houston-Port Arthur, Tex., area is generally less than 300 feet above sea level. This comparison suggests that the Wahweap was deposited fairly near sea level, and the considerably greater thickness of the formation suggests that regional subsidence approximately equaled sedimentation. Basin downwarping may have occurred during deposition of the Wahweap but could not be determined. Likewise, movement on most of the individual folds and faults could not be determined, although northeastward thinning of the part of the formation that lies beneath the upper sandstone unit suggests that the ancestral Rees Canyon anticline subsided slower than the adjacent areas (figs. 20, 66).

Local and regional evidence indicates that the upper sandstone unit of the Wahweap Formation was deposited during or possibly just after the culmination of a phase of steadily increasing tectonic activity and uplift in the Cordillera that began approximately during deposition of the lower part of the formation. This is indicated by the general upward increase in the amount of sandstone in the formation (fig. 20) and by the increasing rate of regression of the shoreline which remained generally in the present Henry Mountains region during deposition of approximately the lower half of the Wahweap and then moved rapidly northeastward and reached northeastern Utah during deposition of the upper sandstone unit (fig. 39). The upper sandstone unit of the Wahweap is similar to the Drip Tank Member of the Straight Cliffs Formation and the Calico bed at the top of the Smoky Hollow Member of the Straight Cliffs in that each of these units was deposited at the end of a phase of steadily increasing tectonic activity in the Cordillera.

The Kaiparowits Formation was deposited in nonmarine conditions during middle to late Campanian time. Robison (1966, p. 28) and Lohrengel (1969) indicate that the formation was deposited in fluvial and possibly deltaic conditions and that the sediments probably came from the west.

Little is known about the structural history of the region during deposition of the Kaiparowits Formation because there is little published information on it and the formation was not studied for this report. The nearest correlative marine formations are in northwestern New Mexico and southwestern Colorado (Cobban and Reeside, 1952; Dickinson, 1965), and the relations indicate that the shoreline was approximately 100-200 miles east of the Kaiparowits region when the formation was deposited. Comparison with the northwestern Gulf Coastal region does not appear valid because of the relatively great distances involved, but it seems unlikely that the alluvial coastal plain on which the Kaiparowits was deposited could have been as much as about 2,750 feet above sea level (the maximum known thickness of the formation), and regional subsidence is, therefore, suggested. Local unconformities in the upper part and at the top of the formation occur on the monoclinal west limb of the Upper Valley anticline in the northwestern part of the region (W. E. Bowers, oral commun., 1969), suggesting that monoclinal flexing on this fold began during late Campanian time. On the basis of similarity of structures, this suggests that movement on Echo and Grand Bench monoclines began during late Campanian time. The formation was not examined in sufficient detail to determine whether or not additional contemporaneous structural deformation had occurred.

The unnamed mudstone and conglomerate unit in the northwestern Kaiparowits region was deposited in continental environments during late Campanian time (Bowers, 1968; oral commun., 1969). The thick conglomerates and red beds indicate rapid deposition in well-drained and probably less vegetated environments than were present during deposition of earlier Cretaceous formations, or at least they indicate deposition in environments that were suitable for the preservation of oxidized sediments. The lithologies are similar to those generally considered typical of the piedmont facies of Spieker (1949).

The nature of structural movements in the region during deposition of these beds is uncertain because they have not been studied in detail. Deposition at the beginning of a period of regional uplift is suggested by the red beds--one interpretation of which is that they were deposited in well-drained upland conditions which would accord well with regional uplift. A local angular unconformity is present at the base of the unit on the monoclinal west flank of the Upper Valley anticline in the northwestern part of the region (W. E. Bowers, oral commun., 1969), and the conglomerate beds generally are thicker in the adjacent syncline, suggesting that flexing on the monocline occurred before and during deposition of the unit. The similarity of the structures suggests that movement on the other monoclines in the region also occurred during deposition of the mudstone and conglomerate unit.

The amount and type of movement on other structural features in the region is unknown because of insufficient data.

Maestrichtian and Paleocene Time

Strata of Maestrichtian and Paleocene age are not known to be present in the Kaiparowits region. The oldest Tertiary unit in the region is the Wasatch Formation, which is of Eocene age (Bowers, 1968) and could include strata of Paleocene age (Schneider, 1967). The name Wasatch is probably incorrectly applied to these beds, but W. E. Bowers and H. D. Zeller (oral commun., 1969) suggest that it probably is best to avoid confusion by using Gregory and Moore's (1931) old terminology until more definitive studies have been made. Other names that have been applied to these beds include

Claron Formation (Robison, 1966) and Cedar Breaks Formation (Schneider, 1967). The Wasatch lies horizontally or nearly horizontally, truncates the upwarped older beds, and generally marks the end of most of the structural deformation in the region.

Structural deformation in the northwestern part of the Kaiparowits region is fairly well documented and is probably indicative of events that occurred throughout the region. Regional uplift is suggested by the widespread erosional unconformity at the base of the Wasatch Formation. Slight northeastward regional tilting is suggested by the lack of beds of Maestrichtian age in the Kaiparowits region and their presence in northeastern Utah, western Colorado, and northwestern New Mexico (Cobban and Reeside, 1952). Beds of this age were either deposited and subsequently eroded, or Maestrichtian sediments never were deposited. Considering the general westerly or southwesterly source of sediments in Maestrichtian formations farther east or northeast, either possibility suggests slight regional tilting to the northeast. Uparching of the flanks of the structural basin is indicated because the Wasatch Formation truncates successively older formations progressing away from the axis of the basin.

Growth on the monoclines ceased by about Eocene time, if it can be assumed that the tectonic forces that formed them acted equally throughout the region. Considering the rather well documented latest Cretaceous-early Tertiary date of formation of the other datable major monoclines on the Colorado Plateau (Kelley, 1955b, p. 797), this does not appear to be an unwarranted assumption. Escalante monocline, several miles northeast of Escalante, Utah, is the only monocline in the region that is still overlain by the Wasatch Formation. Here, Jurassic formations apparently are truncated by horizontal strata of the Wasatch Formation (W. E. Bowers, oral commun., 1969), indicating that movement ceased by about Eocene time. Evidence discussed in previous paragraphs suggests that growth of these flexures began during deposition of the upper beds of the Kaiparowits Formation or prior to deposition of the overlying unnamed unit of mudstone and conglomerate. On the assumption that all the monoclines are genetically related, the relations indicate that they were formed during latest Campanian, Maestrichtian, and Paleocene time.

Several other types of structural deformation probably occurred in the region during this time. Maestrichtian and Paleocene movement on the

Smoky Mountain and Rees Canyon anticlines is suggested because these folds lie on the axial trends of the Johns Valley and Upper Valley anticlines, respectively, in the northwestern Kaiparowits region, and both of the latter folds are involved in the Maestrichtian-Paleocene folding. There is no way of correlating Nipple Bench anticline with structures in the northwestern part of the region and, consequently, movement on this fold cannot be determined. Likewise, movement on the older faults cannot be determined. The geometry and localized occurrence of normal faults on the upper, or anticlinal, bend of Echo monocline suggest that these fractures were originally formed as conjugate shears during or possibly shortly after the main period of folding on this monocline. The remaining faults in the region are undated; presumably, movement occurred on them during this time interval or possibly later.

Figure 68 shows the structural relations in the southeastern Kaiparowits region as they probably existed by the end of Paleocene time. This is the same structural picture as is present today, and it is based on the hypothesis that most of the tectonism ceased throughout the Kaiparowits region by the beginning of deposition of the Wasatch Formation.

Middle and Late Cenozoic Time

Inferences concerning the middle and later parts of Cenozoic history in the southeastern Kaiparowits region rest on the conclusions of others who have studied the overall character of the Colorado Plateau. General uplift and northeastward tilting of the Colorado Plateau continued during this time (Hunt, 1956, p. 63-64), and the uplift is recorded in the Glen Canyon region by several erosion surfaces that now are as much as about 7,500 feet above sea level (about 4,300 ft above the Colorado River) and that date back to Miocene, Pliocene, and Pleistocene time, according to Cooley (in McKee and others, 1967, p. 23-24, table 1). Several stages of normal faulting occurred in northern Arizona and eastern Nevada during Oligocene, Miocene, Pliocene, and Pleistocene time (McKee and others, 1967, table 1; Armstrong, 1968), and it is likely that many of the preexisting faults in the Kaiparowits region were reactivated and that some of the other faults may have been initiated during one or more of these stages.

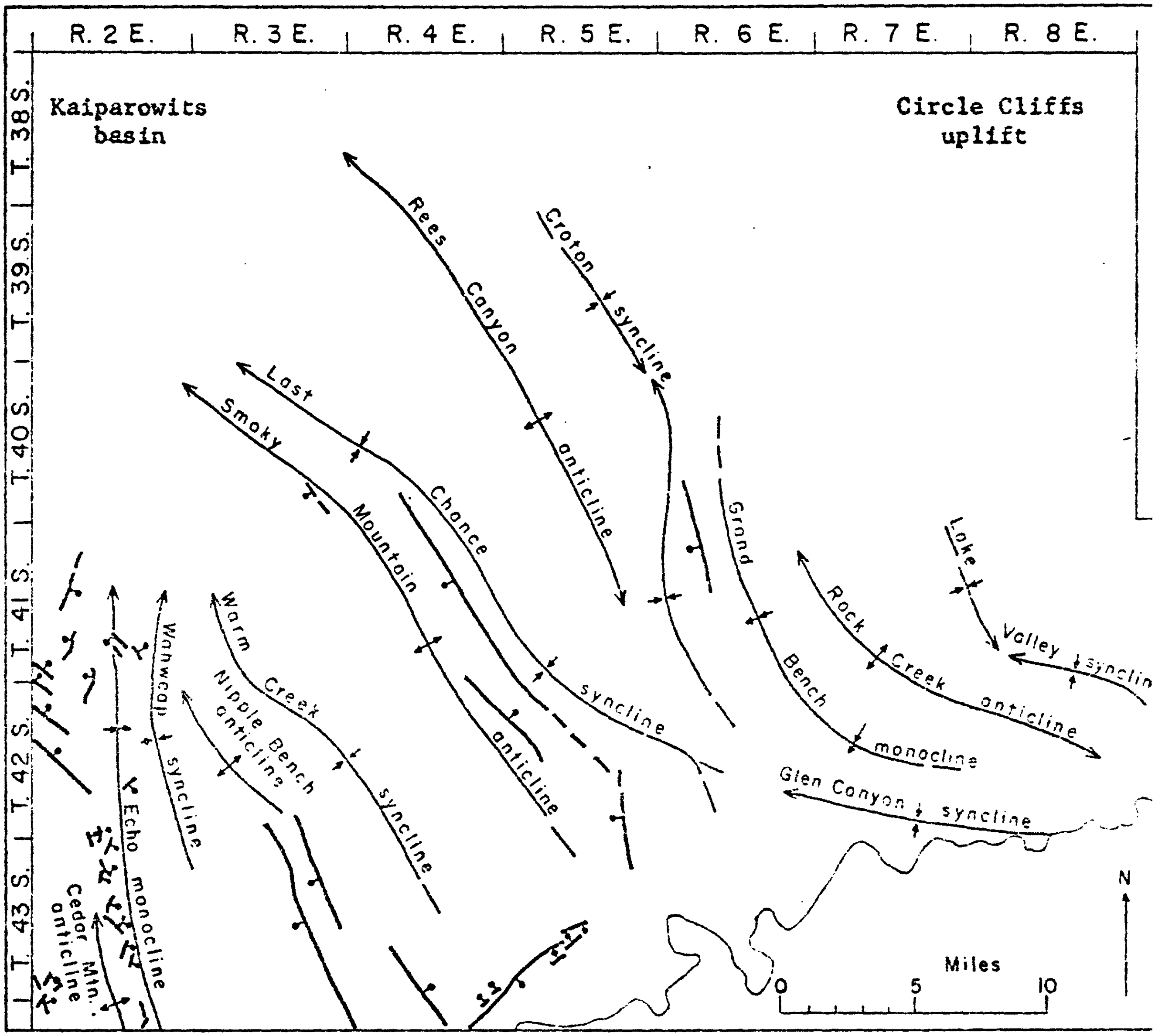


FIGURE 68.--Probable structural relations in the Kaiparowits region by the end of Paleocene time (end of the Laramide orogeny).

General

Laramide tectonism in the Kaiparowits region is clearly separated into two phases of deformation (fig. 69). The early phase was characterized by regional subsidence and lasted from about late Albian to late Campanian time. The later phase was characterized by regional uplift and monoclinal folding and lasted from late Campanian to about late Paleocene time. Regional tilting, basin downwarping, and local folding and faulting occurred during both phases. The two phases of tectonism compare well with tectonic phases that have been recorded in the Sevier orogenic belt to the west and the central Arizona orogenic belt to the south.

The early phase of tectonism occurred during the later part of the Sevier orogeny of Armstrong (1968), which included uplift and thrusting in eastern Nevada and western Utah (the Sevier orogenic belt) during Early Cretaceous to late Campanian time. The Piman phase of the Laramide orogeny in southeastern Arizona (in the central Arizona orogenic belt) included a period of thrusting that lasted from about middle Turonian to late Campanian time (90-72 million years ago; Drewes, 1968). The relations of tectonic events in the Cordillera and in the Kaiparowits region indicate that the Dakota, Tropic, Straight Cliffs, Wahweap, and Kaiparowits Formations were deposited during a period of considerable tectonic activity, including thrusting and uplift, in the Cordillera. Furthermore, the relations of beds below the Calico bed of the Smoky Hollow Member and above and below the Drip Tank Member and the upper sandstone unit of the Wahweap Formation indicate that each of these units was deposited during or possibly just after the culmination of a period of steadily increasing tectonic activity in the Cordillera that was followed by a relatively faster (but not abrupt) decrease in tectonism. Intermittent structural deformation in the Cordillera is therefore indicated, but the changes in intensity were gradual and the periods of maximum thrusting and uplift probably were not abruptly separated from periods of relative quiescence.

The later phase of tectonism in the Kaiparowits region occurred during the Laramide orogeny, as restricted by Armstrong (1968) to events that occurred in the Sevier orogenic belt during late Campanian to about middle Eocene time. The relations between the two regions indicate that the

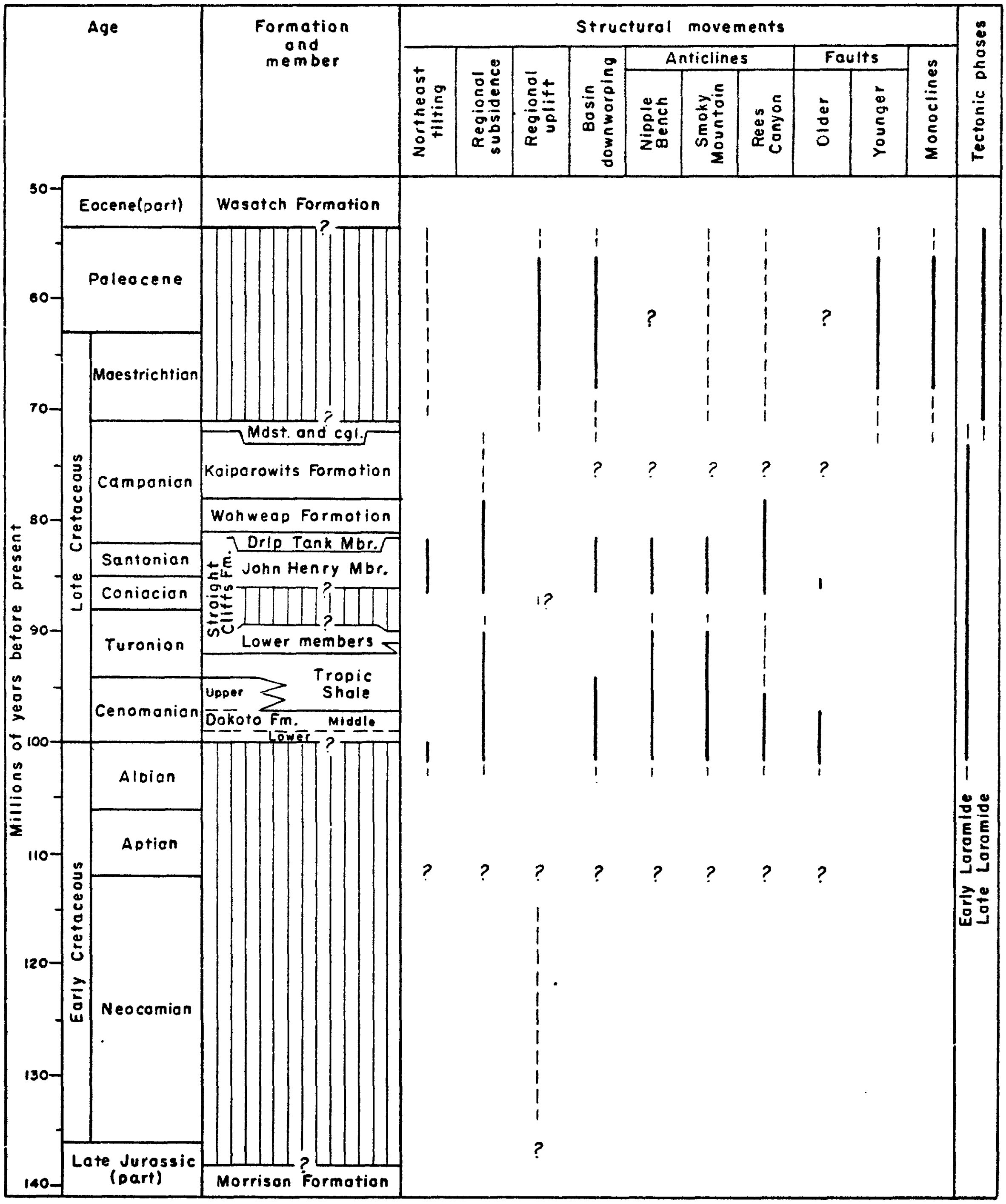


FIGURE 69.--Summary of tectonic activity in the Kaiparowits region. Time-scale in millions of years before present: 62 m.y. and younger from Funnell (1964, p. 188), 63-87 m.y. from Gill and Cobban (1966, p. 35), 88 m.y. and older from Casey (1964, p. 199).

unnamed mudstone and conglomerate unit was deposited at about the beginning of a period of uplift of the southwestern part of the Colorado Plateau that accompanied uplift of large crustal blocks on vertical or nearly vertical faults, igneous intrusions, and folding in the Sevier orogenic belt. Tectonic events in southeastern Arizona at this time include igneous intrusions, a phase of quiescence, and northwestward thrusting (Drewes, 1968) that do not appear to be related to events in the southwestern part of the Colorado Plateau.

The northwest-trending structures that were repeatedly reactivated from about late Albian to Paleocene time were probably inherited from earlier northwest structural trends that were well established in the Colorado Plateau by the end of the Permian-Pennsylvanian period of tectonism (Kelley, 1955a, p. 74-80). These were probably guided by northwest-trending Precambrian faults and joints such as those that occur in the Grand Canyon (Maxson, 1966, 1967). Several stages in the Late Cretaceous-early Tertiary structural history of the Colorado Plateau have been noted by Kelley and Clinton (1960, p. 97), who thought that the monoclines were formed before the northwest-trending anticlines and synclines. This study indicates that the anticlines and synclines formed earlier in the Kaiparowits region, and because the northwest trends are such an integral part of the structure of the Colorado Plateau (Kelley, 1955a, p. 58-63), it would appear that this sequence of events also may apply to the Colorado Plateau in general. This study also indicates that downwarping of the Kaiparowits structural basin occurred at least as far back as Cenomanian time. The basin does not appear to have undergone an appreciably different structural history from any of the other basins on the Colorado Plateau, and the evidence that the basins originated during latest Cretaceous-early Tertiary time (Kelley, 1955a, p. 84) probably should be reevaluated.

An approximation of the amount of vertical movement that occurred in the region from Cenomanian time to the present can be given for the No. 4 coal bed at the top of the middle member of the Dakota Formation, which probably was deposited close to sea level. Calculations from the thickness of overlying formations and the assumption that the upper part of the Kaiparowits Formation was deposited approximately 400 feet above sea level indicate that approximately 5,200 feet of subsidence occurred in Last Chance syncline by late Campanian time at the end of deposition of the Kaiparowits Formation. The No. 4 coal bed is now about 3,800 feet above sea level in this area, indicating that approximately 9,000 feet of uplift occurred from Maestrichtian time to the present. If a potential error of plus or minus 500 feet is considered for eustatic changes in sea level, the result is an approximate figure of 8,500-9,500 feet of uplift since about the beginning of Maestrichtian time. By similar reasoning, about 10,000-11,000 feet of uplift occurred on the northeastern flank of the basin since about the beginning of Maestrichtian time. These figures give an approximate range of 121-157 feet (37-48 meters) of uplift per million years (37-48 Bubnoff units: Fischer, 1969), which demonstrates that apparently insignificant earth processes can be appreciable when extended over a long part of geologic time.

Coal

DAKOTA FORMATION

Four coal beds are in the middle member of the Dakota Formation, but the beds generally are too thin for commercial endeavors. The lower three coal beds generally are less than 2 feet thick and are cut out by fluvial channel sandstones in many places. Consequently, they are not significant potential resources. Coal bed No. 4 lies above the fluvial channel sandstones and, therefore, is more continuous than the other beds, but differential compaction over some of the channel sandstones that lie a short distance below caused some local thinning of this bed. Throughout most of the region, coal bed No. 4 is too thin for commercial consideration, but in several localities in the northeastern part of the region, the bed is 2-4 feet thick (pl. 16) and mining by augering methods is possible. The stratigraphic relations indicate that basin downwarping occurred during deposition of the middle member and that the coal probably thickens toward the deeper part of the basin. However, a costly drilling program would be necessary to evaluate the Dakota coal deeper in the basin, and this seems unwarranted because of the thicker and more accessible coal deposits in the Straight Cliffs Formation. Thicker coal beds in the Dakota occur west of the Kaiparowits region in the Kanab and Kolob coal fields (Grose and others, 1967).

SMOKY HOLLOW MEMBER OF STRAIGHT CLIFFS FORMATION

Coal beds in the Smoky Hollow Member generally are too thin or contain too many partings to be of economic value. The two seams that occur in Wahweap and Warm Creek synclines, respectively, reach maximum thicknesses of about 3½-5 feet, which is about the minimum thickness that can be considered for mining. These beds are thickest and contain fewer partings on the northeast side of the syncline in which they occur. As shown on plate 17, the coal is locally cut out by fluvial channel sandstones, but the number of channels is considerably smaller than in the Dakota Formation and the channels do not appear to pose as great a problem. Coal beds northeast of Smoky Mountain are less than about 2 feet thick and, therefore, are too thin for commercial operations.

JOHN HENRY MEMBER OF STRAIGHT CLIFFS FORMATION

The John Henry Member contains the thickest and most extensive coal deposits in the region. The coal occurs in four coal zones that are separated by barren or noncoal zones (fig. 16). The lower and middle barren zones are thin on the northeast side of Last Chance syncline where it is difficult to separate the lower, Christensen, and Rees coal zones. Because the coal zones generally thicken northwestward into the depositional basin, it may prove impossible to separate these three coal zones in the subsurface farther northwest.

The total-coal isopach maps and other stratigraphic relations described in a previous chapter indicate that the coal beds thicken northwestward into the Kaiparowits structural basin and also are thicker in the subbasins that were formed in growing synclines. Because the northwest-trending folds in the basin partly governed the distribution of the coal swamps, the coal beds generally are more continuous in a northwesterly direction.

Lower coal zone

Coal beds in the lower part of the lower coal zone are thin (generally less than 3 ft thick) and locally slumped (fig. 56) and, consequently, do not offer much potential for profitable recovery. Total-coal isopachs, shown on plate 18, indicate that the coal thickens northwestward into the Kaiparowits basin, but because of the slumping, it is doubtful that thick beds which might exist farther into the basin in the lower part of the zone could be mined. The beds in the upper part of this zone above the A sandstone bed are thicker on the northeast side of Last Chance syncline where several coal beds thicker than 4 feet are present and the thickest bed found measured 12.6 feet. These beds are not slumped, and it is probable that well-planned drilling would indicate that these beds could be exploited.

Christensen coal zone

This coal zone contains the thickest and probably the most extensive coal beds in the region. The zone generally includes one to four coal beds that are 4 or more feet thick, and the thickest bed found measured 29.6 feet (pl. 10, sec. S23). Total-coal isopachs (pl. 19) indicate that the coal thickens northwestward into the Kaiparowits basin, and the distribution of facies indicates that the most continuous seams occur in Warm Creek syncline and especially in Last Chance and Croton synclines. The coal beds in Wahweap syncline are near the edge of the depositional basin where streams emptied into the lagoonal and paludal areas, and these coal beds are probably cut out in many places by fluvial sandstones.

Rees coal zone

This zone contains several thick coal beds in Last Chance syncline where as many as three beds are 4 or more feet thick and the thickest bed found measured 9.5 feet. Total-coal isopachs shown on plate 20 indicate that the coal thickens northwestward into the Kaiparowits basin and that thicker and more continuous seams probably occur underground in that direction. The coal beds in the other synclines are too thin and too lenticular to constitute an economic resource.

Alvey coal zone

Most of this zone has been eroded from the region, but one coal bed in a well-preserved section at the head of Trail Canyon (pl. 11, sec. S5) measured 11.8 feet. Doelling (1967, p. 8, coal zones A and B) and Zeller (1968a, b, c) found several seams that were more than 5 feet thick in this zone near Escalante, Utah, and their work indicates that coal also occurs in the uppermost beds of the John Henry Member in that area. As far as known, the Alvey coal zone does not occur southwest of Rees Canyon anticline (fig. 38).

ANALYSES AND QUALITY

Coal samples taken from outcrops give misleading results because of weathering, and for this reason outcrop samples were not taken during the investigation. The analyses shown in table 8 were from samples obtained

TABLE 8.--As-received analyses of coal in the southeastern Kaiparowits region

Lab. No.	Location	Formation[1]	Thickness of sampled bed (ft)	Type of analysis					Heating values (Btu)
				Proximate				Ultimate	
				Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	
H-91897--	Abandoned mine in NE¼NW¼ sec. 7, T. 43 S., R. 4 E. North side of small canyon.	Kdm4	1.8	5.3	45.1	44.1	5.5	1.6	10,670
H-97252--	Abandoned prospect in NW¼SW¼ sec. 12, T. 42 S., R. 3 E. West side of Warm Creek canyon.	Ksjc	7.3	8.0	36.5	48.6	6.9	0.6	10,130
H-97253--	Abandoned mine in SW¼SW¼ sec. 3, T. 42 S., R. 3 E. Southwest side of Tibbet Canyon.	Ksjc	3.1	5.9	40.9	47.5	5.7	0.5	11,880
I-27711--	Drill core in SE¼ sec. 23, T. 41 S., R. 4 E. On Smoky Mountain.	Ksjc	3.9	5.5	39.0	40.3	15.2	0.7	10,800

[1] Kdm4: Dakota Formation, middle member, coal bed No. 4.
Ksjc: Straight Cliffs Formation, John Henry Member, Christensen coal zone.

from fresh or nearly fresh materials. The samples were analyzed by the laboratories of the U.S. Bureau of Mines; other analyses of Kaiparowits coals given in Robison (1964) were analyzed by commercial laboratories in which the analytical procedures may have been somewhat different. Analyses of samples taken from outcrops are given by Grose, Hileman, and Ward (1967, p. 76-77), but the noticeable difference between their analyses and those given in table 8 clearly demonstrate that outcrop samples are of little value.

Only one reasonably representative sample was obtained from the Dakota Formation. Sample H-91897 was taken from the abandoned C. H. Spencer mine that is in a small tributary canyon to Warm Creek canyon. A fresh face could not be worked in this mine because of the danger of cave-in, and the sample was taken from a face that probably had not been worked for 55 or more years. The sample, therefore, was somewhat weathered, but it is the least altered sample of Dakota coal that thus far has been obtained from the region. Accordingly, the heating value is probably rather low. The slightly higher sulfur content relative to coals in the Straight Cliffs Formation is consistent with the findings of Grose, Hileman, and Ward (1967, p. 60).

The other samples came from the Christensen coal zone in the Straight Cliffs Formation. Sample H-97252 was taken from the face of a prospect that goes back only about 10 feet from the surface and evidently was not worked for many years. Accordingly, the heating value is probably low. Sample I-27711 came from a drill core that was analyzed about 6 months after it had been recovered. Accordingly, the heating value of this sample is probably low. Sample H-97253 was taken from a fresh face that was worked in the abandoned C. H. Spencer mine in Tibbet Canyon and is probably more representative of Straight Cliffs coals in the region than any of the other samples.

Rank determinations have not been made on Kaiparowits coals, but the heating values indicate that they range from subbituminous B to subbituminous A or high-volatile C bituminous. The difference between the last two ranks is based on agglomerating and weathering characteristics which have not been determined. Inasmuch as Kaiparowits coals generally are considered best suited for electric-power generation or conversion to liquid hydrocarbons, the difference between these closely related ranks is probably not important.

CLEATS

Cleats are distinctive closely spaced joints in coal seams that are perpendicular to the bedding and commonly trend in slightly different directions from joints in other lithologies. Generally, there are only two sets of cleats--the face cleat which is the more persistent, and the butt cleat which is generally oriented nearly normal to the face cleat and commonly terminates at face cleats.

Cleats are important in mining because coal breaks more easily along them and the miners can take advantage of this in laying out mines and speeding recovery of the coal. The orientation of cleating in Dakota and Straight Cliffs coals throughout the region is illustrated in figure 70 which shows that the face cleat generally trends about N. 23° E. and the butt cleat trends about N. 70° W. Local variations occur where the coal is overlain by a fluvial channel sandstone or at the monoclines where secondary sets of cleating have been found.

The origin of cleating is not well understood. Studies of jointing in Pennsylvanian and Permian rocks of the Appalachian Plateau in Pennsylvania led Nickelsen and Hough (1967, p. 627) to conclude that, "Coals, which are both relatively weak and capable of being jointed early, are sensitive indicators of early and small stress differences, perhaps resulting from warping of the sedimentary basin or some other epeirogenic activity." Cleating in the Kaiparowits coals is probably related to structural deformation that occurred during or immediately after deposition of the beds, but the relation to regional stresses and the role of desiccation (Ball, 1934) are unknown.

POTENTIAL RESOURCES AND PRODUCTION

The Kaiparowits region contains far larger quantities of coal than previously estimated. As recently as 1961, Averitt (1961, p. 79) gave a gross provisional estimate of 3 billion tons for the region. Since that date, drilling, surface mapping, this study, and calculations by W. E. Bowers, H. D. Zeller, and the writer have indicated that a gross provisional estimate of potential coal resources in the entire coal field is approximately 40 billion tons. This includes coal in beds 1 or more feet thick and overburden of a maximum of about 3,000 feet. This figure is extremely misleading,

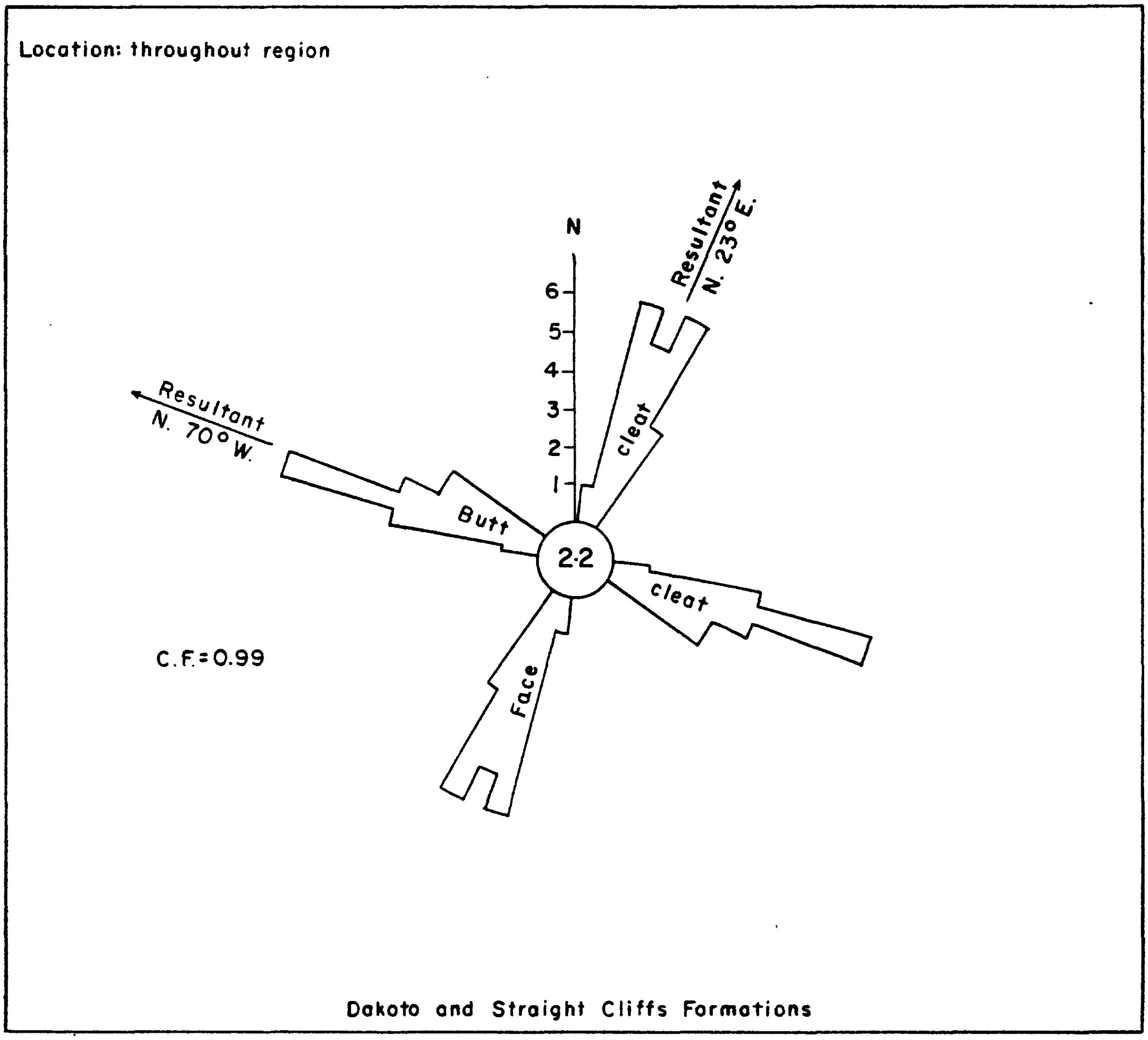


FIGURE 70.--Regional orientation of cleats in Kaiparowits coals. Number of measurements in center; C.F. = consistency factor (butts and cleats).

though, because little of the coal can be recovered by present mining methods or by technological innovations that might be envisioned in the near future. A rough estimate is that perhaps as much as one-tenth of this, or 4 billion tons, could be recovered by present mining techniques.

Indicated coal resources is another type of estimate that is more closely related to actual measurements in the coal field. Indicated resources are "* * * computed partly from specific measurements and partly from projection of visible data for a reasonable distance on the basis of geologic evidence. In general, the points of observation are about 1 mile apart, but they may be as much as 1½ miles apart for beds of known continuity" (Averitt, 1969, p. 25). The indicated coal resources in the entire coal field as calculated by W. E. Bowers, H. D. Zeller, and the writer are approximately 7.3 billion tons. This figure includes coal in beds 1 or more feet thick and overburden of a maximum of about 3,000 feet.

Two reasons for the large amount of coal in the region are that there is less than 3,000 feet of overburden throughout most of the coal field and the coal beds occur layered in a more or less vertical sequence like a stack of plates rather than spread out in a few beds over a wide area as occurs in many other coal fields in the Western Interior. For example, a single coal lease in many townships will include as many as eight potentially minable coal beds with 1,500 or less feet of overburden.

Kaiparowits coals are generally considered best suited for coal-fired, steam electric generating plants, but another potential use involves conversion to liquid hydrocarbons. A conservative estimate is that 1 ton of coal will yield the equivalent in liquid hydrocarbons of two or more barrels of crude petroleum. Considering that 4 billion tons of coal in the field are potentially recoverable, the Kaiparowits coal field could produce the equivalent of approximately 8 billion barrels of crude petroleum. This figure can be compared with some of the largest oil fields in the United States: the East Texas field had an original reserve of about 6 billion barrels, and the newly discovered Prudhoe Bay field in Alaska is estimated to contain about 5-10 billion barrels of oil (Burke and Gardner, 1969).

Coal production in the southeastern Kaiparowits region has been relatively insignificant and limited to the unsuccessful endeavors of C. H. Spencer during about 1910-12. Production from the mine in the Dakota

Formation located in a small tributary canyon to Warm Creek canyon was about 145 tons (Waldrop and Peterson, 1966). The other Spencer mine in the Straight Cliffs Formation located in Tibbet Canyon produced 115 tons (Grose and others, 1967, p. 58). Production from mines in other parts of the region are given by Grose, Hileman, and Ward (1967) who estimate that only about 25,000 tons of coal have been produced from the entire coal field.

Some of the most significant problems affecting the development of the coal field include (1) isolation from potential markets and sources of supply, (2) the rugged character of the terrain, and (3) the need for underground mining in most of the region. Some of the specific mining problems are discussed by Grose, Hileman, and Ward (1967, p. 60-62).

Oil and Gas Exploration

The various stratigraphic relations in the Cretaceous formations have some bearing on oil and gas exploration. Once formed, oil and gas are capable of migrating considerable distances if porosity and permeability are adequate and the structural framework of the region is favorable. This study has utilized several methods of determining the evolution of the structures in the region, and it seems likely that these methods could be used in other regions in attempting to determine the history of migration of oil and gas. The thickness and distribution of coal beds comprise some of the best evidence of former structural movements and, therefore, indirectly of oil and gas migration, but exploration geologists commonly do not consider coal in their studies. This report has indicated that the coal can offer clues to oil and gas migration and that it should at least be considered along with the more commonly used exploration techniques.

An example of this concerns the possibility of hydrocarbons in ancestral Rees Canyon anticline. If oil and gas were present in this fold and if porosity and permeability were adequate, the hydrocarbons probably would have migrated southeast up the flank of the ancestral Kaiparowits structural basin to the area of the present Rock Creek anticline, or possibly farther southeast. Subsequent downfolding of Grand Bench monocline divided the ancestral fold into two anticlines, of which the present Rees Canyon anticline offers the least potential for trapped oil and gas. Three wells have been drilled on the Rees Canyon anticline and these were dry, as would be expected by this study, but the Rock Creek anticline has not been drilled because it is in relatively inaccessible terrain. This study, aided mainly by an evaluation of the coal deposits, indicates that the Rock Creek anticline is the better exploration target for oil and gas.

Ground Water

Several of the sandstone units in the region contain water that could be developed in sufficient quantities for limited endeavors. The Tibbet Canyon and Drip Tank Members of the Straight Cliffs Formation and the upper sandstone unit of the Wahweap Formation are probably the best aquifers in the region, and springs have been found in each of these units at the heads of many canyons. In addition, springs have been found at the base of many of the barrier sandstone beds in the John Henry Member of the Straight Cliffs Formation, particularly the A, C, and G sandstone beds. The water has not been analyzed, but the writer and several acquaintances have tasted it or used it for several days at a time with no ill effects. The Calico bed in the Smoky Hollow Member of the Straight Cliffs and the various barrier sandstone beds in the upper member of the Dakota Formation are cemented by calcite or contain relatively large quantities of silt- and clay-size materials which have reduced the porosity and permeability and left them as poor units for potential ground-water development. The only reliable sources of large quantities of ground water are the Triassic and Jurassic eolian sandstone formations which probably are recharged by underground seepage from Lake Powell.

Black Sandstone Deposits

The black sandstone deposits are a potential source of titanium, zirconium, and other heavy metals, but the isolation of the region and the economic factors noted by Dow and Batty (1961) make it unlikely that the deposits can be developed in the near future. The deposits were not studied in detail, but this study has indicated that future underground prospecting for more of these deposits should be directed to the area on the crest or northeast flank of the ancestral Rees Canyon anticline.

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APPENDIX

Fossil Localities

[All fossil locality numbers are USGS Mesozoic locality numbers unless otherwise noted]

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
DAKOTA FORMATION					
Lower member					
52	-----	F. Peterson 1964	N. Hotton 3d D.H. Dunkle	Turtle, undet.	Pl. 6, sec. 52.
Middle member					
14	D3753 (USGS paleobot. loc.)	H.A. Waldrop 1965	R.A. Scott	Fossils similar to colln. 50 but lacks tricolpate and other complex pollen grains.	Pl. 6, sec. 3. Could be older than Albian.
20	D6421	do., 1964	W.A. Cobban	*Unio* n. sp.	Pl. 6, sec. 7.
50	-----	do., 1964	R.A. Scott	Spores and pollen *Cicatricosisporites* *Appendicisporites* *Gleicheniidites* *Monosulcites* *Tricolpopollenites* *Retitricolpites* Fragmentary wood tissue Resin blebs	Pl. 6, sec. 19. Albian or younger age.
135	D3786 (USGS paleobot. loc.)	F. Peterson 1965	R.H. Tschudy	Spores and pollen *Botryococcus* *Anemia* *Gleichenia* Fern spores Monosulcate and tricolpate pollen Bisaccate conifer pollen	Pl. 7, sec. 85. Albian or Cenomanian age.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
DAKOTA FORMATION--continued					
Upper member Zone of *Dunveganoceras pondi* Haas					
12	D4622	H.A. Waldrop 1964	W.A. Cobban	*Ostrea prudentia* White *Brachidontes* sp.	Pl. 6, sec. 2.
51	D4351	do., 1963	do.	*Ostrea* sp.	Pl. 6, sec. 52.
57	-----	do., 1963	do.	*Ostrea* sp. *Brachidontes* sp.	Pl. 6, sec. 22.
61	-----	do., 1963	do.	*Ostrea* sp. *Corbicula*? sp.	Pl. 6, sec. 25.
64	D4624	do., 1963	do.	*Ostrea* sp. *Brachidontes multilinigera* (Meek)	Pl. 6, sec. 26.
76	D5080	do., 1965	do.	*Ostrea prudentia* White *Ostrea* sp.	Pl. 6, sec. 2.
113	D4350	H.A. Waldrop F. Peterson 1963	do.	*Ostrea* sp. *Brachidontes multilinigera* (Meek) *Cardium* sp.	Pl. 6, sec. 29.
114	-----	do., 1963	do.	*Ostrea* sp.	Pl. 6, sec. 29.
115	D5230	F. Peterson 1964	F. Peterson	*Brachidontes multilinigera* (Meek)	Pl. 6, sec. 31.
118	-----	do., 1964	do.	*Ostrea prudentia* White *Ostrea* sp.	Pl. 6, sec. 35.
119	D5237	do., 1965	do.	*Plicatula hydrotheca* White	Pl. 6, sec. 35.
136	-----	do., 1965	do.	*Ostrea prudentia* White *Ostrea* sp.	Pl. 7, sec. 101.
202	-----	do., 1966	do.	*Barbatia* sp. *Ostrea* sp. *Anomia* sp. *Lucina* sp. *Corbula* sp.	Pl. 8, sec. 115.
407	-----	do., 1965	do.	*Ostrea* sp. *Corbula* sp.	Pl. 8, sec. 140.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
DAKOTA FORMATION AND TROPIC SHALE					
Zone of *Dunveganoceras conditum* Haas					
25	-----	F. Peterson 1965	F. Peterson	*Corbula* sp. Fish scale, undet.	Pl. 6, sec. 11.
35	-----	do., 1964	N. Hotton 3d D.H. Dunkle F. Peterson	*Corbicula*? sp. Osteichthyes Pycnodontoid tooth, undet.	Pl. 6, sec. 18.
36	-----	do., 1965	F. Peterson	*Cardium* cf. *C. pauperculum* Meek	Pl. 6, sec. 18.
129	-----	do., 1964	do.	*Exogyra levis* Stephenson	Pl. 7, sec. 79.
137	-----	do., 1965	do.	*Exogyra levis* Stephenson	Pl. 7, sec.101.
201	D5232	do., 1964	do.	*Exogyra levis* Stephenson	Pl. 8, sec.114.
203	D5231	do., 1964	do.	*Exogyra levis* Stephenson *Plicatula hydrotheca* White	Pl. 8, sec.115.
301	D5233	do., 1964	do.	*Exogyra levis* Stephenson *E. olisiponensis* Sharpe *Plicatula* cf. *P. hydrotheca* White	Pl. 7, sec.100.
304	D5238	do., 1965	do.	*Exogyra levis* Stephenson	Pl. 8, sec.133.
401	D5240	do., 1965	do.	*Ostrea* sp. *Cardium* sp.	Pl. 8, sec.138.
406	D5239	do., 1965	W.A. Cobban F. Peterson	*Pinna petrina* White *Phelopteria* sp. *Ostrea* sp. *Exogyra levis* Stephenson *E. olisiponensis* Sharpe *Plicatula* sp. *Cardium* sp. *Callistina*? sp. *Corbula* sp. *Gyrodes*? sp. *Metoicoceras defordi* Young	Pl. 8, sec.140.
408	D6054	do., 1966	W.A. Cobban	*Metoicoceras* cf. *M. whitei* Hyatt	Pl. 8, sec.137.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
DAKOTA FORMATION AND TROPIC SHALE--continued					
Zone of *Dunveganoceras albertense* (Warren)					
10	D5235	F. Peterson 1965	F. Peterson	*Exogyra levis* Stephenson *E. olisiponensis* Sharpe	Pl. 6, sec. 1.
21	D5234	do., 1965	do.	*Ostrea prudentia* White *Exogyra levis* Stephenson *E. olisiponensis* Sharpe	Pl. 6, sec. 9.
26	-----	do., 1965	do.	*Gryphaea newberryi* Stanton *Plicatula hydrotheca* White	Pl. 6, sec. 11.
32	D5241	do., 1965	do.	*Ostrea* sp. *Brachidontes multilinigera* (Meek) *Corbula* sp.	Pl. 6, sec. 31.
33	D5274	do., 1965	W.A. Cobban F. Peterson	*Inoceramus* aff. *I. concentricus* Parkinson *Cymbophora*? sp. *Corbula* sp.	Pl. 6, sec. 31.
37	D5236	do., 1965	do.	*Inoceramus* sp. *Corbula*? sp. *Neocardioceras*? sp.	Pl. 6, sec. 18.
38	-----	do., 1964	N. Hotton 3d D.H. Dunkle F. Peterson	*Exogyra levis* Stephenson Chondrichthyes *Scapanorhynchus subulatus* (Agassiz)	Pl. 6, sec. 18.
TROPIC SHALE					
Zone of *Sciponoceras gracile* (Shumard)					
9	D4623	H.A. Waldrop 1964	W.A. Cobban	*Gryphaea newberryi* Stanton *Exogyra olisiponensis* Sharpe *Parmicorbula*? sp. *Euspira* sp. *Sciponoceras gracile* (Shumard)	Pl. 6, sec. 1.
11	D4627	do., 1964	do.	*Exogyra olisiponensis* Sharpe *Cerithium* sp. *Sciponoceras gracile* (Shumard) *Allocrioceras annulatum* (Shumard)	Pl. 6, sec. 1.
13	D4626	do., 1964	do.	*Gryphaea newberryi* Stanton *Turritella whitei* Stanton *Sciponoceras gracile* (Shumard)	Pl. 6, sec. 2.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
				TROPIC SHALE--continued	
				Zone of Sciponoceras gracile (Shumard)--continued	
16	D5243	F. Peterson 1965	F. Peterson	Inoceramus sp. Gryphaea newberryi Stanton Exogyra sp. Psilomya meeki (White) Lucina subundata Hall and Meek Euspira sp. Cerithium? sp. Sciponoceras gracile (Shumard) Allocrioceras annulatum (Shumard) Metoicoceras whitei Hyatt	Pl. 6, sec. 4.
18	D4625	H.A. Waldrop 1964	W.A. Cobban	Gryphaea newberryi Stanton Sciponoceras gracile (Shumard) Metoicoceras whitei Hyatt	Pl. 6, sec. 5.
19	D5252	F. Peterson 1965	F. Peterson	Solemya? obscura Stanton Gryphaea newberryi Stanton Psilomya meeki (White) Lucina subundata Hall and Meek Corbula kanabensis Stanton Euspira sp. Turritella whitei Stanton Drepanochilus ruida (White) Sciponoceras gracile (Shumard) Allocrioceras annulatum (Shumard) Worthoceras sp. Kanabiceras septemseriatum (Cragin) Metoicoceras whitei Hyatt	Pl. 6, sec. 6.
22	D5244	do., 1964	do.	Solitary coral, undet. Serpula intrica White Inoceramus sp. Lucina sp.	Pl. 6, sec. 9.
24	D4628	H.A. Waldrop 1964	W.A. Cobban	Inoceramus sp. Exogyra sp. Camptonectes platessa White Psilomya meeki (White) Lucina sp. Parmicorbula? sp. Sciponoceras gracile (Shumard) Allocrioceras annulatum (Shumard) Metoicoceras whitei Hyatt	Pl. 6, sec. 10.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
TROPIC SHALE--continued					
Zone of *Sciponoceras gracile* (Shumard)--continued					
27	D5251	F. Peterson 1965	F. Peterson	*Camptonectes platessa* White *Psilomya meeki* (White) *Lucina subundata* Hall and Meek *Corbula* sp. *Sigaretus* (*Eunaticina*?) *textilis* Stanton *Euspira* sp. *Sciponoceras gracile* (Shumard) *Allocrioceras annulatum* (Shumard)	Pl. 6, sec. 11.
28	-----	do., 1964	J.F. Mello	Foraminifera *Nodosaria* cf. *N. obscura* Reuss *Citharina*? sp. *Dentalina* sp. *Lagena*? sp. *Neobulimina canadensis* Cushman and Wickenden *Bulimina reussi* Morrow var. *navarroensis* Cushman and Parker *Guembelitria cretacea* Cushman *Heterohelix moremani* (Cushman) *Hedbergella planispira* (Tappan) *H.* cf. *H. delrioensis* (Carsey) *Planulina dakotensis* (Fox) *Virgulina tegulata* Reuss	Pl. 6, sec. 11.
28	D5254	do., 1964	F. Peterson	Annelida *Serpula intrica* White Mollusca *Solemya*? *obscura* Stanton *Gryphaea newberryi* Stanton *Exogyra* sp. *Camptonectes platessa* White *Lima utahensis* Stanton *Psilomya meeki* (White) *Lucina subundata* Hall and Meek *Corbula kanabensis* Stanton *Sigaretus* (*Eunaticina*?) *textilis* Stanton *Euspira* sp. *Turritella whitei* Stanton *Arrhoges prolabiata* (White) *Sciponoceras gracile* (Shumard) *Allocrioceras annulatum* (Shumard) *Kanabiceras septemseriatum* (Cragin) *Metoicoceras whitei* Hyatt	Pl. 6, sec. 11.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
TROPIC SHALE--continued					
Zone of *Sciponoceras gracile* (Shumard)--continued					
28	-----	F. Peterson 1964	J.E. Hazel	Ostracoda *Cythereis eaglefordensis* Alexander	Pl. 6, sec. 11.
30	D5255	do., 1964	F. Peterson	*Serpula intrica* White *Solemya*? *obscura* Stanton *Gryphaea newberryi* Stanton *Exogyra* sp. *Psilomya meeki* (White) *P. concentrica* (Stanton) *Lucina subundata* Hall and Meek *Corbula kanabensis* Stanton *Sigaretus* (*Eunaticina*?) *textilis* Stanton *Euspira* sp. *Turritella whitei* Stanton *Drepanochilus ruida* (White) *Arrhoges prolabiata* (White) *Sciponoceras gracile* (Shumard) *Allocrioceras annulatum* (Shumard) *Worthoceras* sp. *Kanabiceras septemseriatum* (Cragin)	Pl. 6, sec. 13.
31	D4353	H.A. Waldrop F. Peterson 1963-64	W.A. Cobban F. Peterson	*Trochocyathus*? sp. *Gryphaea newberryi* Stanton *Turritella whitei* Stanton *Sciponoceras gracile* (Shumard) *Allocrioceras annulatum* (Shumard) *Actinocamax* sp.	Pl. 6, sec. 14.
39	D5258	F. Peterson 1964	F. Peterson	*Inoceramus* sp. *Gryphaea newberryi* Stanton *Exogyra* sp. *Turritella whitei* Stanton *Sciponoceras gracile* (Shumard) *Kanabiceras septemseriatum* (Cragin)	Pl. 6, sec. 18.
53	-----	do., 1964	do.	*Serpula intrica* White *Gryphaea newberryi* Stanton *Exogyra olisiponensis* Sharpe *Exogyra* sp. *Botula*? sp. *Psilomya meeki* (White) *Turritella whitei* Stanton *Drepanochilus ruida* (White) *Sciponoceras gracile* (Shumard) *Kanabiceras septemseriatum* (Cragin) *Metoicoceras whitei* Hyatt	Pl. 6, sec. 20.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
			TROPIC SHALE--continued		
			Zone of *Sciponoceras gracile* (Shumard)--continued		
58	D5256	F. Peterson 1964	F. Peterson	*Gryphaea newberryi* Stanton *Exogyra olisiponensis* Sharpe *Exogyra* sp.	Pl. 6, sec. 22.
62	D5259	do., 1964	do.	*Arrhoges prolabiata* (White) *Sciponoceras gracile* (Shumard)	Pl. 6, sec. 25.
101	D5253	do., 1964	do.	*Serpula intrica* White *Solemya*? *obscura* Stanton *Gryphaea newberryi* Stanton *Exogyra* sp. *Camptonectes platessa* White *Lima utahensis* Stanton *Psilomya meeki* (White) *P. concentrica* (Stanton) *Veniella mortoni* Hall and Meek *Lucina subundata* Hall and Meek *Corbula kanabensis* Stanton *Euspira* sp. *Turritella whitei* Stanton *Cerithium*? sp. *Sciponoceras gracile* (Shumard)	Pl. 6, sec. 28.
117	-----	do., 1964	do.	*Serpula intrica* White *Gryphaea newberryi* Stanton *Exogyra* sp. *Camptonectes platessa* White *Psilomya meeki* (White) *Euspira* sp. *Turritella whitei* Stanton *Sciponoceras gracile* (Shumard)	Pl. 6, sec. 34.
120	-----	do., 1964	do.	*Serpula intrica* White *Solemya*? *obscura* Stanton *Gryphaea newberryi* Stanton *Exogyra* sp. *Psilomya meeki* (White) *P. concentrica* (Stanton) *Lucina subundata* Hall and Meek *Corbula kanabensis* Stanton *Sigaretus* (*Eunaticina*?) *textilis* Stanton *Euspira* sp. *Turritella whitei* Stanton *Cerithium*? sp. *Drepanochilus ruida* (White) *Arrhoges prolabiata* (White) *Mesorhytis*? *walcotti* Stanton *Sciponoceras gracile* (Shumard) *Allocrioceras annulatum* (Shumard) *Worthoceras* sp. *Kanabiceras septemseriatum* (Cragin) *Metoicoceras whitei* Hyatt	Pl. 6, sec. 35.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
TROPIC SHALE--continued					
Zone of Sciponoceras gracile (Shumard)--continued					
120	-----	F. Peterson 1964	N. Hotton 3d D.H. Dunkle	Chondrichthyes *Oxyrhina* cf. *O. angustidens* Reuss Osteichthyes Pycnodontoid tooth, undet.	Pl. 6, sec. 35.
127	D5260	do., 1964	F. Peterson	*Serpula intrica* White *Gryphaea newberryi* Stanton *Exogyra* sp. *Lucina subundata* Hall and Meek *Corbula kanabensis* Stanton *Euspira* sp. *Turritella whitei* Stanton *Cerithium*? sp. *Drepanochilus ruida* (White) *Arrhoges prolabiata* (White) *Sciponoceras gracile* (Shumard)	Pl. 6, sec. 41.
130	D5247	do., 1965	do.	*Gryphaea newberryi* Stanton *Exogyra* sp. *Euspira* sp. *Arrhoges prolabiata* (White) *Sciponoceras gracile* (Shumard) *Metoicoceras whitei* Hyatt	Pl. 7, sec. 82.
138	D5250	do., 1965	do.	*Serpula intrica* White *Gryphaea newberryi* Stanton *Exogyra* sp. *Veniella mortoni* Hall and Meek *Lucina subundata* Hall and Meek *Corbula kanabensis* Stanton *Euspira* sp. *Turritella whitei* Stanton *Cerithium*? sp. *Arrhoges prolabiata* (White) *Mesorhytis*? *walcotti* Stanton *Sciponoceras gracile* (Shumard) *Allocrioceras annulatum* (Shumard) *Kanabiceras septemseriatum* (Cragin) *Metoicoceras whitei* Hyatt	Pl. 7, sec. 105.
204	-----	do., 1966	do.	*Serpula intrica* White *Inoceramus* cf. *I. pictus* Sowerby *Arrhoges prolabiata* (White) *Sciponoceras gracile* (Shumard) *Metoicoceras whitei* Hyatt	Pl. 8, sec.116.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
TROPIC SHALE--continued					
Zone of Sciponoceras gracile (Shumard)--continued					
205	D5249	F. Peterson 1964	F. Peterson	Serpula intrica White Solemya? obscura Stanton Inoceramus cf. I. pictus Sowerby Ostrea sp. Gryphaea newberryi Stanton Exogyra sp. Lucina subundata Hall and Meek Corbula kanabensis Stanton Sigaretus (Eunaticina?) textilis Stanton Euspira sp. Turritella whitei Stanton Arrhoges prolabiata (White) Sciponoceras gracile (Shumard) Allocrioceras annulatum (Shumard) Kanabiceras septemseriatum (Cragin) Metoicoceras whitei Hyatt Chondrichthyes Shark tooth, undet.	Pl. 8, sec.115.
404	-----	do., 1965	do.	Serpula intrica White Gryphaea newberryi Stanton Camptonectes platessa White Psilomya meeki (White) Corbula kanabensis Stanton Euspira sp. Turritella whitei Stanton Drepanochilus ruida (White) Arrhoges prolabiata (White) Sciponoceras gracile (Shumard) Allocrioceras annulatum (Shumard) Metoicoceras whitei Hyatt	Pl. 8, sec.140.
405	D5246	do., 1965	do.	Solemya? obscura Stanton Gryphaea newberryi Stanton Exogyra sp. Lucina subundata Hall and Meek Corbula kanabensis Stanton Sigaretus (Eunaticina?) textilis Stanton Euspira sp. Turritella whitei Stanton Sciponoceras gracile (Shumard) Allocrioceras annulatum (Shumard) Metoicoceras whitei Hyatt	Pl. 8, sec.140.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
				TROPIC SHALE--continued	
				Zone of *Inoceramus labiatus* Schlotheim	
17	D5269	F. Peterson 1965	F. Peterson	*Inoceramus* cf. *I. labiatus* (Schlotheim)	Pl. 6, sec. 4.
23	D5270	do., 1965	W.A. Cobban F. Peterson	*Inoceramus labiatus* (Schlotheim) *Lucina subundata* Hall and Meek *Kanabiceras* sp. *Watinoceras*? sp.	Pl. 6, sec. 9.
29	D5268	do., 1965	F. Peterson	*Inoceramus labiatus* (Schlotheim) *Phelopteria* cf. *P. gastrodes* (Meek) *Lucina subundata* Hall and Meek *Watinoceras*? sp. Decapod chela, undet.	Pl. 6, sec. 11.
40	D5264	do., 1964	do.	*Inoceramus labiatus* (Schlotheim)	Pl. 1, sec. T1; 175 ft above base of formation.
41	D5265	do., 1964	do.	Planktonic Foraminifer, undet. *Ostrea* sp.	Pl. 1, sec. T1; 271 ft above base of formation.
42	-----	do., 1964	J.F. Mello	Foraminifera *Bulimina* sp. *Heterohelix moremani* (Cushman) *Hedbergella* cf. *H. delrioensis* (Carsey) ?*Ticinella aprica* Leoblich and Tappan *Planulina dakotensis* Fox	Pl. 1, sec. T1; 280 ft above base of formation.
42	D5266	do., 1964	F. Peterson	Mollusca *Inoceramus labiatus* (Schlotheim) *Ostrea* sp. *Lucina subundata* Hall and Meek *Rostellites*? sp. *Baculites* sp. *Watinoceras*? sp.	Do.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
TROPIC SHALE--continued					
Zone of *Inoceramus labiatus* Schlotheim--continued					
43	-----	F. Peterson 1964	J.F. Mello	Foraminifera *Proteonina difflugiformis* (H. B. Brady) *Haplofragmoides*? sp. *Dentalina*? sp. *Frondicularia* sp. *Marginulinopsis*? sp. *Heterohelix moremani* (Cushman) *Hedbergella* cf. *H. delrioensis* (Carsey)	Pl. 1, sec. T1; 286 ft above base of formation.
55	D5263	do., 1964	F. Peterson	*Inoceramus labiatus* (Schlotheim) *Ostrea* sp.	Pl. 1, sec. 22; 116-120 ft above base of formation.
55	-----	do., 1964	N. Hotton 3d D.H. Dunkle	Chondrichthyes *Oxyrhina* cf. *O. angustidens* Reuss Shark vertebra, undet. *Ptychodes whipplei* Marcou *P.* cf. *P. polygyrus* Agassiz	Do.
56	D5262	do., 1964	F. Peterson	*Inoceramus* sp. *Ostrea* sp. *Lucina* sp.	Pl. 1, sec. 22; 85 ft above base of formation.
56	-----	do., 1964	N. Hotton 3d D.H. Dunkle	Osteichthyes *Xiphactinus audax* Leidy	Do.
63	D5261	do., 1964	F. Peterson	*Inoceramus labiatus* (Schlotheim) *Phelopteria* cf. *P. gastrodes* (Meek) *Lucina subundata* Hall and Meek *Corbula* sp. *Drepanochilus ruida* (White) *Watinoceras*? sp. Fish scales, undet.	Pl. 6, sec. 25.
65	D4365	H.A. Waldrop 1963	W.A. Cobban	*Inoceramus labiatus* (Schlotheim) *Ostrea* sp.	Pl. 1, sec. T1; 90 ft above base of formation.

TROPIC SHALE--continued

Zone of *Inoceramus labiatus* Schlotheim--continued

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
102	D4355	H.A. Waldrop F. Peterson 1963	W.A. Cobban	*Inoceramus labiatus* (Schlotheim) *Ostrea* sp. *Mammites* sp.	Pl. 1, sec. T2; 65 ft above base of formation.
103	D4356	do., 1963	do.	*Inoceramus labiatus* (Schlotheim) *Ostrea* sp. *Watinoceras*? sp.	Pl. 1, sec. T2; 135 ft above base of formation.
104	D4357	do., 1963	do.	*Inoceramus labiatus* (Schlotheim)	Pl. 1, sec. T2; 141 ft above base of formation.
105	D4359	do., 1963	do.	*Inoceramus labiatus* (Schlotheim) *Metoicoceras* sp.	Pl. 1, sec. T2; 150 ft above base of formation.
106	D4358	do., 1963	do.	*Inoceramus labiatus* (Schlotheim) *Anomia* sp. *Drepanochilus ruida* (White)	Pl. 1, sec. T2; 180 ft above base of formation.
107	D4360	do., 1963	do.	*Inoceramus labiatus* (Schlotheim) *Baculites* sp.	Pl. 1, sec. T2; 220 ft above base of formation.
112	D4354	do., 1963	do.	*Inoceramus* sp. *Drepanochilus ruida* (White) *Baculites*? sp. *Kanabiceras*? sp. *Watinoceras*? sp.	Pl. 1, sec. T2; 80 ft above base of formation.
122	D5271	F. Peterson 1965	W.A. Cobban F. Peterson	*Inoceramus labiatus* (Schlotheim) *Baculites* sp. *Neocardioceras* sp. *Watinoceras*? sp.	Pl. 6, sec. 35.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
TROPIC SHALE--continued					
Zone of *Inoceramus labiatus* Schlotheim--continued					
131	D5273	F. Peterson 1965	F. Peterson	*Inoceramus labiatus* (Schlotheim) *Ostrea* sp. Chondrichthyes Shark teeth, undet. *Ptychodus* sp.	Pl. 1, sec. T5; 120-130 ft above base of formation.
142	-----	do., 1964	N. Hotton 3d D.H. Dunkle	Reptilia Mosasaur (small), undet. Chondrichthyes Shark vertebra, undet. *Ptychodus whipplei* Marcou	Pl. 1, sec. 35; 100-250 ft above base of formation.
206	D5267	do., 1964	F. Peterson	*Ostrea* sp. *Gryphaea* sp.	Pl. 8, sec.115.
207	-----	do., 1964	do.	*Inoceramus labiatus* (Schlotheim) *Ostrea* sp.	Pl. 1, sec. T7; 96 ft above base of formation.
208	-----	do., 1964	do.	*Inoceramus labiatus* (Schlotheim)	Pl. 1, sec. T7; 147 ft above base of formation.
403	D5272	do., 1965	do.	*Inoceramus labiatus* (Schlotheim) *Phelopteria* sp. *Drepanochilus ruida* (White) *Watinoceras*? sp. Fish scale, undet.	Pl. 8, sec.140.
Zone of *Collignoniceras woollgari* (Mantell)					
44	D5276	do., 1964	do.	*Collignoniceras woollgari* (Mantell)	Pl. 1, sec. T1; 403 ft above base of formation.
45	-----	do., 1964	do.	*Collignoniceras woollgari* (Mantell)	Pl. 1, sec. T1; 509 ft above base of formation.

TROPIC SHALE--continued

Zone of Collignoniceras woollgari (Mantell)--continued

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
46	-----	F. Peterson 1964	F. Peterson	Collignoniceras woollgari (Mantell)	Pl. 1, sec. T1; 511-541 ft above base of formation.
108	D4361	H.A. Waldrop F. Peterson 1963	W.A. Cobban	Inoceramus sp. Ostrea sp. Baculites sp. Collignoniceras woollgari (Mantell)	Pl. 1, sec. T2; 315-340 ft above base of formation.
109	D4363	do., 1963	do.	Ostrea sp. Collignoniceras woollgari (Mantell)	Pl. 1, sec. T2; 325 ft above base of formation.
110	D4364	do., 1963	do.	Ostrea sp. Collignoniceras woollgari (Mantell)	Pl. 1, sec. T2; 380-400 ft above base of formation.
111	D4362	do., 1963	do.	Ostrea sp. Collignoniceras woollgari (Mantell)	Pl. 1, sec. T2; 406 ft above base of formation.
132	D5281	F. Peterson 1965	F. Peterson	Inoceramus sp. Collignoniceras woollgari (Mantell)	Pl. 1, sec. T5; 371 ft above base of formation.
133	D5278	do., 1965	do.	Collignoniceras woollgari (Mantell) Fish scale, undet.	Pl. 1, sec. T5; 396 ft above base of formation.
134	D5280	do., 1965	do.	Yoldia? sp. Inoceramus sp. Cardium sp. Collignoniceras woollgari (Mantell)	Pl. 1, sec. T5; 616-621 ft above base of formation.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
TROPIC SHALE--continued					
Zone of Collignoniceras woollgari (Mantell)--continued					
209	-----	F. Peterson 1964	F. Peterson	Inoceramus sp. Ostrea sp. Collignoniceras woollgari (Mantell)	Pl. 1, sec. T7; 372 ft above base of formation.
210	D5277	do., 1964	do.	Collignoniceras woollgari (Mantell)	Pl. 1, sec. T7; 467-471 ft above base of formation.
402	D5279	do., 1965	do.	Collignoniceras woollgari (Mantell)	Pl. 1, sec. T8; 394 ft above base of formation.
TROPIC SHALE AND TIBBET CANYON MEMBER OF STRAIGHT CLIFFS FORMATION					
Zone of Collignoniceras hyatti (Stanton)					
67	D5300	do., 1964	do.	Inoceramus howelli White	Pl. 9, sec. S12; in talus from Tibbe Cany. Mbr.
69	D4366	H.A. Waldrop F. Peterson 1963-64	W.A. Cobban	Inoceramus howelli White Crassostrea soleniscus (Meek) Cymbophora sp. Gyrodes conradi Meek G. depressus Meek Cryptorhytis utahensis (Meek) Heterotissotia? sp.	Pl. 9, sec. S14.
69	-----	do., 1963-64	N. Hotton 3d D.H. Dunkle	Chondrichthyes Scapanorhynchus raphiodon (Agassiz)	Pl. 9, sec. S14.
72	D5302	F. Peterson 1964	F. Peterson	Inoceramus sp. Ostrea sp. Corbicula? sp. Cardium sp. Cymbophora? sp. Corbula? sp. Gastropod fragments, undet.	Pl. 9, sec.S16.

TROPIC SHALE AND TIBBET CANYON MEMBER OF STRAIGHT CLIFFS FORMATION--contd

Zone of *Collignoniceras hyatti* (Stanton)--continued

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
73	-----	F. Peterson 1964	F. Peterson	*Crassostrea soleniscus* (Meek)	Pl. 9, sec.S13.
123	-----	do., 1964	do.	*Crassostrea soleniscus* (Meek) *Brachidontes*? sp. Gastropod fragments, undet.	Pl. 10, sec.S18.
128	D5299	do., 1964	do.	*Inoceramus howelli* White	Pl. 1, sec. T4; in talus from Tibbe Cany. Mbr.
139	-----	do., 1965	do.	*Inoceramus* sp. *Ostrea*? sp. *Corbula* sp. Gastropod fragments, undet.	Pl. 10, sec.S22.
141	-----	do., 1964	do.	*Ostrea* sp. *Cardium* cf. *C. pauperculum* Meek	Pl. 10, sec. S20.
211	-----	do., 1964	do.	*Inoceramus* sp. *Cardium* cf. *C. pauperculum* Meek *Cymbophora*? sp.	Pl. 1, sec.S29; in Tibbet Cany. Mbr. 75 ft above base.
212	D5303	do., 1964	do.	*Inoceramus howelli* White	Pl. 1, sec.S29; in talus from Tibbe Cany. Mbr.
302	-----	do., 1965	do.	*Cardium* cf. *C. pauperculum* Meek	Pl. 11, sec.S30.
305	-----	do., 1965	do.	*Cardium* cf. *C. pauperculum* Meek	Pl. 11, sec.S34.
703	D6056	do., 1967	W.A. Cobban	*Inoceramus* sp. *Ostrea* sp. *Legumen* cf. *L. ellipticum* Conrad	Pl. 11, sec. S6; in talus; the inocer am resembl an undescribed species frc *Collignoniceras hyatti* zone of Black Hills region

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
JOHN HENRY MEMBER OF STRAIGHT CLIFFS FORMATION					
Barren and coal zones					
145	D3785 (USGS paleobot. loc.)	R. McCurdy 1965	R.H. Tschudy	Spores and pollen *Cicatricosisporites* *Appendicisporites* *Lycopodiumsporites* *Gleicheniidites* *Verrucatosporites* *Taurocusporites* *Ceratosporites*? *Krauselisporites* *Laevigatosporites* *Inaperturopollenites* *Monosulcites* *Classopollis* *Abietineaepollenites* *Rugubivesiculites* *Vitreisporites* *Araucariacites* *Ephedra* *Eucommiidites* *Proteacidites* *Triatriopollenites* *Plicapollis* *Latipollis*? *Sporopollis*? *Tricolpopollenites* *Tricolporites* *Nyssapollenites* *Periporopollenites*	From drill hole in the SE¼NW¼ sec. 34, T. 41 S. R. 4 E. Cuttings and core samples from each barren and coal zone in member. Sampled interval about 84-552 ft above base of member.
Christensen coal zone					
66	-----	F. Peterson 1964	F. Peterson	*Unio*? sp.	Pl. 9, sec. S12.
144	-----	do., 1965	do.	*Crassostrea soleniscus* (Meek) *Brachidontes* sp.	Pl. 10, sec. S22.
501	D5058	G.A. Izett 1965	W.A. Cobban	*Serpula* cf. *S. tenuicarinata* Meek and Hayden *Crassostrea soleniscus* (Meek) *Anomia* sp. *Brachidontes* sp.	NW¼NW¼ sec. 34, T. 40 S., R. 4 E.; from about middle of formation.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
JOHN HENRY MEMBER OF STRAIGHT CLIFFS FORMATION--continued					
Christensen coal zone--continued					
502	D5059	G.A. Izett 1965	W.A. Cobban	*Crassostrea soleniscus* (Meek) *Anomia* sp. *Brachidontes* sp. *Corbula* sp.	Center, sec. 25, T. 40 S., R. 4 E.; from about middle of formation.
513	D6058	F. Peterson 1967	W.A. Cobban N.F. Sohl	Calcareous worm tube *Inoceramus* cf. *I. mesabiensis* Berquist "*Corbula*" sp. *Stenomelania*? sp. *Pachychiloides*? sp. Ammonite fragment, undet.	Pl. 11, sec. S5.
514	D6059	do., 1967	W.A. Cobban	Bryozoan, undet. *Crassostrea coalvillensis* (Meek) *C. soleniscus* (Meek) *Brachidontes* sp.	Pl. 11, sec. S5.
516	-----	do., 1967	F. Peterson	*Crassostrea soleniscus* (Meek) *Anomia* sp.	Pl. 10, sec. S23.
Middle barren zone					
74	D4629	do., 1964	W.A. Cobban	*Anomia*? sp. *Cymbophora*? sp. *Melania*? sp.	SE¼NW¼ sec. 4, T. 42 S., R. 2 E.; 373 ft above base of member.
Rees coal zone					
140	D5301	do., 1964	F. Peterson	*Crassostrea soleniscus* (Meek)	Pl. 10, sec. S21.
Upper barren zone					
60	10034 (USGS paleobot. loc.)	H.A. Waldrop 1964	J.A. Wolfe	Palm leaves *Geonomites*? sp.	NW¼NW¼ sec.12 T. 43 S., R. 3 E.; 520 ft above base of member.
143	-----	do., 1967	do.	Conifer shoot impressions, undet., probably representative of Taxodiaceae	Pl. 10, sec. S19.
602	-----	G.A. Izett 1965	R. A. Scott	Coniferous wood, undet.	Center, sec. 7, T. 40 S., R.4 E.; upper part of member.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
JOHN HENRY MEMBER OF STRAIGHT CLIFFS FORMATION--continued					
Lower marine mudstone tongue					
213	-----	F. Peterson 1964	N. Hotton 3d D.H. Dunkle	Chondrichthyes *Lamna appendiculata* Agassiz	Pl. 1, sec. S29; from basal sandstone bed.
214	-----	do., 1964	F. Peterson	*Ostrea* sp. *Cardium* cf. *C. pauperculum* Meek	Pl. 1, sec. S29; 9 ft above base of member.
218	D5286	do., 1965	W.A. Cobban	*Inoceramus* sp. *Ostrea* sp. *Baculites asper* Morton *Scaphites* sp. *Placenticeras* sp.	NW¼NW¼ sec 36, T. 40 S., R. 7 E.; 70 ft below A sandstone bed.
307	-----	do., 1965	F. Peterson	*Inoceramus* cf. *I. stantoni* Sokolow *Ostrea* sp. *Ophiomorpha* sp.	Pl. 11, sec. S34; in talus block.
308	D5285	do., 1965	W.A. Cobban F. Peterson	*Inoceramus* sp. *Gyrodes* cf. *G. depressus* Meek *Placenticeras* sp. *Protexanites shoshonensis* (Meek) Chondrichthyes *Ptychodes* sp.	Pl. 11, sec. S34; indicates zone of *Scaphites depressus*.
311	D5288	do., 1965	W.A. Cobban	*Nucula* sp. *Inoceramus stantoni* Sokolow *Oxytoma* sp. *Ostrea* sp. *Anomia subquadrata* Stanton *Cardium* sp. *Tellina* sp. *Cymbophora* sp. *Dentalium* sp. *Gyrodes* aff. *G. depressus* Meek *Euspira*? sp. *Xenophora* sp. *Turritella* sp. *Anomalofusus*? sp. *Actaeon*? sp. *Baculites asper* Morton *Scaphites* sp. *Placenticeras* n. sp. Heteromorph ammonite, undet.	SW¼NW¼ sec. 23, T. 41 S., R. 7 E.; in talus block, possibly from the A sandstone bed.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
JOHN HENRY MEMBER OF STRAIGHT CLIFFS FORMATION--continued					
Lower marine mudstone tongue--continued					
508	-----	F. Peterson 1965	F. Peterson	*Inoceramus* sp. *Anomia*? sp. *Cardium* sp. Shark teeth, undet.	Pl. 10, sec. S27,
704	D6057	do., 1967	W.A. Cobban	*Baculites codyensis* Reeside *Placenticeras* sp. *Protexanites shoshonensis* (Meek)	Pl. 11, sec. S6; in talu indicates zone of *Scaphites depressus*.
A sandstone bed					
217	-----	do., 1964	F. Peterson	*Inoceramus* sp. *Ostrea congesta*? Conrad *Ostrea* sp.	Pl. 1, sec. S29; 86-15 ft above base of member.
503	D5305	do., 1965	do.	*Inoceramus* (*Volviceramus*) *involutus* Sowerby *Crassostrea soleniscus* (Meek) Shark teeth, undet.	Pl. 10, sec. S24,
504	D5284	do., 1965	W.A. Cobban F. Peterson	*Inoceramus* sp. *Ostrea congesta* Conrad *Crassostrea soleniscus* (Meek) *Gyrodes* cf. *G. depressus* Meek *Placenticeras* sp. Shark teeth, undet. Turtle carapace fragments, undet.	Pl. 10, sec. S24,
505	D5306	do., 1965	F. Peterson	*Crassostrea soleniscus* (Meek) *Cardium* cf. *C. curtum* Meek and Hayden *Cymbophora*? sp. Gastropod fragments, undet.	Pl. 10, sec. S24,
507	D5283	do., 1965	W.A. Cobban	*Baculites asper* Morton	Pl. 10, sec. S27; in talus,

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
JOHN HENRY MEMBER OF STRAIGHT CLIFFS FORMATION--continued					
A sandstone bed--continued					
511	D5304a	F. Peterson 1965	F. Peterson	_Inoceramus_ sp. _Ostrea_ sp. _Cardium_ cf. _C._ _pauperculum_ Meek Gastropod fragments, undet.	Pl. 10, sec. S27.
512	D5304b	do., 1965	do.	*_Inoceramus_ cf. _I._ _stantoni_ Sokolow _Inoceramus_ sp. _Crassostrea_ _soleniscus_ (Meek) Shark teeth, undet.	Pl. 10, sec. S27; *in talus block.
B sandstone bed					
309	D5307	do., 1965	do.	_Inoceramus_ sp. _Gyrodes_ cf. _G._ _conradi_ Meek _G._ cf. _G._ _depressus_ Meek _Rostellites_? sp.	Pl. 11, sec. S34.
C sandstone bed					
506	-----	do., 1965	do.	_Inoceramus_ sp. _Crassostrea_ _soleniscus_ (Meek)	Pl. 10, sec. S24.
D sandstone bed					
303	D5287	do., 1965	W.A. Cobban F. Peterson	_Ostrea_ sp. _Baculites_ sp. _Ophiomorpha_ sp.	Pl. 11, sec. S30.
E sandstone bed					
510	-----	do., 1965	F. Peterson	_Inoceramus_ sp. _Ostrea_ sp. _Ophiomorpha_ sp. Shark teeth, undet.	Pl. 10, sec. S27.
Upper marine mudstone tongue					
310	-----	do., 1965	do.	_Serpula_ sp. _Inoceramus_ sp. _Ostrea_ sp. _Cardium_ cf. _C._ _pauperculum_ Meek _Ophiomorpha_ sp.	Pl. 11, sec. S34.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
JOHN HENRY MEMBER OF STRAIGHT CLIFFS FORMATION--continued					
Upper marine mudstone tongue--continued					
515	D6592	F. Peterson 1968	W.A. Cobban	*Inoceramus* (*Sphenoceramus*) sp. *I.* (*Endocostea*) cf. *I. balticus* Böhm *Crassostrea soleniscus* (Meek)	Pl. 10, sec. S28; the inocerams suggest a position low in zone of *Scaphites hippocrepis*.
701	D5296	do., 1966	do.	*Inoceramus* sp. (with a truncate anterior margin)	Pl. 11, sec. S6; suggests zone of *Scaphites hippocrepis*.
G sandstone bed					
702	D5308	do., 1966	do.	*Inoceramus* cf. *I.* (*Cordiceramus*) *mülleri* Petrascheck	Pl. 11, sec. S6.
DRIP TANK MEMBER OF STRAIGHT CLIFFS FORMATION					
124	-----	do., 1966	N. Hotton 3d D.H. Dunkle	Soft-shelled turtle *Trionyx*? sp.	Pl. 10, sec. S18.
WAHWEAP FORMATION					
1	D4717	H.A. Waldrop F. Peterson R.L. Sutton G.W. Horton 1964	W.A. Cobban	*Viviparus* sp.	Fig. 20, sec. W1.
1	D597 (fossil vertebrate loc. No.)	do., 1964	G.E. Lewis	Osteichthyes, undet., and *Lepidosteus* sp. Reptilia, undet., and Chelonia, undet. Crocodilia, undet. Hadrosaurian ornithischian dinosaur, undet.	Fig. 20, sec. W1.
1	-----	do., 1964	R.A. Scott	Coniferous wood, undet.	Fig. 20, sec. W1.
2	D4714	do., 1964	W.A. Cobban	*Plesielliptio*? sp. *Proparreysia* aff. *P. baueri* (Stanton) *Tulotomops* aff. *T. laevibasalis* Yen	Fig. 20, sec. W1.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
WAHWEAP FORMATION--continued					
3	D4715	H.A. Waldrop F. Peterson R. L. Sutton G.W. Horton 1964	W.A. Cobban	*Plesielliptio* sp. *Proparreysia* cf. *P. gardneri* (Stanton) *Campeloma* cf. *C. nebrascensis* (Meek and Hayden) *Tulotomops* aff. *T. laevibasalis* Yen	Fig. 20, sec. W1.
3	-----	do., 1964	R.A. Scott	Coniferous wood, undet.	Fig. 20, sec. W1.
4	-----	do., 1964	W.A. Cobban I.G. Sohn R.E. Peck	*Plesielliptio*? sp. *Cypridea* spp. Ostracodes, undet. Charophytes *Chara* n. sp. *Mesochara* n. sp.	Fig. 20, sec. W1.
6	-----	do., 1964	I.G. Sohn R.E. Peck	*Cypridea* sp. Ostracodes, undet. Charophytes *Chara* n. sp. *Mesochara* n. sp.	Fig. 20, sec. W1.
7	-----	do., 1964	W.A. Cobban	*Tulotomops* sp.	Fig. 20, sec. W1.
8	D4716	do., 1964	do.	*Plesielliptio*? sp. *Proparreysia* sp. Tulotomops? sp. *Physa* sp.	Fig. 20, sec. W1.
75	-----	do., 1964	G.E. Lewis	*Lepidosteus* sp. Chelonia, undet. Crocodilia, undet.	Various fragments from collns. 2,3, 4,6,7,8.
601	D5060	G.A. Izett 1965	W.A. Cobban	*Proparreysia gardneri* (Stanton) *Viviparus* sp. *Campeloma* sp. *Physa* sp.	Pl. 11, sec. S3.
601	-----	do., 1965	G.E. Lewis	Osteichthyes *Lepidosteus* sp. Reptilia, undet., and Chelonia, undet. Crocodilia, undet.	Pl. 11, sec. S3.
601	-----	do., 1965	R.A. Scott	Plant fruit *Cercidiphyllum*? sp.	Pl. 11, sec. S3.
603	-----	F. Peterson 1968	F. Peterson	*Tulotomops*? sp.	Fig. 20, sec. W3.
604	-----	do., 1968	do.	*Lepidosteus* sp.	Fig. 20, sec. W3.

Collection No.	USGS fossil loc.	Collector and year	Identified by	Fossils	Location and notes
KAIPAROWITS FORMATION					
MS-5-1	D4008A (USGS paleobot. loc.)	W.E. Bowers 1966	R.H. Tschudy S.D. Van Loenen	Pollen *Proteacidites* *Araucariacites* *Aquilapollenites* *Tricolpites interangulus* Newman	SE¼ sec. 16, and NE¼ sec. 21, T. 36 S. R. 1 E., Garfield County, Utah; in uppermost part of formation; suggests middle Campanian age.
MUDSTONE AND CONGLOMERATE UNIT					
MS-5-2	D4008B (USGS paleobot. loc.)	do., 1966	do.	Pollen *Proteacidites* *Araucariacites* *Aquilapollenites* *Tricolpites interangulus* Newman *Aequitriradites* *Schizaea* *Rugubivesiculites*	Same loc. as above; in lower part of unit; suggests middle to late Campanian age.
PL-148-SC	D4100 (USGS paleobot. loc.)	do., 1967	R.H. Tschudy	Pollen *Proteacidites* *Araucariacites* *Aquilapollenites* cf. *A. senonicus* B. Tschudy (provisional) *Tricolpites interangulus* Newman *Rugubivesiculites* *Erdtmannipollis* *Classopollis* *Hemitelia* *Ghoshispora*	NE¼NW¼ sec. 12, T. 35 S. R. 2 W., Garfield County, Utah; in mudstone; suggests late Campanian age.

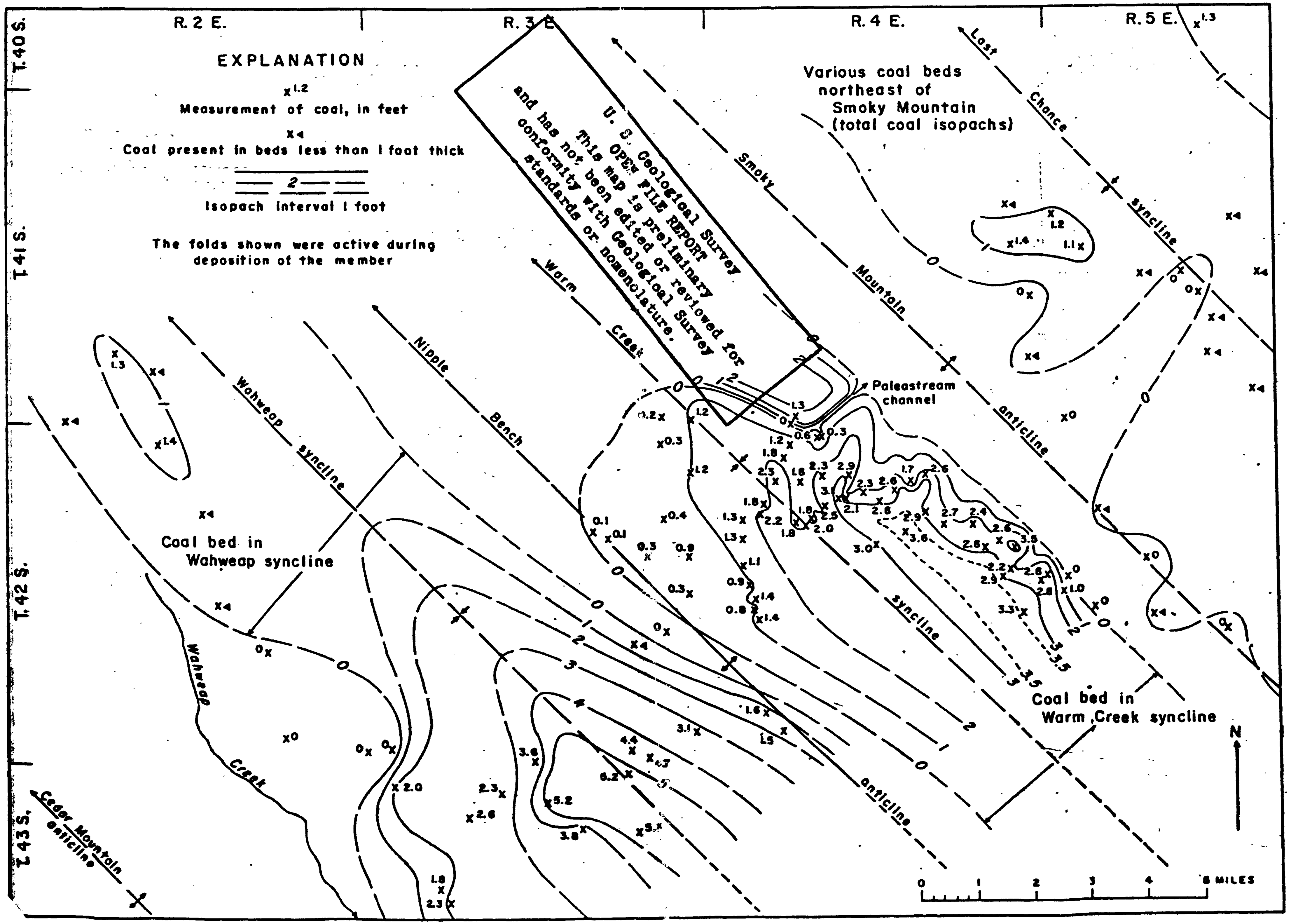

PLATE 17 DISTRIBUTION OF COAL IN SMOKY HOLLOW MEMBER OF STRAIGHT CLIFFS FORMATION

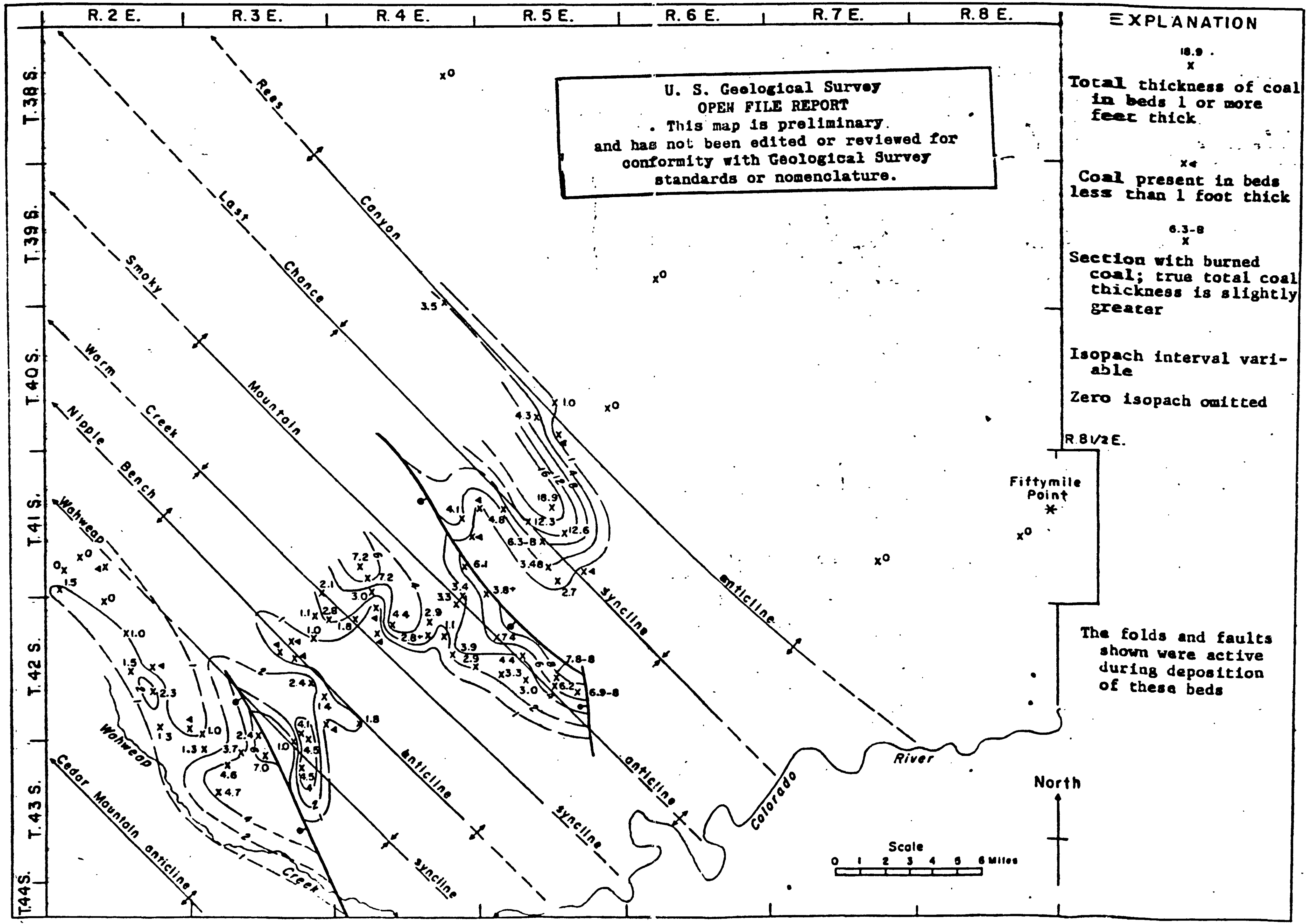

PLATE 18.--Isopach map of total coal in lower coal zone of John Henry Member of Straight Cliffs Formation

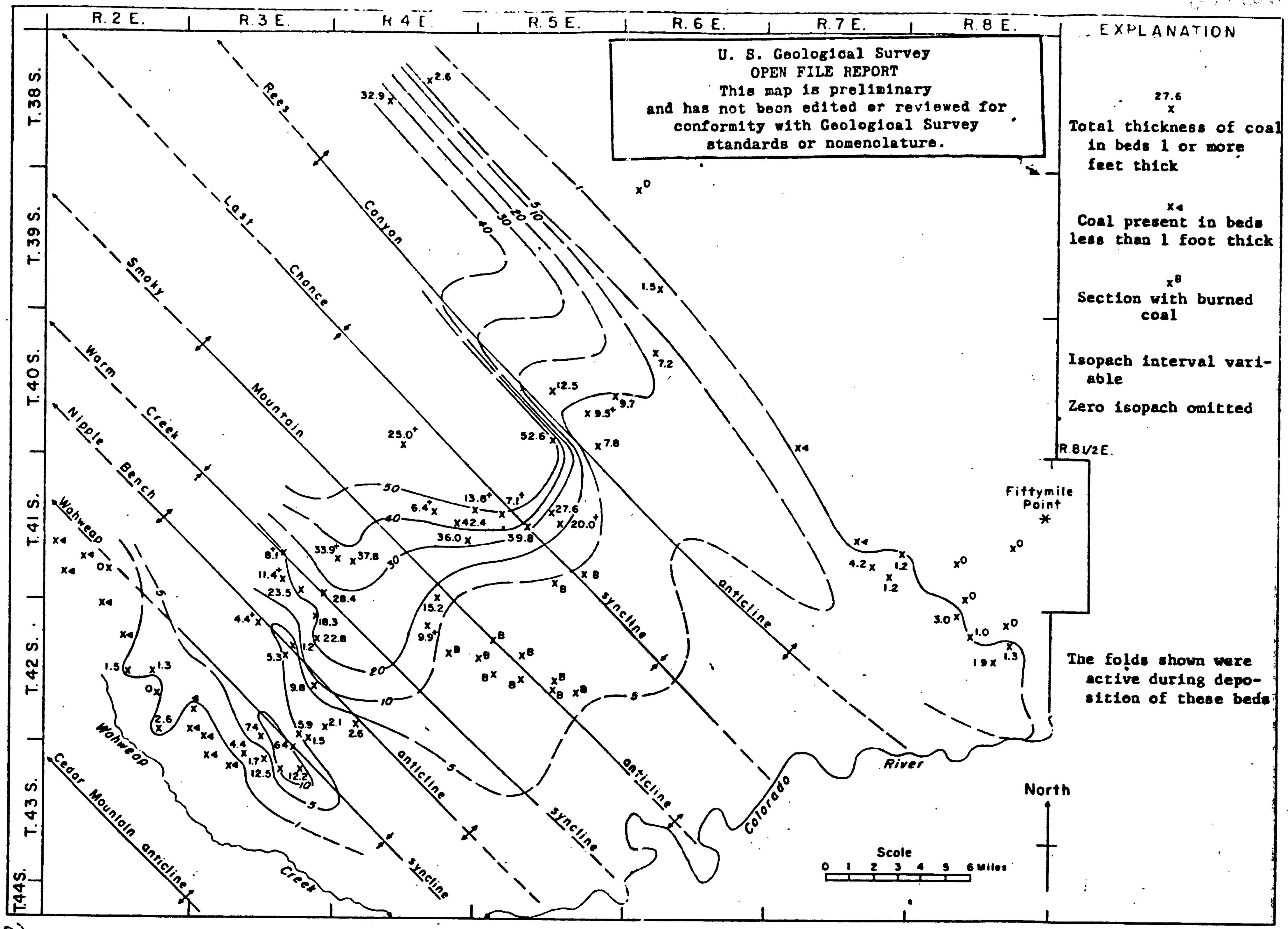

PLATE 19.--Isopach map of total coal in Christensen coal zone of John Henry Member of Straight Cliffs Formation

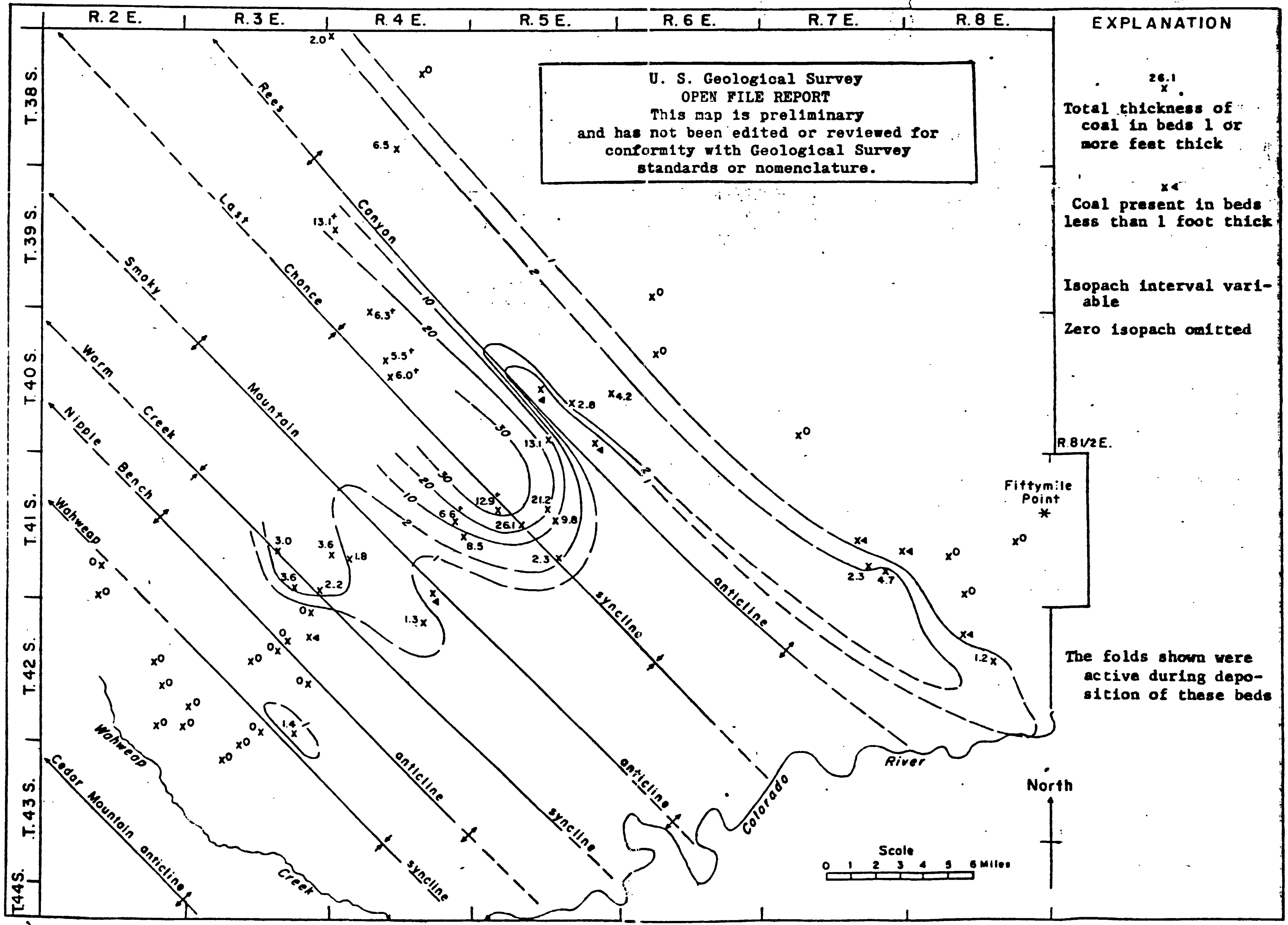
U. S. Geological Survey
OPEN FILE REPORT
This map is preliminary
and has not been edited or reviewed for
conformity with Geological Survey
standards or nomenclature.

PLATE 20.--Isopach map of total coal in Rees coal zone of John Henry Member of Straight Cliffs Formation

69-202

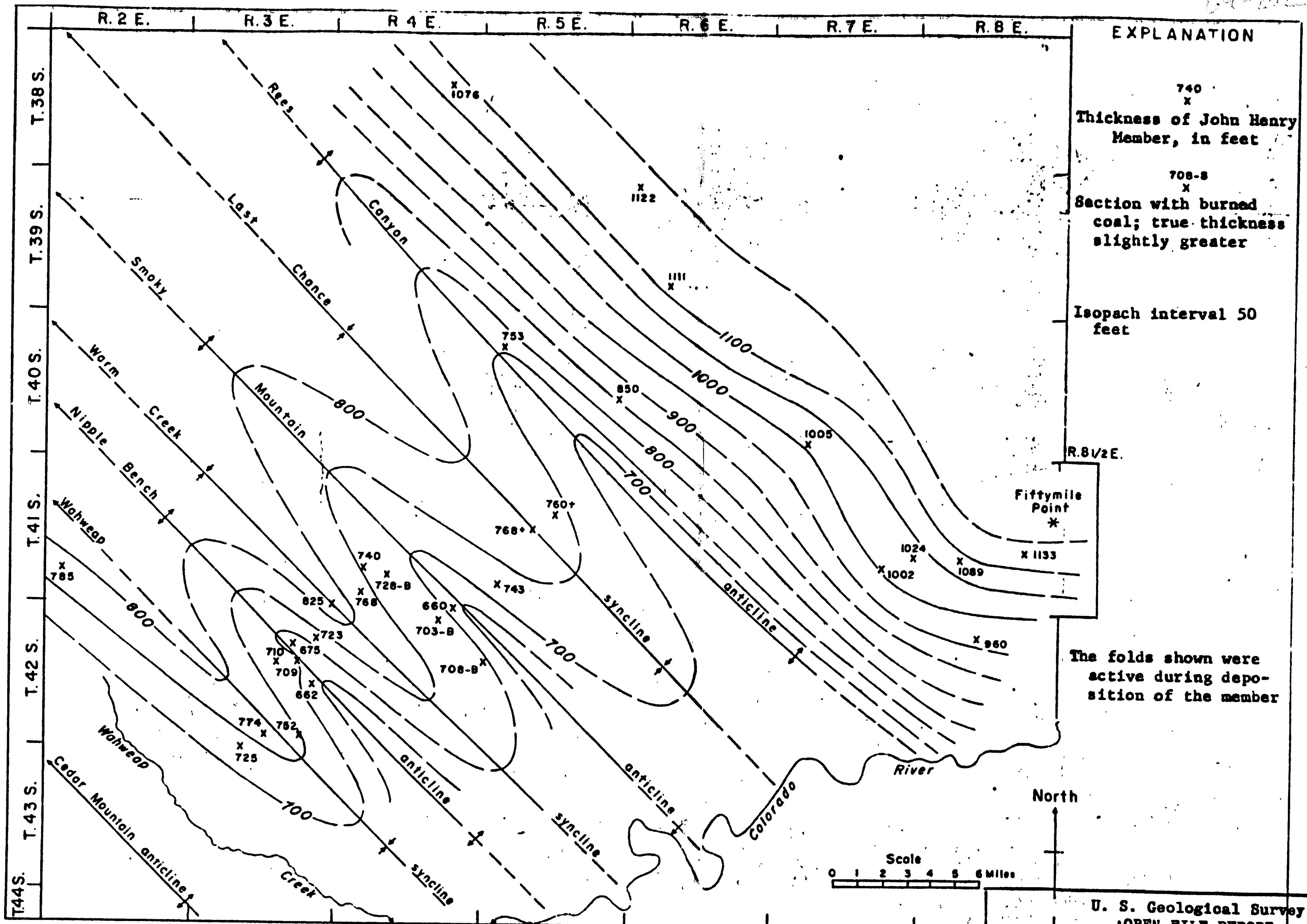

PLATE 21.--Isopach map of John Henry Member of Straight Cliffs Formation

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conformity with Geological Survey
standards or nomenclature.

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