Geology and Uranium Deposits of Elk Ridge and Vicinity San Juan County, Utah

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SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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GEOLOGY AND URANIUM DEPOSITS OF ELK RIDGE AND VICINITY, SAN JUAN COUNTY, UTAH

By Richard Q. Lewis, Sr., and Russell H. Campbell

ABSTRACT

The Elk Ridge area covers approximately 1,000 square miles in San Juan County, Utah. It lies between the Abajo Mountains and the White Canyon area and includes Elk Ridge, The Needles, and Beef Basin. The top of Elk Ridge ranges in altitude from 7,000 to 9,000 feet above sea level, and forms a broad convex mesa bounded by steep-walled canyons. On the basis of physiography, two general divisions can be made of the area: (1) Elk Ridge and (2) surrounding lower mesas. Both subareas are dissected by deep, steep-walled canyons.

The exposed sedimentary rocks range from Pennsylvanian to Quaternary in age and attain an aggregate thickness of approximately 6,000 feet. They overlie approximately 5,000 feet of unexposed sedimentary rocks of early and middle Paleozoic age.

The Elk Ridge area is on the north end of the Monument upwarp, one of the major structural features of the Colorado Plateau. The crest of the Monument upwarp enters the map area from the south and plunges out north of Sweet Alice Hills. The axis of the fold on Elk Ridge has been mapped as the Elk Ridge anticline—one of several asymmetrical anticlines superimposed on the major structure.

There appear to be two groups of minor folds on Elk Ridge: those within the major upwarp and undoubtedly associated with it, and those transverse to the major fold axis and north of the upwarp.

The major faults in the area are high-angle graben faults. The major grabens on Elk Ridge proper trend east or northeast and form a system en echelon and continuous with similar grabens in the Abajo Mountains and Verdure areas to the east. The numerous grabens in the northwesternmost part of the map area are probably collapse structures associated with movement of salt in the Paradox Member of the Hermosa Formation. They apparently bear little or no relation to the major graben systems.

Joints, well developed in all rocks, are best exposed in massive sandstone beds of the Cedar Mesa Sandstone Member of the Cutler Formation and in the Wingate and Navajo Sandstones. Most joints are closely related to the major upwarp, but some are related to small folds. Joints controlled the direction of the faulting in the northern part of the area, where collapse structures are common.

Uranium ore is produced almost exclusively from fluvial sandstone beds at the base of the Chinle Formation. In the southwestern, central, and eastern parts of Elk Ridge the host beds are sandstone lenses at the base of a unit that is predominantly mudstone. In the northeastern part of the area, where the mudstone unit is generally thin and locally absent, sandstone of the overlying Moss Back Member of the Chinle Formation is the host rock. Where the lowermost beds of the Chinle Formation are exclusively mudstone no uranium ore has been found. As a result, the Elk Ridge area includes two ore-bearing parts: (1) a beltlike area that trends west-southwest across the central part of Elk Ridge; and (2) an irregular area to the northeast, separated from the central belt by a generally barren area.

A few hundred tons of uranium ore were produced from the map area prior to 1953, notably from the Notch No. 1 claim and the Carl-Look-Payday No. 3 group of claims. In the period 1953–55 prospecting activity increased considerably, many claims were staked, and exploratory drilling was done by the U.S. Atomic Energy Commission and private interests. Some private exploratory drilling continued. Production from sandstone at the base of the Chinle in the central belt increased continually during 1953, and by the end of 1956, production totaled nearly 50,000 tons of ore averaging 0.25 percent U_3O_8. The rate of production was greatest during 1955. Production figures suggest that individual ore bodies range in size from a few tons to more than 15,000 tons. None of the larger deposits are known to have been mined out, so the maximum might be considerably greater.

The ore deposits are in lenticular beds of sandstone and conglomeratic sandstone that have been deposited in and built up above shallow paleostream channels cut into the top of the Moenkopi Formation. The ore deposits are generally flat-lying lenticular bodies, and are commonly elongated in the direction of the channels, but there are many local variations in shape and dimension. The grade of ore deposits generally is not uniform. Run-of-mine ore is generally a mixture of high-grade ore to barren material. The areal distribution of the ore deposits appears to be controlled by the distribution of fluvial sandstone at the base of the Chinle Formation. The outlines of the central belt indicate approximately the limits of distribution of channel sandstones at the base of the mudstone unit of the Chinle Formation. The southwestern outline of the northeastern area of ore-bearing rocks indicates approximately the southwestern limit of an area where sandstones at the base of the Moss Back Member have been deposited in channels cut through the underlying mudstone unit and lie directly on the Moenkopi. No ore deposits are known to occur in Chinle sandstones that are not in contact with the Moenkopi Formation, although small amounts of low-grade material occur in some stratigraphically higher beds of the Chinle.

Ore deposits in the lenses of permeable channel sandstone are almost invariably overlain by mudstone or very argillaceous sandstone lenses. The ore-bearing sandstone lenses also appear to grade longitudinally and laterally into less permeable argillaceous sandstone and mudstone. In some mines ore was deposited in the lowermost parts of the channel sandstone lenses,

in places extending a few inches to 2 feet (locally more along fractures) down into the Moenkopi. In other mines (or, more rarely, other ore bodies in the same mine) ore has been deposited as high as 20 feet above the top of the Moenkopi, and the basal sandstone beds of the Chinle are virtually barren.

The only major structural control for ore deposits indicated is that which controlled the deposition of the favorable host rocks of the central belt. Considering the shallow nature of the channel scours into the top of the Moenkopi Formation (generally less than 10 feet deep), and considering the relatively uniform thickness of Moenkopi as opposed to the variations in thickness of the Chinle mudstone unit, the depositional basin that received the pre-Moss Back Chinle sediments appears to have been controlled by a structural trough of early Chinle, post-Moenkopi time. It is believed that the central favorable belt probably represents the position and direction of the deepest part of the structural basin.

Ore deposits are largely restricted to Chinle sandstone that is in contact with the Moenkopi Formation and, conversely, ore is not found in Chinle sandstone that is separated from the Moenkopi by lower mudstone. The permeable sandstones at the base of the mudstone unit are apparently not interconnected by permeable channelways that would allow widespread lateral migration within the pre-Moss Back rocks of the Chinle Formation. Ore does not occur in the Moss Back Member where it is separated from the Moenkopi by lower mudstone even though the Moss Back is known to be an aquifer and could have provided permeable channelways for the lateral migration of ore solutions.

The regional stratigraphic associations of the ore deposits suggest that the solutions from which the ore was deposited were introduced into the host beds from their areas of contact with the underlying Moenkopi Formation. The detailed stratigraphic setting of the ore bodies suggests that ascending solutions were impounded by overlying impermeable barriers. This would require an important ascending component to their direction of flow. Dilute, virtually nonreactive, low-temperature ore solutions might have passed along the Moenkopi-Chinle contact, or even upward through the Moenkopi and older rocks, leaving little or no trace.

Impermeable barriers above the ore-bearing parts of the host sandstones were probably an important control for the deposition of ore minerals from solution. Organic material is associated with ore in many places and may have facilitated deposition. Overlying impermeable barriers may have served as semipermeable membranes at which hypofiltration of metallic constituents from ascending solutions took place. Alternatively, or perhaps in combination, impermeable barriers may have formed stratigraphic traps for H_2S gas or fluid hydrocarbons and thus localized a reducing chemical environment in which ore minerals were later precipitated.

INTRODUCTION

LOCATION AND ACCESS

The Elk Ridge area covers about 1,000 square miles in the northwestern part of San Juan County, southeastern Utah (fig. 1). The area is bounded on the south by the Grand Gulch Plateau, a small part of which was mapped, on the west by the White Canyon area, on the north by the Colorado River and the Moab area, and on the east by the Abajo Mountains and the Sage Plain. The nearest settlements are Blanding, Utah, about 30 miles to the east, an established town of about 2,000 people, and Fry Canyon and White Canyon to the west, both small communities of miners and prospectors.

The Elk Ridge area is accessible from Blanding, Utah, by either old State Highway 95, now maintained by the county, or the new Highway 95, locally called the low road, which goes to White Canyon. Another route into the area, known as the Indian Creek or Home of Truth road, leaves U.S. Highway 160 about 15 miles north of Monticello, Utah, and connects with Forest Service roads in the northern part of the map area. A network of Forest Service and newly constructed mine roads connects with these roads and makes it possible to drive to within a few miles of nearly any point on Elk Ridge.

PREVIOUS INVESTIGATIONS AND EXPLORATIONS

There is no record as to when the first white man may have visited the Elk Ridge area. Fray Alonzo de Posada and Don Juan Maria de Riveria crossed the Colorado River near the present site of Moab, Utah, in 1761, having come north from New Mexico and Arizona across the Sage Plain to the east of Elk Ridge (Gregory, 1938, p. 2). In 1859, Capt. J. N. Macomb, a topographic engineer of the U.S. Army, traveled around the east side of the Abajo Mountains and down Indian Creek just north of Elk Ridge.[1] In 1869, Maj. J. W. Powell (1875) passed through Cataract Canyon on his historic trip down the Colorado River. In 1875 and 1877, W. H. Jackson (1878) of the Hayden Survey traveled up Comb Wash, then called Epsom Creek, from the San Juan River and crossed the upper part of Butler Wash and Cottonwood Creek en route to the Abajo Mountains. He was probably the first man to observe and record the natural phenomena. At about the same time W. H. Holmes (1878) of the Hayden Survey made a reconnaissance study of the geology of the Abajo Mountains, which he referred to as Sierra Abajo. He observed the broad features of Elk Ridge and noted the nature and magnitude of the Comb monocline.

The name Elk Ridge first appears in print on the Abajo, Utah, topographic sheet in an area credited to reconnaissance maps by Holman.[2] The name Elk

[1] Information given by J. S. Newberry, 1859, San Juan Report: Exploring expedition from Santa Fe to junction of the Grand and Green Rivers of the Great Colorado of the West (in 1859) under Capt. J. H. Macomb (U.S. Army Engineer Rept., unpub.).

[2] P. Holman, 1892, topog. maps, in U.S. Geol. Survey, Abajo, Utah, topog. sheet, 1 : 250,000 scale, ed. of 1892; also in U.S. Geol. Survey, Henry Mountains, Utah, topog. map, 1 :250,000 scale, ed. of 1892, repr. 1928. Both maps credited to Henry Gannett, Chief Geographer; A. H. Thompson, Geographer-in-charge; triangulation by A. P. Davis. Index maps show P. Holman, 1884, as source of mapping in area south and east of Colorado River to Arizona State line on south and to meridian through Bluff and Abajo Mountains on east.

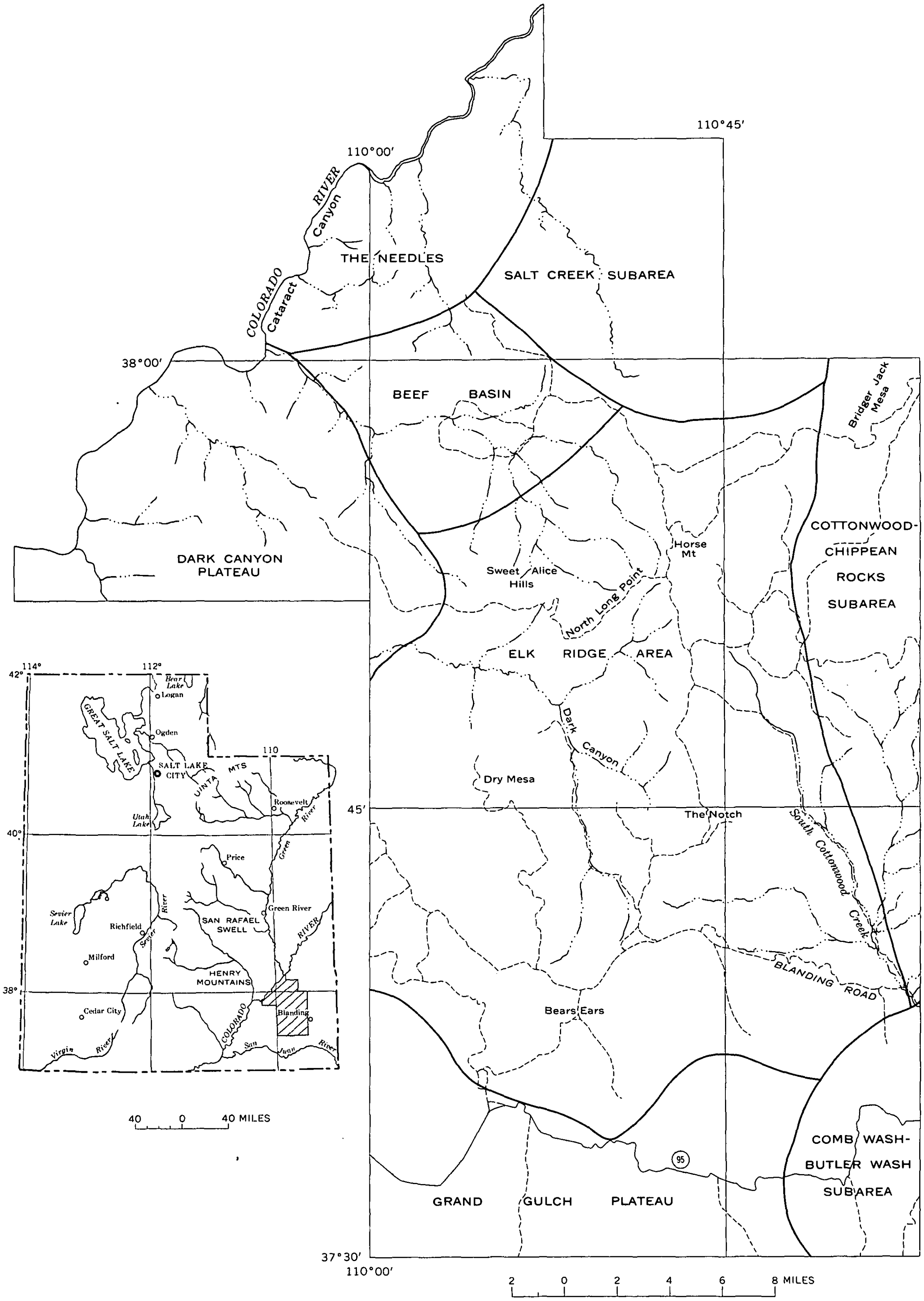

Figure 1.—Index maps of the Elk Ridge area and physiographic subareas.

Ridge was used to replace the name Bear Ears Plateau, used earlier by Holmes, and the names Comb Wash, Cottonwood Wash (now called Cottonwood Creek), and Butler Wash were adopted.

In 1915, H. E. Gregory of the U.S. Geological Survey conducted a 2-week preliminary study of the geology in the Elk Ridge and White Canyon areas. During the years 1925 and 1927 he studied the area in detail (Gregory, 1938). His report contains a vast store of information on the history, culture, and geography of southeastern Utah.

The regional stratigraphy was studied and reported on by Baker (1933; 1936), and Baker and Reeside (1929). These reports are very good summaries of the regional geology and stratigraphy and are cited throughout the present report.

PRESENT INVESTIGATION

The present investigation was undertaken on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission. The main objective was general geologic mapping of the area with special emphasis on those parts of the Chinle Formation of Triassic age that were favorable host beds for uranium ore deposits. The fieldwork was done during the summer seasons of 1953, 1954, 1955, and 1956, and the spring of 1957. The mapping was done chiefly on aerial photographs at a scale of about 1:20,000 and transferred by radial planimetric plotter, multiplex, and Kelsh plotter to topographic base maps at 1:24,000 scale. In a few small areas field mapping was done on the 1:24,000 scale topographic base maps by use of planetable and alidade.

Because of the economic importance of the Chinle Formation as a host for uranium deposits, preliminary geologic maps with structure contours were published at the 1:24,000 scale in the U.S. Geological Survey MF series for most of the map area in which the Chinle is exposed (Lewis and Campbell, 1958a–f; 1959a–d). In addition some of the salient features of the uranium deposits were summarized by Campbell and Lewis (1961); and the structural geology was summarized by Lewis (1958) in the interest of exploration for oil.

Mines were mapped in as much detail as time permitted. Those parts of the area believed to be most favorable for uranium deposits were mapped during the earlier years of the project, and many of the important mines were developed after field mapping in their vicinity had been completed. Attempts were made to keep pace with the development of the mines by revisiting them periodically, but it was not possible to acquire accurate up-to-date maps and geologic information for all mines.

A network of Forest Service access roads and recently constructed mine roads makes most of the area accessible by automobile. However, horses were useful in reaching the more remote canyon country along the western margin of the map area.

During the summer of 1956 a party of six men, including the writers, made a boat trip through Cataract Canyon in rubber boats from about 40 miles above the mouth of the Green River to Hite, Utah, a distance of about 130 miles, to study and observe rocks exposed in the lower part of Cataract Canyon.

ACKNOWLEDGMENTS

The ability and industry of Paul H. Reitan, Paul Bieber, Fred Gustafson, and Bennett F. Brock, who served as assistants for one or more field seasons, contributed greatly to the success of the project. The help of R. W. Schnabel and W. B. Krummel, members of the party during the 1953 field season, and of R. E. Thaden, during the 1954 field season, is gratefully acknowledged. The writers would also like to acknowledge the help and encouragement afforded by Robert Morris and Charles Pillmore of the U.S. Geological Survey, and of C. Marshall who assisted in the compilation of part of the Needles area, and of Richard Rezak of the U.S. Geological Survey, who spent several weeks in the field collecting fossils and assisting the field party. We wish also to express our thanks to Jess Kateron and W. W. Wilson who served as cooks and packers and to Julian Thomas of the U.S. Forest Service for his many courtesies, aid, and cooperation. We would also like to thank Lyman D. and Joe Nielson and the many other people of Blanding, Utah, for their friendship and help.

GEOGRAPHY

The map area encompasses the broad high mesas and includes the adjacent lower mesa and canyon country. Elk Ridge, the central dissected mesa, is capped by a resistant sandstone and is thickly covered with yellow pine, aspen, and shrubs. The upper slopes of the canyons are densely covered with juniper, piñon pine, and brush. Except in the Cottonwood-Chippean Rocks subarea, the lower slopes everywhere are cut in massive sandstone strata and are bare or sparsely covered with vegetation. More detailed discussions of the vegetation of the region may be obtained from Gregory's report (1938) on the San Juan country, the report by Hunt (1953) on the Henry Mountain area, or the report by Kleinhampl (1962) on the botanical studies on Elk Ridge.

There is no weather station within the map area and the only information on annual rainfall and mean temperature in the region is from weather stations at Hite, Blanding, Monticello, Bluff, and Mexican Hat. Inasmuch as these are all at much lower altitudes there can be little direct comparison. Measurements made in the Henry Mountain area (Hunt, 1953, p. 27) indicate that the maximum rainfall there is at altitudes between 7,000 and 8,000 feet; and that in the Henry Mountain area the mean annual rainfall at that altitude range is about 16 inches. Hence it may be reasonably concluded that the higher parts of the Elk Ridge area receive about 16 inches of rainfall annually.

For convenience of discussion the map area is divided geographically into Elk Ridge and several subareas: Grand Gulch Plateau, Dark Canyon Plateau, Beef Basin, The Needles, The Salt Creek subarea, the Comb Wash-Butler Wash subarea, and the Cottonwood-Chippean Rocks subarea. These subareas, shown in figure 1, are all somewhat different physiographically and geologically.

Elk Ridge (fig. 1) is a high elongate mesa capped by a resistant sandstone. The somewhat irregular top reflects local folds in the sedimentary rocks. Elk Ridge is divided in two by a deep topographic saddle, The Notch, between the heads of Notch Canyon and Dark Canyon. The area to the south of The Notch is known as South Elk Ridge and that to the north as North Elk Ridge. With the exception of the long dip slope extending down the northeast side, the mesa is completely surrounded by steep-walled canyons.

The Grand Gulch Plateau is a broad, relatively flat area south of Elk Ridge extending from Comb Wash on the east to the Red House Cliffs to the west of the area of figure 1, and from Elk Ridge south to the canyon of the San Juan River. The plateau is capped by a thick resistant sandstone, and viewed from a distance it appears to be a rather featureless expanse of juniper and piñon woodland and sagebrush flats. Actually, the plateau is crossed by a number of deep, impassable canyons which are tributary to Comb Wash and the San Juan River. Closer inspection shows the area to have considerable relief. It is nearly devoid of water.

The Dark Canyon Plateau is a dissected surface carved into the top of a massive sandstone which dips gently westward toward the Colorado River. The subarea is bounded on the south by Dark Canyon, on the north by Gypsum Canyon, and on the east by the highlands of the Sweet Alice Hills and North Long Point. The surface of the plateau is covered by dense juniper and piñon growth. Sweet Alice Spring, at the west end of the Sweet Alice Hills, is the only known spring on the plateau; a few small seeps occur in the heads of the canyons.

The Beef Basin subarea lies north and northwest of Elk Ridge and east of the Dark Canyon Plateau. Beef Basin is a broad, shallow basin dotted with sandstone buttes and spires that stand above the sage- and grass-covered plains. Beef Basin is bounded on the south by Elk Ridge, on the north and east by a long low ridge, and on the west by Gypsum Canyon. The basin is largely covered with a thin layer of alluvium and windblown sand that supports a good growth of grass and sagebrush. The basin has a number of springs and it is a haven for deer during the winter months.

The Needles subarea lies to the north of Beef Basin and is separated from it by a low divide. It is bounded on the north and west by the Colorado River and on the east by the Salt Creek drainage. The subarea is crisscrossed by numerous faults and large joints which give a complex grain to the topography; the surface consists of sculptured and weathered sandstone standing as blocky mesas, buttes, and spires above long, narrow box canyons. Travel through the area is difficult, and the area is nearly devoid of water.

The Salt Creek subarea is extremely rough canyon country. It is bounded on the south by Elk Ridge, on the west by The Needles subarea, on the north by the broad valley of Indian Creek, and on the east by Bridger Jack Mesa. Salt Creek and its tributaries have cut an intricate system of narrow steep-walled meandering canyons. The canyons are bounded by sheer cliffs of sandstone, which form narrow, sinuous, arcuate ridges. The area is nearly devoid of vegetation and characterized by bare sandstone surfaces. Travel is possible only along the main canyon of Salt Creek and the larger tributaries.

The Comb Wash-Butler Wash subarea in the southeasternmost part of the map area is characterized by steep-walled south-trending canyons and east-dipping cuestas. It is a transition zone of strike valleys along the flank of the Monument upwarp that separates Elk Ridge from the Sage Plain to the east. Comb Ridge, commonly known as The Comb, and Comb Wash, are striking features of the terrain. The Comb is a hogback ridge, surfaced by massive thick-bedded sandstones. It extends south from Elk Ridge to the San Juan River and thence southwest to a point near Kayenta, Ariz., a total distance of about 70 miles. Comb Wash and Butler Wash, which bound The Comb, are broad strike valleys carved into the less-resistant beds above and below the massive sandstones.

The Cottonwood-Chippean Rocks subarea extends along the east edge of the map area. It is characterized by steep, narrow canyons and mesas separating Elk Ridge on the west from the Abajo Mountains on the east. The canyons are cut into soft mudstone, and the mesas are capped with sandstone. Bare sandstone ledges and domes are surrounded by dense forests of pine. The area encompasses the canyons at the heads of Cottonwood and North Cottonwood Creeks and the ridge along the principal divide. It is an area of low relief, light rainfall, and sparse vegetation.

STRATIGRAPHY

The exposed sedimentary rocks in the Elk Ridge area range from Pennsylvanian to Quaternary in age, and attain an aggregate thickness of about 5,000 feet. These rocks overlie approximately 4,000 feet of unexposed lower and middle Paleozoic rocks which rest on Precambrian crystalline rocks. The oldest exposed rocks crop out in Cataract Canyon and its tributaries in the northwestern part of the map area, whereas the younger rocks are exposed along the crest of Elk Ridge and in The Comb along the east boundary of the map area. In general the rocks are marine, fluvial, and eolian deposits.

PALEOZOIC ROCKS, SUBSURFACE

The unexposed sedimentary rocks in the Elk Ridge area range from Cambrian to Pennsylvanian in age. The rocks are in part clastic and in part chemical precipitates. There is a diversity of opinion regarding the exact correlation of the units with the nearest exposed rocks of approximately the same age in southwestern Colorado and western Utah.

CAMBRIAN, ORDOVICIAN, AND SILURIAN SYSTEMS

Interpretation of well data indicates that Cambrian rocks in the Four Corners area (New Mexico, Arizona, Utah, and Colorado) range from 0 to 1,300 feet in thickness (Cooper, 1955, p. 59). The lower part of the Cambrian consists of arkosic sandstone, conglomeratic at the base, and an overlying shale. These units have been correlated by Cooper (1955) with the Tintic Quartzite and the Ophir Formation described by Gilluly (1932) in the Stockton and Fairfield quadrangles in western Utah. In the Elk Ridge area wells penetrated a clastic unit that probably correlates with the units noted by Cooper in the Four Corners area (pl. 1).

The upper part of the Cambrian is characterized by limestone and dolomite. These units are considered by Cooper (1955, p. 61) to be possibly equivalent to the Hartmann and Bowman Limestones, and the Lynch Dolomite (Gilluly, 1932). Dolomite reported from the same stratigraphic position in the Elk Ridge area indicates the presence of units similar to those described by Cooper.

The presence of rocks of Ordovician and Silurian age in the Four Corners area has not been confirmed. At present, most geologists believe that rocks of Silurian age are absent. Some rocks presently assigned to the Cambrian are possibly of Ordovician age according to W. E. Hallgarth (oral commun., 1957).

DEVONIAN SYSTEM

Devonian rocks are known to underlie most of the Colorado Plateau. These rocks are better known than units underlying them, but the exact correlation with exposed Devonian rocks is subject to some speculation. Geologists of oil companies working in the Four Corners area have assigned various formation names to the recognizable lithologic units. These include the Aneth Formation described by Knight and Cooper (1955); the Elbert Formation originally described by Cross (1904) and extended into the Four Corners area by Knight and Cooper (1955); and the Ouray Limestone named and described by Spencer (1900) and projected into the Four Corners area on the basis of fossils obtained in the Shell Oil Co. test well near Bluff, Utah (Cooper, 1955, p. 63). Fossils from these rocks are all of Late Devonian age, and no fossils of Early or Middle Devonian age have been reported from any part of the Colorado Plateau.

MISSISSIPPIAN SYSTEM

Rocks of Mississippian age in the Colorado Plateau of southwestern Utah range from 200 to 1,000 feet in thickness. On Elk Ridge 300 to 400 feet of limestone and dolomite, penetrated by drill holes, contains a fauna that indicates a Kinderhook to early Meramec age. These beds are considered equivalent to the Madison and Leadville Limestones by geologists in the Four Corners area. The Mississippian rocks are probably separated from the underlying Devonian rocks by an unconformity that represents at least part of Early Mississippian time.

PENNSYLVANIAN SYSTEM

Unexposed Pennsylvanian rocks in the Elk Ridge area include rocks assigned to the Molas Formation, the lower member of the Hermosa Formation, and part of the Paradox or middle member of the Hermosa Formation.

The Molas Formation was first described by Cross and Howe (1905b) from outcrops at Molas Lake in the Needle Mountains quadrangle, Colorado.

The Molas Formation is largely red calcareous mudstone and shale containing abundant fragments of limestone and chert derived from the weathering of the underlying limestone of Mississippian age. It is easily recognized in well logs and has become an important stratigraphic marker throughout the region. The Cedar Mesa well of the Carter Oil Co., located about 2 miles south of the map area on the Grand Gulch Plateau, penetrates 178 feet of rocks that are probably Molas.

The lower member of the Hermosa Formation below the Paradox Member ranges from 350 feet to 500 feet in thickness in the Elk Ridge area. It is composed largely of limestone, with lesser amounts of dolomite, sandstone, and shale. The basal member is similar lithologically to the member above the Paradox and the two are not separated where the intervening Paradox Member is absent. However, dolomite is more abundant in the lower member and clastic rocks are more abundant in the upper member.

PALEOZOIC ROCKS, EXPOSED

HERMOSA FORMATION

The Hermosa Formation of Pennsylvanian age is the oldest formation exposed in the Elk Ridge area. Part of the Paradox Member of the Hermosa Formation and about 850 feet of overlying limestone and clastic deposits is exposed in the deep canyons of the Colorado River in the western part of the area. That part of the Hermosa Formation overlying the Paradox Member was mapped as the upper member of the Hermosa Formation (pls. 1 and 2).

PARADOX MEMBER

The Paradox Formation was named by Baker (1933, p. 13) and the type locality given as the Paradox Valley, Colo. Owing to the soluble nature of the material, outcrops are poor and, at the time of Baker's report, well data were meager. Baker (1933, p. 16) considered his Paradox to be older than the Hermosa but had no means of dating it more accurately. Bass (1944, p. 8), utilizing well-log data that indicated that the gypsiferous beds were underlain and overlain by similar rocks, proposed that the Paradox be considered a member of the Hermosa Formation in southwestern Colorado and adjacent southeastern Utah.

In the Elk Ridge area the Paradox Member of the Hermosa Formation is exposed along the lower part of Gypsum Canyon, and in the canyon of the Colorado River from Gypsum Canyon to Spanish Bottom just south of the junction of the Green and Colorado Rivers (pl. 2).

About 300 feet of beds assigned to the Paradox is exposed in the lower part of Gypsum Canyon (sec. 9, T. 32 S., R. 17 E.). The lower 200 feet is composed of bedded gypsum and limestone and minor amounts of mudstone and shale. A black shale 6 to 40 feet thick overlies the gypsum. Overlying the shale is a brown calcareous sandstone that contains abundant marine fossils. The thickness of the sandstone averages about 40 feet but locally varies as much as 10 feet. A black cherty dolomite about 12 feet thick that contains a few marine fossils overlies the sandstone. This dolomite is considered the uppermost bed in the Paradox Member. Near Gypsum Canyon the Paradox Member conformably underlies a limestone bed at the base of the upper member of the Hermosa Formation (fig. 2, upper part).

The gypsum beds exposed in Gypsum Canyon range in color from white to black. The local color apparently depends in part on the presence of impurities. Some of the gypsum has a sugary texture and is white on fresh surfaces. In places the rock looks like masses of lopsided mothballs (1–2 inches in diameter) tightly packed in a matrix of mudstone (fig. 2, lower part).

In places the gypsum is either massive or banded with light and dark bands. Above high water level of the river the gypsum forms low cliffs and steep slopes, which are covered with a veneer of talus.

The shale unit that overlies the gypsum in Gypsum Canyon is black to dark gray, very fissile, and contains petroliferous residue. The shale has been sheared and faulted locally by pressure due to flowage of the underlying gypsum.

Masses of gypsum, anhydrite, and limestone have been squeezed up along Cataract Canyon between the mouth of Gypsum Canyon and Spanish Bottom. Most of the material that reached the surface near the river level has been removed by erosion or covered by talus; however, small plugs of anhydrite containing jumbled masses of rock fragments are observable at the mouth of Cross Canyon and at Spanish Bottom.

Fossils were collected from several zones near the top of the Paradox in Gypsum Canyon (table 1; see table 2 for description of localities). *Mesolobus mesolobus* (Norwood and Pratten) and *Chonetina flemingi* (Norwood and Pratten), identified by Ellis L. Yochelson of the U.S. Geological Survey, indicate a Des Moines age for the upper part of the Paradox Member in the Elk Ridge area.

UPPER MEMBER

The upper member of the Hermosa Formation—that part overlying the Paradox Member—consists of interbedded limestone, sandstone, and shale. The unit is approximately 800 feet thick and is exposed in its entirety along the lower part of Gypsum and Cataract Canyons near the mouth of Gypsum Canyon (sec. 8, T. 32 S., R. 17 E.) (pl. 2).

The limestone is gray and ranges from thin bedded to massive. Most of the limestone contains abundant chert nodules, chertified marine fossils, and scattered quartz grains. The sandstone beds are commonly crossbedded, light gray in color, extremely calcareous, and range from 2 to 30 feet in thickness. The shale is gray, thin beeded and calcareous, and ranges from 2 to 15 feet in thickness.

The base of the upper member is defined as the lowest gray limestone overlying black dolomite or shale of the Paradox Member. The top of the upper member is defined as the highest massive limestone underlying arkosic sandstone of the Rico Formation. These

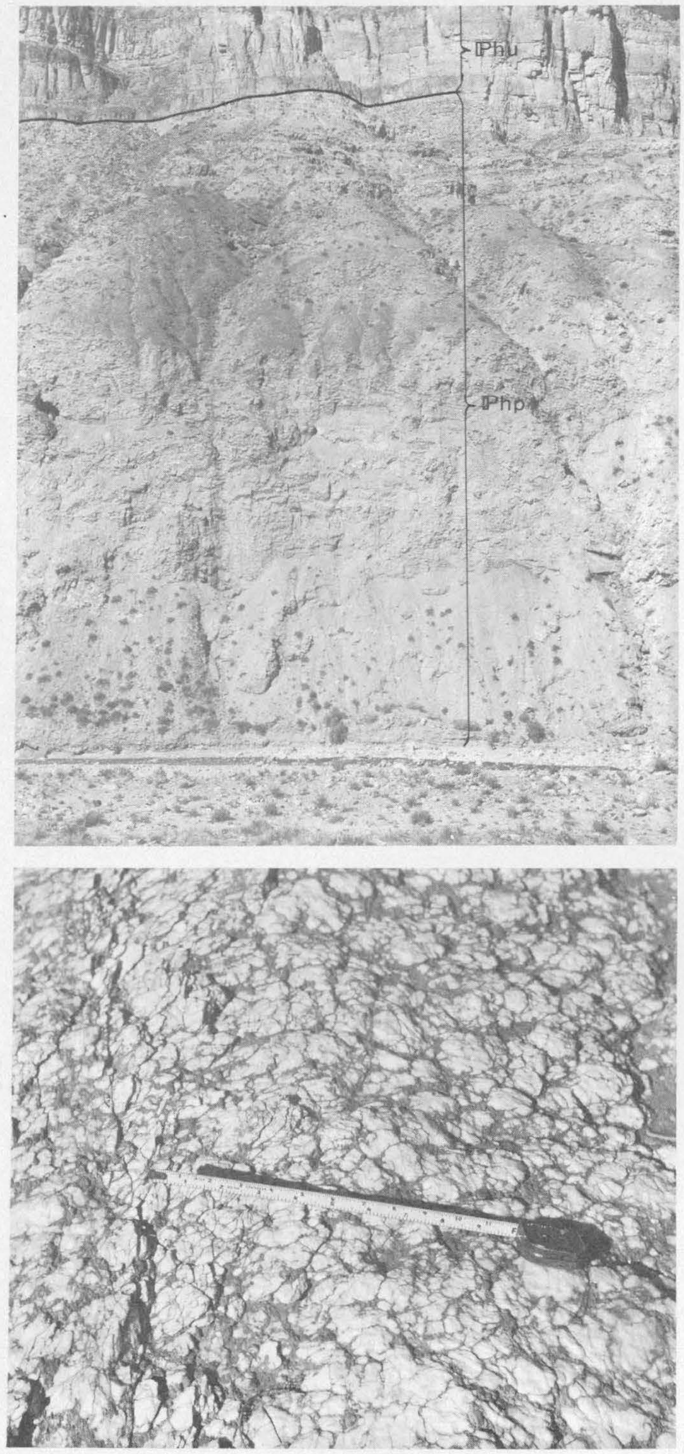

FIGURE 2.—Paradox Member of the Hermosa Formation as exposed in Gypsum Canyon. Upper photograph shows upper part of the Paradox Member (ℙhp), a thick gypsiferous sequence overlain by shale, sandstone, and dolomite. Paradox Member is in conformable contact with the upper part of the Hermosa Formation (ℙhu). Lower photograph shows sugar-textured gypsum in a mudstone matrix, typical of much of the gypsum in the Paradox Member.

boundaries make excellent mappable units in the Elk Ridge area; however, the limestone beds are lenticular

TABLE 1.—*Fauna from the Paradox Member and the upper member of the Hermosa Formation*

[Description of localities given in table 2. Megafossils identified by Ellis Yochelson and Helen Duncan; microfossils (*) identified by L. G. Henbest]

	Colln. No.
Derbyia cf. *D. crassa* (Meek and Hayden)	1, 2
Mesolobus mesolobus (Norwood and Pratton)	[1]2
Chonetina flemingi (Norwood and Pratton)	[1]2
Neospirifer cf. *N. Kansasensis* (Swallow)	3
Enteletes sp	4
Nubecularia sp	6
Epimastopora sp	7
Neospirifer cf. *cameratus* (Morton)	8
Antiquatonia hermosanus (Girty)	8
Composita subtilita (Hall)	8
Hustedia mormoni (Marcou)	8
Rhomboporella sp	8
Fenestella sp	8
**Trepeilopsis* sp	9
**Climacammina* sp	9
**Endothyra* or *Endothyranella* sp	9
**Bradyina* sp	9
**Globivalvulina* sp	9, 10
**Miliolid?*	9
**Ozawainella*? sp	9, 10
**Schubertella* sp	9, 10
**Triticites* sp	9, 10
**Triticites* sp. aff *T. confertus* (Thompson)	9
**Triticites kellyensis*? (Needham)	10
**Plummerinella* sp	10
**Bradyina* sp	10
**Trepeilopsis*? sp	10
**Climacammina* 2 sp	10
Osagia sp	11
Diplopora sp	12
Giruanella sp	12

[1] Des Moines age.

and are not good stratigraphic units for long-distance correlation.

In Dark and Gypsum Canyons, a resistant limestone bed at the top of the formation weathers to form a bench within the broad canyons with a narrower steep canyon below. This abrupt change in topography is easily seen in Dark Canyon but is less evident to the north and west along the Colorado River in the vicinity of Gypsum Canyon, where the uppermost limestone is thinner and interbedded with sandstone (fig. 3).

Cliffs formed by the upper member are gray and contrast with the overlying Rico Formation, which is dominantly red. In isolated outcrops, however, it is rather difficult to distinguish the uppermost limestone bed of the Hermosa from the lower limestone beds of the Rico.

In Dark Canyon, near the mouth of Trail Canyon, the uppermost limestone bed is approximately 60 feet thick. This bed, which can be traced by continuous outcrop, is only 15 feet thick to the north in Cataract and Gypsum Canyons. Microfossils collected at two localities from this bed (table 1) were determined by

TABLE 2.—*Description of fossil localities in the Elk Ridge area*

[Numbers refer to collections listed in tables 1 and 3]

Colln. No.	Stratigraphic position or lithology	Geographic location
	Paradox Member of Hermosa Formation	
1	Uppermost beds, bioclastic limestone.	Gypsum Canyon, near mouth.
2	Upper part, fossils in sandy limestone.	Do.
	Upper Member of Hermosa Formation	
3	Black cherty limestone within 100 ft of top.	Mouth of Clearwater Canyon.
4	Light-gray bioclastic limestone, 5–9 ft above colln. 3.	Do.
5	Black cherty limestone (above colln. 3).	Do.
6	5-ft bed of dense light-gray limestone, many microfossils.	Mouth of Dark Canyon.
7	Sandstone, brown to gray, 20–25 ft thick, above colln. 6.	Mouth of Dark Canyon, about 60 ft above creek level.
8	Cherty limestone with abundant fossils. 200 ft below top.	Cataract Canyon at west end of Imperial Valley. Lat 38°01′55″ N., long 110°03′04″ W.
9	Limestone within 30 ft of the top of the formation.	Intersection of Trail and Dark Canyons. Lat 37°49′45″ N., long 109°55′23″ W.
10	Dark-gray limestone forming top ledge of the formation.	Cataract Canyon at west end of Imperial Valley. Lat 38°01′55″ N., long 110°03′04″ W.
11	100 ft below colln. 10	Do.
12	Upper part	Upper part of Gypsum Canyon.
	Rico Formation	
13	About 300 ft below top (near base)	Gypsum Canyon. Lat 37°55′56″ N., long 109°57′50″ W.
14	Upper part	Hill on south side of Cross Canyon. Lat 38°00′35″ N., long 109°55′26″ W.
15	Limestone	Cross Canyon, 1½–2 mi. north of intersection with Imperial Valley.
16	do	Do.
17	100–150 ft below top	Cross Canyon.
18	Topmost bed	West end of Ruin Park.
19	Near top	In Peavine Canyon, about midway between its junctions with Kigalia and Dark Canyons.
20	do	Do.

L. G. Henbest of the U.S. Geological Survey to indicate either a very late Virgil or early Wolfcamp age. W. E. Hallgarth of the U.S. Geological Survey made an extensive collection of microfossils from the Hermosa in the vicinity of Mexican Hat, Utah, about 25 miles south of Elk Ridge. This collection, also studied by Henbest, indicated an early and middle Des Moines age. The results of these determinations indicate that in the Elk Ridge area the Hermosa was deposited during Middle and Late Pennsylvanian time and possibly in very Early Permian time.

RICO FORMATION

The Rico Formation, which is of Pennsylvanian and Permian age in other areas, is of Permian age in this area.

The rocks referred to in this report as the Rico Formation are underlain by the dominantly marine sedimentary rocks of the Hermosa Formation and conformably overlain by the subaerial sedmentary rocks of the Cutler Formation.

FIGURE 3.—Cliffs on the west side of Cataract Canyon, showing the upper member of the Hermosa Formation (Phu), the Rico Formation (Pr), and the lower part of the Cedar Mesa Sandstone Member of the Cutler Formation (Pcc).

The Rico Formation is characterized by a sequence of beds deposited under alternating marine and subaerial conditions. It is composed of alternating beds of thin gray limestone, red shale, purple and gray siltstone, and fluvial crossbedded sandstone. The Rico is conformable with the overlying Cedar Mesa Sandstone Member of the Cutler Formation (fig. 3).

In the Elk Ridge area the Rico is exposed on the lower slopes of many of the deep canyons and in numerous outcrops in The Needles subarea and Beef Basin (pl. 2). The upper part of the formation is exposed over a wide area but the base is exposed only in the lower part of Dark, Woodenshoe, and Gypsum Canyons and in the canyon of the Colorado River. Measurements in Dark and Gypsum Canyons and in The Needles subarea indicate that the formation ranges in thickness from 300 to 450 feet and averages about 400 feet.

The Rico differs from the underlying Hermosa Formation in gross appearance. In general, the clastic sedimentary rocks of the Rico are red to buff and give a general reddish color to the formation, particularly when viewed from a distance. This contrasts with the general gray of the Hermosa. Individual beds of limestone, shale, and sandstone of the Rico Formation are thinner than similar units in the Hermosa. The thinner units weather to form steep, stairlike slopes that contrast with the massive cliffs characteristic of the Hermosa Formation. Limestone in the Rico ranges from light gray to black, but hues of purple are most common. The limestones are thin, impure, and platy. They contain sparse fossils of shallow-water marine invertebrates. The limestone grades both laterally and vertically in calcareous sandstone and siltstone. With the possible exception of the Shafer Limestone of Baker (1933, p. 25), individual beds are not traceable throughout the area.

Sandstone in the Rico Formation is largely medium to fine grained, and most of the grains are of quartz with lesser amounts of plagioclase and potash feldspar; mafic minerals are very rare. The grains are angular to subrounded and generally are well cemented by calcite. There is little or no fine-grained matrix material. Some of the sandstone shows well-defined crossbedding of eolian type. The clastic rocks probably represent material deposited on a broad, low coastal flood plain, which at frequent intervals was covered by shallow marine waters.

Microscopic examination indicates that the shale and siltstone contain quartz and feldspar grains in a matrix of clay minerals. Calcite is the dominant cementing material, and the clastic units grade into impure limestone over short distances.

The rocks of the Rico Formation are in general finer grained than those noted by Baker (1933, p. 23) in the Moab area. The finer grain of the rocks considered with other observable sedimentary features indicates a probable northeastern source area of Rico sediments.

The Rico Formation contains a wide variety of shallow-water marine fossils. Brachiopods are common, though not as numerous as in the Hermosa Formation. Segments of crinoid stems and echinoid spines are common in the limestone along with bryozoan and algal debris. Gastropods and pelecypods occur in siltstone, particularly near the top of the formation. Most common is a large *Bellerophon.* A faunal list for the Rico Formation is given in table 3.

Algal material was collected and examined by Richard Rezak of the U.S. Geological Survey, who identified several genera indicative of Early Permian age. These include *Epimastopora* cf. *E. permianum* Johnson (Early Permian) and *Mizzia* sp. The identification of these algae and determinations of foraminiferal material from the top of the underlying Hermosa as of very Late Pennsylvanian or very Early Permian age by Henbest, indicate that the Rico Formation in the Elk Ridge area is of Early Permian age.

The Rico Formation of Elk Ridge is similar in lithology and stratigraphic position to the Rico of the type area in Rico Mountain, Colo. (Cross and Spencer, 1900). Comparison of the fossils from the two areas, however, indicates that the Rico Formation at Elk Ridge is much younger than at the type section. Henbest (1948) noted that the Rico Formation at the type locality contains fossil fusilinids indicative of Des Moines age. By comparison, Des Moines fossils were found in the Elk Ridge area in the upper part of the Paradox Member of the Hermosa Formation 800 to 900 feet stratigraphically below the Rico. This indicates that the strata mapped as the Rico Formation are representative of deposition in an environment or magnafacies that transcends time from east to west.

TABLE 3.—*Fauna from the Rico Formation*

[Description of localities given in table 2. Megafossils identified by Ellis Yochelson and Helen Duncan; microfossils (except algae) identified by L. G. Henbest; algae identified by Richard Rezak]

	Colln. No.
Epimastopora sp	13
Anchicodium cf. *A. nodosum* (Johnson)	13
Stringoporia cf. *S. multattenuata* McChesney	13
Fenestella sp	14
Septopora sp	14
Epimastopora cf. *E permianum* Johnson	[1] 15
Gyroporella sp	15
Osagia sp. (algal-foraminiferal colonies)	15
Composita cf. *C. subtilita* (Hall)	15
Cf. *Anthracoporella* sp	16
Girvanella sp	16, 17
Permophorus sp	16, 19
Aviculopecten cf. *A occidentalis* (Shumard)	16
Aviculopecten sp	16
Allorisma cf. *A terminale* Hall	18
Bellerophon sp	18
Septimyalina sp	19
Euphemites sp	19
Knightites (Retispira) sp	19
Nucleospira sp	20
Aviculopecten sp	20
Echinocrinus sp	20
Solenopora sp	20
Mizzia sp	[2] 20
Girvanella sp	20

[1] Early Permian.
[2] Guadalupian (?).

CUTLER FORMATION

The Cutler Formation of Permian age was named by Cross and Howe (1905a) for exposures of arkosic conglomerate near Ouray, Colo. At the type area it is the lower part of strata originally referred to the Dolores Formation (Cross and Spencer, 1900). Use of the name Cutler Formation was extended into the Monument Valley region, Arizona and Utah, by Baker and Reeside (1929) where the Cutler Formation contains eolian sandstone and red siltstone. In the Elk Ridge area, two members of the Cutler Formation were recognized and mapped. In ascending order they are: the Cedar Mesa Sandstone Member, an eolian sandstone, and the Organ Rock Tongue, a red siltstone.

CEDAR MESA SANDSTONE MEMBER

The Cedar Mesa Sandstone Member of the Cutler Formation was named by Baker and Reeside (1929) for exposures at Cedar Mesa, which is about 30 miles south of Elk Ridge. In the area covered by this report the Cedar Mesa Sandstone Member ranges from 1,000 to 1,200 feet in thickness. It caps the broad plateau areas south, west, and north and forms the steep-walled canyons on the ridge (pl. 2).

The Cedar Mesa is composed mostly of quartz grains with small amounts of plagioclase and microcline, and minor amounts of limonite. The sand grains range in size from coarse to fine and in shape from angular to well rounded; they are cemented chiefly by calcite. Small concretions and patches of limonite are locally abundant. In the southeastern part of the map area, the Cedar Mesa Sandstone Member contains a few thin discontinuous limestone and chert lenses, and is light gray to orange. In the northwesternmost part of the map area, the Cedar Mesa is generally red and contains numerous lenses of siltstone. The Cedar Mesa is composed of a number of thick-bedded sandstone lenses within which eolian cross-lamination is common. Individual lenses can be traced for miles and appear to be continuous in outcrop.

No fossils were found in the Cedar Mesa Sandstone Member within the map area, but a few smooth-shelled ostracodes were collected from a thin limestone in the lower part of the Cedar Mesa just south of the map area along Fish Creek. The ostracodes were identified by I. G. Sohn of the U.S. Geological Survey as *Bairdia* and *Bairdiocypris*. Both genera have a stratigraphic range from Devonian to Permian. In Monument Valley, Utah, the Cedar Mesa Sandstone Member overlies the Halgaito Tongue and underlies the Organ Rock Tongue. Both the Halgaito and Organ Rock contain Permian fossils (Baker, 1936, p. 30–35), indicating a Permian age for the Cedar Mesa Sandstone Member.

ORGAN ROCK TONGUE

The Organ Rock Tongue of the Cutler Formation was named by Baker and Reeside (1929) for rocks exposed at Organ Rock in Monument Valley, Utah. In Monument Valley, the Organ Rock Tongue attains a maximum measured thickness of 696 feet (Baker, 1936, p. 39). It thins northward to the Elk Ridge area, where it is about 270 feet thick on South Elk Ridge and about 130 feet thick in the north part of the area. The Organ Rock Tongue can be traced in nearly continuous outcrop from the type area in Monument Valley along the Red House Cliffs and across White Canyon into the Elk Ridge area.

The Organ Rock Tongue crops out in a steep slope around Elk Ridge proper (pl. 2). It is soft and easily eroded and commonly is completely stripped away except where protected by overlying resistant sandstone units. The slopes in general are smooth and contrast sharply with the blocky weathering typical of the overlying Hoskinnini Member of the Moenkopi Formation, making it possible in most places to locate the contact from a distance.

The Organ Rock Tongue is composed almost entirely of red sandy siltstone and thin lenses of red silty sandstone. Individual grains range from silt to fine sand in size, and much of the material contains a matrix of clay. Quartz is the most abundant mineral and feldspar, mica, and rock fragments are present in lesser amounts. Calcite is the common cement.

No fossils were noted in the Organ Rock Tongue in the Elk Ridge area; however, Baker (1936, p. 35) collected a few fossil plant remains and a single bone fragment from the Organ Rock Tongue in Monument Valley.

The contact between the Organ Rock Tongue and the underlying Cedar Mesa Sandstone Member is characterized by a transition zone within which red siltstone, typical of the Organ Rock, is interbedded with light-gray sandstone, typical of the Cedar Mesa. This zone of interbedded red and gray rocks was mapped as a part of the Cedar Mesa, and the base of the Organ Rock is placed at the top of the uppermost gray sandstone of Cedar Mesa type.

The Organ Rock Tongue is in conformable contact with the overlying Moenkopi Formation. The contact is characterized by an abrupt change in grain size, and the uppermost several feet of the Organ Rock is commonly bleached to gray or greenish gray. The bleached zone is easily observable and aids in separating the units in the field.

Along the northeasternmost edge of the map area the Organ Rock intertongues with coarse purple and red arkosic sandstone that was mapped in the Moab area as Cutler (Baker, 1933). The boundary between siltstone and arkose is sharp and distinct (fig. 4), and although these units are tongues, there is no gradation or intermingling of material. The nature of the boundary suggests that the two units were deposited as a series of overlapping tongues. Because of its limited extent and intimate association with the Organ Rock siltstone, the arkosic unit is not shown separately on the geologic map (pl. 2), but is included with the Organ Rock.

Measured sections of the two units show that the arkosic sandstone thickens to the north and east, and the Organ Rock thickens to the south (fig. 4). The intertonguing of arkose and siltstone where both units are thin suggests that separate basins of deposition and separate source areas are involved. This transition zone indicates that the rocks mapped as Cutler in the Elk Ridge area, and to the south and west in White Canyon (Trites and others, 1956) and in Monument

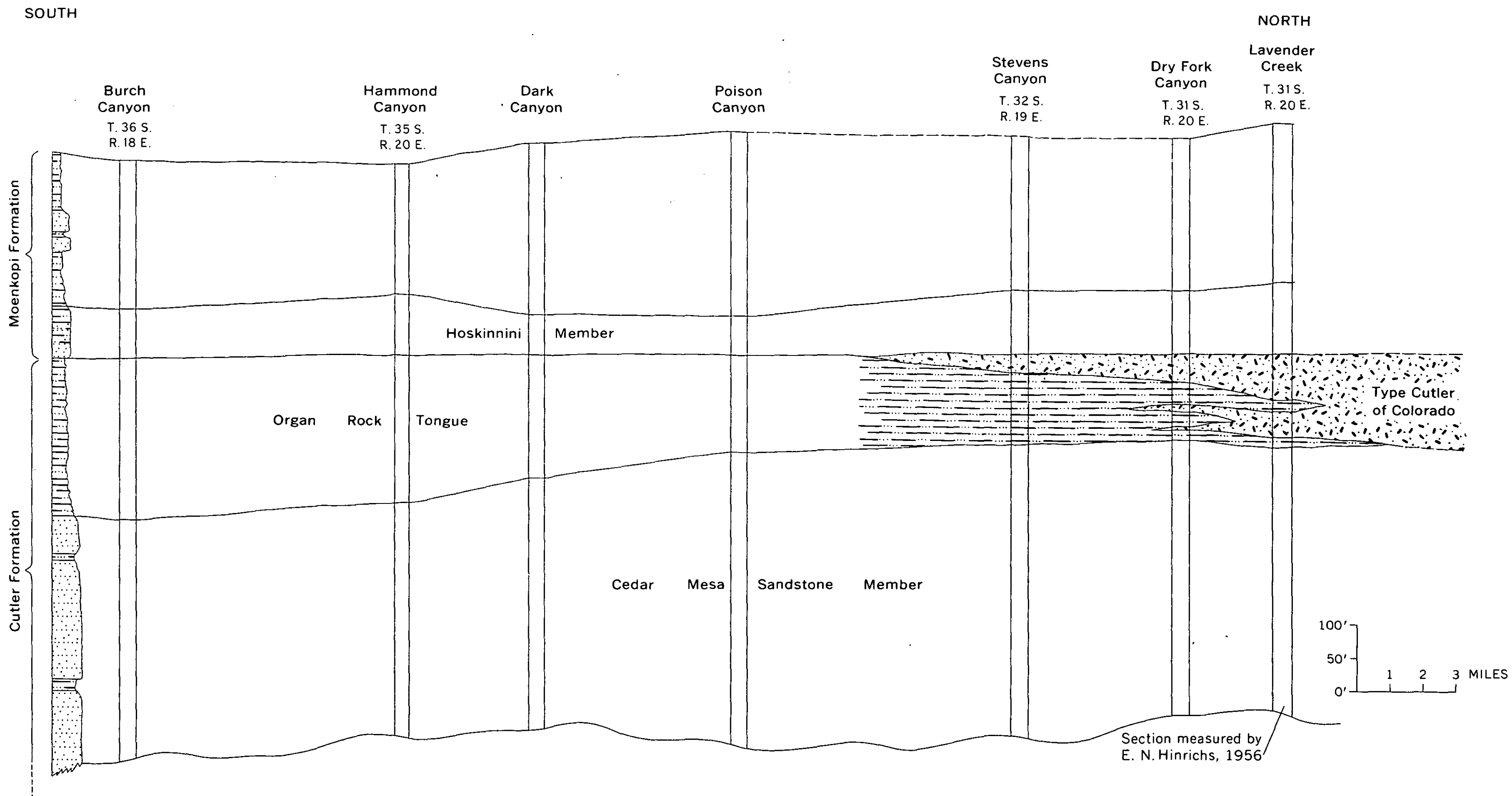

Figure 4.—Correlation diagram of a part of the Cutler Formation along a north-south line across Elk Ridge, showing the relation of the Organ Rock Tongue and the type Cutler of Colorado.

Valley (Baker, 1936), are more closely related to the rocks of Permian age in the Grand Canyon region of Arizona than to the type Cutler of Colorado, and are not gradational with the type Cutler as suggested by Baker and Reeside (1929).

MESOZOIC ROCKS

MOENKOPI FORMATION

The name Moenkopi Formation has recently been extended to include the unit formerly designated the Hoskinnini Tongue of the Cutler Formation (Stewart, 1959). The Hoskinnini is now known as the Hoskinnini Member of the Moenkopi Formation and is assigned to a Triassic(?) age. As a result, rocks designated Moenkopi Formation in earlier maps and reports (Lewis, 1958; Lewis and Campbell, 1958a-f, 1959a-d) are referred to as the upper member of the Moenkopi Formation in this report.

HOSKINNINI MEMBER

The Hoskinnini Tongue was named and described by Baker and Reeside (1929) in Monument Valley, Utah. They considered the Hoskinnini to be a member of the Cutler Formation of Permian age because of its similarity to the Organ Rock and Halgaito Tongues. Mullens (1960) and Trites and others (1956) mapped the Hoskinnini northward from the type locality in Monument Valley across the Clay Hills and White Canyon areas adjacent to Elk Ridge. Later work by Stewart (1959) indicates that the Hoskinnini is continuous with a member of the Moenkopi Formation in southwestern Colorado and is probably of Triassic rather than Permian age in that area. Because of this relation the Hoskinnini has been assigned a Triassic(?) age.

The Elk Ridge area, which is between the type locality and the southwestern Colorado outcrops, contains evidence supporting both the conclusions of Baker and Reeside (1929) and of Stewart (1959). In the southwestern part of Elk Ridge and in parts of White Canyon, the Hoskinnini is separated from the overlying Moenkopi Formation by a disconformity, and in composition, color, and weathering characteristics it closely resembles the Organ Rock Tongue of the Cutler Formation; in the northeastern part of Elk Ridge, however, the contact with the overlying Moenkopi Formation is gradational, and the upper part of the Hoskinnini shows bedding and other features characteristic of the Moenkopi.

The Hoskinnini is about 100 feet thick in the northeastern part of the area near Bridger Jack Mesa, and it thins to about 70 feet in the southern part of the area. It is slightly more resistant to erosion than the underlying Organ Rock and overlying upper member of the Moenkopi Formation, and it commonly forms steep low cliffs, particularly on bare south-facing slopes. Most of the Hoskinnini is red but locally it is greenish gray to light brown. It weathers to rounded blocky masses and crude columnar forms that are characteristic of only the Hoskinnini in the Elk Ridge area.

The Hoskinnini is composed chiefly of medium- to coarse-grained silty sandstone with lesser amounts of siltstone. The lower part of the unit commonly contains beds of coarse to medium sandstone. The grain size decreases progressively upward to silt size near the top of the unit. A distinguishing feature of the Hoskinnini is the presence of numerous large (as much as 5 mm) well-rounded frosted quartz grains. These are particularly abundant in the lower beds either as scattered single grains or in aggregates forming thin lenses. The presence of these larger grains, together with the coarseness of the sandstone beds, helps in distinguishing fragments and small isolated outcrops of the Hoskinnini from other units.

Calcite is the common cement, particularly in the sandstone beds. Individual sand grains are chiefly quartz and feldspar, with minor amounts of rock fragments. Though most of the material is poorly sorted, individual grains are well rounded.

No fossils were found in the Hoskinnini Member and none have been reported from the Hoskinnini elsewhere.

UPPER MEMBER

The upper member of the Moenkopi Formation is of Early and Middle(?) Triassic age. The rocks are predominantly dark-brown to reddish-brown siltstone and fine-grained to very fine grained sandstone. The member ranges from 180 to 280 feet in thickness and averages about 250 feet thick. A few lenses of thick-bedded fine- to medium-grained sandstone, locally as much as 40 feet thick, are commonly present in the middle third of the member.

The contact of the upper member of the Moenkopi with the underlying Hoskinnini Member is conformable and locally gradational in most of the Elk Ridge area, but is locally disconformable on Elk Ridge and in the White Canyon area to the west (Thaden, 1964).

Rocks of the upper member are generally darker in color than the underlying red siltstone and sandstone of the Hoskinnini. Most outcrops are along steep-walled canyons where they are commonly eroded to a steep slope interrupted by steplike ledges whose nearly vertical faces mark the more resistant beds. These slopes generally contrast with the steep cliffs of the underlying Hoskinnini and the gentler slopes of the overlying Chinle mudstone.

Sandstone and siltstone of the upper member of the Moenkopi are both composed chiefly of quartz grains with lesser amounts of mica, feldspar, and a few dark

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unidentified mineral fragments. Quartz makes up as much as 80 percent of the rocks, commonly as subangular or angular grains many of which show strain shadows under crossed nicols. The mica is muscovite; detrital flakes as large as 1 mm in diameter are numerous on bedding planes. Grains of microcline and soda plagioclase are present in small amounts. The grains are commonly coated with red iron oxide.

The rock generally is moderately cemented with calcite and with minor amounts of finely divided red material—probably the "reddish iron-oxide-stained hydromica clay" reported by Cadigan (1959). The calcite occurs chiefly as minute disseminated subhedral crystals interstitial to the detrital grains. Cadigan (1959) indicated that hydromica is the chief clay mineral and kaolin the common minor clay mineral in Moenkopi sandstone and siltstone of northeastern Arizona, with the total clay ranging from 4 percent in sandstone to 13 percent in siltstone. Visual estimates suggest that similar rocks of the Elk Ridge area contain about the same proportions of clay.

The upper member of the Moenkopi in the Elk Ridge area is probably of Early and Middle(?) Triassic age. No fossils have been found in the Moenkopi in the Elk Ridge area, but fossil evidence elsewhere on the Colorado Plateau suggests an Early and Middle(?) Triassic age for the unit (McKee, 1954, p. 2, 10–11).

The mid-Triassic erosional unconformity that separates the Moenkopi and the Chinle Formations throughout the Elk Ridge area is indicated chiefly by shallow stream channels scoured into the upper member of the Moenkopi and filled with fluvial sandstone and mudstone of the overlying Chinle. There is little evidence of regional discordance. The bedding of the Moenkopi appears to be generally parallel to the bedding in the overlying Chinle except where shallow channels filled with Chinle rocks truncate a few feet of Moenkopi rocks. The thickness of the Moenkopi is relatively uniform throughout the area, except that the formation is generally thinner by a few tens of feet in the vicinity of the central part of Elk Ridge (fig. 5). The general parallelism of the mid-Triassic unconformity and the bedding in the Moenkopi, and the relatively uniform thickness of the Moenkopi Formation suggest that pre-Chinle erosion was minor.

CHINLE FORMATION

The Chinle Formation was named and described in Chinle Wash on the Navajo Indian Reservation in northeastern Arizona by Gregory (1917).

The Chinle Formation of Late Triassic age crops out over most of the Elk Ridge area between Comb Ridge on the east and the canyons adjacent to White Canyon on the west (pl. 2). In most of the Elk Ridge area the Chinle Formation is readily divisible into three units: a lower mudstone unit, the Moss Back Member, and the upper part of the Chinle. In the southeastern part of the area, south of the head of Comb Wash, the mudstone unit and the Moss Back Member were mapped as the "lower part of the Chinle Formation, undifferentiated" (pl. 2). The mudstone unit is chiefly massive mudstone with variable but generally minor amounts of interbedded sandstone and conglomeratic sandstone mostly in thin discontinuous lenses. Some of these lenses contain economically important uranium deposits in the Elk Ridge area. The mudstone unit is overlain by the Moss Back Member, a massive ledge-forming bed of fluvial sandstone and conglomeratic sandstone, which is continuous throughout the Elk Ridge area. The upper Chinle overlies the Moss Back Member and underlies the Wingate Sandstone of Late Triassic age. It consists of variegated shales and thin, even beds of mudstone, sandstone, siltstone, and minor limestone, most of which were probably desposited in a lacustrine environment.

MUDSTONE UNIT

The mudstone unit generally ranges in thickness from 5 to 150 feet but is locally absent. Stewart (1957) and Johnson and Thordarson (1959) referred to the local sandstone lenses at its base as the Shinarump Member and to the upper part as the Monitor Butte Member. The writers preferred to include both of these members under the informal term "mudstone unit," as they are parts of a continuous depositional sequence. The discontinuous sandstone lenses at the base were mapped individually because of their economic importance, but they probably are not all at the same stratigraphic horizon within the mudstone unit, and no distinct, continuous, readily mappable contact separates them in the Elk Ridge area.

The mudstone unit is predominantly massive blue to gray mudstone. Lenticular beds of sandstone are relatively abundant in the lower part of the unit within the central belt of ground favorable for uranium deposits (fig. 6). Many of these lenses occupy shallow paleostream channels cut into the underlying Moenkopi Formation. Others are separated from the Moenkopi by several feet of Chinle mudstone. South of the central favorable belt sandstone lenses are locally abundant but are generally separated from the Moenkopi by several feet to a few tens of feet of mudstone. In the southeastern part of the area near the head of Comb Wash, the mudstone unit is thin and sandstone predominates. North of the central belt, sandstone lenses are rare in the unit and few occur at its base. The mudstone thins northward and is about 5 feet thick near Bridger Jack Mesa. It pinches out a short distance

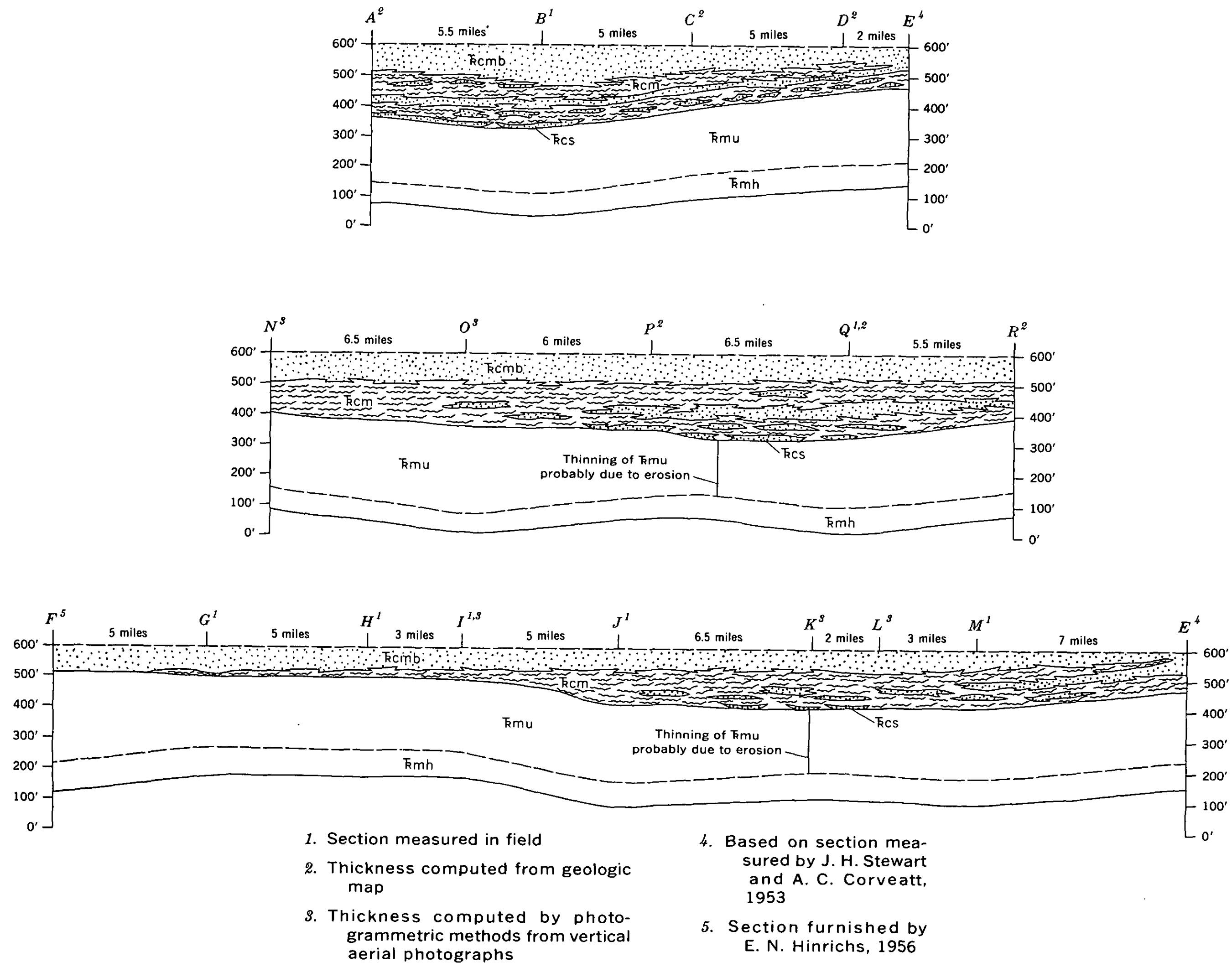


FIGURE 5.—Correlation diagrams along lines *A–E*, *N–R*, and *F–E* (see fig. 6), showing variations in thickness and lithology of the lower part of the Chinle Formation and relatively uniform thickness of the Moenkopi Formation. Datum is approximate top of the Moss Back Member. Hoskinnini Member (Ŧmh) and upper member (Ŧmu) of the Moenkopi Formation. Basal sandstone lenses (Ŧcs), mudstone unit (Ŧcm), and Moss Back Member (Ŧcmb) of the Chinle Formation.

north of the map area (fig. 5, diagram *F–E*).

The mudstone unit at most places is expressed topographically as a very gentle gray slope below low blocky cliffs of light-gray sandstone of the Moss Back Member and above the steep reddish slopes of the Moenkopi. Interbedded sandstone lenses crop out as low ledges in some places, but over most of Elk Ridge the unit is largely covered by colluvium and vegetation.

The mudstone unit is composed dominantly of montmorillonite and mixed-layer illite (hydromica)-montmorillonite clays (Schultz, 1957) with variable amounts of silt and sparsely disseminated, rounded, medium to fine grains of quartz sand. Schultz (1957, p. 504) indicated that much of the clay material was derived from rhyolitic volcanic debris.

The main host rocks for uranium deposits are sandstone lenses at the base of the mudstone unit in the central favorable belt. Most sandstone lenses are less than 20 feet thick, although locally a few are as much as 60 feet thick. Some lenses at the base of the Chinle fill scours in the underlying Moenkopi, but commonly these are 2 to 10 times as thick as the apparent depth of the scour channels. The lenses appear to have been deposited in paleostream channels whose banks were continually built up by the development of natural levees, thus perpetuating the position of the depositing streams after the scour channels in the Moenkopi had been filled. The paleostream channels trend westward, about parallel to the trend of the central favorable belt.

Sandstone lenses of the mudstone unit are composed of crossbedded medium-grained to very coarse grained, locally conglomeratic sandstone. The sand grains are subangular; most are quartz but some are feldspar. The pebbles are chiefly clear and milky quartz. Interstitial

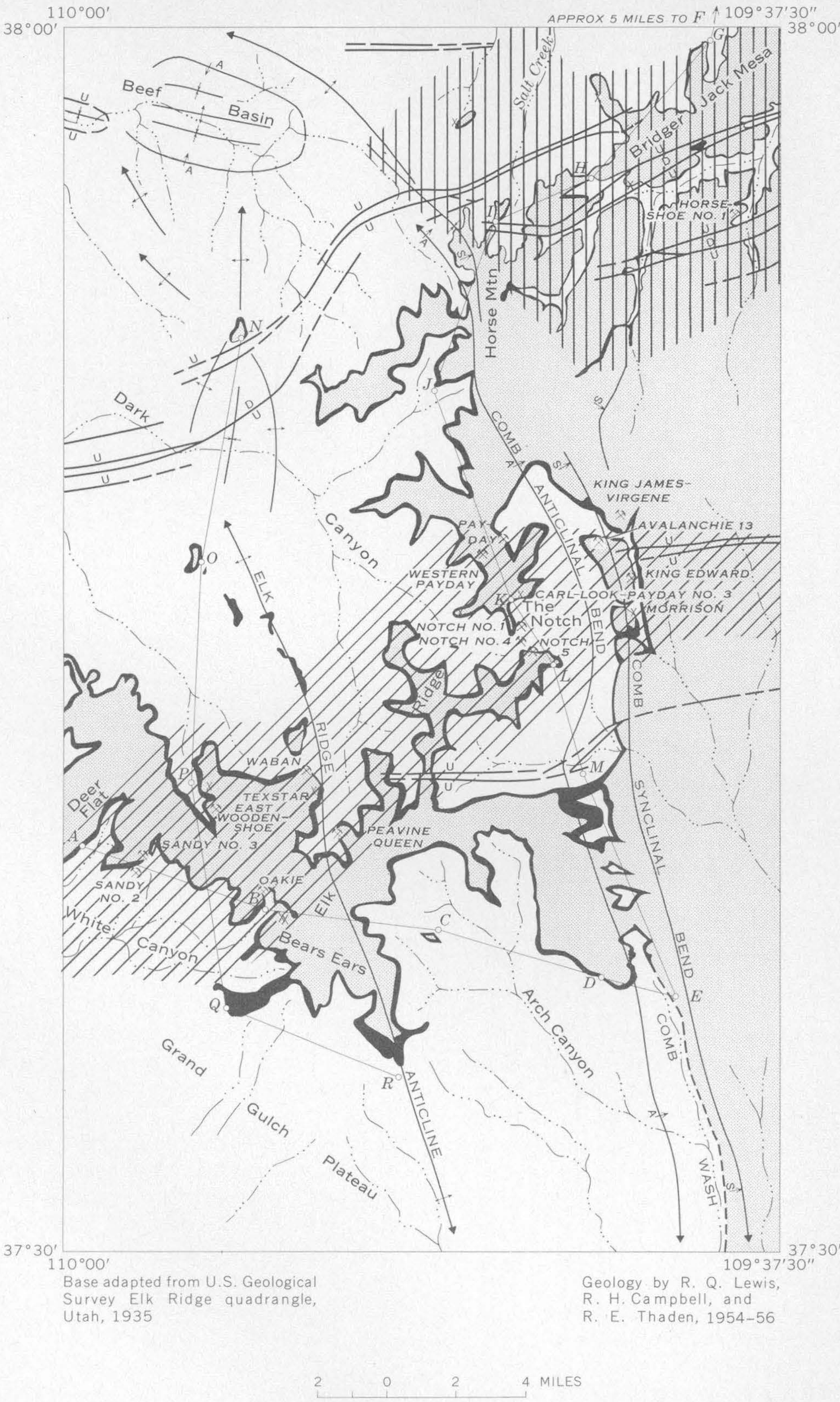


FIGURE 6.—Generalized geologic map of the Elk Ridge area, San Juan County, Utah, showing areas favorable for uranium deposits.

EXPLANATION

Upper Triassic (and younger) — TRIASSIC AND JURASSIC

Moss Back Member of the Chinle Formation and younger sedimentary rocks

Mudstone unit of the Chinle Formation
Predominantly mudstone but includes some interbedded sandstone lenses and ore-bearing sandstone lenses at the base. Heavy dashed line in the southeastern part of the map area represents sandy facies not differentiated from Moss Back

UNCONFORMITY

Lower and Middle (?) Triassic (and older) — PENNSYLVANIAN, PERMIAN, TRIASSIC(?) AND TRIASSIC

Upper member of the Moenkopi Formation and older sedimentary rocks

Area favorable for uranium deposits at the base of the Moss Back Member
Mudstone of the lower Chinle is less than 30 feet thick and is locally absent

Area favorable for uranium deposits in basal sandstone lenses of the lower Chinle
Contains virtually all basal sandstone lenses of the lower Chinle

U D

High-angle fault
Dashed where approximately located. U, *upthrown side;* D, *downthrown side*

Anticline
Showing trace of axial plane and direction of plunge of axis

Syncline
Showing trace of axial plane

A

Anticlinal bend
Showing trace of axial plane and direction of plunge of axis. Dashed where approximately located. Arrow barbed on side of steeper dip

S

Synclinal bend
Showing trace of axial plane and direction of plunge of axis. Arrow barbed on side of flatter dip

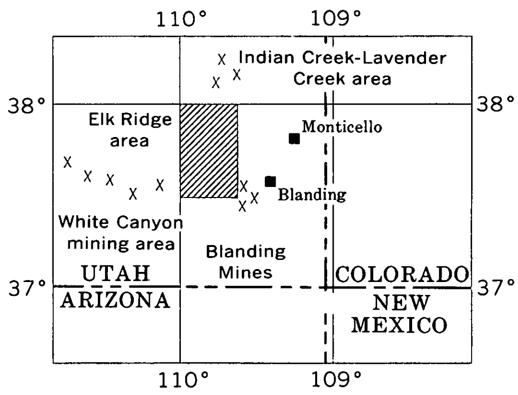
Mines from which there has been a recorded production of uranium ore

x

Prospect

A B C D

Lines of correlation diagrams (fig 5) with approximate location of measured sections



INDEX MAP

clay and silt are present in extremely variable amounts. The lenses range from well-washed, clean sandstone to very muddy sandstone. Mudstone lenses and relatively continuous thin mudstone partings are common. According to Schultz (1957, p. 498), the clay most commonly associated with the sandstone is kaolin. Much of the mudstone interbedded in the sandstone, however, is apparently of the same composition as the more massive mudstone of the unit and montmorillonite clays are probably abundant in the highly argillaceous sandstone. The contacts with the overlying massive mudstone are generally gradational and intertonguing, but in some places mudstone fills small scours in the top of sandstone lenses. Intertonguing and gradational relation between sandstone lenses and massive mudstone prevail both along and across channel trends. There are few differences in composition and sedimentary structure between basal sandstone and sandstone higher in the mudstone unit except that the higher beds are generally a little finer grained and tend to be more evenly bedded. Carbonaceous material is locally abundant in the sandstone as carbonized logs (rare), twigs, and tiny fragments interstitial to sand grains. Carbonized leaves have been found in the mudstone in a few localities. Interstitial blebs of asphaltite(?) and liquid hydrocarbon are locally abundant in the sandstone.

Johnson and Thordarson (1959) described the westward-trending central favorable belt of basal sandstone lenses in the Elk Ridge and White Canyon areas as the "Elk Ridge-White Canyon channel system." They suggest an eastern or northeastern source of sediment, perhaps the ancestral Uncompahgre highland. Studies of sedimentary structure by Poole and Williams (1956, fig. 59) indicate a westerly direction of sediment transport for sandstone deposits of both the mudstone unit and the Moss Back Member.

From southwest to northeast across the Elk Ridge area successively younger Chinle beds lap onto the mid-Triassic erosion surface. The resulting variation in thickness of the mudstone unit is not matched by inverse variation in thickness of the underlying Moenkopi Formation, such as might be expected if Chinle sediments were deposited in depressions formed chiefly by erosion of the Moenkopi. The position and trend of the central favorable belt of basal Chinle sandstone lenses are structurally controlled.

Gentle warping probably accompanied the uplift indicated by the change in sediment at the mid-Triassic unconformity. Because of the relatively uniform thickness of the Moenkopi and the general parallelism of the unconformity to the Moenkopi beds in the Elk Ridge area, the variations in thickness of the Chinle mudstone unit may reflect a topography partly of structural origin at the top of the Moenkopi. The correlation diagrams (fig. 5) suggest that basal Chinle flood-plain deposits lie in a shallow structural depression that was locally deepened by erosion.

On Elk Ridge the mudstone unit contains abundant plant remains. Silicified and carbonized sticks, branches, and logs are common in the sandstone lenses, and pollen and spores are abundant in mudstone at some localities. R. W. Brown and R. A. Scott of the U.S. Geological Survey have examined material from the area. Most of the fossils are gymnospermous and include representatives of the cycads, Ginkgoales, Ephedrales, and conifers. Scott identified *Alisporites opii* Daugherty, *Ephedra* sp., *Spencerites* (?) *chinleana* Daugherty, *Pityosporites* sp., and other common forms, in the Chinle Formation. Though positive age determination is not possible, Scott believes all the recognized forms to be representative of plants that grew in Late Triassic time.

MOSS BACK MEMBER

The Chinle mudstone unit is capped everywhere in the area by the Moss Back Member of the Chinle Formation, a massive ledge-forming bed of fluvial cross-bedded sandstone and conglomeratic sandstone that ranges in thickness from 55 to about 150 feet. In the northeastern favorable area (fig. 6), where the lower Chinle is generally thin, channel sandstone at the base of the Moss Back is locally in contact with the Moenkopi. The basal part of the Moss Back is similar in composition and sedimentary structure to the sandstone of the underlying units. Higher sandstone beds of the Moss Back are generally finer grained, contain relatively little interstitial clay or silt, and have relatively minor amounts of interbedded mudstone. The few differences between basal Moss Back and sandstones of the mudstone unit appear minor compared with their similarities, and compared with their differences from the other rocks of the area. In many places the contact of the Moss Back with the mudstone unit is a surface of erosion, but it probably does not represent a significant break in deposition. The Moss Back conformably underlies the upper part of the Chinle with a gradational or intertonguing contact.

LOWER PART UNDIFFERENTIATED

South and southeast of the central favorable belt (fig. 6) sandstone is locally abundant in the mudstone unit but several feet to a few tens of feet of mudstone are generally present at the base. Farther southeast, near the head of Comb Wash, sandstone is even more abundant and intertongues with the lower part of the Moss Back Member; only a few feet of sandy mudstone separates Chinle sandstone from the top of the Moenkopi. Farther south, along the east side of Comb Wash, the two units could not be differentiated and were mapped together (pl. 2). Near the confluence of Comb Wash and Arch Canyon intermittent outcrops show sandstone, in part equivalent to the Moss Back Member, on and near the top of the Moenkopi.

UPPER PART

The upper part of the Chinle Formation consists of generally thin and even-bedded red, pink, and gray variegated clay shales containing interbedded mudstone, siltstone, shaly sandstone, and minor amounts of limestone. The uppermost 40 feet commonly includes from one to three beds of maroon medium- to coarse-grained sandstone, at least partly of fluvial origin, which locally intertongues with the lowermost part of the overlying Wingate Sandstone. The upper Chinle of this report includes the Petrified Forest, Owl Rock, and Church Rock Members according to correlations by Stewart and others (1959).

The upper Chinle ranges from 480 to 530 feet in thickness in the Elk Ridge area. The rocks are very similar to the upper members of the Chinle elsewhere on the Colorado Plateau.

A few fossils characteristic of fresh-water environment were collected in the Elk Ridge area and in the White Canyon area to the west.

GLEN CANYON GROUP

Rocks of the Glen Cayon Group conformably overlie the Chinle Formation in the Elk Ridge area. The Glen Canyon Group consists of three formations which are, in ascending order, the Wingate Sandstone of Late Triassic age, the Kayenta Formation of Late Triassic(?) age, and the Navajo Sandstone of Late Triassic(?) and Jurassic age. The name Glen Canyon Group was first used by Gregory and Moore (1931, p. 61) for the Wingate, Kayenta (Todilto(?)), and Navajo Formations in the Glen Canyon area of Arizona and Utah. The Wingate is predominantly red eolian sandstone. The Kayenta consists of maroon, purple, and gray strata: fluvial sandstone and siltstone of fluvial and lacustrine origin. The Navajo is a light-gray thick, massive eolian sandstone.

No fossils have been found in these rocks in the Elk Ridge area. The Glen Canyon Group was originally considered to be of Jurassic(?) age (Gregory and Moore, 1931). Harshbarger and others (1957, p. 25–32) summarized the stratigraphy and faunas and concluded that the Triassic-Jurassic boundary is within the Glen Canyon Group. Age assignments in this report are based on paleontologic and stratigraphic evidence recently reported by G. E. Lewis and others (1961).

WINGATE SANDSTONE

The Wingate Sandstone of Late Triassic age is the basal formation of the Glen Canyon Group. It is a conspicuous cliff-forming unit in the Elk Ridge area and over most of the central Colorado Plateau. The Wingate forms a continuous prominent, massive cliff above the slope-forming Chinle Formation along The Comb in the southeastern part of the area. North of The Comb it forms a series of steep hogback ridges along the east flank of Elk Ridge above Cottonwood Creek. In addition to the continuous line of outcrop along the east edge of the map area, the Wingate crops out as remnants on the higher ridges and isolated buttes on Elk Ridge. It caps the Bears Ears, Woodenshoe Buttes, and Round Mountain; and forms cliffs near the top of Horse Mountain; Seven Sisters, Boundary, and Cathedral Buttes; and Bridger Jack Mesa (pl. 2).

The Wingate ranges from about 230 to about 270 feet in thickness in the Elk Ridge area. It thickens slightly to the northeast where E. N. Hinrichs (written commun., 1956) reported an average of 285 to 300 feet of Wingate along Indian Creek north of the Elk Ridge area.

In most of the Elk Ridge area the Wingate forms a massive unbroken cliff. The cliff face is formed by spalling along joint surfaces and viewed from a distance appears to be devoid of bedding planes or other sedimentary features. Along the east-central part of the area from sec. 35, T. 35 S., R. 20 E., to sec. 14, T. 35 S., R. 20 E., the Wingate is thick bedded and friable and weathers to form a slope continuous with the underlying Chinle.

The Wingate ranges from red to maroon in color. It is composed almost entirely of medium- to fine-grained subangular to well-rounded quartz grains well cemented by calcite. Small stringers of coarse quartz sand grains are common along the surfaces of crossbeds in the lower 2 feet of the formation. Most of the quartz grains are heavily coated with iron oxide, which imparts a red color to the formation. Minor minerals include feldspar, zircon, and garnet. Pebbles of sandstone and mudstone, probably derived from the Chinle, are common near the base of the Wingate.

KAYENTA FORMATION

The Kayenta Formation of Late Triassic(?) age is composed of sandstone and siltstone that were probably deposited in fluvial and lacustrine environments. It crops out along the east boundary of the Elk Ridge area, forms the upper section of the Comb Ridge cliff, and caps most of the mesas in the Chippean Rocks subarea. It also crops out in small isolated remnants on

Horse Mountain and on Seven Sisters and Cathedral Buttes (pl. 2).

The Kayenta is thinnest, about 130 feet, along The Comb in the southeasternmost part of the area. It is thicker to the north and exceeds 200 feet in thickness throughout most of the map area. E. N. Hinrichs (written commun., 1956) reported an average thickness of 220 feet in the Indian Creek area just north of Elk Ridge, and Witkind (1964) reported approximately 180 feet of Kayenta on the flanks of the Abajo Mountains to the east.

The Kayenta is composed of red to maroon, poorly sorted, fine- to coarse-grained micaceous sandstone with interbedded silty shale, limestone, and conglomerate. The sandstone beds are generally crossbedded and lenticular and many contain small stringers and lenses of quartz grit and conglomerate. The thin beds of shale are commonly gray to purplish red. The limestones are gray, unfossiliferous, and rarely more than a few inches thick. The common cement throughout the formation is calcite.

In general the Kayenta is darker in color than the underlying Wingate Sandstone or the overlying Navajo Sandstone. The color and ledged outcrop of the Kayenta are distinctive. The sandstones generally form a series of low cliffs above the sheer cliffs of the Wingate.

The Kayenta of the Elk Ridge area is conformable and intertongues with both the underlying Wingate and the overlying Navajo. The top of the Kayenta is placed at the top of a thin purple sandy siltstone that underlies a massive crossbedded sandstone. Immediately below the sandy siltstone is a 40-foot-thick light-gray and white sandstone that looks much like sandstone of the Navajo and might well be considered either Kayenta or Navajo.

No fossils were found in the Kayenta of the Elk Ridge area. Baker (1933) reported *Unio* from the Moab area, and Lewis (1958) collected a number of vertebrate fossils near the type locality at Kayenta, Ariz.

NAVAJO SANDSTONE

The Navajo Sandstone of Late Triassic(?) and Jurassic age is the youngest formation of the Glen Canyon Group. It crops out along the east side of The Comb and the upper end of Butler Wash in the southeastern part of the map area and extends north in continuous outcrop along the east boundary of the map area to North Cottonwood Creek (pl. 2). In the Elk Ridge area the Navajo averages about 300 feet in thickness. Inasmuch as the lower and upper contacts of the Navajo are generally widely separated and are exposed in areas where the dip is not uniform, measurements of the thickness are not precise.

The Navajo in most places is light gray in color and when viewed from a distance appears white in contrast with the adjacent rocks. In the Cottonwood-Chippean Rocks subarea, adjacent to to the Abajo Mountains, the Navajo is commonly pink or red.

The Navajo weathers to rounded cliffs, cones, intricate arches, and spires, in contrast with the blocky weathering forms characteristic of the adjacent sedimentary units. Erosion has in many places etched the surfaces, emphasizing the sedimentary structure.

The Navajo is composed of broadly lenticular intercalated lenses of high-angle crossbedded eolian sandstone. Individual lenses are bounded by nearly horizontal truncation planes, commonly marked by thin lenses of impure limestone or chert.

The sandstone is chiefly composed of rounded to subangular quartz grains, many with multiple overgrowths. Accessory minerals include feldspar, zircon, and small amounts of tourmaline and garnet. Near the top of the unit, scattered angular gray chert nodules are common and thin limestone lenses, most of them less than 6 inches thick, are locally present. Chalcedony is the common cement.

No fossils have been found in the Navajo of the Elk Ridge area, and the only fossils reported from the region are of dinosaur remains and nondiagnostic invertebrate and plant remains from near Shonto, Ariz. (Harshbarger and others, 1957, p. 22–23).

The Navajo is conformable and probably intertongues with the underlying Kayenta Formation. It appears to be conformable with the overlying Carmel Formation in the southeastern part of the area along Butler Wash but unconformable northward in the vicinity of Black Steer Knoll.

SAN RAFAEL GROUP

The Carmel Formation, the Entrada Sandstone, the Summerville Formation, and the Bluff Sandstone of the San Rafael Group crop out in the Elk Ridge area. The San Rafael Group was named and described by Gilluly and Reeside (1928, p. 73) in the San Rafael Swell of central Utah. In the type area, the San Rafael Group also includes the Curtis Formation (not present on Elk Ridge) but does not include the Bluff Sandstone.

CARMEL FORMATION

The Carmel Formation of Middle and Late Jurassic age was named by Gregory and Moore (1931) for Mount Carmel in southwestern Utah. In the Elk Ridge area the Carmel is composed of approximately 100 feet of friable gray, brown, and yellow sandstone and siltstone. It crops out in a narrow belt from Butler Wash in the southeasternmost part of the map area north to a point near the mouth of Allen Canyon where it leaves the area (pl. 2). Commonly the Carmel forms a low cliff, generally in two distinct sections, above the Navajo Sandstone, and weathers into blocky ledges that contrast with the rounded forms typical of the Navajo.

In the southernmost part of the map area the Carmel is a heterogeneous unit composed of gray to brown sandstone and red, green, and blue siltstone. Northward the Carmel becomes more sandy, and in the vicinity of the Elk Ridge-Blanding Road it is composed almost entirely of gray to brown sandstone. This lithologic change appears to be a continuation of a similar change noted by Sears (1956, p. 199) along Butler Wash to the south: "Northward in Butler Wash the thickness of the Carmel remains nearly constant. The composition changes, however; the unit becomes more and more sandy and lighter in color until it is made up chiefly of gray to buff sandstone with a notable reddish soft band in the middle." North of Butler Wash the "notable reddish soft band in the middle" becomes less conspicuous until the whole unit is a rather uniform gray to brown sandstone not easily differentiated from the underlying Navajo (fig. 7).

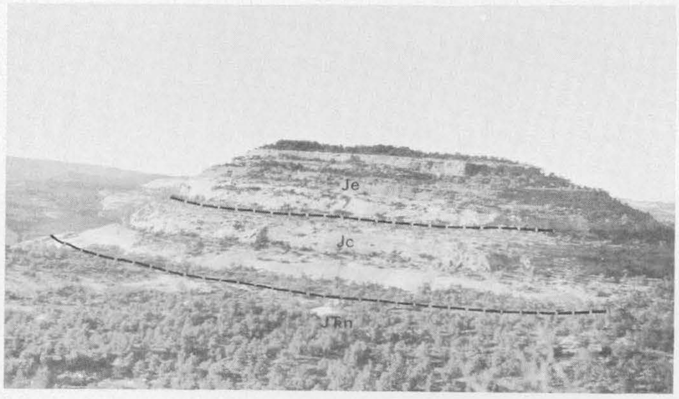


FIGURE 7.—Upper part of the Navajo Sandstone (JTRn), the Carmel Formation (Jc), and the Entrada Sandstone (Je), as exposed in sec. 29, T. 35 S., R. 21 E., showing their general similarity in appearance.

The sandstone of the Carmel in the Elk Ridge area is medium to coarse grained, brown to gray, and is composed of angular to subrounded sand grains. It is weakly cemented near the south edge of the area but more strongly cemented to the north. Calcite is the dominant cement. The Carmel can be differentiated from the sandstone of the Navajo by its darker color and lack of the high-angle crossbedding characteristic of the Navajo Sandstone. The Carmel also contains a greater variety of minerals, including mafic minerals not common in the Navajo.

No fossils were found in the Carmel Formation in the Elk Ridge area; however, abundant marine fossils have been reported from the Carmel in central and southwestern Utah (Imlay, 1952, p. 963). These fossils indicate that the Carmel in those areas is of Middle and Late Jurassic age.

In the vicinity of Elk Ridge much of the base of the Carmel forms a nearly flat surface that truncates the sweeping eolian crossbeds of the Navajo Sandstone. However, elsewhere in the map area the basal sediments of the Carmel were obviously deposited on a surface with local relief of as much as 20 feet. Whether the apparent irregularities are due to erosion of the Navajo prior to the deposition of the Carmel or are relic dune structures at the top of the Navajo cannot be ascertained. Wright and Dickie (oral commun., 1956) reported an erosional(?) unconformity north and east of the Elk Ridge area.

Baker and others (1936, p. 7) noted little evidence of unconformity between the Navajo and the Carmel in central Utah and concluded that in most places the contact was gradational. This combination of data indicates an unconformable relation with the Navajo to the east and continuous deposition to the west. Both relations are present in the Elk Ridge area, where the contact is mostly conformable but locally disconformable.

The predominance of sandstone in the Carmel of the Elk Ridge area, compared to the predominance of finer clastic material and large amounts of limestone and gypsum to the west in the Henry Mountains (Hunt, 1953), suggests that the Elk Ridge area was much nearer the source of clastic sediments. This, coupled with the unconformity observed by Wright and Dickie (oral commun., 1956), indicates that the Elk Ridge area was fairly close to the east edge of the Carmel basin.

The contact between the Carmel and the overlying Entrada Sandstone is conformable, which shows that the eolian standstone of the Entrada encroached upon water-laid Carmel deposits.

ENTRADA SANDSTONE

In the Elk Ridge area the Entrada Sandstone of Late Jurassic age crops out in a series of low "slick rim" cliffs above the Carmel Formation and beneath the Summerville Formation. The uppermost 80 feet of the formation forms a prominent and continuous smooth-faced cliff of salmon-red color from the south edge of the map area in Butler Wash to the mouth of Allen Canyon.

In the Elk Ridge area the Entrada ranges from 140 to 150 feet in thickness and is divisible into three units: a lower cliff-forming unit of light-gray, white, or brown sandstone; a middle slope-forming unit of red to maroon sandy slitstone and thin-bedded sandstone and an upper cliff-forming unit of massive salmon-red sandstone.

The lower unit is 20 to 30 feet thick and is composed of clean well-sorted, medium- to coarse-grained crossbedded eolian sandstone. It contains scattered well-rounded and frosted quartz grains averaging about 2 mm in diameter. These larger grains are abundant throughout the unit, though somewhat more numerous near the base. They are easily seen on the weathered surfaces of outcrops and facilitate field identification of the Entrada.

The middle unit is composed of 30 to 40 feet of dark-red water-laid siltstone and fine-grained red silty sandstone and a few thin resistant light-gray and pink sandstone beds near the top. This part of the Entrada is the least resistant part of the formation, and its outcrop area is usually a broad bench or shallow slope between the upper and lower cliff-forming units. In places where the middle unit is more resistant it forms the lower part of the upper "slick rim" cliff.

The upper unit is a massive salmon-red crossbedded fine- to medium-grained eolian quartz sandstone. It is about 80 feet thick and stands as a continuous resistant cliff throughout the map area and is one of the most easily recognizable marker beds in the Jurassic section.

No fossils were found in the Entrada in the Elk Ridge area or elsewhere; however, at the type locality in the San Rafael Swell, formations stratigraphically below and above the Entrada contain Late Jurassic marine fossils (Gilluly, 1929, p. 99–108). In the Elk Ridge area the contact between the Entrada and the underlying Carmel Formation was placed at the top of a thin (2–4 ft.) blue-green mudstone that separates the uppermost sandstone of the Carmel Formation from the basal sandstone of the Entrada. Although the upper sandstone of the Carmel and the lower sandstone of the Entrada look very much alike viewed from a distance, the steep, sweeping crossbeds and coarser grain of the sandstones in the Entrada are easily distinguished from the finer grained sandstones of the Carmel with their low-angle crossbeds. The contact of the Entrada with the overlying Summerville Formation is a flat surface at which the high-angle crossbeds of the Entrada abruptly terminate.

SUMMERVILLE FORMATION

The Summerville Formation of Late Jurassic age was named by Gilluly (1929, p. 80) for Summerville Point in the San Rafael Swell.

The Summerville Formation crops out in the southeastern part of the map area in Butler Wash, Whiskers Draw, North Fork, and near the mouth of Dry Wash.

In the Elk Ridge, Butler Wash, and Abajo areas the stratigraphic interval between the top of the Entrada and the base of the Salt Wash Sandstone Member of the Morrison Formation is approximately 200 feet. This interval is occupied by the Summerville Formation and the Bluff Sandstone. The Summerville attains a maximum thickness of 208 feet in the Elk Ridge area just south of the Blanding Road near North Fork and Whiskers Draw. The Summerville thins southward and is about 100 feet thick near the south boundary of the area.

The Summerville Formation is a heterogeneous unit composed of sandy siltstone, sandstone, mudstone, and shale. At the south boundary of the area in Butler Wash, the Summerville contains much light-gray mudstone and shale, particularly in the lower part. Northward it becomes progressively more sandy and its color changes to orange and red. In the vicinity of the Blanding Road, the Summerville is thin-bedded red sandy siltstone containing a few thin ledge-forming orange, red, and brown sandstones. The sandstones are similar in color and composition to the Bluff Sandstone, which overlies and intertongues with the Summerville in the Elk Ridge area. Gypsum is locally abundant in thin veinlets and stringers, and thin beds and nodules of chert are near the top of the formation, particularly in the northernmost outcrops.

The Summerville Formation is overlain by the Salt Wash Sandstone Member of the Morrison Formation in the east central part of the Elk Ridge area, and by the Bluff Sandstone in the southeastern part. The Summerville intertongues with the Bluff. Where the Summerville is in direct contact with the Salt Wash, a disconformity is evident; deep scours into the Summerville are filled with sandstone and mudstone of the Salt Wash.

The Summerville is composed of sedimentary rocks deposited in a shallow basin. They were deposited above the eolian sandstone of the Entrada and were in turn buried under sandstone beds of the Bluff Sandstone or, where absent, the fluvial deposits of the Morrison Formation. The intertonguing relation to the Bluff Sandstone indicates that the upper part of the Summerville was deposited simultaneously with the lower part of the Bluff in the Whiskers Draw area.

Fossils have not been found in the Summerville Formation, and its Late Jurassic age is inferred from its close relation to other formations of the San Rafael Group, particularly the Curtis Formation in the San Rafael Swell (Gilluly, 1929).

BLUFF SANDSTONE

The Bluff Sandstone of Late Jurassic age was named by Gregory (1938, p. 58) for the small town of Bluff, San Juan County, Utah, where it is exposed in spectacular cliffs along the San Juan River. Gregory considered the Bluff to be a basal member of the Morrosion Formation. Craig (Craig and others, 1955, p. 133) noted that the Bluff intertongued with the Summerville in southeastern Utah and with the Salt Wash Sandstone Member of the Morrison in northeastern Arizona. Because of the lithologic characteristics, particularly bedding, he placed the Bluff in the San Rafael Group rather than in the Morrison Formation.

The Bluff Sandstone crops out only in the southeasternmost part of the Elk Ridge area along the east side of Butler Wash and in the vicinity of Utah State Highway 95 (pl. 2).

At the southeastern corner of the map area, the Bluff ranges from 80 to 100 feet in thickness. It thickens slightly northward to a point near the mouth of Whiskers Draw. North of Whiskers Draw it thins abruptly and is completely missing at the Elk Ridge-Blanding road. For several miles south from the northernmost wedge edge of Bluff Sandstone, a wedge of Summerville rocks 15 to 20 feet thick separates the Bluff from the overlying Salt Wash Sandstone Member of the Morrison Formation. Farther south, the Bluff is in direct contact with the Salt Wash. The thin wedge of Summerville that locally overlies the Bluff is not shown separately on the geologic map (pl. 2), but was mapped together with the Bluff as a single unit.

The Bluff is composed of light-gray to brown crossbedded medium-to coarse-grained well-cemented quartz sandstone. It typically forms one massive homogeneous bed, but locally it is separated into individual sandstone lenses by thin red clay and shale lenses.

The Bluff intertongues with the Morrison Formation in northeastern Arizona (Craig and others, 1955). However, in the Elk Ridge area the Bluff is unconformably overlain by the Salt Wash Sandstone Member of the Morrison and intertongues with the Summerville. The unconformity between the Bluff and Salt Wash in the Elk Ridge area is part of an unconformity, widespread on the Colorado Plateau, between the Morrison and older formations.

MORRISON FORMATION

In southeastern Utah the Morrison Formation has been subdivided into four members (Craig and others, 1955): the Salt Wash Sandstone Member, the Recapture Shale Member, the Westwater Canyon Sandstone Member, and the Brushy Basin Shale Member. All these members are exposed a short distance east of the map area, but only the Salt Wash Member crops out within it.

SALT WASH SANDSTONE MEMBER

The Salt Wash Sandstone Member of the Morrison Formation of Late Jurassic age crops out along the east boundary of the map area between Butler Wash and Cottonwood Creek. Most of the Salt Wash has been stripped away by erosion, and only a few feet of the basal sandstone remains as a capping of the low mesas. Consequently no measurements of thickness were made. Wright and Dickey (oral commun., 1956) measured 276 feet of Salt Wash strata on Mancos Jim Butte immediately east of the area, and it can be assumed that a similar thickness was once present across Elk Ridge.

The Salt Wash Sandstone Member, composed of ledge-forming sandstones separated by weak thin beds of red and blue-green shale, is characterized by stairstep topography.

The sandstones of the Salt Wash, unlike those of the Glen Canyon and San Rafael Groups, contain numerous pebbles of quartz, quartzite, and chert. Clay galls and pebbles are common, and in general the sand grains are coarser than those of the subjacent units. The sedimentary features—low-angle cross beds and scour-and-fill structure—indicate that the beds are stream deposits.

No fossils were found in the Salt Wash in the Elk Ridge area; however, extensive collections from the Colorado Plateau contain algae, fresh-water mollusks, and ostracodes.

The Salt Wash is unconformable on the Summerville Formation and the Bluff Sandstone in the Elk Ridge area. The basal sandstone of the Salt Wash fills channels cut into the underlying units to a maximum depth of 40 feet.

There are no known uranium deposits in the Salt Wash in the Elk Ridge area; however, east of the Elk Ridge area the uppermost sandstone strata of the Salt Wash contain uranium-vanadium ore deposits.

CENOZOIC DEPOSITS

The Cenozoic Era is represented only by Quaternary deposits of dune sand and silt and of alluvium, talus, and mixed valley fill unconformably overlying the consolidated sedimentary rocks. The Quaternary deposits are generally small in areal extent, thin, and restricted to the valleys and basins. Though much of the bedrock is covered with a thin residual mantle of soil and colluvium the contacts of the underlying units are shown on the map wherever it was possible to project them with reasonable certainty.

DUNE SAND AND SILT

Deposits of windblown sand and silt-size material are common at lower altitudes in the southeastern part of the area, particularly in Comb and Butler Washes, and in the northwestern part of the area in The Needles. The deposits are small and are generally on the east side of north-trending ridges and on the north sides of west-trending ridges, indicating prevailing winds from the southwest. Only the larger deposits are shown on the map (pl. 2).

LANDSLIDE AND SLUMP DEPOSITS

Small landslide and slump blocks are numerous in the Elk Ridge area, particularly on the steep slopes of Elk Ridge proper; however, only two landslides are of sufficient size to map; one on the Elk Ridge-Blanding Road north of Milk Ranch Point and the other on the west side of South Long Point. In these areas, sandstone blocks of the massive Moss Back Member of the Chinle Formation have broken away from the rim and slid down over the lower mudstone unit of the Chinle (pl. 2).

Along the Elk Ridge-Blanding Road an area of several square miles contains numerous landslide deposits. Blocks of the Moss Back Member are scattered on a surface of lower Chinle mudstone. Some of the blocks appear to be as much as one-half mile from their point of origin. The area on South Long Point is much smaller in extent and in most places the blocks of Moss Back have slumped and slid only a few feet.

VALLEY FILL

In the northern part of the area the canyons, basins, and graben valleys have been partly filled with a mixture of windblown and water-deposited sediments. No attempt was made to differentiate the two as they are intimately interbedded and individual units are thin. Most of the sediments are sand and silt with minor amounts of pebbles and gravel.

ALLUVIUM

Alluvium with minor amounts of gravel is common along the larger valleys. The larger areas of alluvium are shown on the map, but many smaller patches along the canyons are not shown. The alluvium ranges from a few feet to more than 60 feet in thickness. Minor unconformities are numerous in the alluvium, indicating alternating periods of alluviation and degradation. In places, artifacts indicate that at least part of the alluvium was deposited after human occupancy of the area.

The alluvium has been recently dissected by erosion, and in many places the bedrock is exposed. Erosion of the alluvium has apparently been accomplished largely during the last 100 years. In the valley of North Cottonwood Creek a cabin built in the 1870's on the top of an alluvial fill was subsequently partly covered by alluvium prior to the recent downcutting. The stream that deposited the alluvium over the cabin site is now entrenched in a gulley about 30 feet below the former valley floor.

TALUS

Talus has been mapped along the upper part of Comb Wash in the southeastern part of the map area. Although in many places thin deposits of talus and colluvium cover the surface, it is only in Comb Wash (pl. 2) that the deposits are sufficiently extensive to obscure the bedrock relations.

ALLUVIUM AND TALUS, UNDIFFERENTIATED

One area in the upper end of Comb Wash contains several hundred feet of talus, colluvium, alluvium, and windblown material so well intermixed that it was impossible to show the units separately on the map.

STRUCTURE

Three regional structural elements control and dominate the structure of most of the Elk Ridge area: The Monument upwarp, the Comb monocline, and the deformation caused by the flowage of salt and gypsum in the northwestern part of the area. The exposed sedimentary rocks generally dip gently (2°–3°) away from a low dome near the center of the Elk Ridge area. Minor undulations on the gently dipping surfaces are locally abundant, and high-angle normal faults bounding east- and northeast-trending grabens are prominent in the central part of the area. In the northwesternmost part of the area, east- and northeast-trending grabens define a complex collapse area along and near Cataract Canyon of the Colorado River (fig. 8).

The Monument upwarp is a broad, low arch that trends nearly north for about 100 miles from Monument Valley, Ariz., to the Elk Ridge area. It is 30 to 40 miles wide. The west flank is broader and generally more gently dipping than the east flank, which is bounded by the steeply dipping Comb monocline. The north ends of both the Monument upwarp and the Comb monocline are within the Elk Ridge area (pl. 2 and fig. 9).

Because of the broad gentle nature of the Monument upwarp and the smaller folds, the positions of most fold axes were located on structure-contour maps in the office as they could not be reliably placed in the field. Because of the lenticular character of many of the beds, the structure contours have been drawn on two horizons instead of attempting to extrapolate to a single horizon.

FOLDS

The dominant folds of the area are the Monument upwarp and the Comb monocline, both of which trend slightly west of north. In the northwestern part of the area (pl. 2 and fig. 9) many smaller folds trend generally eastward across the broad north-plunging end of the Monument upwarp.

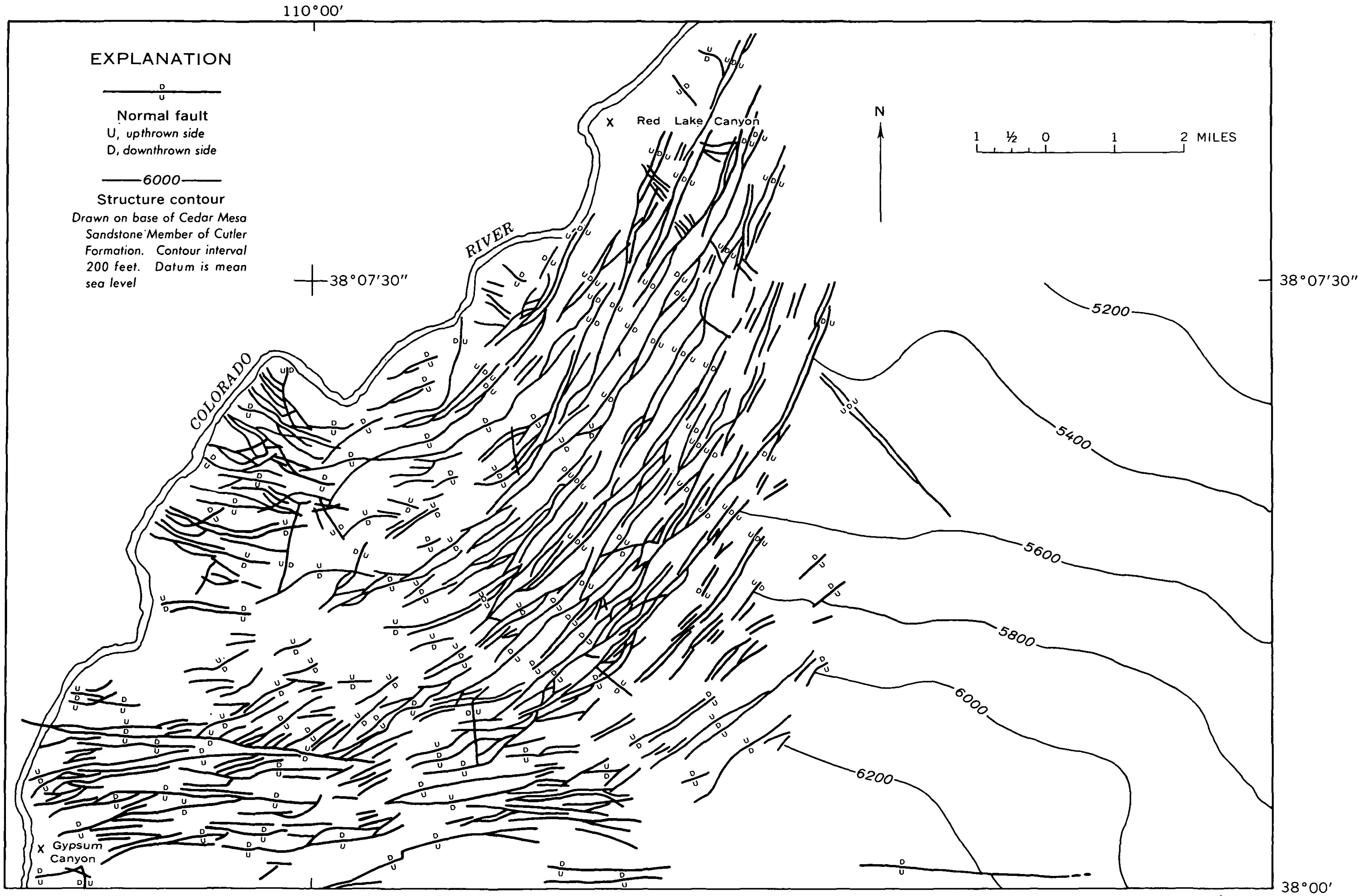


Figure 8.—Generalized structural map of part of The Needles subarea.

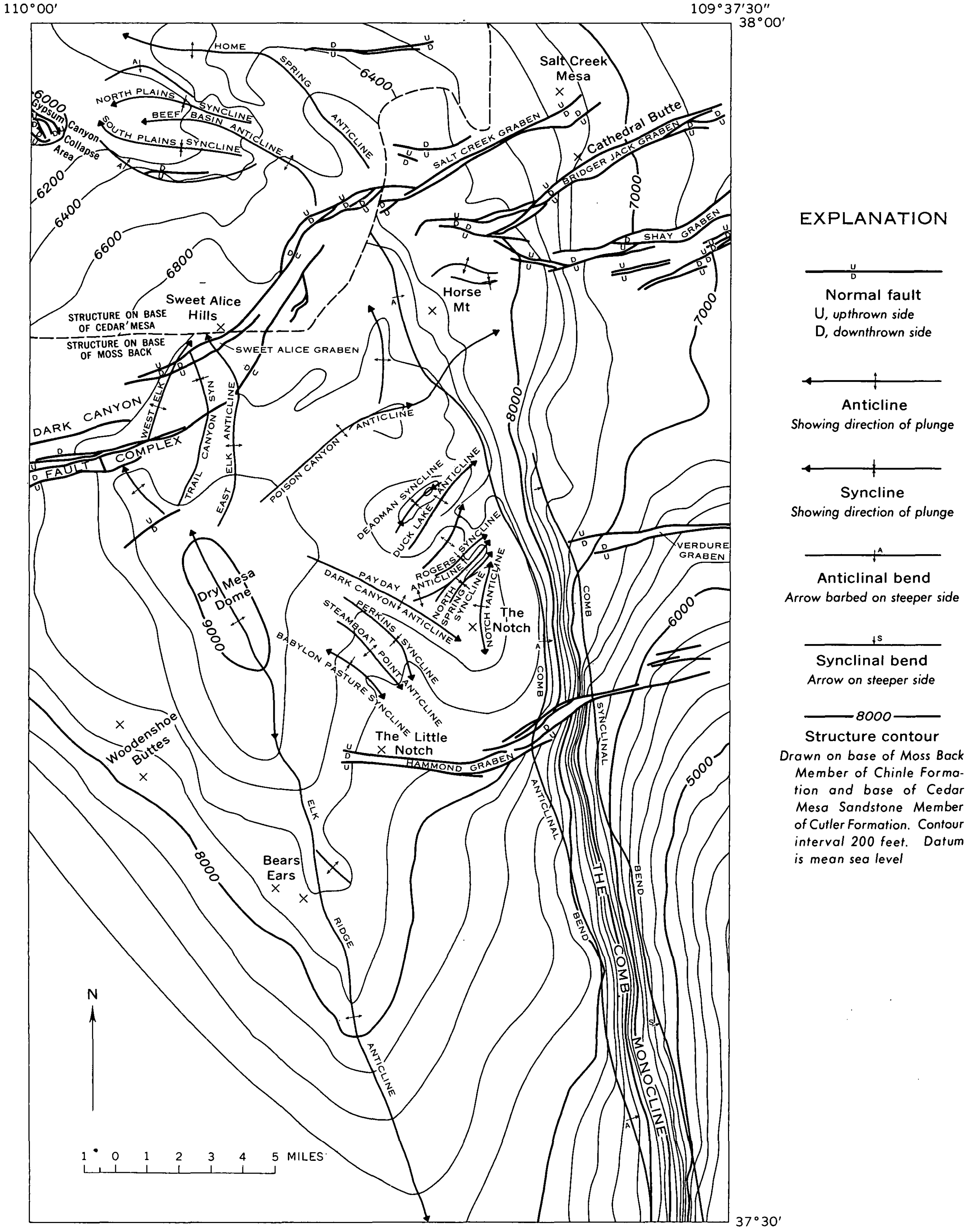


FIGURE 9.—Generalized structural map of the Elk Ridge area.

Along the broad crest of the Monument upwarp are a number of minor folds that trend generally north, northeast, and southeast. The most continuous of these is the Elk Ridge anticline, which forms the crest of the Monument upwarp. The Dry Mesa dome is at the apex of the Elk Ridge anticline in the central part of the Elk Ridge area. The other minor folds along the crest appear to generally radiate from the north and east sides of the Dry Mesa dome. North of the Dry Mesa dome, the crest of the Monument upwarp is generally expressed by two or three short, discontinuous minor anticlines that plunge northward.

Northeast of Dry Mesa dome the most prominent of the minor folds is the Poison Canyon anticline. In the vicinity of Dead Man Canyon the Poison Canyon anticline has an apex with a local closure of nearly 200 feet. From this apex several minor folds radiate north, northeast, and east.

To the east of Dry Mesa dome the Dark Canyon anticline trends southeast. Abundant minor folds to the north of Dark Canyon anticline trend northeast across North Elk Ridge. At its southeast end, the Dark Canyon anticline appears to join the south-trending Notch anticline to form a broad nose, plunging southeast. Along the south flank of the Dark Canyon anticline, several les.er parallel folds trend southeast across South Elk Ridge. These small folds associated with the Dark Canyon anticline are well expressed topographically by undulations in the top of the Moss Back Member of the Chinle Formation which caps Elk Ridge in that area.

As the field maps were at a scale that made possible the mapping of the anticlinal and synclinal bends of monoclines separately, the writers chose to represent the monoclines on the map by two trace lines instead of one. The use of this map notation makes it possible to illustrate the similar paired or unpaired bends of lesser structures elsewhere in the area. The anticlinal and synclinal bends are represented by the traces of planes of inflection between gently dipping and steeply dipping beds on the structure-contour horizon. These coincide in some places with the traces of axial planes of the bends. Anticlinal and synclinal bends do not always occur in pairs of nearly equal abruptness outlining monoclines or structural terraces. Several anticlinal bends of relatively low structural relief are not paired with corresponding synclinal bends, but the steep limbs become gradually shallower in dip without the development of a well-defined plane of inflection.

Most of the monoclines and unpaired or geographically isolated anticlinal bends appear to be similar folds. The plane of inflection appears to be generated nearly vertically in contrast to the inclined axial planes of the individual beds. The monoclines and the isolated anticlinal bends appear to have been formed by the draping of bedded sediments over deep-seated, high-angle faults or fault systems. This hypothesis of the generation of the monoclines and anticlinal bends is not clearly established by direct observation, and the manner of origin is debatable.

The Comb monocline trends northwest in the Elk Ridge area. It enters the map area near the southeast corner and continues northwest to the headwaters of Cottonwood Creek, where it apparently grades into a series of radiating monoclines and terraces of smaller structural relief. In the southeastern part of the area the Comb monocline has a structural relief in the Triassic beds of 1,000 to nearly 3,000 feet within a horizontal distance of about 1½ miles. Dips on the steep limb are locally as much as 30°. North of the headwaters of Cottonwood Creek the total structural relief of the lesser monoclines and terraces is less than 1,000 feet in a horizontal distance of more than 5 miles.

The symmetrical association of the Comb monocline with the Monument upwarp suggests that the two elements are genetically related. The undeflected entrenchment of the San Juan River across both of these major structural elements suggests that the Monument upwarp and the Comb monocline were formed contemporaneously. If the arching and the uplift associated with these two structural elements occurred simultaneously, it seems likely that both structures were the result of the same deforming stresses. The minor folds along the crest of the Monument upwarp are also probably results of these stresses for they form a crudely radial pattern about the Dry Mesa dome.

In the Beef Basin subarea low-amplitude folds of east trend cut across the plunging north nose of the Monument upwarp (pl. 2). Beef Basin is a sag area incompletely bounded on the north and south by arcuate anticlinal bends. It is crossed medially by the Beef Basin anticline, which trends east. This anticline is separated from the southern anticlinal bend by the South Plains syncline and from the northern anticlinal bend by the North Plains syncline (fig. 9). North of Beef Basin, the Home Spring anticline of northwest to west trend may represent the extension of the Comb monocline. Farther to the north the beds dip generally north and northeast (fig. 8), and because good exposures of contacts are widely separated, control adequate to define such minor structures is lacking.

The east-trending folds in the Beef Basin subarea may possibly be older than the Monument upwarp and perhaps are associated with the Middle Triassic warping inferred from stratigraphic evidence (p. B18), or they may have formed as intimate parts of the Monument upwarp.

It seems probable that Beef Basin may be a collapse area formed by plastic flow of material from the Paradox Member of the Hermosa Formation toward the mouth of Gypsum Canyon. Sagging may be responsible for the south dips on the south flank of the Home Spring anticline, which otherwise might have been a simple modification of the north-plunging nose of the Monument upwarp.

FAULTS

Nearly all the faults in the Elk Ridge area are high-angle normal faults that bound well-defined grabens. The grabens are prominent in two parts of the area, but fault blocks (grabens) in one part apparently formed by different processes and at a different time than those in the other part. In the east-central and northeastern part of the area (pl. 2 and fig. 9) several large east- and northeast-trending grabens are in an echelon group. Two of these, the Shay and the Verdure grabens, extend eastward beyond the map area into the Sage Plain and Lisbon Valley areas where they were named for topographic features outside the Elk Ridge area (Baker, 1933; L. C. Huff, written commun., 1956). The other grabens of this group are the Hammond, Bridger Jack, Salt Creek, and Sweet Alice, all named by R. Q. Lewis (1958). The bounding faults of the Sweet Alice and Salt Creek grabens together with the Dark Canyon fault complex (R. Q. Lewis, 1958) form an east-northeast-trending braided system that cuts across most of the Elk Ridge area and extends west to Mille Crag Bend in the White Canyon area. In The Needles area adjacent to Cataract Canyon, east-northeast- to north-trending grabens are abundant in an arcuate zone that extends east from the mouth of Gypsum Canyon, gradually swings northeast, and finally north near the confluence of the Green and Colorado Rivers (fig. 8). This zone is bounded on the northwest by Cataract Canyon (pl. 2).

If the Monument upwarp and the minor folds associated with it were formed as a result of general east-west compressive stresses, the grabens on its east and northeast side may have been formed at virtually the same time as a result of related north-south tensional stresses. However, the grabens appear to bend and follow along the strike of the beds around structural noses on the Monument upwarp, suggesting that the faults were pre-Monument upwarp. Also, as noted earlier, some of the grabens extend a considerable distance beyond the Elk Ridge area into the Sage Plain and Lisbon Valley areas. The writers feel that these structures resulted from tension caused by the differential compaction of the sediments overlying the Precambrian crystalline rocks. As shown by Hunt (1956, figs. 8 and 10), Paleozoic and Mesozoic rocks are relatively thin, totaling about 13,000 feet in thickness. North and west of the Elk Ridge area the Paleozoic and Mesozoic rocks are much thicker, and it is reasonable to assume that greater compaction took place in the sedimentary section in that area creating tension along the edge of the basin causing the large-scale graben faulting. The faults bounding the grabens appear to converge at a shallow depth (pl. 2, section *C–C′*) and primarily displace the competent sandstone of the Cedar Mesa Sandstone Member of the Cutler Formation and the overlying units.

HAMMOND GRABEN

The Hammond graben is a long narrow structure extending east through the Little Notch along the south flank of Hammond Canyon and across The Comb (pl. 2). The Hammond graben actually comprises two en echelon grabens with the east graben overlapping to the north of the west graben. The fault that forms the north side of the west graben and separates it from the east graben can be traced across The Comb. It is a scissors fault with the pivot point in the vicinity of The Comb; to the east the north side is down, thus forming the south side of the east graben, and to the west the south side is down and the fault bounds the west graben on the north. The structure bends to the south around the broad nose formed by the plunging Dark Canyon and Notch anticlines. The maximum displacement measured in the vicinity of the Little Notch on the north fault of the west graben is about 100 feet, and the displacement diminishes eastward to the pivot point. Displacement on the south fault of the west graben is approximately 80 feet at the Little Notch; it increases eastward to about 150 feet along the lower part of Hammond Canyon, but decreases beyond that point toward The Comb. The east graben is somewhat shallower; the maximum vertical displacement is about 120 feet on the south fault, and about 40 feet on the north fault.

VERDURE GRABEN

The long, narrow Verdure graben extends east from Cottonwood Canyon about 30 miles to Hovenweep Canyon (L. C. Huff, written commun., 1956). Only the west end of the structure is in the map area. In the Elk Ridge area the graben is bounded by nearly parallel faults. The north fault has a maximum vertical displacement of about 100 feet and the south fault about 80 feet. Both faults have progressively less displacement to the west and terminate on The Comb monocline.

East of the map area, the Verdure graben crosses the south flank of the Abajo Mountains. Witkind (1964) reported that dikes of diorite porphyry have been intruded along the faults of the Verdure graben. This indicates that the faulting is at least as old as the intrusion of the Abajo Mountains laccolith; it is the only direct evidence as to the age of graben faulting. Hunt (1956) placed the age of the Abaio Mountains laccolith between late Miocene and middle Pliocene.

SHAY GRABEN

The Shay graben extends east and northeast of the map area across the north flank of Shay Mountain and across Indian Creek to U.S. Highway 60 about 15 miles north of Monticello.

Only the southwest end of the graben is exposed in the Elk Ridge area. The north fault of the graben starts on the mesa west of Stevens Canyon and trends about N. 10° E. across the canyon. The bounding faults converge at the west end of the graben (fig. 10).

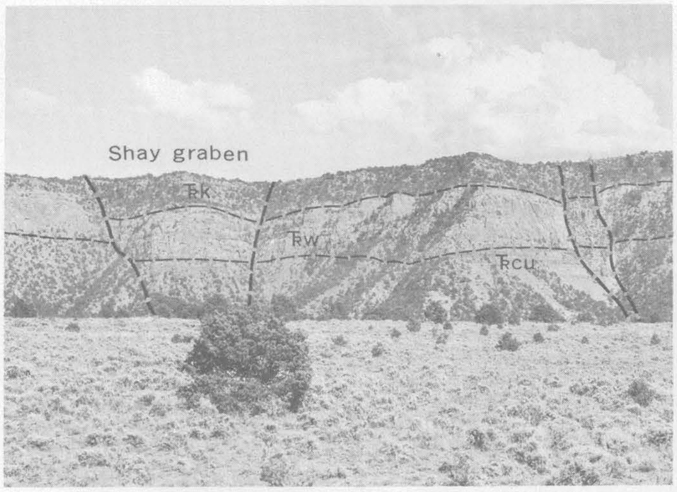


FIGURE 10.—Shay graben and boundary faults as exposed on the west side of Maverick Point (sec. 14, T. 33 S., R. 20 E.). Upper part of the Chinle Formation (Ŧcu), Wingate Sandstone (Ŧw), and Kayenta Formation (Ŧk). View looking east. Photo by R. E. Thaden.

The vertical displacement is about 150 feet on the north fault, and about 20 feet on the south fault. The displacement on both faults increases to the east so that the graben is dropped between 200 and 250 feet at the east edge of the map area.

BRIDGER JACK GRABEN

The Bridger Jack graben extends northeast from near Horse Mountain to the canyon of North Cottonwood Creek near the south end of Bridger Jack Mesa. Throughout most of its length the graben is bounded by only two faults (fig. 11). At the southwest end, however, the graben is bounded and crisscrossed by several faults in a braided pattern. The graben is roughly canoe shaped with the greatest displacement in the broadest central part south of Cathedral Butte. The maximum vertical displacement is about 375 feet on the north fault and slightly less on the south fault.

SALT CREEK GRABEN

The Salt Creek graben extends northeast from a point south of Beef Basin to Salt Creek Mesa. At Salt Creek Mesa the displacement is less than 20 feet. Displacement increases to nearly 600 feet farther west. Where exposed, the north fault appears to be nearly vertical whereas the south fault dips steeply north. West of the Beef Basin road the graben becomes a complex of anastomosing faults. These bound small overlapping graben structures which swing around and over the north nose of the Monument upwarp, cross the heads of Calf and Bull Canyons, and diminish in the vicinity of the Sweet Alice Hills.

SWEET ALICE GRABEN

The Sweet Alice graben trends southwest across the Sweet Alice Hills from the head of Bull Canyon and is continuous with the Salt Creek graben faults and the fault complex in Dark Canyon. The bounding faults have as much as 80 feet of displacement in the Sweet Alice Hills.

DARK CANYON FAULT COMPLEX

The Dark Canyon fault complex is a set of faults that extends southwest down Trail and Dark Canyons from the west end of the Sweet Alice Hills (pl. 2). The faults extend west of the map area into the White Canyon area and terminate in the vicinity of Mille Crag Bend on the Colorado River. In Dark Canyon the complex is composed of four or five roughly parallel faults that bound small horsts and grabens. The displacements are relatively small but are readily observed where the faults cut limestone of the Hermosa and Rico Formations. Eastward this complex is represented by a single fault that extends up Trail Canyon and through the saddle between North Long Point and the Sweet Alice Hills where it closely parallels the east end of the Salt Creek graben faults. This fault has about 80 feet of vertical displacement where it crosses the Forest Service road. The Dark Canyon faults are nearly continuous with those of the Salt Creek and Sweet Alice grabens and appear to be genetically related to them and to faults of the other major grabens.

THE NEEDLES FAULT ZONE

The Needles is a remarkable, picturesque area north of Beef Basin where the massive sandstone of the Cedar Mesa Sandstone Member of the Cutler Formation, and the underlying Rico and Hermosa Formations have been complexly jointed and faulted (pl. 2). The faults outline a series of closely spaced overlapping

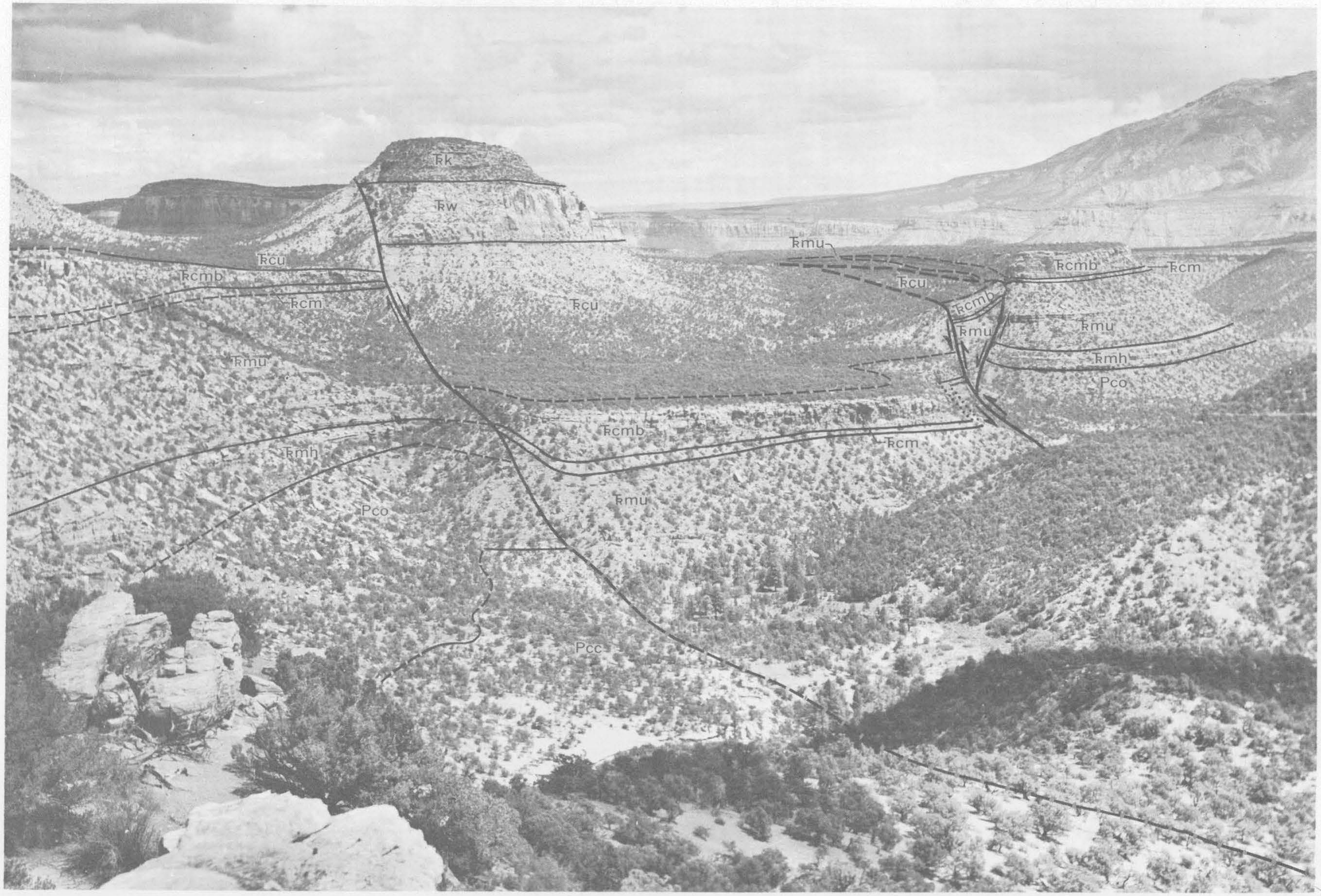


FIGURE 11.—Bridger Jack graben. View looking east from north rim above head of Davis Canyon. Cedar Mesa Sandstone Member (Pcc) and Organ Rock Tongue (Pco) of the Cutler Formation. Hoskinnini Member (R̄mh) and upper member (R̄mu) of the Moenkopi Formation. Mudstone unit (R̄cm), Moss Back Member (R̄cmb), and upper part (R̄cu) of the Chinle Formation. Wingate Sandstone (R̄w) Kayenta Formation (R̄k). Photograph by R. E. Thaden.

grabens, which form a large arc along the Colorado River. The grabens are a complex structural system of merging and braided normal faults that Baker (1933, p. 73) called ribbon faults. Displacement on individual faults generally ranges from a few feet to about 100 feet, although near Cataract Canyon some faults have displacements of as much as 300 feet. The down-dropped blocks of the grabens commonly underlie valleys and basins, which are partly filled with soil, alluvium, and small dunes (fig. 12). Travel through the area is restricted to routes along the connected valleys. The faults are relatively recent for they disrupt a drainage pattern developed on the Cedar Mesa Sandstone Member. Remnants of the prefaulting drainage can be observed on the surfaces of the blocks between the grabens. Only the Butler Canyon drainage now crosses the grabens in the area. Although Cross Canyon crosses the area, its through drainage is blocked by a low divide at the north side of a large northeast-trending graben valley where surface drainage from the southern half of the canyon is temporarily ponded and percolates rapidly underground. When runoff is heavy, most of the water flows into the topographic and structural basins from hanging valleys on the scarps and disappears into sink holes distributed along faults buried under the valley fill.

Ranchers familiar with the area report that movement has occurred along some of the faults within the memory of older residents of San Juan County. Many faultline sinks in the graben valleys appear to have been formed by the physical separation of the rocks along the fault rather than by solution. At places these faultline sinks resemble crevasses in glaciers with sheer walls a much as 20 feet high and as much as 7 feet apart. In many places these crevasses are bridged by unconsolidated valley fill in a manner resembling snow bridges across glacial crevasses.

Baker (1933, p. 74–76; and 1946, p. 101–103) postulated that the intense faulting in The Needles area was caused by flowage of salt and gypsum from the Paradox Member of the Hermosa Formation into the Meander anticline immediately to the north and northwest of the map area. Studies made along the Colorado River during the present investigation showed that the Paradox is exposed from a point near the mouth of Red Lake Canyon to a point southwest of the mouth of Gypsum Canyon (pl. 2 and fig. 8). The overlying beds of the Hermosa, Rico, and Cutler have been arched up along the river in a steep narrow anticline, in places only a few hundred feet wider than the riverbed. This structure was originally described by Harrison (1927), who gave it the name Meander anticline because of the fashion in which the structure parallels the course of the river. Harrison (1927, p. 125) postulated that the load on the Paradox Member was locally decreased by removal of material in the canyon of the Colorado River. This caused a lateral flow of salt and gypsum into the area. The Paradox crops out along the river, particularly on the east bank, as a series of separate intrusive masses in the northern part of the area, and as a nearly concordant unit for about 10 miles along the river in the vicinity of Gypsum Canyon. At least one-third cubic mile of the evaporites of the Paradox must have been removed from beneath The Needles area to account for the grabens.

The removal of material at relatively shallow depths has caused the collapse of the overlying competent limestone and sandstone. The trends of the faults, and consequently the graben valleys, apparently were determined by a strong preexisting joint system.

OTHER FAULTS

Two minor fault systems within the area do not appear to be related to the major graben faults or belong to The Needles fault complex. One system of several small faults is roughly parallel to the Shay graben at the east edge of the map area in T. 33 S., R. 21 E. (pl. 2). The other system forms a long, narrow north-trending graben that coincides with the crest of the Comb anticlinal bend (pl. 2, section *D–D′*).

The faults parallel to the Shay graben are interesting in that they displace the rocks of the Wingate and Kayenta Formations but do not displace the lower rocks of the Moss Back Member of the Chinle Formation. The faults are on the west flank of Shay Mountain, one of the laccolithic mountains of the Abajo Mountain group. The writers believe that the faults probably resulted from the intrusion of igneous rocks into the upper part of the Chinle Formation; the pressure of the intruding mass ruptured and faulted the overlying sandstone beds of the Wingate and Kayenta but did not disturb the strata below the level of intrusion.

The faults parallel to The Comb along the steeper part of the flexure are tension faults associated with the folding. The narrow graben is keystone-shaped in cross section, and its bounding faults converge at the base of the Cutler Formation.

GEOLOGIC HISTORY

The lowermost rocks exposed in the area are Middle Pennsylvanian in age. The earlier record must be inferred from well logs and surface outcrops in central Utah and western Colorado. The presence of Lower Cambrian arkosic conglomerate and Middle and Upper Cambrian limestone, dolomite, and shale indicates that

FIGURE 12.—Aerial view of The Needles showing the large graben faults and the complexly jointed surface of the Cedar Mesa Sandstone Member of the Cutler Formation. View looking west toward the Henry Mountains. U.S. Army Air Corps photograph.

the area received water-laid sediments throughout most of the Cambrian Period. The absence of Ordovician, Silurian, and Lower and Middle Devonian rocks indicates a prolonged period of nondeposition or the complete removal of rocks of any or all these ages. The latter seems unlikely. The fairly uniform thickness of the Cambrian is believed to indicate nondeposition rather than complete erosion of rocks of Ordovician, Silurian, and Devonian age.

From Late Devonian to Early or Middle Permian the region appears to have been a fairly stable shelf area, receiving fine clastic and chemical sediments at a fairly uniform rate. Minor unconformities between the Devonian and Mississippian, and between the Mississippian and Pennsylvanian, suggest minor orogenic uplift and brief interruption of the otherwise continuous deposition. The unconformity between the Devonian and the Mississippian is indicated by the absence of rocks of Early Mississippian age. The unconformity between the Mississippian and Pennsylvanian is indicated by the nature of the rocks of the Molas Formation. The Molas appears to have been largely formed of terra rossa from the subaerial weathering of the underlying rocks equivalent to the Leadville Limestone. The material has been locally reworked and transported to form shale, sandstone, and conglomerate. The relief of the area must have been very low during this interval.

The Hermosa Formation was deposited in a shallow sea, which quickly spread across the area from west to east and withdrew slowly. The Hermosa in southwestern Colorado is of Middle Pennsylvanian age. Roth (1934, p. 947) described the fauna of the type Hermosa as Cherokee (early Des Moines) in age, whereas in the Elk Ridge area the upper beds are at least Late Pennsylvanian (Virgil) in age (table 1).

The overlying Rico Formation at the type locality in Colorado is Middle Pennsylvanian (Des Moines) in age, but at Elk Ridge it is Early Permian in age (Henbest, 1948, table 2). Rocks of typical Rico lithology seem to become progressively younger from east to west. However, there is a possibility that the rocks mapped as Rico in the Elk Ridge area are not contiguous with the type Rico. Deep drilling in the Elk Ridge area and to the east in the Four Corners area indicates that the Monument upwarp was elevated during the Permian. The elevation appears to have taken place during or prior to the deposition of the Cutler Formation and may have been early enough to have affected the deposition of rocks mapped as Rico in the Elk Ridge area; that is, Rico beds of the Elk Ridge area may have been deposited in an isolated seaway separated from the type area by a lowland barrier.

The Permian uplift in the Elk Ridge-Monument Valley area appears to have very closely paralleled the post-Cretaceous uplift described by Hunt (1956). The Permian uplift was of a magnitude of 4,000 feet and is reflected in an abrupt thinning and change in composition of Cutler deposits. Structure contours drawn on Triassic horizons indicate a structural relief of approximately 3,700 feet in the Elk Ridge area, whereas lower Paleozoic horizons recorded in well logs indicate a structural relief of as much as 7,800 feet in the same area. The difference in structural relief is compensated by an abrupt thinning of the Cutler Formation of Permian age. To the east of the map area in the vicinity of Blanding and Hovenweep Canyon, the Cutler Formation ranges from 4,000 to 5,000 feet in thickness and is composed entirely of water-laid shale, siltstone, and evaporites (Reynolds Mining Hatch 1 well, sec. 4, T. 39 S., R. 24 E.). West, toward Elk Ridge, the Cutler is progressively more sandy and thins abruptly to an average thickness of about 1,500 feet, 1,000 feet of which is eolian sandstone of the Cedar Mesa Sandstone Member at the present crest of the upwarp. The abrupt change in thickness and lithology is nearly coincident with the position of The Comb monocline. In Fish Creek Canyon and small adjacent canyons in T. 38 S., R. 20 E., the lower part of the Cedar Mesa Sandstone Member intertongues with limestone, shale, and anhydrite. A few miles to the east, well logs indicate that the Cedar Mesa is absent and the Cutler is almost entirely composed of water-laid clastics and evaporites, the upper part of which is equivalent in time to the Cutler of Elk Ridge. The lower part of the Cutler in the Blanding area, however, is probably in part Pennsylvanian in age.

By the end of Cutler time the basin to the east had been entirely filled and the Hoskinnini Member of the Moenkopi Formation covered the entire area. The Hoskinnini apparently was deposited in a very broad, nearly flat basin as indicated by the small range in thickness over the region (Stewart, 1959). The upper member of the Moenkopi, like the Paleozoic formations, generally thickens to the west and north indicating a broad regional downwarping in central Utah. The marine limestones of the Moenkopi of central Utah (McKee, 1954) are absent in the Elk Ridge area where the deposits have the characteristics of near-shore tidal-flat or lagoonal deposits. The formation thins rapidly to the east and probably pinches out somewhere near Blanding, Utah (Taylor, oral commun., 1958).

Following the close of Moenkopi time (post-middle(?) Triassic), the Elk Ridge area was subjected to north-south compressional forces which gently folded the Moenkopi and older rocks. These very small folds trend west (fig. 5).

Following the folding, Late Triassic sediments were deposited as the Chinle Formation, first filling the shallow structural basins on the Moenkopi and later spreading completely over the area (fig. 5). Though the post-Moenkopi-pre-Chinle folds were of small magnitude, locally they appear to have controlled deposition of the lowermost Chinle sediments and hence to some extent determined the location of uranium deposits in the area.

During the Late Triassic and throughout the Jurassic and Cretaceous Periods the area appears to have been stable.

Though Upper Jurassic and Cretaceous formations are absent within the map area, the Morrison, Dakota, and Mancos Formations undoubtedly once extended across the area (Craig and others, 1955; Stokes, 1944).

Following Mancos time the Monument upwarp was elevated to its present level. Hunt (1956) placed the major uplift in the late Paleocene. This date is compatible with the evidence in the Elk Ridge area where the upwarping took place in post-Mancos, pre-Abajo Mountain time, which would place the uplift in the Late Cretaceous or early Tertiary.

The faults of the large east- and northeast-trending grabens in the Elk Ridge-Abajo Mountain area were probably formed prior to the emplacement of the Abajo Mountain intrusive bodies as diorite porphyry intrudes along the north fault of the Verdue graben (Witkind, 1964).

The youngest significant structural features are the numerous small grabens in The Needles area adjacent to Cataract Canyon near the mouth of the Green River. These grabens were formed very late in the Tertiary or possibly even in the Quaternary after the Colorado River had cut its present canyon.

The drifting of windblown sand and silt, the deposition of alluviumin in the valleys and basins, and minor recurrent movement on some of the faults in The Needles area are events that still are in progress.

ECONOMIC GEOLOGY

The discovery of economic deposits of uranium in the Elk Ridge area in 1954 and 1955, and the discovery of oil in the Aneth field shortly thereafter, have shifted interest in the natural resources of an area which until recently was exploited chiefly as grazing land, and secondarily for timber. Because of the urgency of the uranium program at the time the project was begun, considerable time was spent in studying the uranium deposits, which received more emphasis than other aspects of economic geology. Of lesser immediate importance but probably much greater importance over a long period of time are the resources of ground water and petroleum.

GROUND WATER

The Elk Ridge area is mostly surrounded by plateau and semiarid desert. Most of the Colorado Plateau ranges from 4,000 to 5,000 feet above sea level and receives from 2 to 7 inches of rainfall annually, but ridges and plateaus such as Elk Ridge, because of their higher altitude, receive considerably more precipitation than the low country. They are important areas for recharge for the region. Because of the arid climate, sparse vegetation, and the fact that most of the rainfall is received in torrential summer showers, only a very small part of the rainfall enters the ground-water system, particularly in the lower altitudes. The surface-water supply is now inadequate because of the increase in population, and ground-water resources have become increasingly important.

Elk Ridge is a high (8,000–9,000 ft alt) well-forested area, which receives 16 or 17 inches of rainfall annually (Kleinhampl, 1962), considerably more than the average for the Colorado Plateau. Most of the rain falls as summer showers and is largely lost in runoff. More important to the ground-water recharge is the snowfall which often exceeds 4 feet per year. The snow usually melts slowly, and much of the water finds its way into the ground-water system by way of the soil cover on the well-forested mesa.

Core drilling in the Elk Ridge area indicates that the Moss Back Member of the Chinle Formation is the only important aquifier. The Moss Back, about 100 feet thick, is a highly permeable, medium- to coarse-grained conglomeratic sandstone. It is underlain in most of the area by mudstones of the lower Chinle, which contain a large amount of bentonite clay and are relatively impervious. This combination results in a perched ground-water reservoir within the Moss Back Sandstone Member. Small folds control the migration of ground water in large parts of Elk Ridge. Water migrates into synclines and is discharged in springs at the base of the Moss Back where the synclines have been breached by erosion (table 4).

The Cedar Mesa Sandstone Member of the Cutler Formation is thick, porous, and permeable, but it receives little recharge. Most of the water entering the Cedar Mesa is discharged in small springs and seeps along bedding planes or at the base of the Cedar Mesa. Only one large spring drains water-bearing rocks of which the Cedar Mesa is probably the main aquifier. This spring, known locally as Big Spring, is in Gypsum Canyon at the west end of the South Plains syncline (pl. 2; table 4). The south limb of the syncline receives most of the ground-water recharge of a large part of North Elk Ridge, and apparently most of the water is discharged at Big Spring. The spring actually issues from rocks in the uppermost part of the Rico Formation. Relatively impermeable limestone beds at the top of the Rico apparently prevent further downward percolation of water migrating through the overlying Cedar Mesa Sandstone Member, and the structural configuration of the Rico-Cedar Mesa contact confines and controls the lateral migration. Big Spring is located where the erosion of Gypsum Canyon has breached a structural basin.

TABLE 4.—*Important springs on Elk Ridge and vicinity*

Spring	Geographic location [1]	Horizon	Rate of flow (gpm)	Structural control
Babylon Pasture (east).	East end Babylon pasture, sec. 23, T. 35 S., R. 20 E.	Base of Moss Back Member of Chinle Formation.	±50	Axis of syncline.
Babylon Pasture (west).	West end Babylon pasture, sec. 22, T. 35 S., R. 20 E.	do	±10	Axis of shallow syncline.
Bears Ears	Head of Burch Canyon, SW ¼ sec. 24, T. 36 S., R. 18 E.	do	±20	Terrace.
Beaver Dam	Head of Dead Man Canyon, NW ¼ sec. 24, T. 24 S., R. 19 E.	do	±20	Axis of syncline.
Burch	Head of Burch Canyon NW ¼ sec. 24, T. 36 S., R. 18 E.	do	±15	Terrace.
Big	West end Beef Basin SE ¼ sec. 29, T. 32 S., R. 18 E.	Top of Rico Formation.	100+	Base of syncline.
Campground	South side North Long Point, NE ¼ sec. 8, T. 34 S., R. 19 E.	Base of Moss Back Member of Chinle Formation.	±30	Do.
Causeway	Head of Vega Canyon, SW ¼ sec. 8, T. 34 S., R. 21 E.	Alluvium	[2] ±5	None obvious.
Chippean	On Chippean Point Road SW ¼ sec. 30, T. 34 S., R. 21 E.	Kayenta Formation.	[2] ±5	Do.
Cooper	Dry Mesa, NW ¼ sec. 35 T. 34 S., R. 18 E.		[2] ±5	Do.
Crystal	North side North Long Point, NE ¼ sec. 27, T. 33 S., R. 19 E.	Base of Moss Back Member of Chinle Formation.	[2] ±5	Axis of syncline.
Gooseberry	At Gooseberry Ranger Station, NW ¼ sec. 18, T. 34 S., R. 20 E.	do	[3] ±5	Do.
Hideout	Head of Hideout Canyon, NW ¼ sec. 30, T. 35 S., R. 18 E.	do	±40	None obvious.
Home	North Plains, NW ¼ sec. 24, T. 32 S., R. 18 E.	Top of Rico Formation.	±10	Flank of anticline.
Hop Creek	Flank of Hop Creek Canyon, NE ¼ sec. 16, T. 33 S., R. 21 E.	Wingate Sandstone.	+200	Fault control.
Iron	Head of Beef Basin Wash, sec. 32, T. 32 S., R. 19 E.	Cedar Mesa Sandstone Member of Cutler Formation.	[2] ±5	Syncline.
Kigalia	Head of Kigalia Canyon, sec. 3, T. 36 S., R. 19 E.	Base of Moss Back Member of Chinle Formation.	[2] ±20	Axis of shallow syncline.
Maverick	On Maverick Point, SE ¼ sec. 36, T. 36 S., R. 18 E.	do	[2] ±5	None obvious.
Morman Pasture	At Morman pasture cow camp, SE ¼ sec. 10, T. 34 S., R. 20 E.	Upper part of Chinle Formation.	±40	Axis of syncline.
Nielson	North of Nielson's cabin, sec. 7, T. 36 S., R. 19 E.	Base of Moss Back Member of Chinle Formation.	[2] ±5	Axis of shallow syncline.
North Cottonwood.	End of road south of Cottonwood Ranger Station, NW ¼ sec. 17, T. 33 S., R. 21 E.	Moss Back Member of Chinle Formation.	±20	Possible fault or fracture control.
Notch	North side of The Notch, SW ¼ sec. 6, T. 35 S., R. 20 E.	Base of Moss Back Member of Chinle Formation.	±20	Axis of shallow syncline.
Oakie	Head of Burch Canyon, SE ¼ sec. 28, T. 36 S., R. 18 E.	do	±15	Terrace.
Payday	½ mi. south of Pay Day mine, sec. 29, T. 34 S., R. 20 E.	do	[2] ±5	Axis of syncline.
Rodgers	Behind Rodgers cabin, NE ¼ sec. 25, T. 34 S., R. 19 E.	do	±10	Do.
Stanley	Beef Basin (east end), NE ¼ sec. 36, T. 32 S., R. 18 E.	Top of Rico Formation.	±5	None obvious.
Sweet Alice	West end Sweet Alice Hills, NE ¼ sec. 35, T. 33 S., R. 18 E.	In Cedar Mesa Sandstone Member of Cutler Formation.	±10	Fractures in Cedar Mesa.
Twin	Scorip cattle camp, SE ¼ sec. 1, T. 36 S., R. 18 E.	Moss Back Member of Chinle Formation.	±20	None obvious.

[1] Most locations unsurveyed. Following springs are on surveyed land: Bears Ears, Burch, Cooper, Maverick, Notch, Oakie.
[2] Springs may be dry during very dry summers or prolonged drought.
[3] Dug spring.

The several large faultline springs in the Glen Canyon Group along the east boundary of the map area (table 4, Hop Creek Springs) receive recharge from the Abajo Mountain area to the east. The Wingate, Navajo, Entrada, and Bluff Sandstones, which are important aquifers in other parts of the Colorado Plateau, have been almost completely removed by erosion except in the easternmost part of the area.

The alluvium in the larger valleys contains appreciable amounts of water in some areas and could be utilized locally. Small springs issuing from the alluvium were observed in Cottonwood, North Cottonwood, and Salt Creek canyons, and in Beef Basin.

PETROLEUM

To date, oil has not been discovered within the boundaries of the map area. However, production from nearby wells to the east and north raises the possibility of the occurrence of economic pools on Elk Ridge. Several test wells have been completed and several others are in progress. Most are tests to the Paradox but deeper wells have penetrated Precambrian rocks.

Petroleum residue was noted in several formations and localities. Minor amounts of petroleum residue were observed by the writers in the Moenkopi and Rico Formations, and prospectors have reported blebs of petroleum in limestones of the upper member of the Hermosa Formation. Crude petroleum in sandstone lenses of the lower mudstone unit of the Chinle Formation is abundant in the workings of the Waban mine and has been reported from numerous drill holes in the Twin Springs area. Asphaltite(?), a black vitreous organic solid, is common in the sandstone lenses of the lower part of the Chinle and is a common associate of uranium minerals in the uranium ore deposits.

In the Elk Ridge area the Monument upwarp has approximately 3,700 feet of closure and is an excellent structural trap. However, in the Aneth field to the east, the discoveries in the Paradox Member of the Hermosa Formation indicate that stratigraphic porosity traps are probably more important in the accumulation and localization of oil in that region than the major structures.

At the present time nearly all the oil produced in the region is from the Paradox. Minor amounts have been recovered from the Goodrich oil sand of the Rico Formation at the old San Juan oil field near Mexican Hat, Utah, and from the Cutler Formation in the Boundary Butte area. Recent discoveries indicate the possibility of large reserves in Mississippian rocks on the Big Flat, north of Elk Ridge.

The first well in the area was a dry hole drilled in 1926–27 by the Midwest Refining Co. This well, known as the Gerald Hughes 1 Elk Ridge, penetrated 4,422 feet of strata and bottomed in Precambrian, referred to as "granite schist". The well was located near the highest point on the Monument upwarp. Following the drilling of this unsuccessful well, the area received little attention until the last few years.

The Paradox Member of the Hermosa Formation is known to be petroleum bearing in nearby areas. In the Elk Ridge area its outcrops in Cataract Canyon include those of petroliferous shales. The Paradox is the most logical target for exploratory drilling for petroleum in the Elk Ridge area.

The possibility that economically important accumulations of oil may be found in higher or lower beds, however, cannot be ignored. Dead oil and asphaltite have been found in Chinle rocks, and petroliferous blebs are present in the Hoskinnini Member of the Moenkopi Formation. Because the Chinle and Hoskinnini have been cut through by many deep canyons, they are not now suitable for oil accumulation. Stratigraphic traps might be found in the Cutler Formation in the eastern part of the map area, where facies change from continental to shallow marine.

URANIUM DEPOSITS

Uranium ore has been produced from two zones in the Chinle Formation. In the southwestern, central, and east-central parts of the Elk Ridge area, uranium ore has been mined from sandstone and conglomeratic sandstone at the base of the mudstone unit of the Chinle. The general limits of distribution of these basal sandstones define a belt (fig. 6), which extends west into the Deer Flat and White Canyon areas. In the northeastern part of Elk Ridge, uranium ore has been produced from sandstone and conglomeratic sandstone of the Moss Back Member of the Chinle Formation. The favorable Moss Back area (fig. 6) appears to contain the southwesternmost significant uranium mineralization in that unit; the Moss Back also contains important uranium deposits in the Indian Creek and Lisbon Valley areas to the northeast.

There are a few uraniferous deposits in other stratigraphic zones on Elk Ridge. Ore in the Moenkopi Formation is generally restricted to the uppermost few feet and is almost invariably overlain by ore in basal sandstone of the Chinle Formation. The only known exception is at the Notch No. 5 mine where some uranium ore was mined about 40 feet below the top of the Moenkopi. A single small deposit is near the Rico-Cutler contact in Salt Creek canyon in the north part of the map area. The Salt Wash Sandstone Member of the Morrison Formation contains several uranium-vanadium ore deposits in adjacent areas to the east, particularly in the Blanding district, but none are known within the Elk Ridge area. In adjacent areas to the north, ore deposits occur in arkosic facies of the Cutler Formation (Hinrichs, 1956, p. 63). Abundant radon, inferred to have come from the Paradox Member of the Hermosa Formation, was noted in 1953 in samples of mud from the sump of the Danvers 1 well (sec. 2, T. 37 S., R. 18 E.); its presence suggests the possibility of uraniferous deposits in rocks below those that crop out at the surface.

The belt indicated in figure 6 outlines what may be termed the Elk Ridge mining area. Although the known deposits of this belt are in eastern and western groups, much of the intervening area has not been adequately explored and appears at this time to be equally promising.

The ore deposits are generally restricted to basal sandstone and conglomerate beds of the Chinle Formation that fill paleostream channels at the top of the Moenkopi Formation. They are tabular to lenticular bodies that generally conform to the shape and orientation of the channel. Although few deposits have been measured precisely, there appears to be considerable variation in size. Some deposits are at least 300 to 500 feet in length, from 50 to 150 feet across, and from 2 to 10 feet thick in the central part.

The grade of some ore shipments has been as high as 5.0 percent U_3O_8, but that of most shipments has ranged from 0.7 to 0.10 percent U_3O_8. Ore-grade material is distributed evenly throughout large parts of some deposits. More commonly, however, erractically distributed and irregularly shaped zones of relatively high-grade ore are intermixed with low-grade ore, submarginal material, and barren host rock.

Detailed investigation of uranium deposits was confined chiefly to deposits in the Chinle Formation, which contains all the known economically significant ore bodies in the map area.

HISTORY AND PRODUCTION

The discovery of small amounts of gold in the gravels of the San Juan River near Animas City, Colo., in 1879, led to exploration of the lower reaches of the river. After unsuccessful attempts to locate gold in sufficient quantities in the river gravels, attention was directed to the Abajo Mountains and during the next twenty years over 300 claims were staked in that area. Small strikes were made at the heads of Johnson and Recapture Creeks. However, the failure to discover commercial amounts of gold led to the abandonment of most of the properties prior to 1900.

Prospecting in the White Canyon area led to the discovery and location of claims at the sites of the Dolly Varden mine and Blue Dike mine (presently the Happy Jack mine) shortly after the discovery of gold in the San Juan River gravels and in the Abajo Mountain area. These deposits were discovered about 1906 or 1907 (Butler and others, 1920), and small shipments of copper ore were made from the Dolly Varden in 1916. However, the remoteness of the area and the small size of the ore bodies discouraged development, and little was done with these prospects prior to World War II, at which time the increased interest in uranium brought prospectors back into the White Canyon area. The old Blue Dike mine, which was known to contain uranium as well as copper sulfides, was sold and further developed. The new owners renamed the mine the Happy Jack and under this name it has become one of the biggest and best known uranium mines in the White Canyon district.

At about the same time that prospecting first took place in White Canyon, interest in vanadium and the newly discovered element radium spurred prospecting and exploration in the Morrison Formation along Butler Wash, Cottonwood Creek, and Recapture Creek. Prospecting of these areas in 1912 resulted in the filing of numerous claims. The boom was short lived, and most of the present mines and prospects date from 1942.

Large-scale prospecting for uranium deposits on Elk Ridge did not start until about the end of World War II. Most of the early prospecting in the area was conducted by individuals living in the nearby communities of Blanding and Monticello, Utah. The earlier uranium claims were located by members of the Shumway family in the vicinity of The Notch, by Lyman D. Nielson on South Elk Ridge, and by Walter Duncan, Jr., mostly on South Elk Ridge. In the spring of 1953 the Atomic Energy Commission conducted an extensive drilling program in the vicinity of The Notch, and the Geological Survey started mapping in the Elk Ridge area. This activity, and the shipment of small amounts of ore from Elk Ridge and the Hideout mine on Deer Flat, attracted numerous prospectors to the area. Government drilling located an ore body on the Oakie claims on South Elk Ridge in 1954, and subsequent drilling by private companies located several additional ore bodies in the area. At the end of the field study in 1957, the prospecting phase was almost over on Elk Ridge; the exploratory work, however, was only well started.

A few hundred tons of uranium ore was produced from the Elk Ridge area prior to 1953, notably from the Notch No. 1 claim and the Carl-Look-Payday No. 3 group of claims. Production from the central belt increased continually from 1953, and by the end of 1956 about 50,000 tons of ore that averaged 0.25 percent U_3O_8 had been produced from deposits in the Elk Ridge area. The rate of production increased rapidly after 1955. Production figures suggest that individual ore bodies range in size from a few tons to more than 15,000 tons. None of the deposits are known to have been mined out completely, and therefore data are lacking for estimation of their ultimate size.

MINERALOGY

The ores of the district are of the black or unoxidized type (Gruner, 1956a). Uranium minerals and associated sulfides fill interstices in the host rock, and replace carbonized wood, clay, silt, and sand grains of the host sandstone, as well as pre-ore calcite and silica cement. Uranium-bearing asphaltite(?) is abundant in many mines and appears to be a major ore constituent. Clay minerals with adsorbed uranium may form a significant proportion of the ore in some mines. Secondary uranium minerals, copper minerals, and in places molybdenum minerals, are locally abundant on outcrops of mineralized sandstone and as a bloom on the walls of underground workings. In contrast with the uranium-vanadium deposits of the Salt Wash Sandstone Member of the Morrison Formation in the Blanding district to the east, the uranium deposits of the Elk Ridge area only locally contain vanadium, and only in trace amounts. Small amounts of copper, however, form a significant proportion of the metal content of some Elk Ridge deposits, and copper has been recovered from various mines in the area. As much as 3.22 percent copper has been reported in shipments of uranium ore, but the percentage is generally much lower.

Because most of the ore in the mines and prospects is black and contains few readily identifiable ore minerals, and because much of the associated barren host sandstone also contains abundant dark fragments of carbonized wood, asphaltite(?), and dark-colored detrital material, the ore is most easily and reliably distinguished in the field by its radioactivity. Radioactivity detectors are therefore much used underground and in sorting, as well as in prospecting outcrops and logging drill holes. Because different instruments generally give different readings on the same specimens or in the same areas, and because some ores, generally those that have been oxidized, are out of equilibrium between uranium and its radioactive daughter products, no absolute figures for radioactivity can be reliably used to determine grade of ore. The experienced miners and prospectors using their own instruments, however, make generally reliable estimates of grade in mines and prospects with which they are familiar.

PRIMARY MINERALS

Uraninite appears to be the chief ore mineral of the black ores in all the mines of the area. It has been identified in samples from the King Edward, King James, Payday, Notch No. 5, and Notch No. 1 mines (A.D. Weeks, written commun., 1957). Uraninite fills interstices and replaces carbonized wood, clay, silt, and sand of the host sandstone. It occurs as discrete granules and irregular masses within asphaltite(?), and it is possible, therefore, that a large part of the uranium found in the asphaltite(?) is present as uraninite. Chalcopyrite is the most abundant primary copper mineral of the ores, but bornite, domeykite, and tennantite have also been identified (A.D. Weeks, written commun., 1957). Very small amounts of galena and sphalerite are present. No primary vanadium minerals have been identified, and spectroscopic examination indicates that vanadium is rare in known Elk Ridge uranium deposits.

Pyrite is abundant locally in many of the ore deposits. Drill holes show that pyrite is also abundant in nonuraniferous sandstone lenses in the lower part of the Chinle above the ore zone. Disseminated crystals and nodules of pyrite occur in the Moss Back Member of the Chinle Formation. Marcasite, siderite, and barite are locally associated with ore minerals in some deposits. No primary cobalt or molybdenum minerals have been identified from the area, but the abundance of these two metals in secondary minerals suggests that primary minerals are probably present.

SECONDARY MINERALS

Secondary uranium, copper, and copper-uranium minerals are common in or near outcrops of ore-bearing sandstone. They are generally absent in the deeper parts of the ore bodies except where workings have exposed the primary ores long enough for a bloom to form on the mine walls. The secondary minerals that have been identified are:

Uranium minerals.—Andersonite, zippeite, coffinite, uranophane, metaautunite (A. D. Weeks, written commun., 1957), schroeckingerite, uranothollite, tyuyamunite, uranophane (Oertell, written commun., 1956).

Copper minerals.—Malachite, azurite, chalcanthite, chalcocite.

Copper-uranium minerals.—Cuprosklodowskite and metazeunerite (A. D. Weeks, written commun., 1957).

Vanadium minerals (very rare).—Corvusite(?) and volborthite (Laverty and Gross, 1956, p. 199).

Other minerals.—Ilsemannite, jarosite, erythrite (A. D. Weeks, written commun., 1957), limonite, hematite, and bieberite(?).

RELATION OF ORGANIC MATERIAL TO ORE

Much ore of the Elk Ridge deposits is intimately associated with asphaltite(?), and some with fluid petroleum. The asphaltite(?) may be petroliferous and may have originated in other formations and then been introduced into its present hosts. The evidence is inconclusive. Many workers consider a more probable explanation to be that these hydrocarbons were derived from the decomposition of nearby vegetable matter deposited with the host sandstones, inasmuch as they are commonly associated with carbonized logs, branches, twigs, and nondescript small fragments of woody material.

Breger and Deul (1956, p. 505) suggest three mechanisms by which organic material and uranium may become associated: (1) organic material may serve as a reducing agent in converting the soluble uranyl ion (UO_2^{+2}) to an insoluble uranous form; (2) sulfide ion

(S^{-2}), which is normally associated with carbonaceous substances, may serve as a reducing agent to convert the uranyl ion to the uranous form; and (3) the carbonaceous material may serve as a chemical precipitant for the uranyl ion, as where coals absorb uranium from circulating solutions forming insoluble uranyl humates. It is possible that one or more of these mechanisms is responsible for the deposition of a large part of the uranium in the Elk Ridge deposits. The intimate association of uranium and carbonaceous material of various types in much of the ore suggests a close genetic relation such as that between precipitant and precipitate. In addition, fluid decomposition products of carbonaceous material may migrate to parts of the host sandstone in which carbonaceous material is less abandunt and there accumulate to form an environment conducive to deposition of uraninite.

Although much of the uranium of the asphaltite(?) is probably in the form of uraninite, the exact chemical relation between uranium and organic material in most of the ore are not known. A sample of uraniferous asphaltite(?) from the Notch No. 5 that contained 3.23 percent uranium (analysts: S. Furnam, W. Mountjoy, and J. Meadows of the U.S. Geological Survey) showed identifiable X-ray patterns for only quartz and barite (analyst: W. F. Outerbridge of the U.S. Geological Survey). This suggests that uranium occurs in forms other than uraninite in the asphaltite(?), perhaps as amorphous pitchblende, or possibly as a metallo-organic compound (Erickson and others, 1954, p. 2216). Samples from which uraniferous asphaltite(?) has been mechanically concentrated invariably show a uraninite X-ray pattern.

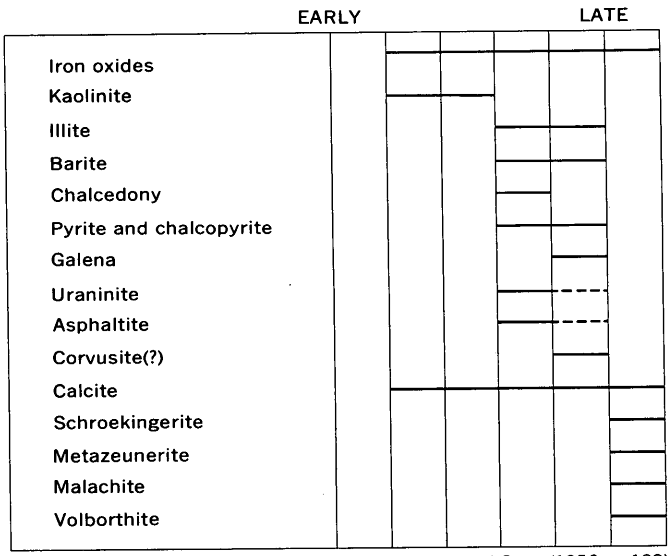
PARAGENESIS

Studies of the paragenesis of Elk Ridge ore minerals have been insufficient to determine a reliable generalized sequence. Field observations and limited metallographic examinations by the writers and observations reported by others suggest a sequence that apparently conforms with that proposed by Laverty and Gross (1956, p. 198–199) for the ores of The Notch area.

Iron oxides, kaolinite, and calcite were the earliest formed minerals; followed by asphaltite(?), uraninite, barite, pyrite, chalcopyrite, and chalcedony (fig. 13). Galena was somewhat later, followed by the secondary uranium and copper minerals. Pyrite and calcite formed both earlier and later at several stages of formation of the deposits.

AGE AND TEMPERATURE OF FORMATION

The ore deposits were probably emplaced during Late Cretaceous or early Tertiary time. Stieff and others (1953, p. 15) determined an age of 65 million years by the lead-uranium method for uraninite from the Happy Jack mine of the White Canyon district. The continuity of the central belt and similarity between the deposits of the White Canyon and Elk Ridge areas suggest that this determination might reasonably be extrapolated into the Elk Ridge area.



Modified after Laverty and Gross (1956, p. 199)

FIGURE 13.—Paragenetic sequence of ores from the Notch mines.

According to the lead-uranium age, the deposits were probably formed at the beginning of the Monument upwarp, perhaps in early Paleocene time (Hunt, 1956, p. 3 and fig. 54). The distribution of the deposits shows no systematic arrangement with respect to structures associated with the upwarp and relative ages cannot be reliably inferred.

Coleman (1957), in a study of ore from the Happy Jack mine of the White Canyon district, concluded that the temperature of formation of that deposit was probably not appreciably higher than that calculated on the basis of normal geothermal gradient. Because of the similarity and physical continuity of the two mining areas, this conclusion reasonably might also apply to deposits of the Elk Ridge area. It is interesting to note that in the Elk Ridge area, the host rocks show little evidence of alteration associated with the deposition of ore except for replacement by ore minerals and associated sulfides. These data suggest that the deposits of Elk Ridge fall within the telethermal zone (Graton, 1933) of the classic hydrothermal zoning sequence.

STRATIGRAPHIC ASSOCIATION

The areal distribution of the uranium ore deposits and inferred favorable ground (fig. 6) is controlled by a twofold stratigraphic association: (1) the host rocks are fluvial sandstone beds of the Chinle Formation, and (2) although such sandstone occurs as lenses interbedded at several horizons in the mudstone unit, and predominates in the Moss Back Member throughout the area, it is ore bearing only at or within a few feet of areas where it is in direct contact with the underlying Moenkopi Formation. In addition, a more detailed association is evident in that all ore-bearing sandstone in the Chinle Formation is overlain by relatively impermeable mudstone ranging from thin lenses and partings in the Moss Back Member to thick and massive beds in the mudstone unit. The association resembles, in part, the association of some hydrothermal deposits with overlying impermeable barriers (as described by Lindgren, 1933, p. 200), and in part resembles the accumulation of gas and oil in stratigraphic traps. The association with the unconformable Moenkopi-Chinle contact resembles that of a barren vein along which ore shoots have formed at intersections with favorable litholigic units.

The above relations all appear to reflect the mode of migration of ore solutions to sites favorable for the deposition of ore minerals. In the absence of any continuous fault or fracture zone with which the deposits might be related, the paths of migration must have been intimately related to the porosity, permeability, and fluid transmissive capacity of the rocks with which the deposits are associated.

HOST ROCKS

The host rock for the uranium ore deposits is almost exclusively fluvial sandstone and conglomeratic sandstone of the Chinle Formation. Although part of the ore formed as replacement of detrital constituents of the host beds, most of it was deposited as pore-filling minerals interstitial to the detrital grains. Consequently, the ore is generally associated with sandstone that had sufficient porosity so that economic concentrations of uranium minerals could form by deposition in intergranular spaces. On the other hand, not all pore spaces were filled with ore minerals, and much of the most porous sandstone is virtually barren. Some interstitial clay, silt, and fine-grained organic material probably contributed to a chemical environment that facilitated the precipitation of ore minerals from solution.

In other parts of the Colorado Plateau, channels, scoured deeply into the Moenkopi and filled with fluvial sandstone of the Chinle Formation, have proved reliable guides to uranium ore deposits. On Elk Ridge, however, because of the shallow depths of the channel scours and the relatively dense cover of colluvium and vegetation, such channels are difficult to recognize in the natural rim outcrops. As a result, the association of the ore deposits with channels is much less distinct here than, for example, in the Monument Valley and White Canyon areas. Although the individual channels of the Elk Ridge area are apparently not continuous for great distances, detailed mapping indicates that, in some parts of the area, groups of channels (herein termed "channel systems") that have somewhat more longitudinal continuity (on the order of 1–4 miles) can be recognized. Such features may be of use in evaluation of targets for exploratory drilling.

The intimate association of many ore bodies in fluvial sandstone with overlying massive to very thin bedded mudstone indicates that detailed local stratigraphic succession was an important ore control.

LITHOLOGY AND POROSITY

The ore deposits appear to show some consistent but not invariant association with certain varieties of host rock. No pronounced lithologic differences were noted between ore-bearing parts of the Moss Back and the sandstone lenses of the mudstone unit. Ore is commonly in silty and argillaceous sandstone and conglomeratic sandstone of the basal part of the Chinle. It is virtually absent in mudstone, very argillaceous sandstone, and sandstones relatively free from silt, clay, and finely divided carbonaceous material. The mudstone and very argillaceous sandstone lenses may be slightly mineralized along fractures and near their contacts with ore bodies. Sandstones relatively free from clay and silt may be mineralized close to their contacts with overlying mudstone and may locally contain small scattered pods of ore-grade material. The moderately silty argillaceous sandstones that appear most favorable for ore also commonly contain abundant minute fragments of carbonized detrital organic material as well as twigs, branches, and logs. The minute organic fragments are not as common in the mudstone and cleaner sandstone, although carbonized wood and leaf material may be locally abundant in those units. The present degree of cementation apparently has little relation to the distribution of ore. The ore-bearing sandstone ranges from friable to well cemented, the cement commonly is calcite. As both pre- and post-ore calcite cement have been recognized, it is difficult to infer the permeability of cemented rocks at the time ore was deposited.

The moderately silty or argillaceous sandstone appears to have been favorable because of the amount and chemical nature of material interstitial to the sand grains. The amount of interstitial material controlled the porosity and permeability of the sandstone, and certain kinds of interstitial material provided a chemical environment favorable for precipitation of ore minerals from solution. Although the permeability of the barren sandstone is varied, the permeability of ore-bearing sandstone before ore deposition was probably less than barren sandstone and more than mudstone. The epigenetic deposition of interstitial material [ore minerals, calcite cement, fluid hydrocarbons, asphaltite(?), and pyrite] may have greatly reduced the permeability of sandstone that was originally relatively free of interstitial material. On the other hand, epigenetic minerals have replaced preexisting interstitial material, and the permeability of the host sandstone may have been only slightly changed thereby from original conditions. In any case, the host rocks were sufficiently permeable for ore solutions to circulate in the interstices and sufficiently porous to accumulate economic concentrations of ore minerals. These requirements were probably not met by the mudstone and very argillaceous sandstone. In addition, the host beds contained some interstitial material (solid, liquid, or gaseous reducing agents) that probably reacted with the solutions and caused deposition of the ore minerals. The relatively clean sandstone associated with some ore bodies is probably barren because interstitial reducing agents are lacking. Deposition might have been prevented in parts of the sandstone because circulation of the ore solutions was too rapid, but this seems unlikely for most of the observed occurrences. Post-ore groundwater migration may have removed previously deposited ore minerals from clean sandstone, but the only place in the Elk Ridge area where this seems likely to have happened is at the King Edward mine. The ore body at the King Edward mine is in a channel sandstone at the base of the Chinle mudstone unit. The sandstone is continuous updip to outcrops on The Comb monocline, from which it receives considerable influent seepage. In contrast with the other mines in sandstone of the mudstone unit of the Chinle, the King Edward is very wet.

CHANNELS

All the important uranium deposits of the Elk Ridge area are closely associated with shallow paleostream channels cut into the top of the Moenkopi. The relatively uniform thickness of the Moenkopi throughout the area and the low amplitude of the observed channel scours (generally less than 10 ft.) makes their recognition very difficult on the natural rim outcrops. The scours apparently controlled the distribution of basal Chinle lithologic types. Sandstone and conglomeratic sandstone, with some interbedded mudstone, commonly fill the basal parts of the scours and are nearly always built up well above the level of the Moenkopi "banks," perhaps as a result of the formation of natural levees or similar features tending to perpetuate the positions of the depositing streams above the channels. The lenticular Chinle sandstone beds deposited in and above these paleostream channels are the present loci of the uranium ore deposits of the Elk Ridge area.

Most of the basal sandstone lenses in and above the channel scours are less than 20 feet thick; locally, however, the lenses are as much as 60 feet thick. Mudstone lenses are commonly interbedded in the channel sediments, and relatively massive mudstone is in contact with the Moenkopi between channels. Single channels have been traced for about 1 mile, and a few appear to be continuous for a maximum distance of about 2 miles. The lenses of channel sandstone pinch and swell in short distances and lack interconnecting permeable zones insofar as can be observed.

Although continuity of individual channels cannot be demonstrated, channel sandstones are in groups termed "channel systems" in certain well-prospected areas. These channel systems have greater longitudinal continuity than individual channels, and their outlines and possible extensions are significant in reducing the size of exploration targets. In the area around The Notch and north to the Payday mine, geologic mapping and exploration by rim stripping and diamond drilling (Dana Kelly, written commun., 1953; and oral commun. with private drillers) indicate four major channel systems. Figure 14 shows their inferred outlines.

The Payday channel system is the northernmost of the four channel systems, and its north boundary probably roughly coincides with the north boundary of the favorable lower Chinle belt of figure 6. The Avalanchie No. 13 and King James mines in the upper part of South Cottonwood Creek to the east are within the projection of this system. Similarly, the eastward projection of the Coral-Sunday channel system includes the King Edward mine and vicinity. The outcrop pattern along the hogback south of the mouth of Notch Canyon suggests that the Notch No. 1 and Notch No. 5 channel systems may join to the east and include the Morrison mine channel. The Notch No. 5 is the only system that can be traced westward; erosion has removed the westward extensions of the other channel systems.

DETAILED STRATIGRAPHIC ASSOCIATIONS

Within the lenses of channel standstone of both the Moss Back and lower members of the Chinle, detailed stratigraphic relations indicate that the ore deposits are almost invariably overlain by mudstone or very argillaceous standstone having a lateral extent equal to or

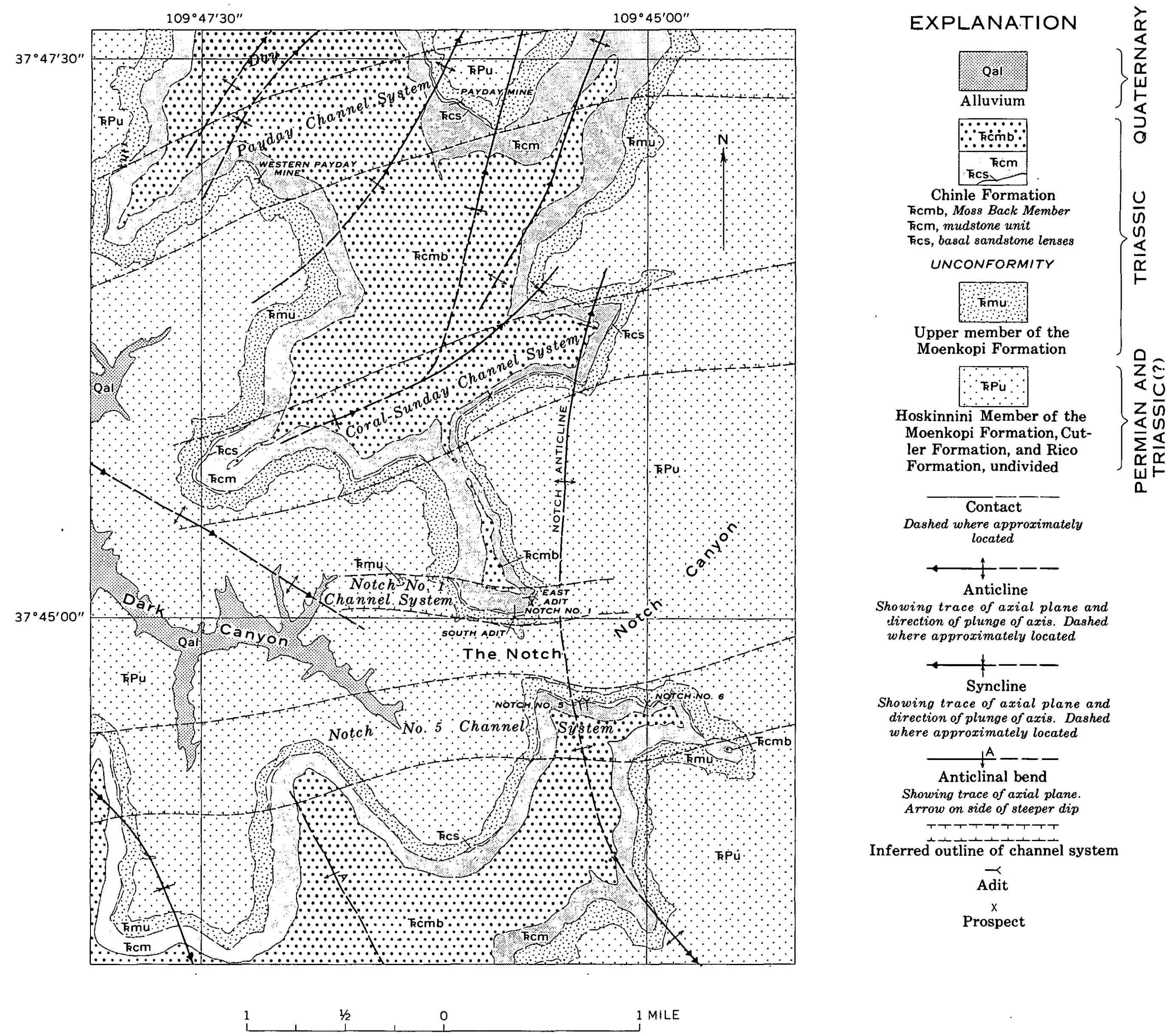


FIGURE 14.—Geologic map of The Notch area, showing inferred outlines of channel systems.

greater than that of the ore. The ore-bearing sandstone lenses also grade longitudinally and laterally into less permeable argillaceous sandstone and mudstone. In some mines the ore is in the lowermost part of the channel standstone lenses and locally extends a few inches to 2 feet (locally more along fractures) down into the Moenkopi. The Notch No. 5, where small amounts of ore have been found in the Moenkopi about 40 feet below its top, is the only place where ore in the Moenkopi is not immediately overlain by ore in Chinle rocks. In other mines, or more rarely, other ore bodies in the same mine, the base of the ore is from 1 to 20 feet above the top of the Moenkopi and the underlying parts of the Chinle sandstone are largely barren. Figure 15 illustrates various positions of ore bodies with respect to detailed stratigraphy.

MOENKOPI-CHINLE CONTACT

The distribution of the ore deposits appears to be controlled by the distribution of the paleostream sediments of the Chinle and their relation to the Moenkopi-Chinle contact (fig. 5). The central belt of Chinle deposits shown in figure 6 outlines approximately the limits of distribution of basal channel standstones of the mudstone unit in contact with the Moenkopi Formation. The basal sandstone lenses of the central favorable belt are not all at the same stratigraphic horizon within the mudstone unit; that is, some sandstone

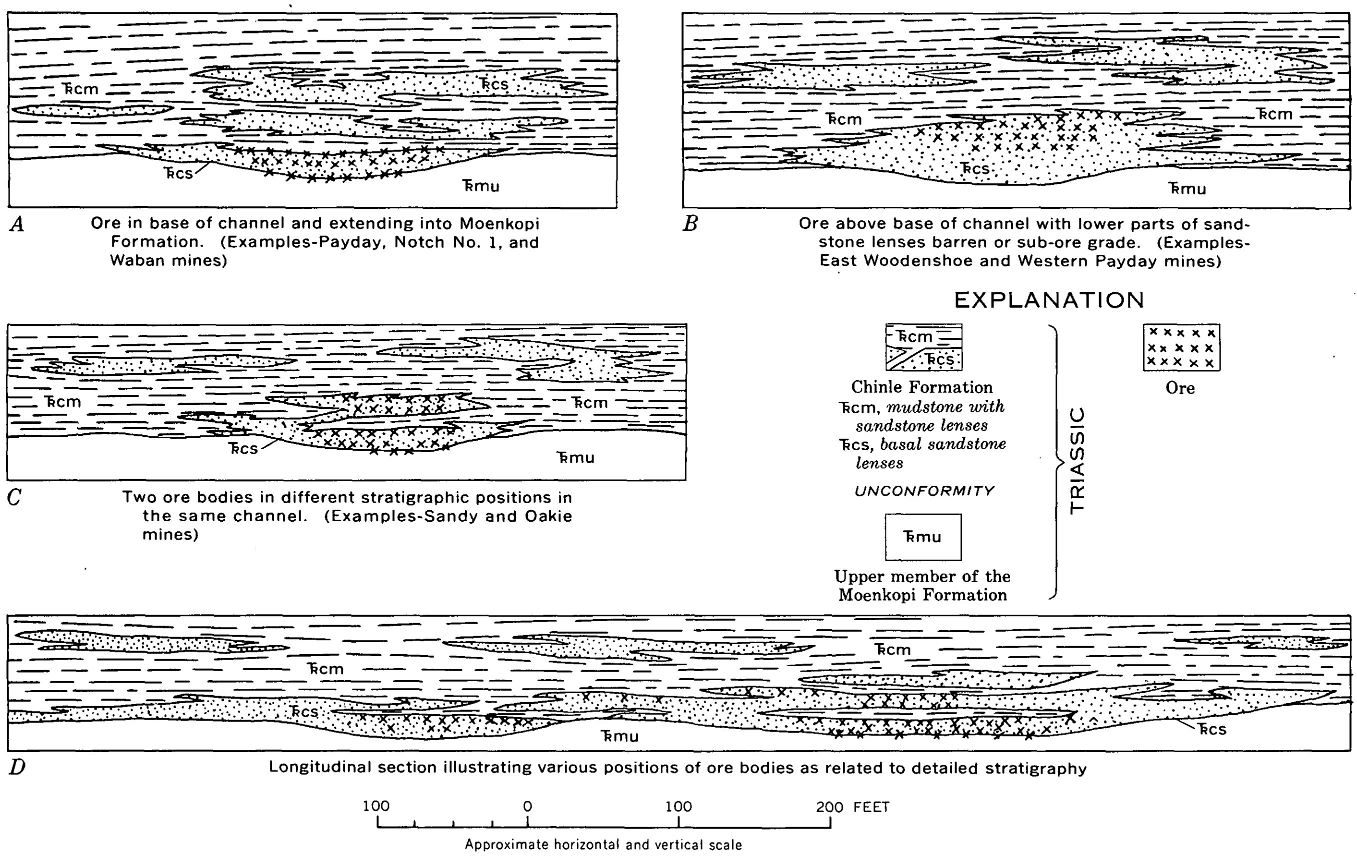


FIGURE 15.—Generalized sections illustrating local stratigraphic associations of uranium deposits.

lenses and zones of such lenses that lie at the base of the mudstone unit in one part of the area are underlain by Chinle mudstone in other parts, in some places with still lower sandstone lenses at the base. Regardless of stratigraphic position within the Chinle, only those sandstones that lie in direct contact with the Moenkopi Formation are ore-bearing, and ore bodies within those sandstones are generally within a few feet of the Moenkopi-Chinle contact. No ore deposits are known to occur in sandstone lenses that are not in contact with the Moenkopi Formation, although some of these lenses are reported to contain small amounts of low-grade material.

In the favorable Moss Back area (fig. 6) the mudstone unit is generally very thin and locally absent. At the one mine in the Moss Back, the mudstone unit is completely missing so that sandstone of the Moss Back Member rests directly on the Moenkopi Formation. Elsewhere in the favorable Moss Back area a few prospects expose submarginal material where a few feet of lower Chinle mudstone separates the Moss Back from the Moenkopi.

Outside the favorable Moss Back area, no potentially economic uranium deposits are known in that unit, although minor amounts of low-grade material have been reported in diamond-drill holes. The lower Chinle mudstone interval between the top of the Moenkopi and the base of the Moss Back Member thickens rapidly to the south and southwest of the outline of the favorable Moss Back area (fig. 6).

STRUCTURAL ASSOCIATIONS

The distribution of the ore deposits shows no systematic relation to the Monument upwarp or to The Comb monocline. The linear zone of deposits in basal Chinle sandstone crosses the north-trending Elk Ridge anticline and Comb monocline in an east-northeast direction (fig. 6). Ore has been produced from the west flank of the Elk Ridge anticline, from near its crest, and east of its crest both above and below the steep limb of the Comb monocline. The absence of ore deposits on the steep limb of the monocline may be due to removal of the lower Chinle from much of that area by erosion.

The only structural control indicated is the inferred mid-Triassic warping which controlled the distribution of the basal Chinle fluvial deposits. Local structural basins apparently controlled the area of deposition of the lower Chinle, and hence indirectly determined the area favorable for uranium deposits. Vertical control is insufficient to determine whether similar smaller structures localized individual channels.

There is no evidence of direct relation between faulting and the ore deposits. Vertical or steeply dipping joints are common in the area and a few of them in red rocks are bounded by thin bleached zones. It seems probable that if the ore solutions ascended through the rocks from depth, tension joints would offer the easiest pathway. Solutions ascending along joints in the Moenkopi and older rocks might tend to spread out laterally immediately below the incompetent and impermeable lower Chinle mudstone in which joints are rare and weak. If the inferred mid-Triassic structural basin was associated with tension joints in a manner similar to that suggested by Finnell and Gazdik (1958, p. 955) for smaller pre-Chinle folds, the mid-Triassic warping may have provided a dual control. In addition to controlling the distribution of favorable host rocks, it may also have produced a joint system that would tend to guide the ore solutions into the areas that contain most of the favorable host rocks. In this connection, it is interesting to note that the Sweet Alice fault system parallels the favorable area on the north and the Hammond fault system parallels part of it on the southeast. Although these fault systems are not intimately associated with the ore deposits and may be younger than the ore, it is possible that they were localized by older zones of fractures associated with the mid-Triassic warping.

ORE GENESIS

The ore was deposited in chemically and physically favorable host rocks probably by precipitation of metallic constituents from migrating ore solutions. The widespread distribution of ore bodies of similar mineralogy suggests that the solutions were correspondingly similar. From this it seems reasonable to infer that relatively homogeneous ore solutions circulated through widespread interconnected pathways. The present data are insufficient to determine whether the solutions were hypogene or supergene in origin. Syngenetic theories of deposition seem to be eliminated by evidence that the ore is appreciably younger than the host rocks.

ORE SOLUTIONS

The source of the mineralizing solutions is chiefly a matter of speculation. If the solutions were of hypogene origin, they possibly represented telethermal terminal phases of stronger hydrothermal activity in the Precambrian crystalline basement complex, the top of which is generally less than 6,000 feet stratigraphically below the ore-bearing horizons of the Elk Ridge area. Hydrothermal activity associated with the same processes that developed the Abajo Mountains magma may have also produced the ore solutions, although the ore deposits show no systematic distribution with respect to the Abajo Mountains, and the instrusives there may be younger than the ore deposits.

Many workers who studied the Colorado Plateau sandstone deposits considered processes by which the ore solutions may have been derived from rocks of the unmetamorphosed sedimentary section. Schultz (1957, p. 504) stated that at least some of the volcanic debris in the rocks of the Chinle Formation was altered after its deposition and that uranium may have been derived during its devitrification. Although such a mechanism could have been important in the derivation of ore-forming fluids on a regional scale in connection with a process similar to that described by Gruner (1956b) as "multiple migration-accretion," it seems insufficient on a local scale as an immediate source for all the uraniferous deposits of the Elk Ridge area. The present data in the Elk Ridge area are insufficient to distinguish whether the source was hypogene or supergene.

Regardless of the ultimate origin of the metallic constituents of the ore solutions (hypogene or supergene), their composition probably was modified by interaction with connate and meteoric ground waters and chemically active constituents in the rocks through which they circulated. The degree of such modification is indeterminate and might be expected to vary widely, but the widespread occurrence of similar uraniferous deposits suggests widespread circulation of relatively homogeneous ore solutions.

Except in and near ore bodies there is little or no evidence that the solutions deposited ore or gangue minerals or otherwise reacted with the rocks through which they probably migrated. Possible exceptions are the small uraniferous deposits in Moenkopi rocks at the Notch No. 5 mine; the widespread moderate radioactivity in the mudstone at the Moenkopi-Chinle contact; and bleaching along some joints in the red rocks of the Moenkopi and Cutler Formations. Even if the solutions migrated only through the Chinle and adjacent Moenkopi rocks, they must have been in or near equilibrium with several different lithologic types while passing through barren areas between deposits. This suggests that the solutions were dilute or chemically neutral, or both.

PATHS OF SOLUTION MIGRATION

The widespread distribution of ore bodies and mineralogical similarities of uranium deposits in the Colorado Plateau must be considered in speculations concerning the migration of ore solutions. If the solutions were hypogene and ascended from some point source at depth in the basement complex, they must also have migrated laterally along fractures in the basement, or along fractures, beds, or sedimentary structures in the overlying sedimentary rocks. This distributary system would have had to be efficient enough to prevent the development of recognizable mineral and intensity zoning. The assumption that hypogene solutions emanated from a number of point sources in a large area might eliminate the complex lateral distributary system required by a single point source but would in turn seem to require contemporaneous emission of very similar solutions from each point. If the solutions originated by supergene processes the wide distribution of mineralogically similar ore bodies and their intimate association with the mid-Triassic unconformity to the exclusion of deposits in favorable rock types not associated with the unconformity, argues against local derivation from a restricted area. It seems likely that the solutions, if supergene at all, were derived by some process such as "multiple migration-accretion" (Gruner, 1956b) involving a much larger area than the map area, and had migrated long distances laterally.

Whatever the mode of general migration from their source, the ore solutions must have circulated in the Elk Ridge area in channelways that provide access to chemical and physical environments favorable for the deposition of ore minerals. If, as seems most likely, a major factor in effecting deposition was a chemically reducing environment provided partly by clastic material (including carbonaceous matter) and partly by fluid reducing agents in the pore spaces of host rocks, the uraniferous deposits are localized where ore solutions had access to such favorable environments. Conversely, areas of barren ground that contain or show evidence of having contained the above reducing agents are probably areas not reached by the ore solutions. In the absence of demonstrated through-going fractures connecting the ore deposits, the required access channelways must have been provided by a combination of permeable beds, joints, and sedimentary structures such as bedding planes or nongradational contacts.

PERMEABILITY AND FLUID TRANSMISSIVE CAPACITY

The permeability and fluid transmissive capacities of the Moenkopi and Chinle Formations are in large part functions of primary sedimentary features of these units. Present conditions probably reflect accurately those that governed migration of the ore solutions. Several features, however, such as jointing and cementation may have been modified subsequent to ore deposition.

The Moenkopi, with its abundant bedding planes, joints, and relative absence of swelling clays, is considerably more permeable than the relatively massive mudstone of the lower Chinle, but is less permeable than the sandstone lenses included in the lower Chinle. Except for those in contact with the Moenkopi, the sandstone lenses of the Chinle mudstone unit are almost entirely surrounded by mudstone of extremely low permeability. The basal sandstones are themselves virtually isolated by mudstone laterally and at least in part longitudinally, from each other and from stratigraphically higher sandstone lenses. Consequently, these basal lenses, despite their high permeability, lie in stratigraphic settings that favor stagnation for circulating solutions.

The present ground-water and surface-water systems offer evidence from which permeability and fluid transmissive capacity may be inferred. The relatively permeable, blanketlike Moss Back Member is a good aquifer throughout the Elk Ridge area. Lower mudstone beds exposed in underground workings are commonly wet, but there is very little seepage from mudstone walls and backs and mudstone is relatively impermeable. Basal sandstone lenses exposed in underground workings are damp in some mines and relatively dry in others. Although many of the workings have local depressions with minor amounts of standing water, no appreciable flow of ground water is known in any of them. This may be partly a result of the small areas of intake, but the writers believe that it also expresses a lack of continuous permeable channelways connecting the permeable Chinle sandstone lenses. The Moenkopi is generally dry and appears to drain readily except in depressions in sills of some underground workings, where it is locally argillaceous or where overlying mudstone of the Chinle has fallen and been worked into the sill by the mine traffic, sealing off pore spaces.

Unimproved roads in the area reflect the permeabilities of the rock units through which they pass, especially during and after rainstorms. Roads in the Moenkopi drain well, and in many places broken Moenkopi rock is used as road metal to repair places where the natural drainage is poor. Where roads cross lower mudstone beds of the Chinle the natural drainage is generally poor. Mud holes form quickly in many places and some persist for days or weeks following storms. Roads crossing sandstone beds of the Moss Back Member drain well in many places, but in some depressions mud holes and ponds reflect underlying lenses of mudstone within the Moss Back Member.

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The mineralogic associations of the ore deposits of the Elk Ridge area suggest that the ores have been protected from oxidizing conditions. Alice D. Weeks of the U.S. Geological Survey studied specimens of ore from many of the mines. She indicated (written commun., 1957) that the primary minerals are stable in a reducing environment but are soluble and easily altered when exposed to oxidizing conditions, and that the ores lack sufficient arsenic, phosphorus, and vanadium to complex and fix uranium in the oxidized zone. She suggested that the conditions for preservation of ore should be considered in appraising the area. The lack of appreciable oxidation of the Elk Ridge ores suggests that they have been protected from circulation of oxidizing ground waters through the ore-bearing sandstone lenses because of the lack of permeable connecting channelways.

The regional transmissivity of the Triassic rocks was studied by Jobin, whose transmissivity map (1956, fig. 39, p. 209) suggests that Elk Ridge is in an area of low regional transmissivity capacity in respect to the lower sandstone unit and Shinarump Member of the Chinle. Jobin (written commun., 1958) supplied additional data for the rocks of Elk Ridge and nearby areas. These data suggest the following permeabilities and transmissive capacities for the Moenkopi Formation and the lower part of the Chinle:

Unit	*Mean permeability (millidarcies)*	*Transmissivity (Darcy-ft)*
Lower part of Chinle Formation	-------	1–0. 5
Sandstone	[1] 10–20	-----
Mudstone	. 0	-----
Moenkopi Formation	-------	0. 5
Sandstone	5	-----
Siltstone	. 1	-----
Mudstone and shale	. 0	-----

[1] 175 maximum at one place on Deer Flat.

Although the permeability of the Moenkopi rocks is low and that of the lower standstone unit of the Chinle is high, the transmissive capacities are of the same order of magnitude because the Moenkopi is much thicker than the lower Chinle sandstones. The measurements and computations do not take into account such factors as the probable absence of permeable channelways interconnecting the lower Chinle sandstone lenses which would further reduce the transmissive capacity of the lower unit of the Chinle. Nor do they allow for the abundance of joints in the Moenkopi which should tend to increase the transmissive capacity of that unit. Jobin also pointed out that in rocks of relatively low permeability, faults and joints should provide a more efficient transmission system than mass permeation.

In addition to faults and joints, continuous bedding planes and nongradational formation contacts are features that facilitate transmission. Observation of the present ground-water and surface-water systems seems to reinforce the conclusions based on observations of lithologic types and their distribution—namely, that vertical migration of solutions through the lower Chinle mudstone is unlikely, and that widespread lateral migration within the mudstone unit of the Chinle is less likely than migration along the mid-Triassic unconformity or through the underlying Moenkopi.

FACTORS CONTROLLING LOCALIZATION

The localization of the ore deposits of the Elk Ridge area is probably a result of two major factors: (1) mineralizing solutions had access to the sites of deposition, probably along and beneath the unconformable Moenkopi-Chinle contact, (2) the host rocks provided chemical and physical conditions favorable for the deposition of significant quantities of ore minerals from the solutions.

The accessibility of the favorable host rocks to the mineralizing solutions was controlled by the permeability of the host beds and subjacent sedimentary rocks. The most permeable rocks associated with the ore deposits are the fluvial sandstone beds of the Moss Back Member and the mudstone unit of the Chinle. The basal sandstone lenses of the mudstone unit, however, appear to be discontinuous and enclosed laterally and above by mudstone of extremely low permeability. Moreover, these basal lenses appear to represent more than one horizon within the mudstone unit. Ore solutions migrating laterally through these rocks would, therefore, circulate with a degree of freedom depending on the permeability of the intervening mudstone rather than the permeability of the sandstone lenses. Moreover, solutions moving laterally from sandstone lens to sandstone lens within the Chinle would not be expected to migrate up or down across interbedded mudstone to deposit ore in sandstone lenses at higher or lower horizons. If, therefore, the ore was deposited from solutions that moved through the Chinle by mass permeation of the sandstone beds and lenses, ore deposits might be expected to occur at any horizon containing reducing agents and having sufficient pore space for appreciable quantities of ore minerals to form interstitially. This does not conform to the observed distribution of the Elk Ridge deposits. Ore is not found in Chinle sandstone lenses that are underlain by Chinle mudstone. In addition, the Moss Back Member, a relatively continuous pervious sandstone bed, is an important host for ore only where the lower Chinle mudstone is missing but, although locally mineralized, contains no ore where it is underlain by lower Chinle mudstone. This too does not seem to conform with postulates of lateral migration of ore solutions through permeable beds of the Chinle Formation.

The rocks of the Moenkopi Formation, although less permeable than the sandstone of the Chinle, are more permeable than the mudstone of the Chinle. The Moenkopi contains abundant joints in contrast to the much less competent mudstone of the lower Chinle, and its relatively thin continuous beds are bounded by numerous bedding planes. The uranium deposit at the Notch No. 5 mine demonstrates that ore solutions had access to Moenkopi rocks, at least locally. It seems possible, therefore, that the Moenkopi provided channelways for migration of ore solutions, possibly by mass permeation of permeable beds but more probably along joints and bedding planes. The virtual absence of ore deposits in the Moenkopi may be attributed to a lack of reducing agents. This hypothesis seems more conformable with the observed associations of the deposits than lateral migration of ore solutions through the Chinle rocks.

The uncomformity that separates the Moenkopi and Chinle Formations may itself have provided sufficient open space to serve as a channelway for ore solutions. This would conform to the observed stratigraphic distribution of the ore deposits in a manner analogous to the association between a relatively barren vein and deposits formed at its intersections with favorable host beds. The thin zone of moderate radioactivity where mudstone of the Chinle lies on the unconformity may reflect the passage of ore solutions. The Notch No. 5 deposit in the Moenkopi, however, would be slightly anomalous with respect to lateral solution migration restricted to the single surface. If migration were dominantly lateral at or near the stratigraphic horizon that is now ore bearing, most probably the path would have been a combination of the mid-Triassic unconformity and bedding planes, joints, and permeable beds in the Moenkopi Formation. This hypothesis would require local ascending components of migration in order to explain formation of deposits in overlying rocks, but that is consistent with the observation that many ore deposits lie below impermeable mudstone barriers.

If the dominant direction of migration were upward through the Moenkopi and older sedimentary rocks, most probably the pathways would have been joints. Along a few joints the red rocks of the Moenkopi and older formations are bleached on either or both sides from a fraction of an inch to a few inches. The bleached zones appear little altered except for the removal of grain coatings of iron oxide. The bleaching may have been associated with migrating ore solutions, but no direct association has been established. It might also reflect the migration of liquid or gaseous reducing agents, perhaps at a time other than that of the migration of the ore solutions. Because joints are poorly developed in the incompetent massive mudstone of the lower Chinle, ascending solutions would tend to be impounded below it.

The intimate association of many ore bodies with overlying impermeable barriers suggests a physical control by those barriers, perhaps by impounding ascending solutions. A differential diffusion mechanism, such as that termed "hypofiltration" by Mackay (1946), at the sandstone-mudstone interfaces may have increased the concentration of metallic solutes in the basal sandstone lenses by allowing the solvent to pass upward through the mudstone more readily than the solutes. Hypofiltration alone might have been responsible for the deposition of ore, but a reducing environment probably also facilitated deposition. The general association of the ore with carbonized wood and asphaltitelike material suggests those materials provided a reducing environment in which the ore minerals were deposited.

An alternative interpretation of the manner of deposition of the ore is suggested by its association, in places, with fluid hydrocarbons and by Jensen's (1957) work on the origin of the sulfur in the sulfides associated with the ore. Fluid hydrocarbons or H_2S gas could have accumulated by gas or water drive in the stratigraphic traps that are now the sites of ore deposits. Such accumulations would have provided a reducing environment and could have precipitated the ore minerals at and near interfaces with underlying solutions that, during Late Cretaceous or early Tertiary time, contained metallic constituents of the ore minerals. If this were the mode of deposition, the ore solution itself need not have had an upward component of flow; the concentration gradient resulting from local precipitation may have been sufficient to cause ions to migrate within the ore solution and accumulate in the sites of deposition in sufficient quantities to form ore.

CONCLUSIONS

The areal distribution of the ore deposits largely coincides with the distribution of fluvial Chinle sandstone beds that lie directly on the mid-Triassic unconformity. The areal distribution of this sandstone reflects the trend, position, and width of sandy reaches in the flood-plain deposits of a stream or stream system of early Chinle time. The valley in which the early Chinle streams flowed may have been structurally controlled by gentle warping of mid-Triassic time. The areas of barren ground (Chinle mudstone) and of favorable Moss Back sandstone reflect the onlap of successively younger Chinle beds on the mid-Triassic unconformity.

Chemically favorable environments were provided by clastic carbonaceous material deposited with the other detrital constituents of fluvial sandstone beds in the Chinle Formation. In addition, gaseous and liquid reducing agents possibly introduced from older marine sedimentary rocks below, or formed by decay of the clastic carbonaceous material, accumulated in stratigraphic traps beneath impermeable mudstone, providing a favorable chemical environment in parts of beds where clastic carbonaceous material was rare or absent.

Physically favorable environments were provided by pore spaces in the fluvial Chinle sandstone in which the ore minerals were deposited in interstices between sand grains. The relatively impermeable Chinle mudstone formed barriers; capping the sandstone and preventing further ascension of gaseous and liquid reducing agents and ore solutions, possibly acting as a semipermeable membrane for the hypofiltration of ore solutions; and generally restricting lateral migration of ore solutions to the parts of Chinle sandstone beds in contact with the underlying Moenkopi.

The uranium ore deposits were formed where migrating ore solutions entered chemical and physical environments favorable for the deposition of ore minerals. The present data are insufficient to determine whether the ultimate source of the ore solutions was hypogene or supergene, or to establish whether the solutions migrated laterally or vertically in the main. It seems very likely that they gained access to the sites of deposition from or across the mid-Triassic unconformity, and they probably had local ascending components along their paths of migration.

GUIDES TO PROSPECTING

The favorable areas indicated in figure 6 should be useful guides to prospecting the general area. They indicate on a quadrangle scale the general distribution of stratigraphic environments in which the known ore bodies of the area have been found. The specific distribution of these favorable environments is best determined by direct field examination within the favorable areas to observe where individual lenses and beds of sandstone of the Chinle (including the Moss Back Member) are in contact with the underlying Moenkopi rocks. Paleostream channels at the base of these sandstone beds and lenses are important guides; however, the positions and trends of channel axes may be difficult to determine because many channels are very shallow, and fluvial sandstone not only fills them but has been deposited well above the level of banks cut in Moenkopi rocks. Where sufficient data are available from rim outcrops or exploratory drilling, the recognition of channel systems may help to reduce the size of exploration targets in the central favorable belt by eliminating many areas where interchannel mudstone occurs at the base of the Chinle.

Most of the latent uranium ore reserves of the Elk Ridge area are probably in basal sandstone of the lower Chinle in the central belt of favorable ground indicated in figure 6. Here the basal sandstone lenses are themselves important prospecting guides. They are thin and discontinuous and in many places do not crop out through the thin cover of colluvium and vegetation. In the northeastern favorable area (fig. 6) a few ore bodies may be found at the base of the Moss Back Member of the Chinle Formation, but because the base of the Moss Back is rarely in contact with the Moenkopi Formation, such possible ore bodies are probably sparse. In this area, identification of paleostream channels at its base should facilitate the search for places where sandstone of the Moss Back is actually in contact with the Moenkopi. The possibility of a third favorable area is suggested by sandstone lenses at the base of the undifferentiated Moss Back and lower Chinle rocks along the east side of Comb Wash. However, no ore deposits have been found in these rocks. In addition, their outcrops form an intermittent linear pattern from which little can be interpreted as to areal distribution and trends of sandstone lenses. West of Comb Wash the Triassic rocks have been eroded off, and east of Comb Wash exploration is difficult because the Moss Back and lower Chinle beds are buried beneath several hundred feet of younger sedimentary rocks.

Within individual lenses of basal sandstone of the Chinle the best guides to ore are high radioactivity and visible uranium minerals. The individual ore bodies generally do not have well-defined halos of alteration or other indicators. Natural and manmade outcrops may display visible ore minerals, most commonly the colorful oxidized uranium and copper minerals. On the other hand, ore minerals, primary or secondary, are not present on the outcrops of many of the sandstone lenses that contain ore a few feet to a few hundred feet behind the outcrop. High radioactivity of outcrops is a good guide to ore in many places, and it is present at some outcrops where there are no visible ore minerals. However, nearly all the basal sandstone lenses of the Chinle show some radioactivity higher than that of surrounding rocks, and the intensity of radioactivity at outcrops is generally not an important indication of size, grade, or distance to an ore body.

Underground, in mine workings and drill holes, the relation of visible minerals and radioactivity is more consistent and direct than at outcrops. Within individual mines experienced miners and prospectors, using instruments with which they are familiar, can make reasonably reliable estimates of grade on the basis of radioactivity. Although visible ore minerals are more reliable guides underground than on outcrops, abundant dark-colored sand grains and fine-grained carbonaceous material locally give barren rock the semblance of black ore.

Much of the prospecting already done has consisted of exposing the Moenkopi-Chinle contact by stripping away vegetation and colluvium so that the presence or absence of sandstone at the base of the Chinle could be determined. Drilling also has been successfully used in locating and delineating basal sandstone lenses of the Chinle beneath mesas capped by younger rocks. As the ore is generally in discrete bodies that occupy only a small part of the volume of the host sandstone lenses, sandstone lenses at the favorable horizon that are thick enough and extensive enough to contain ore bodies commonly must be explored physically by drilling or drifting to determine whether or not they contain ore.

Many of the Elk Ridge ore bodies in basal sandstone of the Chinle are separated from the base of the Chinle Formation by several feet of barren sandstone. If the base of an ore body is above the back of a drift that follows the Moenkopi-Chinle contact (common exploratory practice in the area), such a drift could miss the ore completely. A few inches of barren rock may be sufficient to mask the radioactivity and other local features of nearby hidden ore bodies. Therefore, in exploring underground, provision should be made for testing a thicker basal Chinle interval than the approximate 7 feet exposed for the height of a drift. If an exploratory drift follows the Moenkopi-Chinle contact, there should be raises or drill holes at regular intervals for sampling several feet or even a few tens of feet of the overlying beds. Similarly, the altitude and detailed stratigraphic position of ore discovered in exploratory drill holes from the surface should be carefully noted, and subsequent underground exploration and development should not be planned solely on the assumption that the ore body will be reached by a drift along the Moenkopi-Chinle contact.

MINES AND PROSPECTS

AVALANCHIE NO. 13

The Avalanchie No. 13 (fig. 6, index to mine locations), King Edward, and King James-Virgene mines comprise the property known as the Ransome mine, Sunshine Mining Co. The workings at the Avalanchie No. 13 consist of two adits and a connecting crosscut. Uranium ore at the Avalanchie No. 13 appears to be confined to a relatively continuous bed of Chinle sandstone that immediately overlies sandstone and siltstone of the Moenkopi Formation and is overlain by massive Chinle mudstone. The workings are not sufficiently extensive to define a channel trend or the shape of the ore body. The attitude of the contact of the Moenkopi and Chinle, however, suggests that most of the workings are on the north side of a channel which probably trends westward, roughly paralleling the general trend of the better defined channels in the area. The size of the ore body cannot be inferred from available data; however, the northern limit can be approximately located (fig. 16). North and east of that limit the host standstone is largely barren in the southeastern adit; and in the northwestern adit the exposed host sandstone contains only patches of ore-grade material. Within the ore-bearing parts of the sandstone the grade of ore is varied. Locally, high radioactivity is associated with abundant limonite, but in many places, particularly near accumulations of carbonaceous material, the grade of ore is apparently high where limonite is not abundant.

The ore is black, except for minor amounts of pale-yellow secondary uranium minerals and a pale-lavender mineral (erythrite?) that locally form a bloom on fractures and on the walls. The chief ore minerals are probably uraninite and coffinite. They appear to be chiefly interstitial to sand grains and to replace carbonized wood. Some of the interstitial ore minerals may have replaced clay and fine-grained carbonaceous material.

The host rock is a crossbedded silty coarse- to medium-grained sandstone containing minor amounts of interbedded mudstone in thin discontinuous lenses. In some places it is conglomeratic (chiefly small quartz pebbles) and in others it is slightly argillaceous. No systematic variation in rock type across the boundary of the ore body is observable; however, barren sandstone is generally brown with disseminated limonite spots, whereas ore-bearing parts tend to be darker colored and better indurated, possibly because of the presence of the ore minerals. The overlying mudstone is generally massive but contains a few thin discontinuous beds of silty to very argillaceous sandstone. At the base of the mudstone, a 2- to 6-inch layer of very argillaceous sandstone locally caps the underlying sandstone. Seams and irregular patches of carbonaceous material and carbonized wood fragments are locally abundant in the massive mudstone. In places the carbonaceous material contains abundant pyrite but commonly lacks abnormally high radioactivity. The Moenkopi rocks that

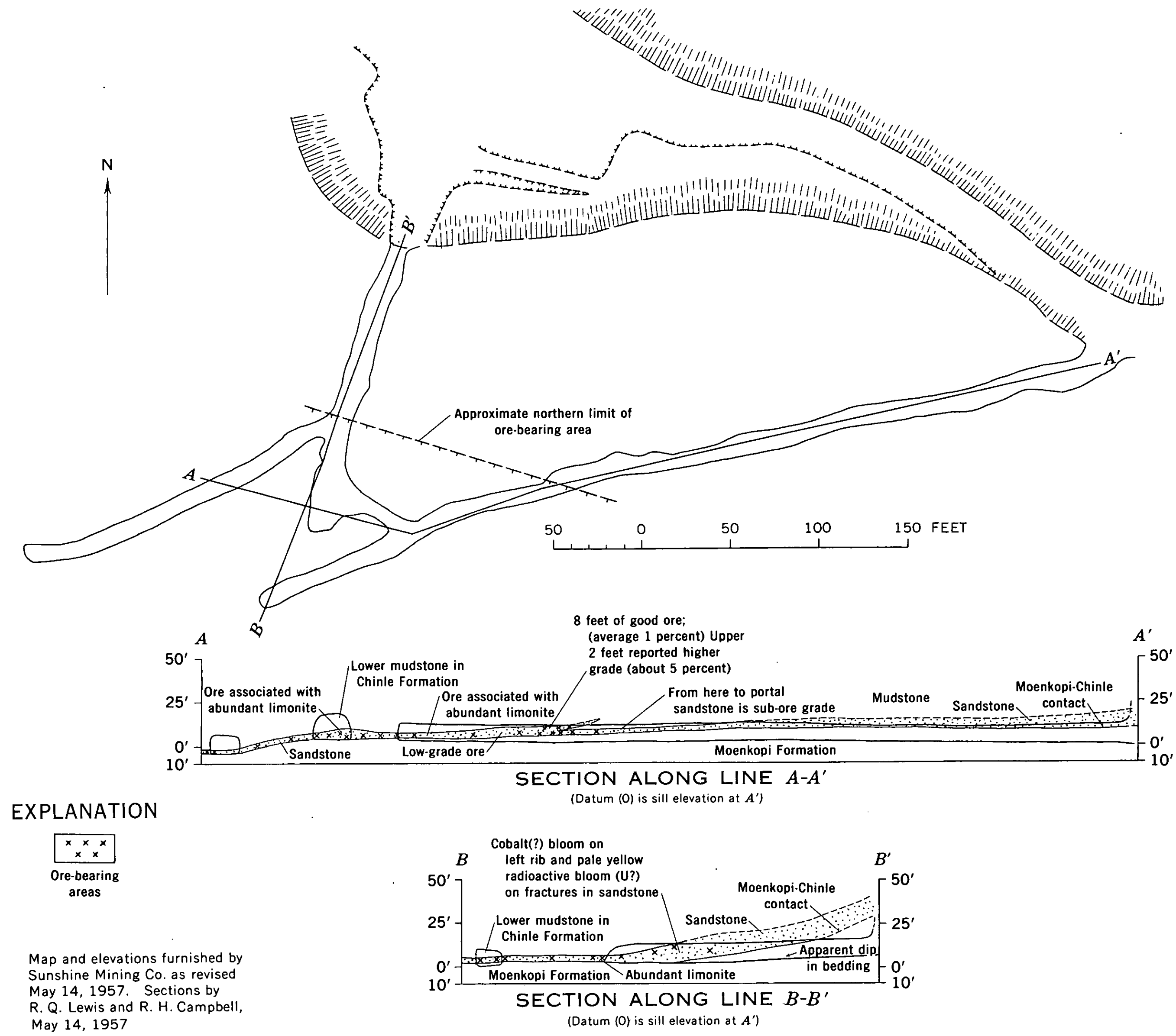

FIGURE 16.—Map and sections of the Avalanchie No. 13 mine.

underlie the Chinle sandstone are chiefly fine to very fine grained sandstone and siltstone that form thin, evenly bedded shaly layers. The Moenkopi is commonly bleached to a gray color at and near its contact with the Chinle. The thickness of this bleached zone is variable but rarely exceeds 1 foot.

HORSESHOE NO. 1

The Horseshoe No. 1 mine is near the old Cottonwood Ranger Station (now abandoned) on the west side of North Cottonwood Creek. The host rock is the Moss Back Member of the Chinle Formation, and it is the only ore deposit known to occur in that unit within the map area, although several mines in the Moss Back are known in areas to the north and east. The Chinle mudstone unit that intervenes between the Moenkopi Formation and the Moss Back over most of Elk Ridge is only 10 to 25 feet thick in this part of the map area and is locally absent in the vicinity of the mine. Wherever the uppermost Moenkopi is exposed underground it is directly overlain by sandstone of the Moss Back.

The geology of the Horseshoe No. 1 mine and the distribution of radioactivity suggest that the ore body has an irregular somewhat elongated shape, whose long axis is oriented east-west (fig. 17). This conforms with the direction of a channel indicated by W. A. Carlson and G. P. Dix of the U.S. Atomic Energy Commission (written commun., 1953) who suggest that the mine is on the north flank of the channel whose axis is approxi-

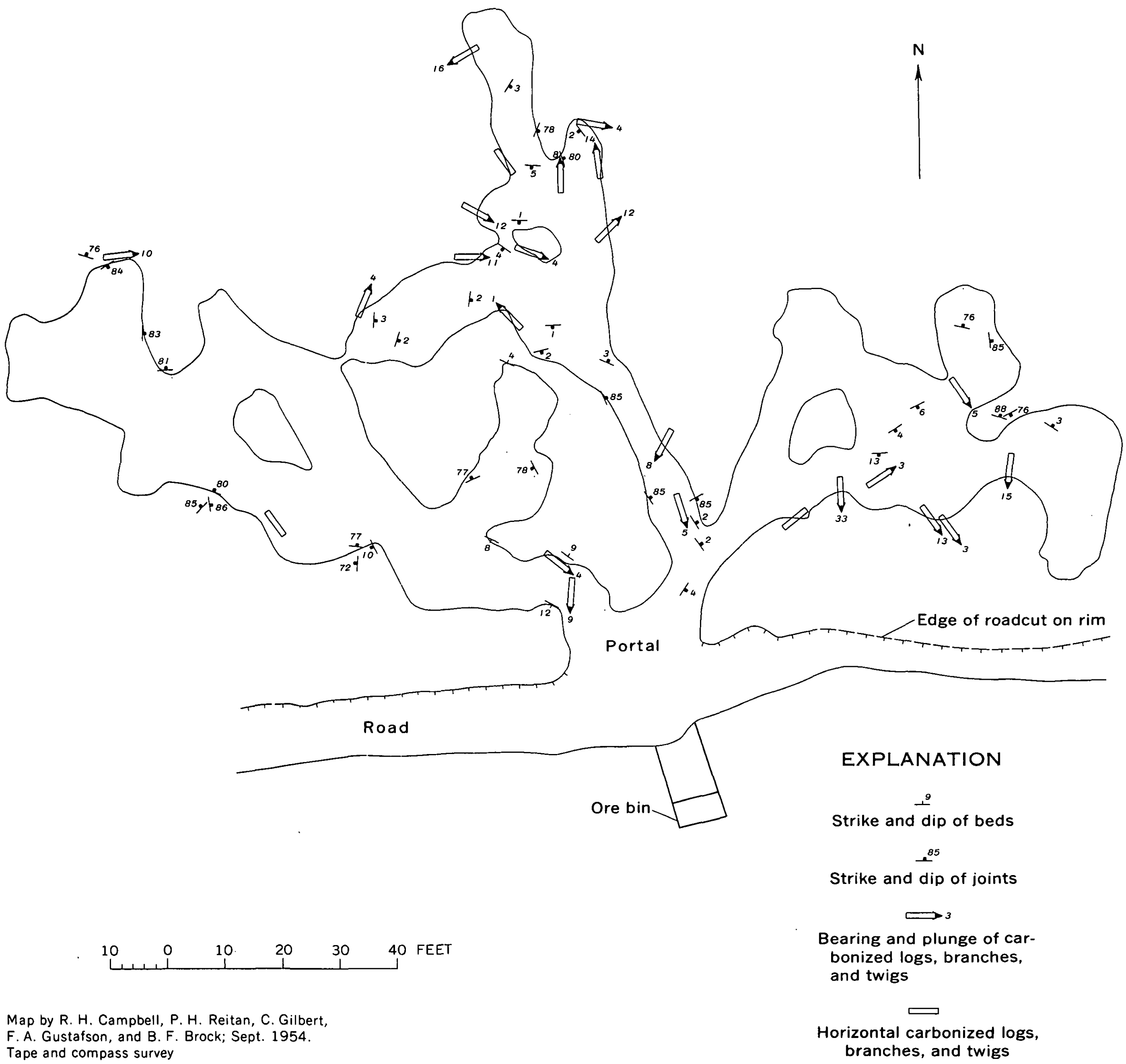

FIGURE 17.—Map of the Horseshoe No. 1 mine.

mately 200 feet south of the portal. The ore body is flat lying and is chiefly confined to the basal few feet of the Moss Back.

In the vicinity of the mine the Moss Back Member is about 100 feet thick. The upper two-thirds is brown crossbedded medium-grained sandstone. Toward the base the sandstone becomes coarser grained and the basal 5 to 15 feet contains abundant interbedded conglomeratic sandstone (with pebbles of quartz, chert, feldspar, and fragments of mudstone up to small boulder size). Silicified wood, including logs as much as 2 feet in diameter, is locally abundant at all stratigraphic levels in the Moss Back, but carbonized wood was observed only in the mine workings.

Uranium ore and abnormal radioactivity appear to be confined to the lowermost conglomeratic silty argillaceous sandstone, at or near the contact with the Moenkopi. Near the portal this sandstone lies on the Moenkopi, but in the inner parts of the workings the top of the Moenpoki is not exposed, and relations are uncertain. In the west drift, the ore-bearing conglomeratic sandstone is overlain by a conglomerate composed of pebbles and small boulders of mudstone in a mudstone matrix. Toward the portal this conglomerate grades to a sandy mudstone with a few thin interbedded sandstone lenses. In the east drift, the ore-bearing standstone is capped by a very argillaceous sandstone that contains abundant interbedded mudstone lenses, and near the base, some conglomerate composed chiefly of mudstone pebbles. In the central part of the mine the ore-bearing sandstone is overlain by a silty argillaceous, locally conglomeratic (with large mudstone pebbles) sandstone that contains abundant interbedded mudstone lenses. The Moenkopi exposed at the portal is an even-bedded fine-grained to very fine grained sandstone.

KING EDWARD

The King Edward mine is one of the group of properties near the head of Cottonwood Creek known collectively as the Ransome mine of the Sunshine Mining Co. The workings (fig. 18) are in basal Chinle sandstone on the north flank of a channel that appears to trend about S. 70° W. The ore body is irregularly shaped and relatively flat lying. Most of the ore is confined to the basal 1 or 2 feet of the host sandstone in contact with the Moenkopi Formation.

The ore-bearing Chinle sandstone is generally 6 to 8 feet thick in the workings, but it thickens to the south. It is a coarse- to medium-grained crossbedded sandstone, locally conglomeratic with small pebbles chiefly of quartz. It is friable, relatively free of silt and clay except near the base, and very light gray to white in color in the relatively barren upper parts. It is overlain in the workings by a massive mudstone which is about 3 feet thick at the portal and appears to pinch out to the south between the underlying ore-bearing sandstone and an overlying similar sandstone. The Moenkopi Formation under the host sandstone is shaly to thin-bedded very fine grained sandstone with some argillaceous siltstone. The upper 1 or 2 feet of the Moenkopi has been bleached and altered, and a persistent zone of wet clay 1 to 4 inches thick immediately underlies the basal Chinle sandstone.

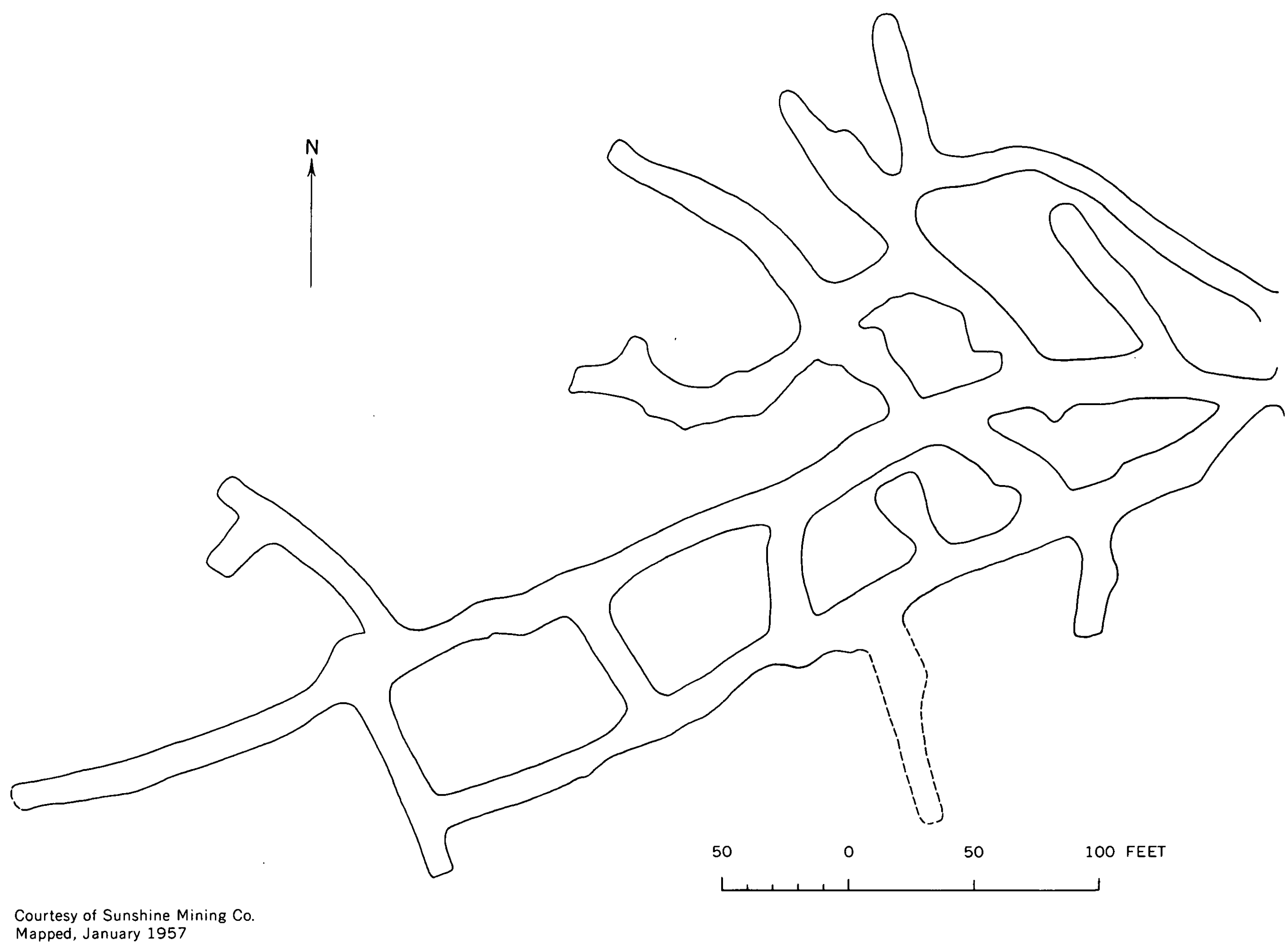

FIGURE 18.—Map of the King Edward mine.

Uraninite, coffinite, pyrite, chalcopyrite, and siderite were identified in the uranium-bearing samples; and kaolinite, quartz overgrowths, and a few pyrite aggregates one-eighth inch in diameter were found in specimens of barren white standstone (A. D. Weeks, written commun. 1957). The uraninite and coffinite are very fine grained and appear to be chiefly in the interstices between the sand grains. They are concentrated in dark layers and irregular pods that contrast with the generally lighter colored sandstone. Colorful secondary uranium minerals, ilsemannite(?), and erythrite(?) are abundant in parts of the workings chiefly as bloom on the walls. Pyrite and chalcopyrite are locally abundant but do not appear to be intimately associated with uranium minerals. In many places where pyrite and chalcopyrite are abundant in the basal few inches of the Chinle sandstone, uranium minerals are sparse and radioactivity is relatively low. The base of the uranium ore zone within the host sandstone is at most places 2 inches to 2 feet above the top of the Moenkopi.

The irregular shape of the ore body, its position on the flank of the channel, the abundance of secondary minerals, and the altered appearance of the upper part of the host sandstone suggest that the ore deposit has been altered and shifted slightly in position and shape by ground waters subsequent to deposition of the primary ore minerals. The absence of vanadium to fix and complex oxidizing uranium minerals permits such secondary mobilization of the deposit. In addition, the structural and stratigraphic relation in the vicinity of the mine indicate that ground-water migration may have occurred in the host rock in this area. The extensive outcrops of basal Chinle sandstone on the hogback to the west of the mine provide influent seepage, and these sandstones are continuous to the mine area. Influent seepage probably was greatest when the stream that cut the canyon west of the hogback was flowing on the basal Chinle. Influent seepage at an earlier date could have been supplied through the graben faults now exposed in the Cedar Mesa Sandstone Member of the Cutler Formation on the slope west of the canyon. These conditions appear to be unique in the Elk Ridge area.

KING JAMES-VIRGENE

The King James-Virgene mine is the northernmost property of the group known as the Ransome mine. The portal (fig. 19) is near the base of a channel that appears to trend N. 75°–80° E. and most of the workings are along the north flank. The channel is shallow, generally about 15 feet deep, and relatively narrow. The north flank is abrupt; at the portal, the Moenkopi-Chinle contact is near the back on the left wall [3] and at or below the sill on the right wall although bedding in both the Moenkopi and Chinle is nearly flat.

Ore is confined chiefly to a basal Chinle sandstone, but locally the basal few inches of the overlying mudstone is also mineralized. The host sandstone is a medium-grained to very coarse grained crossbedded sandstone, locally conglomeratic with some quartz fragments up to small cobble size. The silt and clay content of the matrix ranges from low to moderately high from place to place. The sandstone contains thin discontinuous mudstone lenses, and carbonaceous material is locally abundant. The mudstone is thickest between the portal and a point about 150 feet from the portal. On the right wall it may be as much as 12 feet thick, but on the left wall higher on the flank of the channel it is generally less than 2 feet thick and is locally absent. The hill of Moenkopi 200 feet in from the portal (fig. 19) appears to be a southward bulge of the left side of the channel. The ore-bearing sandstone is overlain by massive mudstone that contains a few thin sandstone lenses and locally abundant coal and carbonized woody fragments. The mudstone ranges from 4 to 8 feet in thickness and is overlain by a brown crossbedded medium- to coarse-grained sandstone. This upper sandstone contains uranium minerals but available data suggest it is mostly submarginal in grade. Near the end of the drift (fig. 19), the upper sandstone is 4 to 6 feet thick and is overlain by mudstone. The Moenkopi exposed in the workings is chiefly buff thin-bedded to shaly, even-bedded very fine grained sandstone containing some interbedded siltstone.

The ore is black and commonly forms all or part of the matrix in coarse-grained, friable sandstone. Specimens of ore show uraninite together with tennantite, pyrite, zippeite, and ilsemanite (A. D. Weeks, written commun., 1957). Pyrite is locally abundant, particularly in association with carbonized wood in the mudstone where pyritohedrons as large as one-fourth inch were observed.

NOTCH NO. 1 AND NOTCH NO. 4

The Notch No. 1 channel trends nearly east-west across the south end of the point north of The Notch. It has been explored by rim stripping, diamond drilling, and two adits. A small amount of ore was shipped about 1952 from the discovery location near the present Notch No. 1 adit (fig. 20). During 1956, the Notch No. 4 adit was driven to the base of the channel where some ore was mined (fig. 21).

[3] "Right" and "left" designate directions as observer faces the nearest working face. These terms are particularly useful for irregular-shaped workings such as those of many of the Elk Ridge mines.

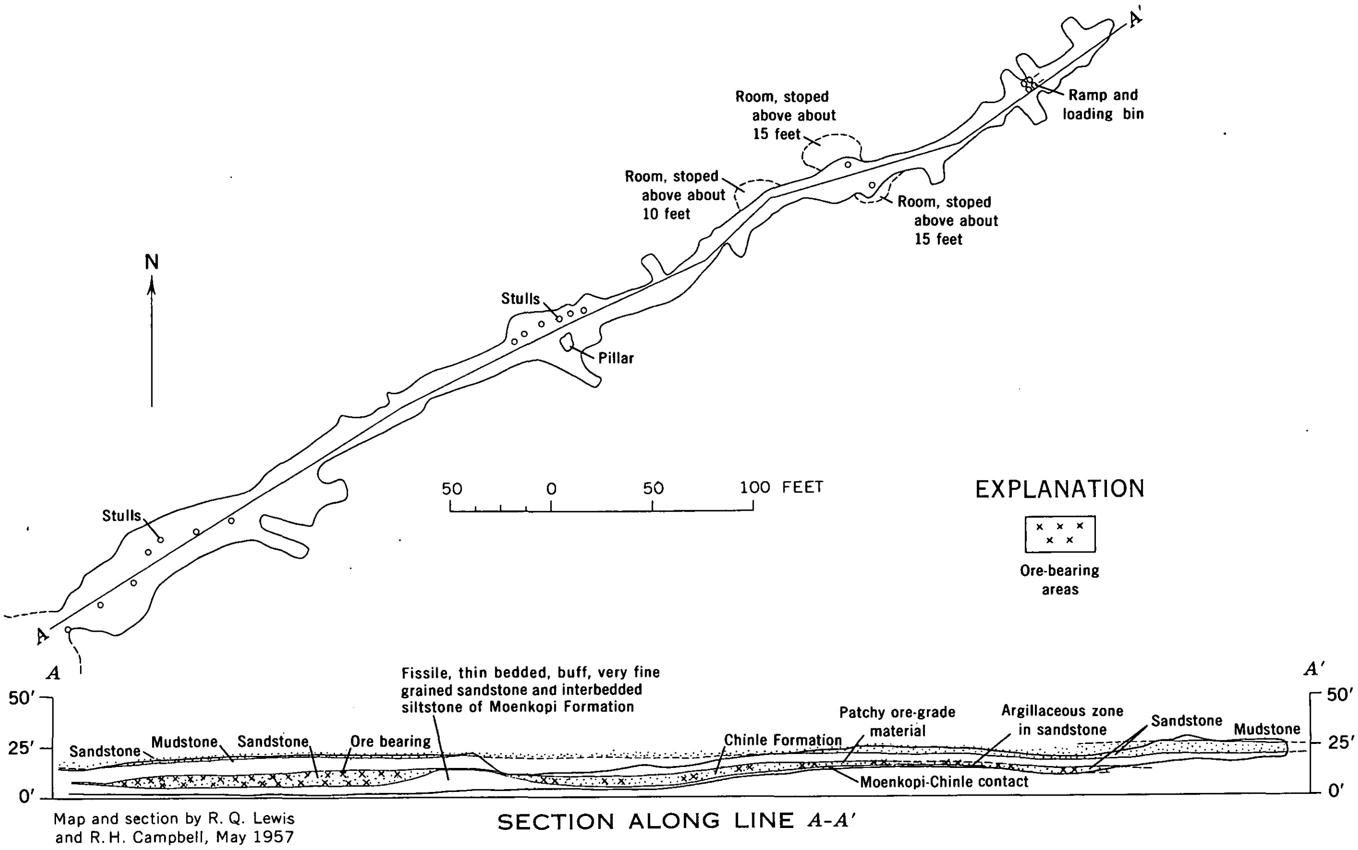

FIGURE 19.—Map and section of the King James-Virgene mine.

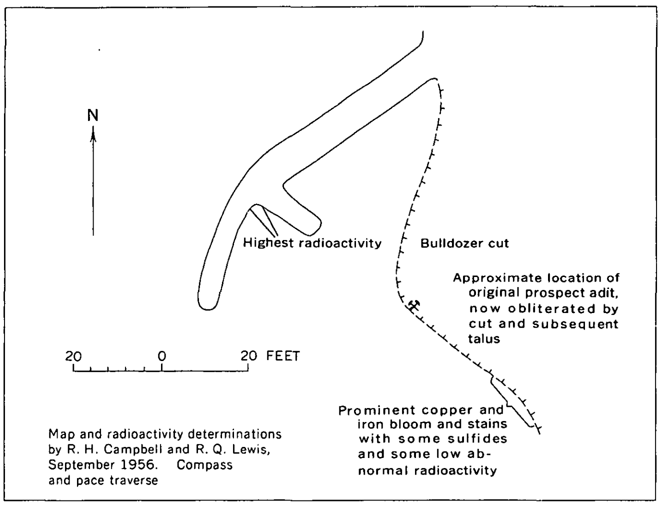

FIGURE 20.—Map of the vicinity of the Notch No. 1 mine.

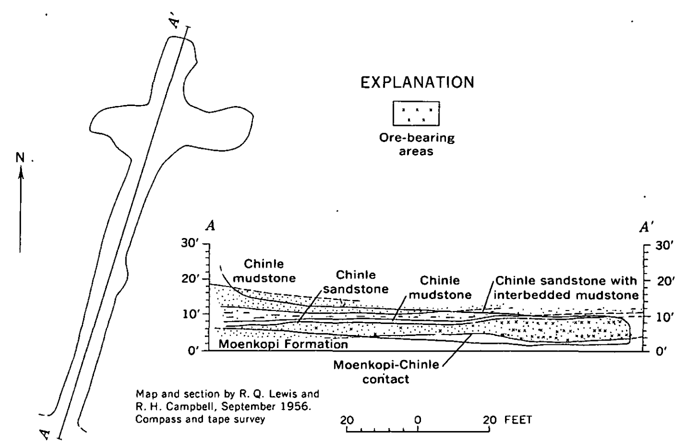

FIGURE 21.—Map and section of the Notch No. 4 mine.

The dimensions of the channel and ore body are not known; however, certain maximum dimensions for the channel may be inferred from the known workings. The discovery location and the Notch No. 1 adit appear to be well up on the north flank of the channel, and the portal of the Notch No. 4 adit is on the south flank. This defines a broad, shallow channel, probably less than 300 feet wide. Although the Moenkopi-Chinle contact is irregular and no good stratigraphic datum for vertical measurement was observed, the deepest part of the channel, as now exposed, appears to be slightly less than 5 feet below the general altitude of the top of the Moenkopi. A maximum length of about 1,600 feet is obtained by projecting the channel trend between the east and west rim outcrops. The channel appears to have continued an unknown distance to the east and west in areas where it has been removed by erosion.

A Chinle sandstone lens, exposed about 20 feet south of the covered discovery location, shows some radioactivity associated with pyrite, chalcopyrite(?), prominent blue, green, yellow, and red secondary copper minerals, and iron minerals. Specimens from the discovery location were examined by Weeks who identified (written commun., 1957) uraninite, metaautunite, cuprosklodowskite, pyrite, marcasite, ilsemannite, and jarosite.

No ore is known to have been shipped from the present workings at the Notch No. 1. Chinle sandstone is not exposed in those workings. Chinle mudstone is in contact with a silty sandstone bed at the top of the Moenkopi Formation. A conglomerate zone, generally less than 4 inches thick, consisting of mud balls in a mudstone matrix, is the basal bed of the Chinle. This zone is moderately radioactive in contrast with the less radioactive overlying mudstone and underlying silty sandstone. No metallic minerals were observed in the east adit.

At the Notch No. 4, the apparent base of the Notch No. 1 channel is exposed in the workings about 83 feet from the portal. Lower Chinle sandstone contains ore above the deepest part of the channel. At the time of examination, all three faces appeared to contain ore (on the basis of radioactivity). The ore zone appeared to be continuous, about 4 feet thick in the west face, 2 feet thick in the north face, and 6 feet thick in the east face. The thinning of the ore zone to the north and south suggests that the ore body is approximately 50 to 60 feet wide (across the channel) at this point. The long dimensions cannot be reasonably inferred. The ore is black and the main ore mineral is probably uraninite; however, no metallic minerals were identified. The radioactive material appears to fill interstices, but replacement of minute carbonized fragments of detrital organic material and other clastic constituents of the host rock is probable. It is closely associated with asphaltitelike material that has a petroliferous odor on a freshly broken surface. No sulfides or secondary bloom were observed. Locally, the upper foot or two of the Moenkopi is mineralized, most commonly along fractures but also as disseminations in the sandstone.

The Chinle host rock is a coarse- to medium-grained, locally conglomeratic sandstone. In places it contains abundant small fragments of carbonized detrital organic material and generally it contains some silt and clay. Above the base of the channel the ore-bearing sandstone is about 5 to 8 feet thick. The ore zone is capped by a continuous mudstone bed. The underlying Moenkopi is fine-grained sandstone and silty sandstone.

NOTCH NO. 5 AND NOTCH NO. 6

The workings in the Notch No. 5 area consist of four adits, known as Tunnels Nos. 1 to 4 (No. 4 is also called the Notch No. 6). Tunnels Nos. 1, 2, and 4 are in basal Chinle sandstone in the Notch No. 5 channel. Tunnel No. 3 develops a small ore body in the Moenkopi Formation about 40 feet below the base of the Notch No. 5 Channel. On plate 2 Tunnels Nos. 1, 2, and 3 are grouped as the Notch No. 5, and Tunnel No. 4 is the Notch No. 6. Because of the unique occurrence of an ore body in the Moenkopi, the area has received special study by several previous workers, notably Oertell (written commun., 1956), and Laverty and Gross (1956, p. 198–199). Laverty and Gross examined ores from the area and suggested the paragenetic sequence indicated in figure 13. Some ore has been produced from each of the adits; however, the total up to January 1, 1957, was less than 500 tons.

According to Oertell (written commun., 1956) the Notch No. 5 channel is about 300 feet wide and contains scours as much as 8 feet deep. It has been delineated for a distance of 3,000 feet along its generally eastward trend. Oertell reported a maximum thickness of 32 feet for the basal Chinle channel sediments. Uranium minerals were reported from two zones that are separated by thin lenses of gray mudstone in this channel. Sub-ore-grade material occurs in sandstone and conglomeratic sandstone at the base of the channel, and ore occurs in a zone of sandstone lenses from 7 to 15 feet above the base.

Tunnel No. 1 (fig. 22) is the westernmost of the workings in the Notch No. 5 channel. The portal is in very clean medium-grained lower Chinle sandstone and the sill is about 5 feet above the Moenkopi-Chinle contact. The sill maintains a fairly constant altitude throughout the workings and nowhere intersects the Moenkopi-Chinle contact. A thick Chinle mudstone lens is exposed in the back in the inner parts of the workings, and appears to form a continuous cap over the sandstone. Except in the right crosscut near the stoped area, radioactivity is not abnormally high in most of the workings. A small area of high radioactivity was observed in a zone of sandstone about 6 inches to 1 foot thick immediately below the mudstone exposed in the back. Radioactivity appears to increase in direct proportion to the abundance of small blebs of asphaltite(?) in the sandstone.

The portal of Tunnel No. 2 (fig. 22) is about 50 feet N. 50° E. from the portal of Tunnel No. 1. As at Tunnel No. 1, the portal and workings of Tunnel No.

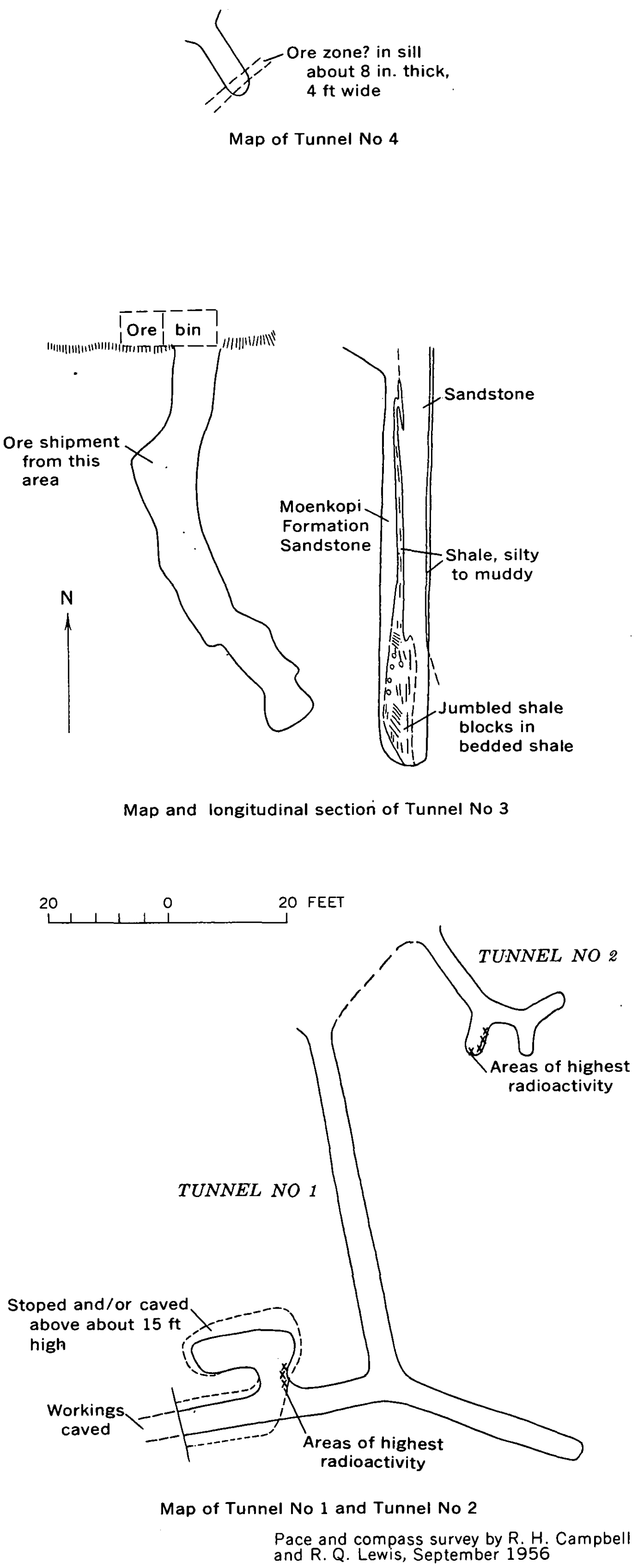

FIGURE 22.—Maps of workings in the Notch No. 5 area.

2 are entirely above the Moenkopi-Chinle contact; the sill is about 5 feet above the contact at the portal. The lowest rock exposed is a fairly clean friable sandstone. A silty sandstone lens about 4½ feet thick at the portal lenses out into clean sandstone about 30 feet from the portal; it is reported to have contained ore. The highest radioactivity observed was in a silty sandstone lens (fig. 22) that is overlain by a mudstone containing blebs of asphaltite(?).

Tunnel No. 4 (fig. 22) is a short adit driven to explore the Notch No. 5 channel on the Notch No. 6 claim. The contact is at the sill level where Chinle sandstone and conglomeratic sandstone is in contact with underlying Moenkopi. Black pods and blebs of highly radioactive asphaltite(?) are in the sandstone, chiefly near the Moenkopi contact. The highest radioactivity observed was at the Moenkopi-Chinle contact (fig. 22). Several lenticular pods of radioactive asphaltite(?) appear to be randomly disseminated through the relatively barren sandstone above the contact. One isolated pod about 5 inches in diameter is in the right wall about 10 feet from the portal and about 5 feet above the Moenkopi-Chinle contact. It is highly radioactive and locally has a blue bloom (ilsemannite?) on the surface. Some ore has been shipped from this adit since the writers' examination.

Tunnel No. 3 (fig. 22) was driven to explore a small ore body in the Moenkopi Formation about 40 feet below the Moenkopi-Chinle contact. The portal is a few feet east of the discovery location where uraniferous asphaltite(?) blebs were observed in outcrops of Moenkopi sandstone in association with the colorful secondary copper minerals azurite and malachite. Some uranium ore has been shipped from the cut at the discovery location and from the adit. The ore appears to be restricted to one reddish-brown medium- to fine-grained sandstone lens underlain and overlain by silty, locally argillaceous shale beds; however, other nearby sandstone lenses show some radioactivity. The sandstone lens thins from the portal toward the inner part of the workings, and according to Oertell (written commun., 1956) drill-hole data indicate that the lens pinches out a short distance south and west of the outcrop. The ore appears to be patchy.

OAKIE

The Oakie mine is near the head of Burch Canyon. The ore deposit is in basal sandstone lenses of the Chinle that fill a scour channel in the top of the Moenkopi Formation, but ore is apparently not restricted to the base of the lenses. The workings (fig. 23) follow the base of the channel, which trends N. 55°–70° E. The writers were unable to make detailed studies of the rocks

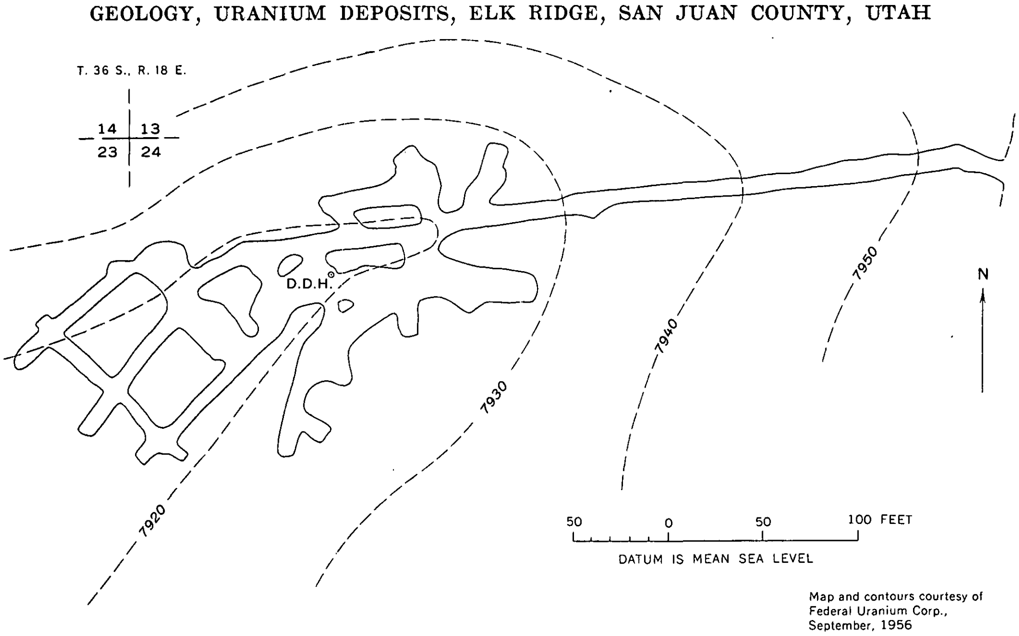

FIGURE 23.—Map of the Oakie mine, showing contours on the top of the Moenkopi Formation. D.D.H., diamond-drill hole.

to determine relations of the ore deposit to permeability barriers. In discussing the results of Atomic Energy Commission drilling in the area, however, Oertell (written commun., 1956) reported that ore occurs in two zones: one at the base of the channel, and another 19 to 21 feet above the base of the channel. From a general knowledge of the stratigraphic relations in the area, it may be inferred that these two ore-bearing zones are separated by less permeable zones of mudstone and very argillaceous sandstone, and that the upper zone is overlain by massive Chinle mudstone.

The present workings explore only the lower of the two ore zones. The ore consists chiefly of fine-grained black minerals disseminated in sandstone and in many places intimately associated with asphalitite(?) and carbonized wood. The chief uranium minerals are probably uraninite and coffinite. Pyrite in irregular nodules as much as 3 inches in diameter is present in the ore as well as in barren parts of the sandstone. Chalcopyrite and minor amounts of azurite and malachite also are present locally.

The host rock is a medium- to coarse-grained sandstone, locally containing abundant carbonaceous material. The lower 1 to 4 feet of strata is relatively friable and contains most of the higher grade ore. Above the very irregular and poorly defined boundary at the top of the friable part, the sandstone is commonly lighter in color and very well cemented with calcite. This upper well-cemented part of the host sandstone lens is generally barren, but there are local patches of submarginal material chiefly associated with sparse small clay pebbles. The underlying Moenkopi rocks are thin even-bedded very fine grained sandstone and siltstone. Commonly from 1 to 2 feet of Moenkopi is exposed in the workings. The top 3 to 6 inches of the Moenkopi is bleached nearly everywhere in the workings.

PAYDAY

The Payday mine is on the east rim of Elk Ridge about 2¼ miles south of Gooseberry Ranger Station. The workings shown in figure 24 have been extended considerably subsequent to examination by the writers (Aug. 15, 1955), and up to December 31, 1956, more ore had been produced from the Payday than from any other mine in the map area. The workings explore a scour channel that trends S. 85°–90° W. and probably is not more than 60 feet wide near the portals. Most of the recent work has been in the southernmost drift, which exposes the south flank of the channel where the Moenkopi-Chinle contact dips steeply (about 20°) to the north. Uranium ore is generally restricted to a basal Chinle sandstone lens, although locally, particularly along fractures, the underlying Moenkopi and the overlying Chinle mudstone are mineralized. The grade of ore in the basal sandstone is sufficiently high to permit shipping of all rock between the sill and the back of the drift. The ore zone averages about 4 feet in thickness and the drift generally ranges from 8 to 10 feet in height.

The host rock is crossbedded medium- to coarse-grained sandstone that contains abundant carbonaceous material. It is generally weakly cemented and friable, particularly near the base. Thin discontinuous mudstone lenses are interbedded in the sandstone, which also contains variable amounts of mudstone pebbles and interstitial clay and silt. Quartz overgrowths on

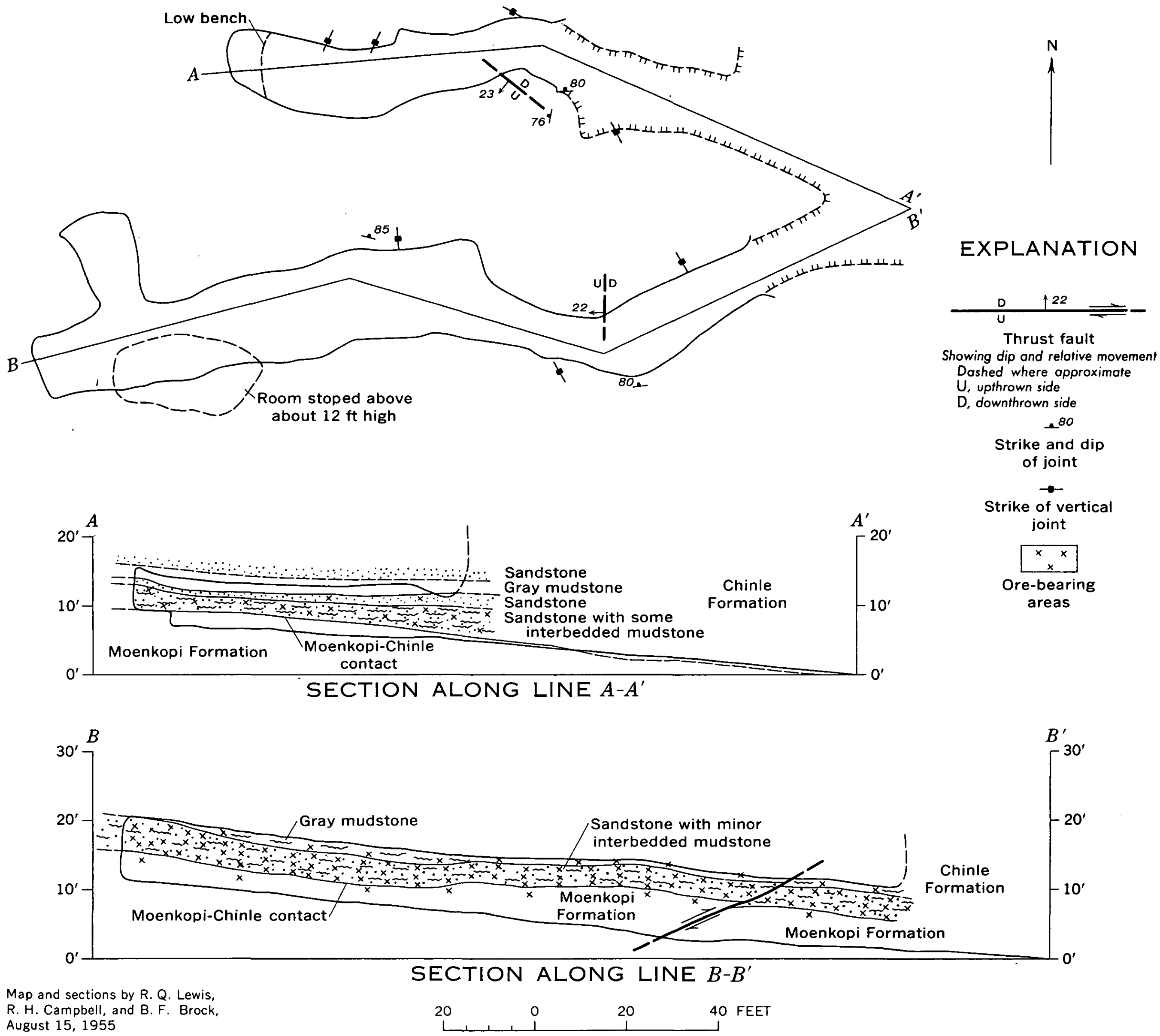

FIGURE 24.—Map and sections of the Payday mine.

the sand grains are locally abundant. The ore-bearing sandstone ranges in thickness from 3 to 6 feet. It is overlain by massive Chinle mudstone, which is about 3 feet thick in the north drift but several feet thicker in the south drift, and which contains interbedded discontinuous lenses of silty argillaceous sandstone. The mudstone is in turn overlain by a thick (perhaps as much as 20 ft) sequence of interbedded mudstone and crossbedded sandstone. The ore-bearing basal sandstone is underlain by silty fine-grained to very fine grained thin- and even-bedded sandstone of the Moenkopi Formation.

The ore minerals are black, fine grained, and appear to fill the interstices between sand grains or replace carbonaceous material. Secondary minerals are rare. Specimens examined by Weeks (written commun., 1957) are reported to contain uraninite, pyrite, galena, chalcopyrite, and bornite; barite interstitial to quartz grains that have euhedral overgrowths; and the secondary minerals andersonite and uranophane.

PEAVINE QUEEN

The Peavine Queen mine is on the east rim of Peavine Canyon about 1 mile west of Kigalia Ranger Station. Less than 20 tons of uranium ore had been produced from the Peavine Queen workings (fig. 25) at the time of examination. The deepest part of the channel at the Peavine Queen mine exposed by rim stripping is located about 120 feet S. 30° E. of the adit. The Moenkopi-Chinle contact is probably exposed near the sill of the workings, which were partly flooded at the time of the examination. Beyond the limits of accessibility indicated (fig. 25), the sill inclines downward possibly as much as 4 feet to the two faces. The contact of the Moenkopi and Chinle is inferred to drop similarly; the miners probably followed the contact at or just above the sill. The rocks exposed in the accessible workings are chiefly argillaceous silty sandstones of the Chinle. Some conglomeratic sandstone is exposed along the stripped rim southeast of the portal.

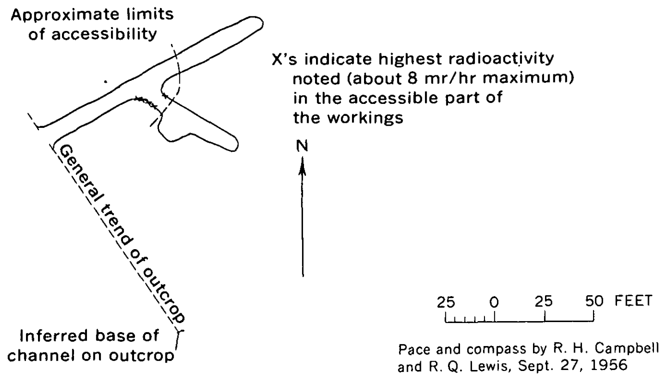

FIGURE 25.—Map of the Peavine Queen mine, showing location of highest radioactivity.

SANDY NO. 2

The Sandy No. 2 mine is on the southeast rim of Upper Lost Parks. The workings are shown in Figure 26. The ore body is in a thick bed of Chinle sandstone, the base of which is not exposed but which appears to be at or near the base of the Chinle Formation. The Chinle strata were not examined in sufficient detail to determine detailed interrelations of stratigraphy and ore. The ore body appears to lie above the south flank of the Sandy No. 3 channel as projected along its S. 70° W. trend from its outcrop on the rim. The ore body is a flat-lying tabular body with very irregular outlines, and is reported to be 6 to 10 feet thick with its base 15 to 20 feet above the Moenkopi-Chinle contact. The ore is black; the chief ore mineral is probably uraninite, mostly in the interstices between sand grains of the host rock and as a replacement of carbonaceous material.

The sill of the workings in the stoped area, which apparently followed an irregular assay boundary at the base of the relatively flat-lying ore body, varies as much as 10 feet in altitude in a horizontal distance of 200 feet. In general the sill of the workings is higher north of the ventilator shaft than to the south of it. The top of the Moenkopi is exposed at or near the sill of the adit from the portal to a point about 250 feet east of the ventilator shaft. From that point to the innermost workings, the contact is below the sill level, and in the stoped area it is reported to be from 6 to 15 feet below the sill.

The host rock is a basal lens of Chinle sandstone that apparently overfills a shallow scour channel in the top of the Moenkopi. It is a crossbedded coarse- to medium-grained sandstone, locally conglomeratic with small quartz pebbles, with some interbedded thin discontinuous lenses of mudstone and fine- to medium-grained sandstone, and variable amounts of interstitial silt and clay. In many places it is well cemented with calcite. Carbonaceous material is locally abundant, particularly near the ore body. The ore-bearing unit is as much as 20 feet thick in places. Near and in the ore body, massive Chinle mudstone caps the ore-bearing unit, but elsewhere the workings appear to be entirely within the thick sandstone lens. The underly-

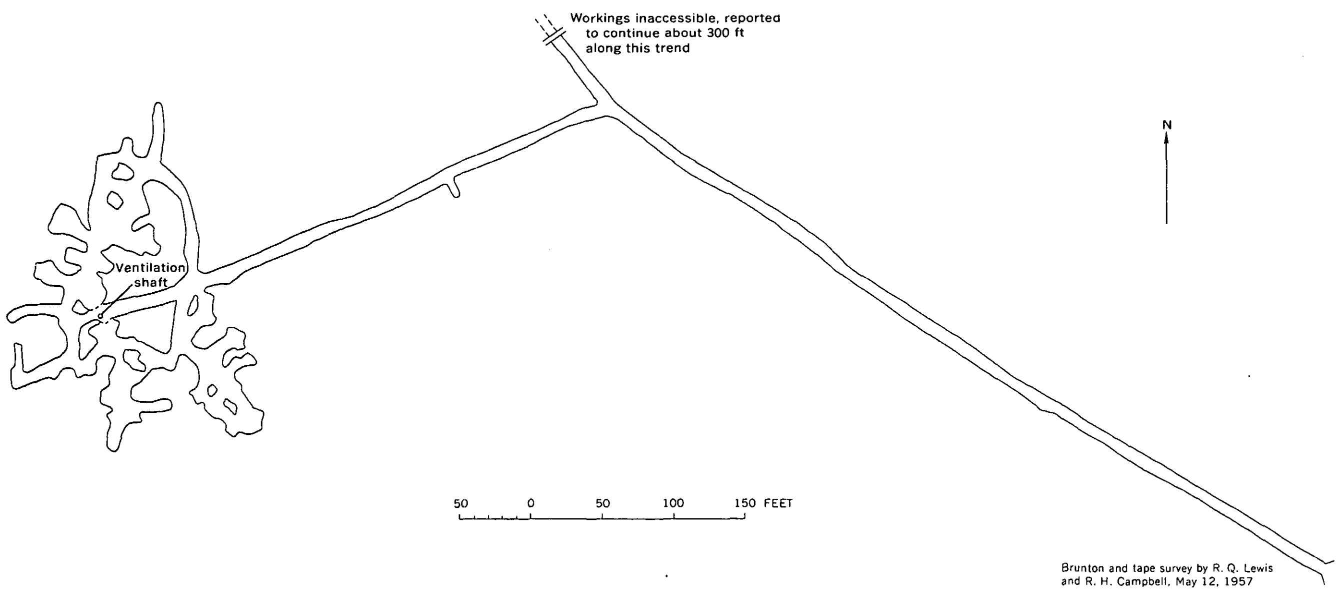

FIGURE 26.—Map of the Sandy No. 2 mine.

ing Moenkopi, where observed in the adit to the east of the ore body, is a thin- and even-bedded siltstone and very fine grained argillaceous sandstone. The upper 1 to 2 feet of Moenkopi is commonly bleached to gray or blue gray.

SANDY NO. 3

The Sandy No. 3 mine is on the east rim of Upper Lost Parks. The portal is approximately 600 feet north of the portal of the Sandy No. 2. T. L. Finnell of the U.S. Geological Survey studied the mine in September 1954 in connection with a U.S. Geological Survey exploration drilling program in the area. (Finnell has contributed much of the information on this mine by oral and written communs., 1956, 1957.) The workings have been extended considerably since they were mapped by Finnell, but because of flooding and an unsafe back the inner parts were inaccessible at the time of the writers' visit. The visit was too brief to allow more than a cursory examination of the stratigraphy of the basal lower Chinle sediments.

The ore body is flat lying, tabular, irregular in outline, and is elongated parallel to an underlying channel cut into the top of the Moenkopi Formation. The ore apparently is restricted to a basal Chinle sandstone lens in and above the channel, which trends about S. 70° W. from the portal. The workings (fig. 27) follow the channel at or near its base. The ore-bearing sandstone is overlain in most of the workings by massive mudstone and is underlain by Moenkopi sandstone and silty sandstone.

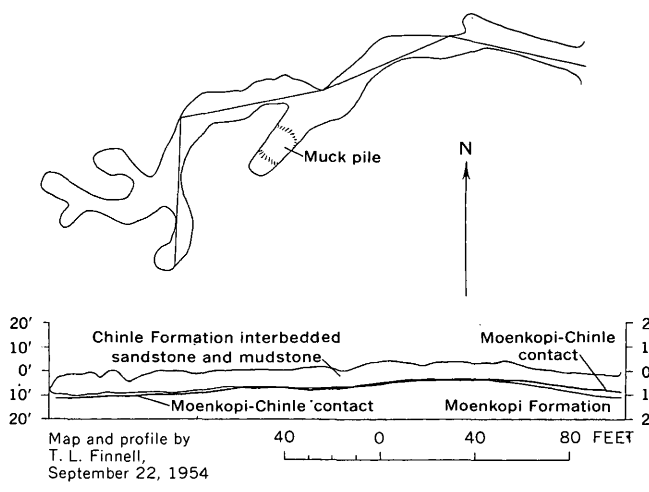

FIGURE 27.—Map and profile of the Sandy No. 3 mine, showing the Moenkopi-Chinle contact.

The host rock is a crossbedded medium-to coarse-grained sandstone with variable amounts of interstitial silt, clay, and fine-grained carbonaceous material. Accumulations of carbonized wood and other carbonaceous material are locally abundant in the ore-bearing sandstone and also in the overlying barren mudstone. Mudstone as pebbles, flattened boulders, and interbedded thin discontinuous lenses, is common in the sandstone. The sandstone is generally friable and poorly cemented, and is locally stained by abundant limonite. Ore is localized chiefly near the base of the host sandstone and is reported to be about 1½ to 2 feet thick.

The ore is chiefly black and very fine grained. Most of the ore minerals are apparently interstitial to the sand grains of the host rock but also are intimately associated with accumulations of carbonized wood, spots and patches of asphaltite(?), and agrillaceous areas (clay galls, mudstone lenses, and pebbles) in the sandstone. Specimens studied by Weeks (written commun., 1957) contain uraninite, pyrite, chalcopyrite, secondary uranophane and metazeunerite. Alunite, allophane, and iron oxides were noted along a vertical fracture in the Moenkopi on the outcrop near the portal.

TEXSTAR

The Texstar mine (fig. 28) consists of an adit driven to explore a shallow channel exposed on the west rim of Peavine Canyon. The workings are almost entirely in Chinle mudstone, which is in contact with the underlying Moenkopi near the sill at the portal. The sill was inaccessible at the time of examination because of flooding (to depths as much as 2 ft) and fallen rock, and if the Moenkopi-Chinle contact were exposed by the workings, it must have been less than 2 feet above the sill. The workings maintain a relatively constant altitude, however, unlike the general configuration of the Moenkopi-Chinle contact, and it is possible that the sill in inner parts of the adit is above the base of the channel. A few thin (as much as 2 ft thick) lenses of sandstone are present in the mudstone exposed by the workings. At the portal the basal mudstone unit is about 15 feet thick and is overlain by a thick (about 15 ft) relatively continuous sandstone lens. Radioactivity is not abnormally high in the mudstone except in the small area indicated in figure 28.

WABAN

The Waban mine located just south of Brushy Knoll on the west side of Peavine Canyon consists of an adit, an irregular lateral on the right, four drifts to the right, and two drifts to the left. Figure 29 shows the plan and a sketched geologic section emphasizing the major joints and close-spaced joint sets. The mine is located near the base of a shallow channel that trends S. 5°–30° W. from the portal.

The ore-bearing sandstone is a brown, limonite-stained silty medium-grained sandstone. It ranges in thickness from about 10 feet at the portal to about 3 feet in the innermost workings. It is overlain by a gray

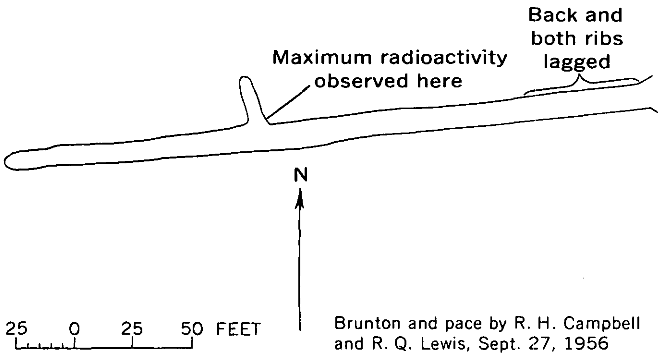

FIGURE 28.—Map of the Texstar mine.

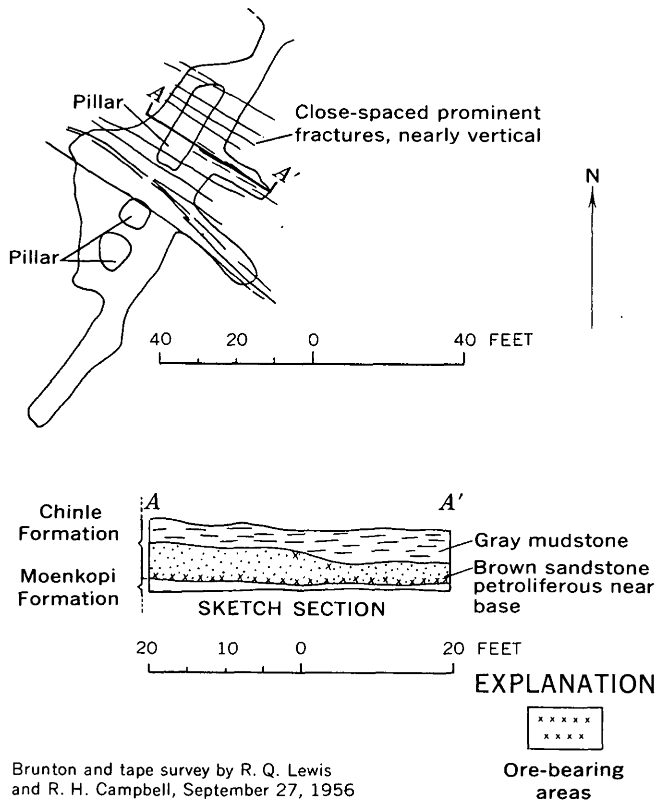

FIGURE 29.—Map and section of the Waban mine.

mudstone, which in places fills scours in the top of the sandstone and elsewhere caps it. The underlying Moenkopi is a silty argillaceous shale that is bleached to a greenish-gray color. The ore is generally restricted to the lower 1 to 2 feet of the basal Chinle sandstone, but some patches of ore-grade material are found higher in the sandstone, particularly in and around clay galls and along some fractures. The ore is intimately associated with asphaltite(?) and petroleumlike carbonaceous material, which is locally abundant at the base of the brown sandstone.

A set of conspicuous vertical joints trends about N. 60° W. across the workings, nearly perpendicular to the adit and the inferred trends of the channel. Although ore-bearing carbonaceous material locally occupies the fractures, there appears to be no consistent association of fractures and ore. The ore body crosses the fracture zone with some local widening of the ore along it.

WESTERN PAYDAY

The workings at the Western Payday mine consist of an adit, short side drifts, and some stopes near the face being driven at the time of examination (fig. 30). The workings explore basal Chinle sandstone and interbedded mudstone that fill and are built up above a broad shallow channel cut into the top of the Moenkopi Formation. The portal appears to be on the south flank of the channel, and the workings drop toward the base at a slight angle. The channel trend appears to be approximately N. 70° E.

Only a small amount of ore had been exposed at the time of examination, all in the innermost parts of the workings where they expose the south(?) side of an ore body of unknown size. Ore is restricted to basal lenses of Chinle sandstone but is not confined to their lowermost parts. On the contrary, the best grade material is in the upper two of three sandstone lenses exposed by stoping at the face. The ore is black and the ore minerals are probably mostly uraninite and coffinite. These are generally very fine grained and appear to be chiefly interstitial to the sand grains of the host rock. Carbonaceous material is not visibly abundant, but much of the fine-grained black material interstitial to the sand grains of the host rock may be carbonaceous.

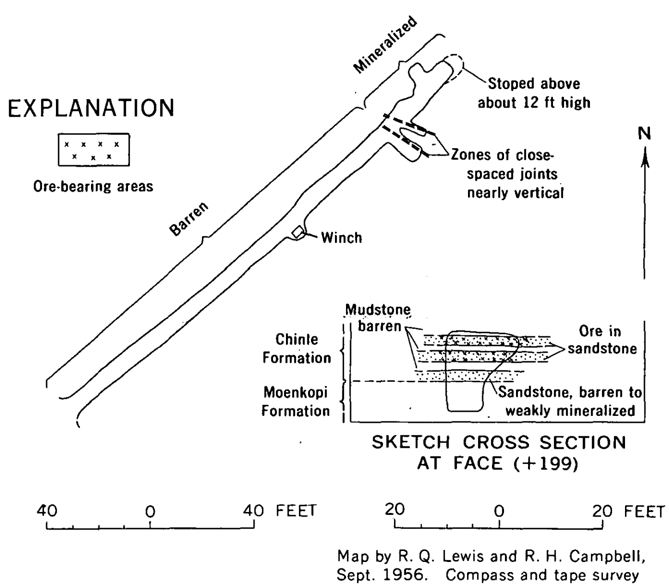

FIGURE 30.—Map and sketch at face, Western Payday mine.

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Throughout most of the adit, 4 or 5 feet of Moenkopi is exposed and the back is cut in the lowermost of the three Chinle sandstone lenses. This lens is largely devoid of uranium between the portal and the area where it is cut by the fracture zones (fig. 30). It is mineralized between the fracture zones and the face, locally containing areas of low-grade ore, particularly along the fractures. At the working face, stoping into the back has revealed the two higher ore-bearing sandstone lenses. The sketch cross section (fig. 30) shows the detailed stratigraphic relation. The three sandstones are lithologically similar. They are crossbedded, medium grained, each about 2 or 3 feet thick, and separated and overlain by barren lenses of gray mudstone. The Moenkopi underlying the lowermost Chinle sandstone is thin bedded and evenly bedded very fine grained sandstone or siltstone.

WOODENSHOE NO. 3

The workings at the Woodenshoe No. 3 (East Woodenshoe) consist of an almost horizontal adit along the base of a channel, and a raise inclined to the northwest with a drift 5 to 8 feet above the adit level (fig. 31). The workings reflect two stages of exploration of the channel, and the mine provides a clear-cut example of ore control by an overlying mudstone. The adit follows the base of the channel so that the Moenkopi-Chinle contact is generally from 6 inches to 2 feet above the sill in both ribs. The Chinle sandstone exposed by the adit is barren. After completing the adit (fig. 31) without exposing any ore, the first operators left and after a few months new operators took over the property. The new operators drove an inclined raise to the left in an area where low but above-normal radioactivity had been noted in the back of the adit. The raise intersected ore in the upper part of the sandstone lens, and mining from the upper level was begun.

The sketch of the outcrop (fig. 32) and the photograph (fig. 33) show some of the details of the lower Chinle stratigraphy in the mine area. The basal Chinle sandstone fills and is built up above a shallow paleostream channel in the top of the Moenkopi Formation. The sandstone is generally medium to coarse grained but locally contains some pebbles and very coarse sand grains. The basal part of the sandstone is relatively free of silt and clay, but the upper part contains a moderate amount of these materials, particularly in the inner part of the workings. This appears to be, at least partly, an original feature of the sandstone; however, much of the fine-grained interstitial material present in the ore zone may have accompanied deposition of the ore minerals. The lower Chinle mudstone that caps the basal sandstone at the portal appears to be continuous

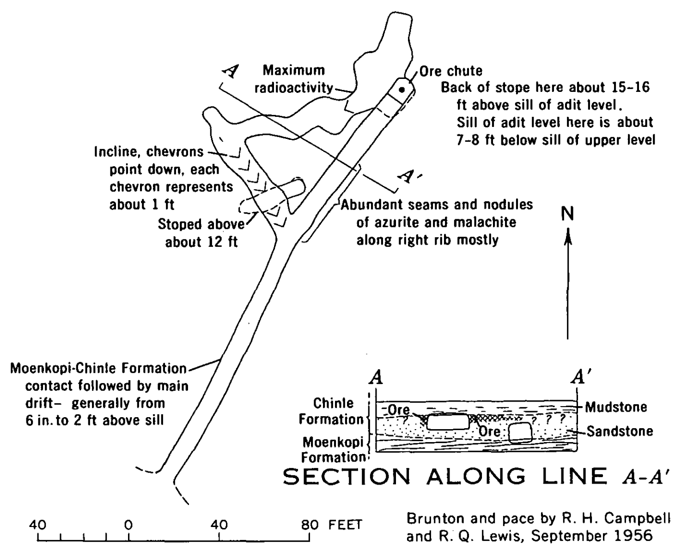

FIGURE 31.—Map and section of the Woodenshoe No. 3 mine (East Woodenshoe).

and identical with the bed shown in the cross section (fig. 31) capping the sandstone in the inner parts of the workings. The capping bed is chiefly massive mudstone with disseminated fine- to medium-size sand grains, and contains a few thin discontinuous lenses of sandy mudstone and argillaceous silty sandstone.

The ore is restricted to the upper third of the basal Chinle sandstone. The lower two-thirds is largely barren of significant radioactivity, although seams, pods, and nodules of azurite and malachite are exposed in the adit level. The ore is black, and the chief ore mineral is probably uraninite. Ore is associated in some places with local accumulations of carbonized organic debris. Asphaltite(?) may be associated with some of the ore but has not been positively identified. The ore minerals appear to be largely interstitial to sand grains of the host rock and may have formed chiefly as a filling of open pores. Replacement of original interstitial clay, silt, carbonized organic matter, and cementing material, however, may have been important in the formation of ore. The detailed stratigraphic setting of the ore body is very clearly exposed at this mine, and the role of relatively impermeable mudstone capping the basal sandstone in controlling the stratigraphic position of the ore body seems obvious.

OTHER MINES AND PROSPECTS

Only the larger prospects are shown in figure 6 to indicate the distribution of prospecting activity. Much of the prospecting has been by diamond drilling and bulldozer stripping of overburden from the rim for long distances, and a few tons of ore has been shipped from rim exposures at some of these prospects.

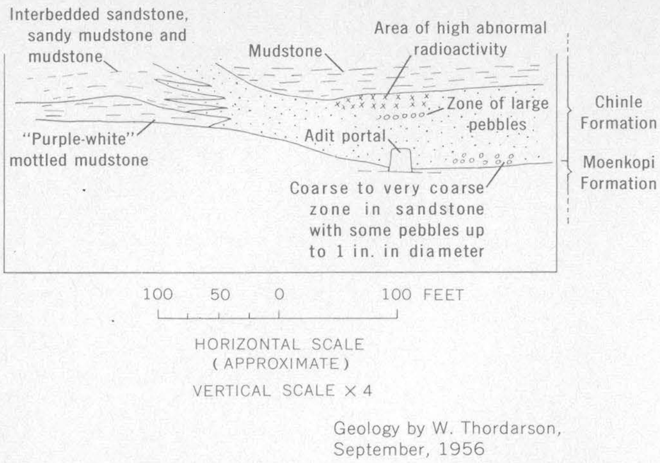

FIGURE 32.—Sketch showing relation of ore to detailed stratigraphy at the Woodenshoe No. 3 (East Woodenshoe) channel rim outcrop.

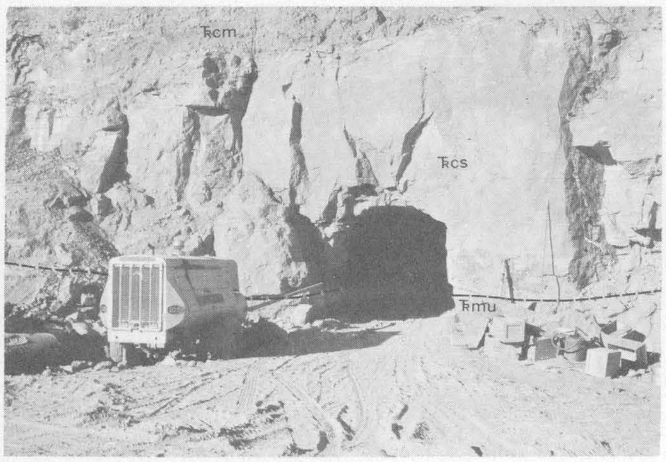

FIGURE 33.—Portal at the Woodenshoe No. 3 mine (East Woodenshoe). Upper member of Moenkopi Formation (T̄Rmu), basal sandstone of Chinle Formation (T̄Rcs) filling shallow paleostream channel, and mudstone unit (T̄Rcm).

Prospects in the lower Chinle rocks explore the basal sandstones. Some, such as those of the Carl-Look-Pay-day No. 3 group of claims, show secondary uranium minerals on outcrops of sandstone exposed by rim stripping. Others such as the Morrison, where exploration was incomplete at the time of the writers' last visit, are adits driven in barren basal Chinle sandstone toward diamond-drill holes in which radioactivity suggests the presence of an ore body. Both methods of prospecting have led to the development of mineable ore bodies in the area.

In the northeast part of the area, the Moss Back Member of the Chinle Formation has been explored by drilling and rim stripping. With the exception of the Horseshoe No. 1 mine, only small quantities of submarginal material have been found. The only significant difference in geologic setting between the Horseshoe No. 1 mine and the more weakly mineralized ground at the prospects is that at the mine basal sandstones of the Moss Back are locally in contact with the Moenkopi, whereas at all the prospects the Moss Back is separated from it by 5 to 20 feet of Chinle mudstone.

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