Yampa Canyon in the Uinta Mountains Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 374-I

Yampa Canyon in the Uinta Mountains Colorado

By JULIAN D. SEARS

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 374-I

A study of some unusual features and the possible origin and development of the canyon

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

CONTENTS

	Page
Abstract	I-1
Introduction	3
Purpose of the report	3
Usage of two terms	3
Sources of information	4
Earlier investigations	4
Newer sources	4
Geologic map in present report	4
Acknowledgments	5
Observed features	5
Yampa Canyon as a whole	5
Statistical details	5
Relation to Yampa fault and other faults	5
Yampa fault	5
Red Rock fault	5
Mitten Park fault	6
Graben between Red Rock and Mitten Park faults	6
Three-part division of canyon	6
Upper section of Yampa Canyon	6
Middle section of Yampa Canyon	7
River pattern and direction	7
Topography of canyon walls	7
South wall	7
North wall	7
Topography of adjoining uplands	8
South of canyon	8
North of canyon	8
Geology	9
South of river	9
North of river	9
Meander-migration scars	9
Anderson Hole scar	10
Tepee Hole scar	10
Browns Hole scar	11
Bower Draw scar	11
Five Springs Draw scar	11
"Half-turn district"—an exception	11
Lower section of Yampa Canyon	12
River pattern and direction	12
Observed features—Continued	
Lower section of Yampa Canyon—Continued	
Topography of canyon walls	I-12
Topography of adjoining uplands	13
South of canyon	13
North of canyon	13
Geology	14
Warm Springs scar—an exception	14
Suggested explanation of the features	15
Concepts of 1922–23	15
Original extent and thickness of Browns Park formation	16
Area of maximum thickness	17
Browns Park formation in Lily Park	17
Possible Browns Park material on Douglas Mountain	17
Browns Park formation near Elk Springs	18
Nearness of Browns Park formation to east end of Yampa Canyon	19
Possible Browns Park material on Blue Mountain	19
Possible Browns Park material on Harpers Corner	19
Possible Browns Park material west of Lodore Canyon	19
Summary	20
Possible development of the canyon—a chronological outline	20
First step	20
Second step	20
Third step	21
Fourth step	22
Fifth step	24
Sixth step	25
River development in Morgan formation	26
River development in Weber sandstone	27
Seventh step	28
Effect of Mitten Park and Red Rock faults	28
Selected bibliography	30
Index	33

ILLUSTRATIONS

PLATE 1. Geologic map of Yampa Canyon and vicinity, Uinta Mountains, Colorado — In pocket

		Page
FIGURE 1.	Entrance to Yampa Canyon	I-6
2.	Upper section of Yampa Canyon	7
3.	Sharpened spur between Tepee Hole (second) and Browns Hole (third) scars	11
4.	"Tiger Wall" in lower section of Yampa Canyon	12
5.	Lower section of Yampa Canyon. Intricate meanders in Weber sandstone	13
6.	Warm Springs (sixth) scar	15
7.	Map of eastern Uinta Mountains and vicinity, showing part of the mapped Browns Park formation	18
8.	Hypothetical course of Yampa River between points B and C when cutting through Browns Park formation	25
9.	Possible former high-level channel of lower part of Yampa River	30

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

YAMPA CANYON IN THE UINTA MOUNTAINS, COLORADO

By Julian D. Sears

ABSTRACT

Yampa Canyon, northwest Colorado, was incised in the southern flank of the Uinta Mountain arch by Yampa River.

Modern topographic and geologic maps and aerial photographs of the canyon and vicinity have disclosed unusual features, among which are: natural division of the canyon into three sections; marked change in river pattern from the middle to the lower section; in the middle section, radical differences in topography and geology on its two sides; also in the middle section, but only north of the river, several scallop-shaped erosion surfaces or scars partly rimmed by cliffs and with moderately sloping floors; in the lower section, still different topography and general absence of scars; geographic and geologic relations between Yampa River and the Yampa, Red Rock, and Mitten Park faults.

The observed features give further clues to the origin and development of the canyons and anomalous courses of Green and Yampa Rivers across the Uinta Mountains.

South of and crudely paralleling Yampa Canyon is the Yampa fault and its branch the Red Rock fault, both with downthrow on the north. Apparently the Red Rock fault ends at the Mitten Park fault, which has downthrow on the southeast. Thus the Yampa River joins the Green within a westward-pointing triangular graben between these two faults.

The upper section of Yampa Canyon, nearly 2 miles long, cuts stratigraphically downward through the Weber sandstone and Morgan formation, both of Pennsylvanian age, at right angles to the northeast strike and against the southeast dip of about 12° that mark the end of the Uinta Mountain arch. The river's course is fairly simple, and topography and geology on the two sides are similar.

The middle section of the canyon is nearly 20 miles long; its fall is 333 feet, an average of about 17 feet per mile. Near the point where the middle section begins, the strike of the beds swings sharply to a direction north of west, parallel to the axis of the arch; the dip is predominantly 6° SW. This changed structure extends westward to and beyond the end of the canyon.

The lower section of Yampa Canyon is nearly 24 miles long. Descent of the river surface is 176 feet, an average of less than 7½ feet per mile.

In the middle section the river's course is marked chiefly by open meanders and straight stretches. An exception is a "half-turn" meander, convex southward.

The south wall is prevailingly simple and uniform—a steep slope ending upward in a cliff. Its height and width average a quarter of a mile each, and it follows and fits closely each curve of the river. Its intersection with the adjoining upland is sharp.

Except in the "half-turn district," the north wall is wider, less steep, and of irregular shape. It consists chiefly of adjoining scallop-shaped erosion surfaces or scars. Southward, however, these moderately sloping surfaces end in a steeper slope down to the river, making a break in slope convex upward.

The Untermanns' geologic map of Dinosaur National Monument shows conspicuously that the south wall serves as a formation boundary. The upper part of the south wall and the upland immediately south of it consist of the Weber sandstone, about 900 feet thick, which is loosely cemented and highly jointed. The lower part of the south wall, the north wall, and the adjoining belt of upland expose beds of the next older Morgan formation (except in the "half-turn district" where the Weber sandstone remains). The Morgan is about 1,200 feet thick, of sandstone and limestone; the lower part is more resistant to erosion.

The hypothesis is advanced that the scallops north of the river are "meander-migration scars" formed by the progressive downdip (southward) migration and lowering of early meanders of Yampa River, by an unusual form of homoclinal shifting on more resistant beds in the lower part of the Morgan formation. In the middle section of the canyon five such scars are distinguished; because they differ somewhat from each other they are named and separately described.

The lower section of the canyon differs markedly from the middle section in several ways, the most striking and significant of which are: (a) A notable change in river pattern. Meanders are more numerous and more intricately curved. (b) Topography of canyon walls and of adjoining uplands generally different from the two types in the middle section. Cross profiles are asymmetric but alternating because of interlocking spurs with slipoff slopes. (c) An abrupt change in the relation between river and geology. The canyon is predominantly cut in the Weber sandstone, whose contact with the underlying Morgan is mostly north of the river. (d) An almost complete lack of "meander-migration scars." The exception is the Warm Springs (sixth) scar where the Morgan formation is again exposed to and along the river.

I am convinced, for the following reasons, that at one time the site of the present Yampa Canyon was buried under the Browns Park formation of Miocene(?) age: (a) The thickest deposits of the Browns Park formation, perhaps 1,700 feet of which still remain, were in the southeastern half of Browns Park and its extension to Little Snake River. (b) Continu-

ous outcrops of known Browns Park formation extend to the upstream end of Yampa Canyon on both sides of the Yampa River. (c) The rest of the canyon site is almost surrounded by patches of conglomerate and whitish tuffaceous sandstone of Browns Park lithology. (d) In September 1959 the Untermanns found sands similar to those of the Browns Park at four places between the Yampa River and the Yampa fault.

My hypothesis of canyon origin and development is offered as a chronologic outline involving seven steps.

First step.—After the Uinta Mountain arch was greatly uplifted during Laramide orogeny, it was extensively eroded and the detritus was laid down in the flanking basins and around its southeastern end. Repeated small uplifts accompanied this deposition. In late Eocene or early Oligocene time, arching was renewed and extended southeastward as the Axial Basin anticline. At this time the Yampa, Red Rock, and Mitten Park faults may have begun, but proof of this seems lacking.

Second step.—In middle Tertiary time, uplift virtually ceased, but continuing erosion reduced the mountain mass to mature topography. The resulting surface may have been what A. D. Howard called a pediplane. Along the mountain crest were high residual peaks, between which the erosion surface formed nearly horizontal pediment passes. Northward and southward these passes opened out into a pediment, cut on the upland rocks through retreat of the mountain front and sloping away from the ridge with gradually decreasing gradient. On the south flank this pediment truncated the older, southward-dipping rocks at an angle less than their dip, and also cut across the Yampa and other faults if then existing. The surface was at places rather smooth and at others undulating, with low residual hills. The pediment also wrapped around the southeastern end of the arch.

On this south flank the evidence now remaining near Yampa Canyon may record only a single erosion surface.

Third step.—During the Miocene(?) the widespread and varied Browns Park formation was laid down on the pediplane. At least as far east as Little Snake River the waterborne part of this material is thought to have come from the Uinta Mountains themselves. The basal conglomerate found at many places is prevailingly composed of the reddish quartzitic sandstone of the Uinta Mountain group of Precambrian age; locally, however, fragments of Red Creek quartzite of Precambrian age or of limestone of Mississippian age predominate. The upper, much thicker part of the formation consists partly of white or light-gray sandstone thought to have come from the Uinta Mountain group through leaching of its reddish cement; this was greatly augmented by windborne volcanic tuffs.

Upper beds of the formation presumably overlapped westward up the Browns Park valley and also laterally on its walls; concurrently, sand from residual peaks along the crest washed down into the pediment passes and some of it was carried down the north flank, where it met and mingled with the material rising in the valley. At the same time, some of the sand from the passes, and sand and some cobbles from the crest as the mountain mass retreated, were carried down the south flank, where they filled hollows and blanketed the beveling surface, perhaps to a depth of 200 or 300 feet above the canyon site.

Fourth step.—Chiefly after—but to a small amount during—deposition of the Browns Park formation, the eastern part of the Uinta Mountain arch collapsed, as a graben. Probably this took place in many small movements. Above the site of Yampa Canyon and its environs, a long narrow trough on the surface of the Browns Park was formed thus: (a) In a narrow zone along the Yampa fault (repeated by the branching Red Rock fault), steep north dips, caused by drag, in the Browns Park cover and the truncated older beds that previously dipped southward. (b) North of the drag zone, a zone 4 to 9 miles wide in which the surface of the Browns Park formation was virtually flat in a north-south direction but (through tilt) sloped gently about N. 80° W. (c) Still farther north, to the crest of the ridge, a zone in which the southward, depositional slope of the Browns Park formation remained because the broad central part of the graben had gone down almost vertically.

This trough probably continued, with gradually rising floor, far to the east above and north of the Axial Basin anticline, for the graben movement had extended in that direction, though with diminishing force and effect. I now suspect that, east of Little Snake River, the westward slope of its floor was erosional and depositional, hence original, rather than due to tilting and reversal as we earlier thought.

Fifth step.—Presumably somewhat overlapping the fourth step, during the fifth step the trough began to affect the location and direction of drainage. Streams flowing from the Continental Divide down the depositional slope of the Browns Park formation came together in the graben and, augmented farther on by other streams, were guided westward down the trough as a new Yampa River. At first the river was rather straight, but later it established incipient meanders.

Being wholly in the Browns Park formation, the river at any one time should have had a pattern and gradient essentially uniform throughout. Above the present middle section of the canyon the channel perhaps became located along the outer, northern edges of what are now called the first to fifth scars. Above the present lower section (with a probable meander around the outside of what is now the Warm Springs scar) the river pattern presumably was like that farther upstream rather than one of intricate meanders as today.

At length the river at some point cut through the Browns Park formation to the underlying rocks.

Sixth step.—Superposition commenced when the river's course began to be affected by the differing lithologic composition and structure of the undermass. It is tentatively suggested that the river first cut through the Browns Park formation at the mountainward ends of the meanders curving around the sites of the present first and sixth scars. Initially this caused some decrease in the rate of downward erosion at those points and created temporary baselevels upstream from them. However, only a thin cover of the Browns Park formation then remained elsewhere along the river, hence the undermass was relatively soon reached at all points.

Because of the structure of the undermass, when the river cut through the cover it ran on the Weber sandstone or the Morgan formation. In what is now the middle section it was on the upper beds of the Morgan, except in the "half-turn district" where it was on the Weber. In contrast, in what is now the lower section it ran on the Weber, except for the northward meander around the site of the present Warm Springs scar where it was again on the upper beds of the Morgan. Further development that brought today's conspicuous differences in river pattern must have been influenced chiefly by differences in the way those two formations affected erosion.

The upper part of the Morgan was more resistant than the soft beds of the Browns Park. In that upper part, downward rather than lateral erosion became dominant and cliffs perhaps 200 feet high were cut. Then at the north ends of its meanders the river reached even more resistant limestones in the lower part of the Morgan while elsewhere it was still in upper beds. Direct vertical erosion practically ceased at the points of greatest stratigraphic penetration; but as the tendency to cut the channel down to lower altitudes persisted, least resistance was found in a gradual downdip shifting on top of the older, stronger beds. At first the curving north ends of the meanders were flattened along the strike, and then the meanders themselves slowly migrated, cutting floors that sloped southward and rims whose bases grew lower in that direction. Between the Tepee Hole and Browns Hole scars a conspicuous sharpened spur was developed.

Concurrently, the meanders grew smaller and the river became shorter and of larger gradient. By its constant encroachment against the less resistant upper beds, the south wall was kept narrow, steep, and in conformity with the river's curves.

In contrast, where the river flowed on Weber sandstone it now has a pattern of rounder and more intricate meanders, with asymmetric cross sections and interlocking spurs having slipoffs slopes. I believe that this greatly changed and more complex pattern was developed after superposition began; that it resulted from jointing and erodibility of the Weber; and that the river's length in what is now the lower section became greater and its gradient smaller.

Seventh step.—Late in the canyon cutting some rejuvenation probably took place. Otherwise, it is difficult to explain how and when the more resistant beds in the lower part of the Morgan were breached and a steeper slope was cut near the river, looking like a "valley-in-valley." This suggested process less satisfactorily explains the steeper banks near the river below "treads" in the slipoff slopes on spurs in the lower section; for those "treads" appear to be related to structure and to harder beds in the Weber.

Effect of Mitten Park and Red Rock faults.—An apparent old high-level channel suggests that in its last few miles the Yampa was once farther north than today; that it joined the Green at the east end of the Mitten Park fault; and that the enlarged Green River flowed westward for more than a mile along that fault until it established its course and was able to leave the fault plane and continue farther west on the upthrow side. If this hypothesis is correct, then because of southward dip and of jointing in the Weber, subsequent erosion of new deeper channels may have formed the elongated canyon of the Green around Steamboat Rock and diverted the lower part of the Yampa to its present junction with the Green.

INTRODUCTION

PURPOSE OF THE REPORT

A detailed office study of modern topographic and geologic maps and aerial photographs of Yampa Canyon and its environs in the Uinta Mountains has brought to my attention some striking features, one of which is very unusual or (so far as I know or can ascertain) even unique. Among the more outstanding features are:

1. A natural division of the 45-mile canyon into three parts—a short upper section, and a middle and a lower section of roughly equal length.
2. A marked change in river pattern from the middle section to the lower section.
3. In the middle section, radical differences in topography and geology on the two sides of the river.
4. Also in the middle section, but only on the north side of the river, several curious scallop-shaped erosion surfaces now partly rimmed by cliffs and with moderately sloping floors; these surfaces, perhaps the most striking feature of the entire canyon, are herein called "meander-migration scars."
5. In the lower section, where the canyon is incised chiefly in the next younger formation, topography different from the two types in the middle section, and (with one significant exception) an absence of the meander-migration scars.
6. The relations (geographic and geologic) between the Yampa River and the Yampa, Red Rock, and Mitten Park faults.

The features observed in this area, apparently not widely known, should be of interest to geologists and geomorphologists, and should offer intriguing problems both in themselves and as clues to further unraveling of the geologic history of the Uinta Mountains and the origin and development of the courses and spectacular canyons of the Yampa and Green Rivers. They are therefore presented, described, and illustrated in this report. The descriptions are followed by suggestions offered in possible explanation of the cause and significance of the major features.

USAGE OF TWO TERMS

The term "meander" is used in this report a little more broadly than is customary. Most writers restrict the term to rather systematic smooth curves or loops of a river whose course may be called serpentine. The somewhat broader application herein is adopted partly for convenience and partly to emphasize the progressive development by which initial irregularities in a river's course tend almost immediately to begin growth, by lateral erosion, into larger and more systematic curves until they fully deserve to be called meanders. This progressive change was particularly well analyzed and described by Davis (1914, p. 4–7), who, however, carefully refrained from indicating the exact point of development at which the initial irregularities (his "bends or turns") become "meanders."

The term "incised" (with its related noun "incision") is herein used with its simple meaning of "cut into." It is intended to be noncommittal as to process of origin, cycle, and shape of cross section (symmetric or asymmetric). The word "incised" and other terms such as "intrenched" (or entrenched), "inclosed," and "ingrown," have been used by numerous writers with either general meaning or varying specialized significance; but as there has been no uniformity or full acceptance they seem confusing rather than helpful.

SOURCES OF INFORMATION

EARLIER INVESTIGATIONS

The geologic history of the Uinta Mountains, the origin of the anomalous courses of Green and Yampa Rivers, and the age relations and significance of the Bishop conglomerate and the Browns Park formation have been subjects for much study and many debates for nearly a hundred years. Among the pioneer students of these problems were J. W. Powell and S. F. Emmons; after the turn of the century, important contributions were made by several geologists, among them J. L. Rich and E. T. Hancock.

My own acquaintance with these problems began in the summers of 1921 and 1922 when I surveyed geology and oil and gas prospects in northwestern Colorado (Sears, 1924b). Interest was intensified and broadened in scope during the second season when, progressing westward, W. H. Bradley, James Gilluly, and I reached the Uinta Mountains and had some opportunity to examine parts of Browns Park, Cold Spring Mountain, and their environs. We realized that our observations and conclusions with regard to the mountain-and-river problems were incomplete, for we could reach only a small fraction of the pertinent region and had to study most of that fraction rather hastily as a sideline to our main assignment. Furthermore, we were handicapped by the lack of satisfactory topographic maps of our area (the one accompanying Powell's classic report on the geology of the eastern portion of the Uinta Mountains, 1876, being quite inadequate for our purpose) and of course the lack of aerial photographs, which would have been invaluable. Nevertheless, our concepts took form and were brought together in a report published 2 years later (Sears, 1924a).

During the subsequent decade Bradley spent three seasons in extending fieldwork westward on the north flank of the Uinta Mountains and far out into the basins to the north and northeast. This additional work enabled him to modify and expand our earlier concepts and to assemble his views in a comprehensive report (Bradley, 1936).

NEWER SOURCES

Since publication of Bradley's report in 1936, much new material bearing directly on the area here discussed has become available. In what was almost wholly an office study, I have derived information particularly from the following sources:

1. Aerial photographs of Dinosaur National Monument, scale 1:31,680; taken chiefly in 1938 for the Soil Conservation Service, U.S. Department of Agriculture.
2. Topographic map of Dinosaur National Monument, Colorado-Utah: U.S. Geol. Survey. Scale 1:62,500; contour interval 50 feet. Surveyed in 1941.
3. Untermann, G. E., and Untermann, B. R., 1954, Geology of Dinosaur National Monument and vicinity, Utah-Colorado: Utah Geol. and Mineralog. Survey Bull. 42.
4. Topographic maps of Hells Canyon and Canyon of Lodore South quadrangles, Colo.: U.S. Geol. Survey, 1954. Scale 1:24,000; contour interval 40 feet.
5. Aerial photographs for the quadrangles named in item 4, scales 1:28,400 and 1:17,000; taken in 1951 for the U.S. Geological Survey.
6. High-altitude aerial photographs of the eastern part of the Uinta Mountains and vicinity; taken in 1953 for the Army Map Service.
7. Topographic map of the Vernal 2-degree quadrangle, Utah-Colorado: Civil edition reprinted by the U.S. Geological Survey from V502 military edition compiled by the Army Map Service in 1955. Scale 1:250,000; contour interval 200 feet.
8. Finally, during a brief reconnaissance of the eastern part of the Uinta Mountains (spring of 1959) in the company of D. M. Kinney and W. R. Hansen of the Geological Survey, J. M. Good of the National Park Service, and Mr. and Mrs. G. E. Untermann of Vernal, Utah, several days spent in the immediate neighborhood of Yampa Canyon.

GEOLOGIC MAP IN PRESENT REPORT

Yampa Canyon and its environs, as discussed in the present report, occupy nearly half of Dinosaur National Monument. Hence the base for the map (pl. 1) of the area is taken from the Geological Survey's topographic map of the Monument, listed above as item 2.

Geologic data—the boundaries of the Weber sandstone and the Morgan formation, the strike-and-dip symbols, and the positions of the Yampa, Red Rock, and Mitten Park faults—are taken wholly from the map forming plate 2 in the report by G. E. and B. R. Untermann listed above as item 3. Though transfer of these data was done as carefully as possible, mechanical difficulties doubtless caused some departures from absolute precision, especially in the true altitude of formation boundaries on steep slopes where contour lines are very crowded. However, I believe that these departures are too slight to cause any injustice to the authors of the original map; certainly they are without significance to the problems herein discussed.

ACKNOWLEDGMENTS

Special obligation and gratitude are felt to Mr. and Mrs. G. Ernest Untermann of Vernal, Utah, for their generous permission to use freely the data in their report on Dinosaur National Monument and for many courtesies and helpful information given later, both in person and through correspondence.

The National Park Service, through Mr. Jess H. Lombard, Superintendent, Dinosaur National Monument, kindly loaned negatives and authorized use of several photographs as illustrations.

Mr. Byrl D. Carey, Jr., and The California Co. furnished valued data on the thickness of the Browns Park formation obtained through drilling.

Dr. Arthur D. Howard, Stanford University, helped me with several discussions on special problems of geomorphology.

To Mr. John M. Good, geologist for the National Park Service, thanks are due for information given by correspondence and during our visit to the Uinta Mountains in the spring of 1959.

Finally, I am grateful to Wilmot H. Bradley, Douglas M. Kinney, and Wallace R. Hansen, of the U.S. Geoogical Survey, who shared with me their knowledge and varied interpretations of Uinta Mountain geology.

OBSERVED FEATURES

The Yampa River, which rises in the Park Range, was described by Hancock (1915, p. 184), who then fully analyzed the development of its middle course across the Axial Basin anticline and Juniper and Cross Mountains by superposition from the Browns Park formation.

The present report deals primarily with that part of the river downstream from Hancock's area.

YAMPA CANYON AS A WHOLE

STATISTICAL DETAILS

Yampa Canyon begins at point A (see pl. 1) where the river, after crossing the low ground at the mouths of the Vale of Tears and of Disappointment Creek, cuts into southeastward-dipping Weber sandstone. This is about 0.7 mile upstream from (southeast of) the point where the river crosses the eastern boundary of Dinosaur National Monument.

The canyon ends at the mouth of Yampa River (point D), where it joins Green River just east of Steamboat Rock.

From the upper end of the canyon to its mouth the airline distance, in a direction N. 78° W., is about 24⅓ miles; but because of the meandering course the distance by river is nearly twice as great, or about 45⅙ miles.[1]

At the upper and lower ends of the canyon (points A and D) the altitudes of the river surface are respectively about 5,589 and 5,064 feet; the river thus falls 525 feet within the canyon, an overall average of more than 11.6 feet per mile.

The maximum depth of canyon noted is about 1,715 feet; this is at a point opposite Warm Springs Draw, 4 miles upstream from Green River, where the Yampa surface is at 5,085 feet and the top of Warm Springs Cliff on the south side (less than 200 yards horizontally away from the river) is at about 6,800 feet.

RELATION TO YAMPA FAULT AND OTHER FAULTS

YAMPA FAULT

Crudely paralleling Yampa Canyon, but south of Yampa River at all points, is the Yampa fault. The Untermanns (1954, p. 151–152) describe it as the largest fault in Dinosaur National Monument, of the normal type with its fault plane dipping to the north at angles of 50° to 75°. They add, "East of Johnson Draw, at the foot of Tanks Peak, Precambrian (Uinta Mountain group) occurs against lower Triassic (Moenkopi), producing a vertical displacement of between 3,600 and 4,000 feet, maximum for faults of the Monument area."

The geographic and geologic relations of the Yampa fault to the ancient and present courses of Yampa River had a significant bearing on the views developed by Bradley, Gilluly, and me, and presented (Sears, 1924a) as a part of our general concept. Those relations, now known with more details and more certainty than in 1922, form an essential base for the hypothesis herein presented.

RED ROCK FAULT

As briefly described by the Untermanns (1954, p. 152), "The Yampa fault has several branches; the largest, which the writers have called the Red Rock fault, begins at Red Rock Draw and runs in a northwesterly direction beyond Pool Creek where it possibly intersects the Mitten Park fault." The downthrow side is to the northeast.

From their map the Red Rock fault has been drawn on plate 1, herewith. Its junction with the main Yampa fault, the repetition of beds that it caused, and

[1] River distances in miles, beginning at the mouth, and altitudes of the river surface are shown on the "Plan and Profile of Yampa River, Colorado," from Green River to Morgan Gulch, 1924, U.S. Geol. Survey.

the steep northeastward dips on both faults, due to drag, are all conspicuous on aerial photographs.

MITTEN PARK FAULT

As mapped by the Untermanns, the Mitten Park fault follows a generally northeastward but curving course. Downthrow is on the southeast side; where the fault crosses Green River downstream from Steamboat Rock, the displacement as estimated by the Untermanns (idem, p. 154) is between 1,500 and 2,000 feet. At the north end of Steamboat Rock the beds on both sides of the fault are greatly steepened by drag. To the east, in the canyon of Green River upstream from its junction with the Yampa, the fault appears to die out sharply and turn into a flexure whose magnitude diminishes eastward.

GRABEN BETWEEN RED ROCK AND MITTEN PARK FAULTS

A glance at plate 1 shows that between the Red Rock and Mitten Park faults is a graben or structurally depressed area with the shape of a westward-pointing triangle. This is perhaps the feature to which Powell (1876, p. 202 and pl. 5) referred as the "Echo Park sag."

This triangular graben is added upon and accentuates the depression effect of the major graben to which Powell (1876, p. 209) called attention with the theory that after Browns Park deposition the eastern end of the Uinta Mountain arch collapsed. Because of the concept that Bradley, Gilluly, and I formed in 1922, the collapse and the major graben were discussed at length and then summarized in the following words (Sears, 1924a, p. 291–303):

"The collapse was caused by a single large fault [the Yampa fault] on the south, by flexures and distributive faulting on the north, by tilting and some faulting on the east, and by tilting on the west."

That Yampa River flows in this major graben, near and roughly parallel to its southern margin, is therefore not a new idea. Because of the later and more detailed mapping by the Untermanns, however, I wish to emphasize that in its lower course Yampa River runs into, and joins Green River within, the added depression or triangular graben between the Red Rock and Mitten Park faults—a complicating problem to be discussed under the last heading of this report.

THREE-PART DIVISION OF CANYON

As mentioned in item 1 of the Introduction, the 45-mile Yampa Canyon is naturally divisible into three parts—a short upper section, and a middle and a lower section of roughly equal length.

It is therefore both logical and convenient to divide the detailed description of the canyon under separate headings for those three sections.

UPPER SECTION OF YAMPA CANYON

The upper section of the canyon, as herein designated, extends from point A (pl. 1), the beginning of Yampa Canyon in sec. 20, T. 6 N., R. 99 W., downstream about 1⅔ miles to point B, just southwest of the high, sharp westward-jutting spur north of the river in the SE. cor. sec. 18, T. 6 N., R. 99 W. Within this section the river's course is rather simple, forming an almost straight line in the upstream half and three small open meanders in the downstream half. In contrast to the longer middle and lower sections of the canyon, this short upper section is noteworthy in that the topography and geology on the two sides of the river are so nearly identical.

Topographically, cross sections of the canyon are almost symmetric; small differences in the angle of slope of the two walls suggest, however, that the meanders may have been slightly enlarged during incision.

Geologically, the upper parts of both walls and the upland behind them expose Weber sandstone, and the lower parts of the walls expose beds of the Morgan formation. (See pl. 1; figs. 1, 2.) As the beds here strike northeastward and dip about 12° SE., the river in its general northwesterly course flows at right angles to the strike and against the dip, cutting stratigraphically down from the top of the Weber into the lower part of the underlying Morgan.

It should be emphasized, however, that structurally the beds exposed in this upper section of the canyon represent only the lower part of a wider zone of southeastward-dipping rocks whose stratigraphic sequence along the river is shown by the Untermanns (1954, pl. 2) to include a dozen formations. At some point in Lily Park (perhaps near the junction of Little Snake River with the Yampa, several miles upstream from and east of Dinosaur National Monu-

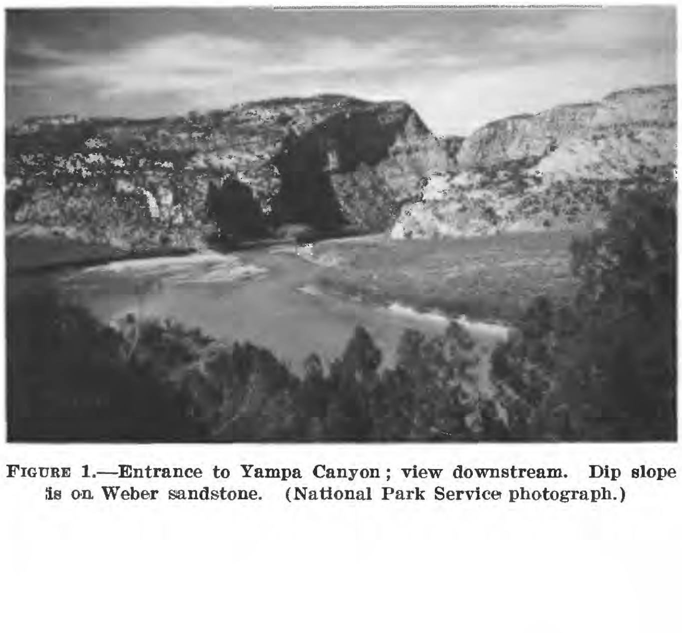

FIGURE 1.—Entrance to Yampa Canyon; view downstream. Dip slope is on Weber sandstone. (National Park Service photograph.)

FIGURE 2.—Upper section of Yampa Canyon; view upstream. Upper part of Morgan formation; probably some Weber sandstone at top in distance. (National Park Service photograph.)

ment and the east edge of the Untermanns' map) the soft lower beds of the mile-thick Mancos shale of Cretaceous age begin the southeastward dip and northwestward rise that here mark the southeast end or nose of the Uinta Mountain arch (Sears, 1924b, pl. 35). From that point the Yampa cuts downward into successively older beds, at last reaching the Weber sandstone and the Morgan formation, whose relative hardness, thickness, and attitude have permitted the erosion of a deep continuous canyon.

MIDDLE SECTION OF YAMPA CANYON

The middle section of the canyon, as herein designated, extends from point B downstream for about 19⅔ miles to point C at the mouth of Big Joe Draw in Starvation Valley. (See pl. 1.) The altitudes of the river surface at points B and C are respectively 5,573 and 5,242 feet; thus in this section the Yampa falls 333 feet, an average of more than 16.9 feet per mile.

In the vicinity of point B, the structure of the rocks in and on both sides of the canyon begins to change in a pronounced manner. From the northeastward strike and southeastward dip that characterize the upper section, the strike swings rather sharply to a direction somewhat north of west (ranging approximately from N. 65° W. to N. 75° W.) and the dip is prevailingly 6° SW. (with an observed range of 3° to 10°). This changed structure, with these strikes and dips, extends westward to and beyond the junction of the Yampa with the Green; southward from Yampa River, generally for 1 to 3 miles, until the Yampa fault is approached; and northward for a number of miles as a part of the south flank of the Uinta Mountain arch.

The north-of-west strike just described is fairly close to the overall direction of flow of Yampa River which, as previously stated, is N. 78° W. for the airline from point A to point D.

RIVER PATTERN AND DIRECTION

Within the middle section the course of the river is marked by large- and medium-sized meanders interspersed with a few almost straight stretches a mile or more in length. With a single exception, all the meanders are of the open type. The exception is the meander in secs. 22 and 27, T. 6 N., R. 100 W., which is convex southward and is about half a mile long and three-tenths of a mile wide; it is of the type called by Davis (1914, p. 23–24) "half-turn." Because this meander and its environs north of the river are exceptional in several other ways as well, they will be mentioned and discussed repeatedly; for brevity, these environs will be referred to in this report as the "half-turn district."

TOPOGRAPHY OF CANYON WALLS

SOUTH WALL

The south wall of Yampa Canyon is very simple and uniform. Except for a few short reentrants where interrupted by side streams, the wall is virtually continuous as a steep slope ending upward in a sheer cliff. The height and width of the south wall in this section average roughly a quarter of a mile each. At places (particularly in sec. 20, T. 6 N., R. 100 W., and in secs. 13, 14, and 15, T. 6 N., R. 101 W.) the cliff at the top is complicated by very small crenulations, but as a whole it is simple. Thus the cliff and slope follow and fit into each curve of the river with noteworthy preciseness.

Almost without a break, the 6,000-foot contour extends along the upper part of the south wall, at varying distances below its top (which ranges in altitude from about 6,300 to about 6,875 feet).

The intersection between the canyon wall and the upland adjoining it is sharp and nearly at right angles, and shows little if any trace of rounding by erosion. Indeed, many knolls and larger hills on the edge of the present upland are partly sheared by the cliff.

NORTH WALL

Except for about 3½ miles along the river in the "half-turn district," the north wall differs radically from the south wall, particularly in being much wider, much less steep, and of very irregular shape. Its width, in contrast to the nearly uniform quarter of a mile for the south wall, averages approximately a mile and ranges from about ¾ to 1½ miles. Only in a general way do the bends of its upper rim correspond to the present curves of the river.

As the greater width, more moderate slope, and irregular shape of the north wall are related to what are herein designated as meander-migration scars, they will be more fully discussed under a heading dealing with those scars (p. I–9).

Another feature of the north wall is of geomorphologic significance. Southward the moderately sloping floors of the scars are terminated by a much steeper slope down to the river, making a convexity upward. This break in slope is conspicuous on the aerial photographs. However, conditions here are somewhat anomalous and puzzling. The photographs show tonal and other differences suggesting that the break in slope is related to some variation in the resistance of rock layers. (The horizon of tonal and presumably lithologic change is discernible also across the river; but the south wall is in general so narrow and steep that at only a few spots is there even a faint trace of any break in slope.) This apparent relation between break of slope and stratigraphic horizon seems to be borne out by two other observations: (a) around each meander the steeper slope looks to be a little wider horizontally and a little higher vertically northward updip; and (b) as a whole the steeper slope is somewhat wider horizontally and higher vertically downstream as the river falls.

The rim or sheer cliff that caps the north wall has some resemblances to and some differences from the one that caps the south wall. Along its top the lowest points, like those on the south wall, are at an altitude of about 6,300 feet. The highest points, however, reach an altitude of about 7,250 feet, as contrasted with a maximum of 6,875 feet on the south. The north rim is less continuous, being interrupted at the north ends of the meander-migration scars (as discussed later). However, where it exists, the north rim resembles the south rim in its sharp angle of intersection with the upland surface behind it, and in its abrupt shearing through knolls and larger hills on that surface.

TOPOGRAPHY OF ADJOINING UPLANDS

SOUTH OF CANYON

The upland south of the middle section of the canyon is rather level and smooth on its eastern half, forming areas called East Cactus Flat and West Cactus Flat.

Farther west, the surface of this upland is much more irregular. Here and there, altitudes are a little higher near the canyon and tend to be somewhat lower within 1 or 2 miles to the south, beyond which they rise fairly steadily to the Yampa fault and Blue Mountain behind it. With this southward rise of the surface, the 7,000-foot contour lies at or south of the Yampa fault as mapped by the Untermanns, except for a stretch of about 1½ miles in secs. 28 and 29, T. 6 N., R. 101 W., north of Tanks Peak. (See pl. 1.) Because this exception, if valid, seems here to present an anomalous relation between structure and topography, the aerial photographs of this vicinity were scrutinized with extra care. These photographs give some indications that a second fault exists here parallel to and about half a mile north of the Yampa fault as mapped; and that it compares and perhaps even connects with the northern of the 2 faults 6 miles farther east.

The irregular topography of the upland between Yampa Canyon and the Yampa fault is accompanied by a no less irregular drainage pattern. Most of the numerous streams (all shown as intermittent) begin on Blue Mountain and extend northward across the Yampa fault for a couple of miles. Thereafter they assemble in a few principal channels which (for no reason obvious on the topographic map, but perhaps related to the jointing in the Weber sandstone) follow pronounced eastward or north-of-westward courses for 2 to 5 miles until a further swing allows them to find their way to the river. To these middle courses are added a few short southward-flowing streams. Especially noteworthy are two that begin at the very edge of the upland above the canyon wall, flow southward and then together eastward until joining the stream in Dry Woman Canyon just before it slips down the steep south wall and into Yampa River.

NORTH OF CANYON

The upland north of the canyon differs topographically from that on the south in several ways. For one thing, it is substantially higher. As already described, the south upland between the canyon and the Yampa fault (with the questionable exception of a small stretch north of Tanks Peak) is lower than 7,000 feet in altitude. In contrast, the 7,000-foot contour line north of the Yampa crudely parallels the river a couple of miles away and also surrounds many headlands and hills in the zone southward to the canyon wall. Still higher land lies to the north, on the flank of Douglas Mountain; a short fragment of the 8,000-foot contour line is seen on the map at the head of Buck Draw, in sec. 16, T. 7 N., R. 101 W.

Between the main 7,000-foot contour and the outliers of that contour around hills and headlands to the south is a zone of somewhat lower altitudes. A number of the longer streams, which prevailingly rise on the high flank of Douglas Mountain and flow southward to the Yampa River, have distinct, short or long, right or left bends in their middle courses where crossing this lower zone, in a manner suggesting stream piracy. The outliers have a general cuesta form; their upper surfaces, eroded into somewhat steplike topography, show southward gentle dip slopes on several beds; whereas their northern, northwestern, and northeastern edges are steep slopes or escarpments cut downward across the dip to the vale (the zone of lower altitudes described above) and face the main 7,000-foot contour to the north, which lies on the southern dip slopes of still older beds. This feature is particularly well shown in the east-west ridge in sec. 11, T. 6 N., R. 100 W.

Still farther north, the older formations below the Morgan are cut by the streams in such a way that they tend to form flatirons dipping gently southward and pointing northward.

GEOLOGY

Perhaps the most conspicuous and hence first-noticed feature shown on the Untermanns' map (1954, pl. 2) is the way in which (within what is here termed "the middle section") the south wall of Yampa Canyon serves as a formation boundary. This feature cannot be fortuitous. Not only is it one of the criteria by which the middle and lower sections of the canyon have been differentiated, but also it is intimately related to the geomorphology of the river.

SOUTH OF RIVER

Except for a very short distance in sec. 27, T. 6 N., R. 100 W., where the top of the south wall of the canyon near the "half-turn" meander is now cut back to the Yampa fault, the upland adjoining the canyon in a belt of varying width is mapped as wholly developed in the Weber sandstone, dipping about 6° a little west of south.

The Untermanns (1954, p. 36) describe the Weber as

> a uniform, well-sorted, buff to white or gray, medium- to fine-grained quartz sandstone. * * * Most of the cementing material is calcareous although it becomes quartzitic locally. * * * The poorly cemented and highly jointed nature of the Weber accelerates its erosion, producing characteristic deep steep-walled gorges and resulting in extremely rough topography.

They add that the thickness of the Weber sandstone in the eastern portion of Dinosaur National Monument is 850 to 900 feet.

The boundary of the Weber with the underlying Morgan formation lies almost continuously high up along the south wall of Yampa Canyon. Because of the steepness or verticality of the upper part of that wall, and because of blurring in black-and-white reproduction of the Untermanns' topographic-geologic map, it was impossible to determine at each point precisely the altitude of the contact or the thickness of Weber sandstone that now remains above that contact at the edge of the upland; fortunately, however, these details are of little if any significance for the problems herein discussed.

From the foregoing description it follows that the lower, major part of the south wall of Yampa Canyon throughout the middle section exposes beds of the next older Morgan formation.

NORTH OF RIVER

The north wall of Yampa Canyon and (again with the exception of the "half-turn district") the belt of upland adjoining it are mapped as wholly developed in the Morgan formation, next older than and dipping under the Weber sandstone south of the river.

According to the Untermanns (1954, p. 33–34):

> The contact between the Weber and Morgan formations was placed at the base of the massive Weber sandstone and at the top of the first limestone bed below it. * * * The sandstone beds in both formations are very similar, consisting of uniform fine-grained quartzitic to calcareous quartz-sandstones. The upper part of the Morgan appears to be transitional into the Weber. The light buff to gray color of the Weber is characteristic of the upper sandstone beds of the Morgan, although both formations contain some red sandstones. * * *
>
> The upper third of the Morgan consists of thin layers of compact, often very cherty, gray limestones which weather red. They alternate with thick fine buff to terra cotta-colored sandstone beds, occasionally somewhat cross-bedded * * * which may exceed 100 feet in thickness.

In their measurements for the Hells Canyon area (a few miles farther west, near the middle of what is herein termed "the lower section of Yampa Canyon") the Untermanns (idem, p. 160–161) give a thickness of approximately 1,200 feet for the Morgan formation.

MEANDER-MIGRATION SCARS

Again with the exception of the "half-turn district," the entire north side of the middle section of Yampa Canyon from point B to point C is made up of adjoining large scallops, each of which is partly rimmed by cliffs or very steep slopes and has a floor that descends with moderate slope nearly to the river.

These scallops are herein referred to as meander-migration scars because they are believed to result from and record the progressive downdip (southward) migration and lowering of early meanders of Yampa River.

The unqualified term "meander scar" has apparently been used but rarely in the literature, and then (whether the meanders are on flood plains or are incised) only with expressed or implied reference to the trace left as an oxbow after a cutoff. (For example, see Thornbury, 1954, p. 130–131.)

Cotton (1949, p. 250) uses the term "meander-scar" as an adjective qualifying alternate terraces developed during side-to-side swinging of a meander belt.

These meanings and applications are mentioned here to emphasize that the term "meander-migration scar" is intended to have a quite different meaning (which, though partly anticipating suggested explanations offered later in this paper, is indicated at this point for convenience).

The cliffs that are so conspicuous on the sides of these scars are now interrupted and absent at their upper or inner (north) ends. I find on aerial photographs and on the topographic map no conclusive evidence as to whether or not the cliffs once were almost continuous. However, I am disposed to think that they were (though probably low at their upper ends); and that later their northern parts were dissected and obliterated by the streams which, rising on the flanks of Douglas Mountain, flowed southward farther and farther to join the migrating river.

As far as I know, these meander-migration scars, all on the north side of Yampa River, have not hitherto been observed or at least have not been mentioned in a published statement. Indeed, rather wide reading, search of maps, and conversations have not brought to my attention any good example of such an extensive feature elsewhere or any clear and specific description of the feature or of the process by which it evolved.

As the meander-migration scars in the middle section of Yampa Canyon differ from each other somewhat in size, shape, and other ways, they are separately but briefly described below.

ANDERSON HOLE SCAR

The Anderson Hole (first) scar begins at point B, which has been selected as marking the boundary between the upper and middle sections of the canyon. On the east the scar adjoins the upland lying north of the upper section, where the beds dip toward the southeast. On the west it adjoins the "half-turn district," where the upland includes a substantial outcrop of Weber sandstone—the only remnant of that formation north of the middle section. This scar, with its rimming cliffs and low inner floor, forms a protected hollow that is known as Anderson Hole.

The conspicuous cliffs that face each other on the east and west sides of the scar are almost 2 miles apart near the river and almost 1½ miles apart at their present north ends. In this instance the south ends of both cliffs are very close to the river. Northward the tops of the cliffs rise in altitude, whereas the cliffs themselves become lower and gradually turn into steep slopes. (The northward-facing steep slopes east of point M and west of point N on plate 1 are believed not to be part of the scar rim described above, but to be a product of the later cuesta development discussed on page I–9.) I picture these rimming cliffs or steep slopes as once extending farther and connecting in a gentle curve that formed the low north rim of the scar, later worn down and obliterated by the streams that now cross its site. (Admittedly, however, the former existence of such north rim, as well as its location, height, and degree of continuity, seem to be questions for deduction and not susceptible of proof. As a collateral question: if such a north rim existed when a meander of the river was at that altitude and position, were there then three tributaries flowing into that meander, and were those tributaries extended as the meander migrated southward down the dip? or did the tributaries begin at some later stage? I would lean to the first alternative.)

The floor of the scar, between the east and west cliffs and the hypothetical north rim, now has considerable relief through dissection by present streams, but overall it has a moderate slope southward nearly to the river, dropping some 1,100 feet in about 1½ miles. An interesting feature, discernible on the topographic map but more conspicuous on aerial photographs, is a low concentric supplementary rim and part of a second, in the middle of the scar. Only partial traces of similar supplementary rims are detectable in any of the other scars.

TEPEE HOLE SCAR

The Tepee Hole (second) scar, whose floor forms what is called Tepee Hole, is sufficiently like the Anderson Hole scar that most of the same description would apply. The chief differences are as follows: (a) The east cliff (rather than the west) adjoins the "half-turn district"; and the south end of this east cliff is close to the river. (b) The south end of the west cliff is nearly half a mile from the river. (c) Between the west cliff of the Tepee Hole scar and the east cliff of the Browns Hole scar is an upland that terminates in a spectacular southward-pointing sharpened spur. (See fig. 3.) (d) The position of the hypothetical north rim is less clear than that in the Anderson Hole scar; for it depends on whether

FIGURE 3.—Sharpened spur between Tepee Hole (second) and Browns Hole (third) scars. View northward across canyon. West Cactus Flat and Haystack Rock in foreground.

the east cliff should be considered to reach point Q (pl. 1) or whether the part northeast of point P is instead the product of, or has been modified by, the later cuesta development discussed on page I–9.

BROWNS HOLE SCAR

Browns Hole is the name given to the sloping floor of the third scar. In many ways this scar resembles the two farther up the river, but it differs from them in other ways that are of interest and significance. For one thing, in horizontal plan the scallop is much shallower—that is, its north-south distance is much shorter than that from east to west. Even more significant, its rimming cliff is much more continuous and complete, being broken only at its northern curve by the gorge (about 1,500 feet wide) through which flows this stream that drains Browns Draw and on its northwest side by an even narrower gorge through which flows the unnamed stream, one of whose upper branches drains Iron Mine Basin. The greater continuity and the curve of this cliff seem to me to illustrate and support the concept, discussed above, that the Anderson Hole and Tepee Hole scars also once had north rims.

The stream that cuts through the cliff on the northwest side is itself unusual; for of all the streams that interrupt the side cliffs in all five scars, it is the only one that flows for any considerable distance on the upland before reaching the cliff. However, its unusual length was perhaps not original but caused by piracy; this is suggested by the sharp bend of the stream (elbow of capture?) about 1 mile northwest of the gorge and by the lowness of the divide between that bend and the west fork of Browns Draw.

BOWER DRAW SCAR

The Bower Draw (fourth) scar (which may be identified by the name of the principal channel, Bower Draw, that crosses it) is much less distinct. Indeed, its size and shape are such that its nature might have gone unsuspected had not the other scars been noticed and analyzed. Perhaps it might more logically be divided into 3 merging scars—2 short and very shallow ones at the east and a larger one up Bower Draw at the west; but this would seem to be an undesirable complication. The general continuity of its cliff, the moderate slope of its floor toward the river, and the approximate accordance of its cliff pattern with the present curves of the river—all together appear to me to be ample evidence that it too was formed by the lateral downdip migration of meanders. I think that the difference was caused by the greater straightness and lack of large meanders in the early as well as the present course of the river through most of this stretch.

FIVE SPRINGS DRAW SCAR

The Five Springs Draw (fifth) scar (identifiable by Five Springs Draw, which crosses it) is the last scar in this section of the canyon. The southwest end of its northwest cliff is close to the river near point C, which has been selected as marking the boundary between the middle and lower sections of the canyon.

The Five Springs Draw scar is much like the Anderson Hole and the Tepee Hole scars, and therefore will not be described in detail. However, it may be well to emphasize that the aerial photographs of the Five Springs Draw scar as well as those of the Bower Draw scar show clearly the break in slope and upward convexity near the river, as discussed on page I–8 under "North wall."

"HALF-TURN DISTRICT"—AN EXCEPTION

At several places, mention has been made of ways in which the "half-turn district" differs sharply from the rest of the north side of the middle section. As these differences are thought to be very significant, for convenience they are assembled and repeated here in a single place, as follows: (a) The "half-turn" meander contrasts with the "open" type of meander and the almost straight stretches seen elsewhere throughout the middle section. Furthermore, at the "half-turn" meander the narrow upland spur projecting into it shows clearly a slipoff slope at its south end and on its west (downstream) side. (b) Around the "half-turn" meander, and upstream and downstream from it, for a total river distance of about 3½ miles, the north wall of the canyon is very narrow and steep. (c) The "half-turn district" forms the only interruption to an otherwise continuous series of adjoining scallops (meander-migration scars) on the north side of the river. (d) The upland in the "half-turn district" includes a substantial outcrop of Weber sandstone—the only remnant of that formation north of the river in the middle section.

Taken together, these marked differences cannot plausibly be explained as due to coincidence. The "half-turn district" not only is exceptional in the middle section; it also shows conditions closely resembling those predominant in the lower section of the canyon, to which it is presumably related. Hence the lower section will next be described, before the "half-turn district" is further discussed.

LOWER SECTION OF YAMPA CANYON

As herein designated, the lower section of the canyon extends from point C (pl. 1), at the mouth of Big Joe Draw and of Starvation Valley, downstream for about 23⅝ miles to point D, where the Yampa joins the Green east of Steamboat Rock.

The river surface has an altitude of 5,240 feet at point C and of 5,064 feet at point D. Thus in the lower section the river falls 176 feet, an average of nearly 7.4 feet per mile, which is less than half of the gradient of 16.9 feet per mile in the middle section.

As previously stated, the lower section differs markedly from the middle section in a number of ways, which will be discussed in detail in the pages that follow.

RIVER PATTERN AND DIRECTION

It will be recalled that in the middle section, except within the "half-turn district," Yampa River follows a course of open meanders interspersed with a few almost straight stretches. The average direction of that part of the river is N. 82° W., which is close to the regional strike of the rocks.

The lower section of the canyon differs notably from the middle section in its river pattern. First, near point C the river turns in a general southwesterly direction to the lower end of Bull Park (an airline distance of about 2½ miles), before resuming its overall northwestward course to its junction with Green River at point D (pl. 1). Second, and more striking, the river's course is much more intricate and meandering; upland spurs alternate on the two sides of the river, and many of the meanders are so curved and interlocking as to be of the type called by Davis (1914, p. 23–24) "dove-tail."

TOPOGRAPHY OF CANYON WALLS

In a general way the two walls of the canyon in the lower section resemble each other. But during their incision the meanders were not cut straight downward, for most cross sections of the canyon are asymmetric. Evidently lateral erosion and lateral movement of meanders have taken place, for in general the projecting ends and downstream sides of the spurs show slipoff slopes, whereas the upstream sides of the spurs and the walls on the outer side of meander curves show very steep slopes or even undercut and overhanging cliffs. (See figs. 4, 5.) Furthermore, meanders have become much more rounded during incision. However, the meander belt is still quite narrow and curving, the slipoff slopes occupy only parts of their respective spurs, and the bottom of the canyon is still very narrow and without conspicuous flood-plain scrolls.

On a number of the interlocking spurs (such as the eight small spurs just downstream from Harding Hole and the several spurs just upstream from Warm Springs) the slipoff slopes are seen on the aerial photographs to be interrupted part way down by crude "treads" of somewhat less slope.

The so-called parks and holes (Bull, Harding, Burro, and Castle) in this section of the canyon are merely small, mostly steep floored, open spaces near the river, and are not comparable to Anderson, Tepee, and Browns Holes in the first, second, and third meander-migration scars of the middle section.

The depth of the canyon in the lower section, as measured from the river surface to the top of the cliff on the south side, differs through a wide range. As already described, the greatest depth observed is

FIGURE 4.—"Tiger Wall," an overhanging cliff of Weber sandstone in lower section of Yampa Canyon. (National Park Service photograph.)

FIGURE 5.—Lower section of Yampa Canyon. Intricate meanders in Weber sandstone. View northward near Harding Hole. (National Park Service photograph.)

about 1,715 feet, at Warm Springs Cliff, 4 miles upstream from Green River. This cliff appears to expose the upper two-thirds of the Morgan formation, the full thickness of the Weber sandstone, and a few feet of the Park City formation that caps it. The least depth noted (excluding the small reentrants at the mouths of side streams) is 235 feet near the west end of Castle Park. Here, because of the southwestward dip of the beds and the large southward meander of the river, the south wall exposes only the upper part of the Weber sandstone just below its top.

TOPOGRAPHY OF ADJOINING UPLANDS

SOUTH OF CANYON

The small area of upland from Schoonover Pasture across Johnson Canyon to East and West Serviceberry Draws is merely the western tip of the upland south of the middle section of the canyon, the topography of which has already been fully described.

The upland west and northwest of East and West Serviceberry Draws has its own characteristic topography. In general the upper beds of the Weber sandstone are exposed only in a narrow, irregular belt at the edge of the upland along the canyon; this belt is augmented here and there by exposures of the Weber up the side streams. Much of the upland is veneered by the overlying Park City formation, which at a number of places approaches, or even is the very top of, the canyon wall and extends southward and southwestward for distances up to a couple of miles. The Park City forms a resistant dip slope, the surface of which is rather smooth but, especially toward the west, is marked by a great number of very shallow channels and a few slightly larger ones draining southwestward down the dip. At or near the bottom of this dip slope these channels gather into larger channels extending northwestward or southeastward approximately along the boundary between the Park City and the next younger Moenkopi formation. In turn these larger channels empty into the few major streams (in Hells, Red Rock, and Sand Canyons) that succeed in flowing against the dip and joining Yampa River. (This topography and stream pattern are well shown on the topographic map and even better on the aerial photographs for the upland on the two sides of Sand Canyon.) It is interesting to note that between the combined Serviceberry Draw and point D, a river distance of nearly 20 miles, only 7 streams enter the south side of the Yampa—the 3 named above, and 4 others too small to be named on the topographic map.

NORTH OF CANYON

Beginning near the river about half a mile downstream from point C, a high ridge extends northwestward to the east edge of the Warm Springs (sixth) scar, approximately parallel to and about half a mile southwest of Starvation Valley and the upper part of Warm Springs Draw. For most of its length the top of this ridge is higher than 7,000 feet; the highest point noted is marked "7365" on the topographic map. West of the Warm Springs scar the ridge resumes (though with a maximum altitude marked "6962") and extends westward for 1 mile to the edge of Lodore Canyon of Green River.

This ridge serves as a drainage divide, for it is not crossed by any of the streams that come from the high country still farther north. On the contrary, all those streams are deflected southeastward or northwestward along its northeastern base and together find a passage to Yampa River or the Green, or join Warm Springs and Iron Mine Draws, which extend down the Warm Springs scar.

The many streams that originate on the southwestern flank of the ridge extend southward and southwestward, down the dip, across a belt which, because of the river's sinuous course, ranges in width from ½ to 3 miles. The topography in this belt has been justifiably called by the Untermanns and others "fantastic." (See fig. 5.) Erosion in the poorly cemented and highly jointed Weber sandstone has produced a bewildering maze of sharp, narrow gorges. Most of these gorges begin at the ridge in deep, rounded or pointed amphitheaters; descend steeply, at places over hard ledges; and some finally drop abruptly to the river over dry "waterfalls" many feet in height.

A few patches of the thin overlying Park City formation are found at high spots on the ridge and in the belt south of it.

From its beginning near the river, northwestward for a distance of about 2 miles, the ridge is generally sharp crested and its northeastern flank is conspicuously crenulated. Farther northwest, the northeastern flank is much smoother.

The boundary between the Weber sandstone and the underlying Morgan formation follows very closely the base of the northeastern flank of the ridge and the adjoining southeastward- and northwestward-flowing streams described above.

Still farther away from Yampa River, in the Morgan and older formations, the topography is similar to that in the lower part of the Morgan and beds below it north of the middle section of the canyon, with many flatirons rising and pointing toward the north.

GEOLOGY

The most conspicuous and significant difference in geology between the middle and lower sections of Yampa Canyon is that, whereas in the middle section the boundary between the Weber sandstone and the underlying Morgan formation lies almost continuously high up along the south wall of the canyon, in the lower section that boundary lies predominantly at a substantial distance north of the river.

As already described, near point C Yampa River turns in an overall southwesterly direction to Bull Park, several miles away. This direction is down the dip, but as the gradient of the river is much less than the angle (6°) of dip, the amount of the Morgan formation exposed in the canyon dwindles rapidly downstream and ceases just below the mouth of Johnson Canyon. If this dwindling wedge of exposed beds of the Morgan is ignored, we may consider that near point C the Weber-Morgan boundary crosses from the south wall to the north side of Yampa River. Thence it extends northwestward up the floor of Starvation Valley and on to Lodore Canyon of Green River in a general course that is interrupted only at the Warm Springs scar, where the Morgan formation is again exposed southward to Yampa River.

Stated in a more summary way: the middle section of Yampa Canyon is eroded chiefly in the Morgan formation; the lower section, chiefly in the Weber sandstone.

Brief descriptions of the Weber and the Morgan, quoted from the Untermanns' report, are given on page I–9. It seems desirable to add here only the comment that on aerial photographs the jointing in the Weber sandstone, with a principal direction essentially that of the strike, is generally much more conspicuous in the lower section than in the middle and upper sections of the canyon.

As already indicated, a veneer of the thin Park City formation, lying above the Weber sandstone, holds up a fairly extensive dip slope south of the river and remains in a few patches north of the river in the lower section. According to the Untermanns (1954, p. 38), the Park City consists of "light gray to yellow, frequently silty or cherty, calcareous shale * * *. Gray thinly bedded cherty fossiliferous limestone and calcareous sandstone occur in the lower portion * * *. [In] the vicinity of Dinosaur National Monument headquarters, [the Park City] is only about 50 feet thick."

WARM SPRINGS SCAR—AN EXCEPTION

Just as the "half-turn district" is an exception to the topographic and geologic conditions that prevail in the middle section of Yampa Canyon, so the Warm Springs scar (see fig. 6) is an exception to the topographic and geologic conditions that predominate in the lower section.

The Warm Springs scar also is on the north side of the river. In size, shape, and degree of preservation, it somewhat more closely resembles the first and second scars than the other three. However, its southward-sloping floor is smoother, and the two streams that flow down it to the river—in Iron Mines and Warm Springs Draws—run in very shallow channels.

Like the five scars in the middle section, the Warm Springs scar is eroded in the Morgan formation, which it exposes southward to the river (and, still farther downdip, in the bottom of the canyon for several miles both upstream and downstream). Perhaps the most noteworthy difference between this scar and the other five is that both the east and west rims of the Warm Springs scar, in their southern half, include a substantial thickness of Weber sandstone above the Morgan formation.

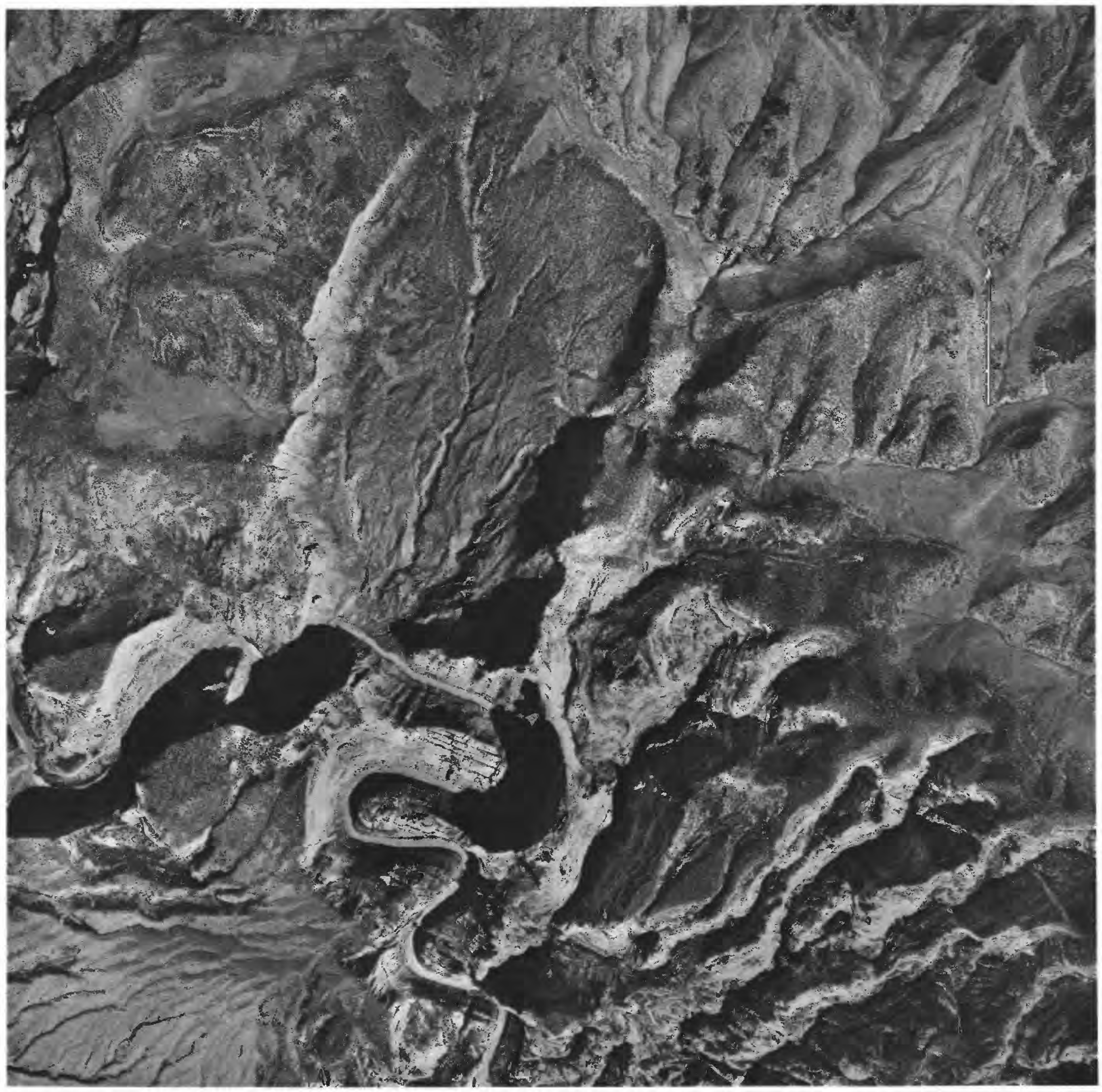

FIGURE 6.—Warm Springs (sixth) scar on north side of lower section of Yampa Canyon. (Aerial photograph for Soil Conserv. Service, U.S. Dept. Agriculture, by Fairchild Aerial Surveys, Inc., 1938.)

SUGGESTED EXPLANATION OF THE FEATURES

CONCEPTS OF 1922–23

As the result of fieldwork in 1922 and of office research and discussions during the following winter, W. H. Bradley, James Gilluly, and I reached certain concepts about the origin and development of the Yampa and Green Rivers in their anomalous course and spectacular canyons (Sears, 1924a).

In our reading we had found particular significance in Powell's conclusion (1876, p. 201, 209) that [chiefly] after the deposition of the Browns Park beds the eastern part of the Uinta Mountain arch collapsed to form a great graben; and in Hancock's summation (1915) of earlier conflicting views and of his reasons for believing that the middle part of Yampa River had established its course by superposition from the Browns Park formation.

Inasmuch as my present suggestions to explain the features of Yampa Canyon in the Uinta Mountains are basically in accord with our concept of 1922–23 about Yampa River, for convenience the pertinent parts of our "Summary of geologic history" (Sears, 1924a, p. 301–304) are quoted in the next five paragraphs.

* * * At some time after the close of Eocene deposition the Uinta Mountain arch was further uplifted. * * * the axis of the Uinta Mountain arch was continued far southeastward as the Axial Basin anticline. * * * At this time or possibly a little later the Axial Basin anticline was further deformed by the sharp domes of Cross and Juniper Mountains.

A long period of quiescence followed, during which the eastern Uinta region was eroded to mature topography. Mountains and ridges were comparatively low and the total relief probably did not exceed 3,000 feet. Strata on the southern flank of the Uinta Mountain arch were beveled * * *.

Climatic changes or, more probably, regional uplift caused a rejuvenation of the streams, which began a vigorous attack on the red quartzite core of the Uintas. * * * There resulted a great outpouring of red quartzite boulders, which were laid down as conglomerate eastward to Little Snake River * * *. On the south flank of the arch the hollows were filled and the beveled surfaces were partly covered. As time went on, streams lost some of their carrying power and brought white sand derived from the quartzite. Browns Park became filled with a great thickness of this sand, which spread up the valley by headward overlap beyond the earlier deposits of conglomerate. Overlap also gradually covered the slopes of the hills and mountains eastward to and including Cross and Juniper Mountains, until in all the eastern part of the Uinta Range only the highest remnants of the older rocks protruded above the cover of white sand.

* * * In Browns Park time, * * * tilting on the south side of Cold Spring Mountain served as the forerunner of a new type of movement, and after deposition was complete the eastern end of the Uinta Mountain arch collapsed, forming a great graben. The collapse was caused by a single large fault on the south [the Yampa fault], by flexures and distributive faulting on the north, by tilting and some faulting on the east, and by tilting on the west. Along the margins of the graben the Browns Park formation was given an inward dip by upward drag on the faults. As far east as Cedar Mountain, the Browns Park formation was tilted westward toward the drag syncline which lies just north of the Yampa fault. Guided by this sloping surface and this syncline, the drainage of the Axial Basin anticline naturally formed a westward-flowing major stream—Yampa River. Its course over the covered portions of Cross and Juniper Mountains was accidental.

* * * * *

With the courses of the rivers once firmly established in the Browns Park beds, only time was needed to lower their channels and carve out their wonderful canyons.

Although it relates to an area east of the Uinta Mountains and does not have an immediate bearing on the origin of Yampa Canyon, a part of one assertion quoted above now seems to me incorrect: "*As far east as Cedar Mountain*, the Browns Park formation was tilted westward * * *." In 1923, no deposits specifically identified as belonging to the Browns Park formation were known east of Cedar Mountain or to the north and south of the area affected by the graben movement. Despite a marked change in the lithology of the basal conglomerate of the Browns Park formation east of Little Snake River (Sears, 1924b, p. 295), the generally uniform nature of the main sandstone body and the continuity of outcrops led us to infer that the whole formation had been derived from the Uinta Mountains (except the tuffaceous component, which came from unknown volcanic vents elsewhere) and that it had reached Cedar Mountain down eastward-flowing drainage. As the lowest part of the Browns Park formation is now at an altitude roughly a thousand feet higher at Cedar Mountain than at the junction of the Little Snake and Yampa Rivers, a later reversal of the slope by westward tilting seemed a logical view. Since then, however, the Browns Park formation has been mapped at many places to the north and much farther northeastward, beyond Saratoga, Wyo., crossing the Continental Divide at present altitudes of more than 8,000 feet. If that identification is correct, much of the Browns Park formation probably had its source in and near the present Continental Divide; and a part of its material was moved southwestward past Cedar Mountain until, in a zone somewhere near the Little Snake River, it met and mingled with the part of the Browns Park formation derived from the Uinta Mountains. On that basis I am now inclined to postulate: (a) that when the upper part of Yampa River established its course on the Browns Park formation it flowed on a surface already sloping to the southwest; (b) that the graben effect near and southwest of Cedar Mountain, although enough to cause the Browns Park formation to have a general synclinal attitude above the Axial Basin anticline, was weaker than farther west; and (c) that only westward from the approximate vicinity of Cross Mountain where the graben movement was more pronounced, "the Browns Park formation was tilted westward toward the drag syncline which lies just north of the Yampa fault."

ORIGINAL EXTENT AND THICKNESS OF BROWNS PARK FORMATION

Our concept of 1922–23 and mine of today both require that at one time the site of the present Yampa Canyon (including its meander-migration scars) was buried at an unknown altitude and to an unknown thickness by deposits of the Browns Park formation.

Until discoveries by the Untermanns in the late summer of 1959, this picture of former presence and burial had been only a deduction. Before then, so far as I am aware, no Browns Park material was known within this specific area. During our reconnaissance in the spring of 1959 (see p. I–4) a day's careful but unsuccessful search was made on West and East Cactus Flats on the south side of the river, where possible remnants had been suspected from aerial photographs. Nevertheless, I felt confident that Browns Park material once covered this specific area. Such former cover seemed a necessary factor in a logical explanation of the course of the river and the evolution of its canyon. Other reasons, based on observations in surrounding areas, pointed more concretely to the former extension and presence of Browns Park deposits in the area here discussed.

Corroborating evidence from the Untermanns (written communication, Sept. 21, 1959) of the presence of Browns Park in this area was most welcome. During a further visit they discovered at four places within the graben, between Yampa River and the main Yampa fault, substantial outcrops of material of Browns Park lithology like that which we had seen at many places nearby during our reconnaissance in the spring of 1959.

AREA OF MAXIMUM THICKNESS

In 1922 we felt that the Browns Park formation in and near the Uinta Mountains had its maximum original thickness approximately in the area comprising the southeastern half of Browns Park (beginning near the junction of Vermilion Creek with Green River) and its extension southeastward to Little Snake River. Although not fully proved, that feeling has been strengthened by later evidence. The old and the newer data bearing on the place of greatest original thickness include the following points:

1. Southeast of Vermilion Creek in T. 9 N., R. 101 W., we calculated that about 1,200 feet of the Browns Park formation now remains, including several hundred feet of basal conglomerate mostly of red quartzite boulders.
2. Carey (1955, p. 48) later mentioned our figure, but added: "* * * a thickness in excess of this estimate has been penetrated in drilling within the Uinta Mountain graben. The estimate by Powell (1876, p. 40) of 1,800 feet for the total thickness of the formation appears to be fairly representative for northwestern Colorado." I have since learned from The California Company (written communication, March 1959) that the drilling mentioned by Carey referred to a hole in the northeastern part of T. 8 N., R. 100 W., which passed through about 1,550 feet of the Browns Park formation, including its basal conglomerate.
3. The present altitude of the lowest beds of the Browns Park formation exposed at river level along Green River at the mouth of Vermilion Creek is about 5,350 feet. For some 20 miles southeastward from that point the present surface of the formation rises to the drainage divide between the Green and Little Snake Rivers. The present divide is at an average altitude of about 6,680 feet; but this divide and the surface of the Browns Park formation that holds it up rise southwestward to the contact (and apparent overlap) of that formation against the Uinta Mountain group in Douglas Mountain (about 2½ miles east of Smelter Ranch) where the present altitude is more than 7,000 feet (see fig. 7). If small structural irregularities and possible faults in the Browns Park formation between the southwest end of this divide and Green River are ignored and essential horizontality of bedding is assumed—an assumption that appears fairly reasonable—then the difference in present altitudes points to a maximum thickness of some 1,700 feet for the Browns Park formation now remaining.

BROWNS PARK FORMATION IN LILY PARK

The continuous exposures of the Browns Park, described above, extend across Little Snake River and far to the east nearly to Craig. They also wrap around Lone Mountain and, west of the Little Snake, extend southward in Lily Park to the SE. cor. sec. 13, T. 6 N., R. 99 W., within a mile of Yampa River (see fig. 7). The latter extension of Browns Park material (with a 100-foot basal conglomerate of gray limestone and reddish quartzite fragments lying on the truncated edges of older beds) rises westward high up the southeastward-dipping nose of the Uinta Mountain arch, reaching a present altitude of more than 7,000 feet at a point northeast of the upper part of Sawmill Canyon.

POSSIBLE BROWNS PARK MATERIAL ON DOUGLAS MOUNTAIN

As the divides between the northward- and southeastward-flowing streams on the eastern part of Douglas Mountain stand at present altitudes of less than 7,200 feet (some less than 7,000 feet), the Browns Park formation is envisioned as formerly continuous across the lower parts of Douglas Mountain, even though higher hills and interstream ridges remained unburied.

This picture is supported by our unmapped observations in the spring of 1959 (see p. I–4) that at several

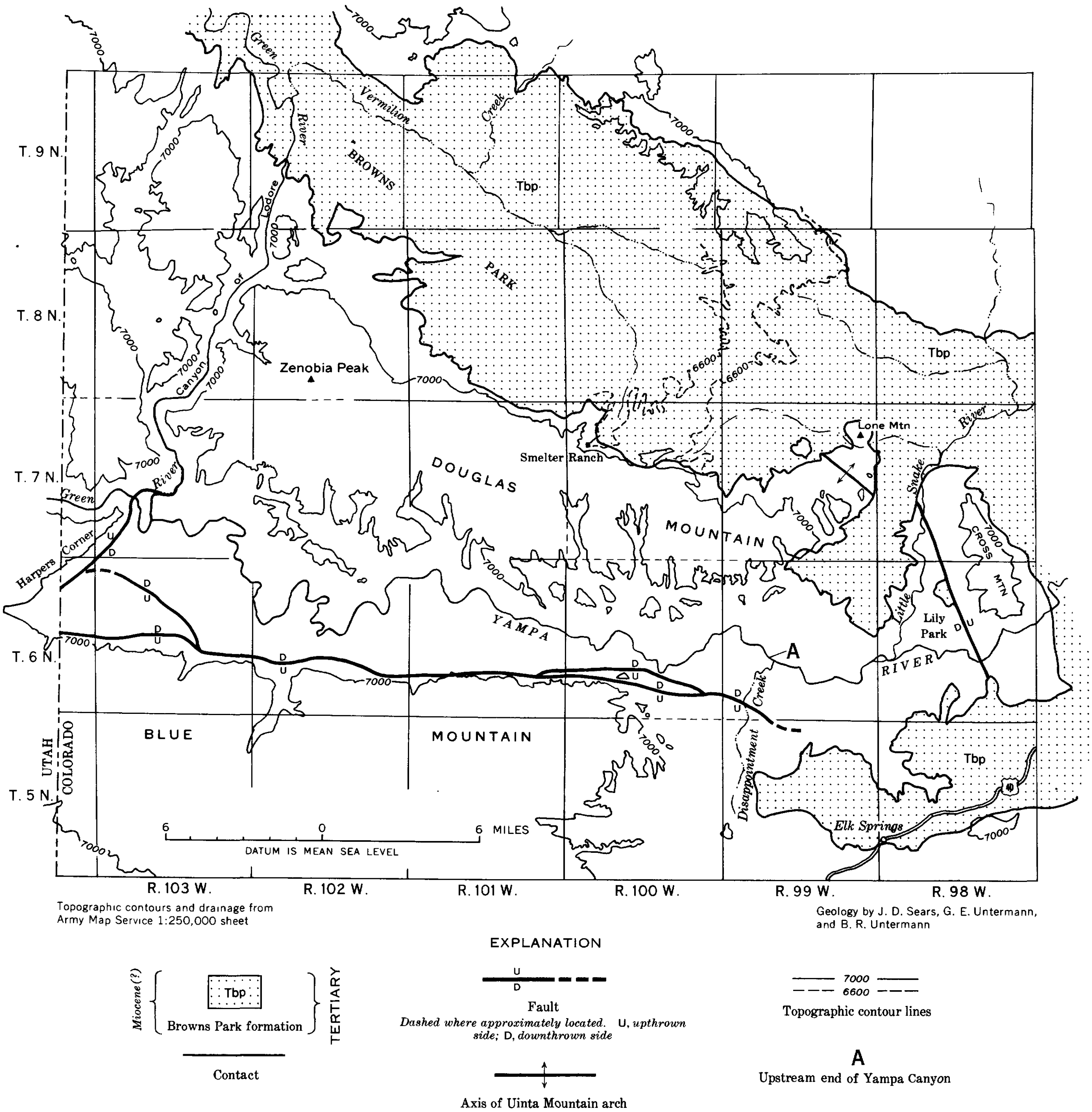

Figure 7.—Map of the eastern Uinta Mountains and vicinity, showing part of the Browns Park formation.

places along drainage lines high on Douglas Mountain outcrops of white tuffaceous sandstone lithologically resembled the identified Browns Park.

BROWNS PARK FORMATION NEAR ELK SPRINGS

The Browns Park formation, continuously exposed from Little Snake River toward Craig, also extends southward across Yampa River upstream from Cross Mountain, thence southward and westward around that mountain, and toward the upper part of Disappointment Creek. (See fig. 7.) Near Elk Springs the outcrops near their southern edge show the topographic and structural form of a partial shallow bowl, sloping northward; and the basal conglomerate, here largely composed of gray limestone boulders, makes a low but fairly conspicuous ridge. (This bowl-shaped structure is interpreted as being caused by a northward sinking into the graben, which, however, is much less pronounced here than farther west because the Yampa fault, near Disappointment Creek, turns into a flexure decreasing in magnitude southeastward.) From Elk Springs the formation continues westward, but less and less of the upper sandstone is preserved; finally, as Disappointment Creek is approached, only the basal conglomerate remains as a capping of isolated hills.

NEARNESS OF BROWNS PARK FORMATION TO EAST END OF YAMPA CANYON

Special attention is here called to the fact that, if a straight line is drawn between the westernmost ends of the mapped outcrops of known Browns Park formation in Ts. 5 and 6 N., R. 99 W., on the two sides of the river, that line will cross Yampa River just a short distance above point A, where the canyon begins. Thus, known Browns Park deposits are preserved next to, and point toward, "the site of the present Yampa Canyon" as herein defined.

POSSIBLE BROWNS PARK MATERIAL ON BLUE MOUNTAIN

Farther southwest (and farther away from the Yampa fault and the river) at several low places in the eastern part of Blue Mountain we found, in the spring of 1959, outcrops of white tuffaceous sandstone, which, like the outcrops on Douglas Mountain, closely resemble the material in the Browns Park formation.

POSSIBLE BROWNS PARK MATERIAL ON HARPERS CORNER

In discussing the Bishop conglomerate, Powell (1876, p. 169–170) stated: "On the south side of the Uinta Mountains a fragment is found west of Echo Park resting on Carboniferous beds." This outcrop of conglomerate was also shown on Powell's geologic map; its areal extent was exaggerated in a northwest-southeast direction, but its location was unquestionably the northeastern, narrow part of the ridge now known as Harpers Corner. In the autumn of 1958 I was told indirectly that John M. Good, geologist for the National Park Service, reported material similar to the Browns Park on Harpers Corner at a present altitude of more than 7,000 feet. During our reconnaissance in the spring of 1959 (see p. I–4) the six of us spent half a day examining the Harpers Corner ridge. For at least 1 mile at its northeastern end the narrow crest of the ridge is strewn with rounded cobbles and subangular fragments mostly of reddish quartzite. Toward the southwest, where the ridge widens, the conglomerate becomes prevailingly of gray limestone cobbles. This seems to pass southwestward under grayish-white tuffaceous sandstone, in part bedded. This sandstone, apparently on the upthrown northwest side of the Mitten Park fault, was seen at a present altitude of about 7,550 feet (according to Good) near the junction of the Harpers Corner and Iron Springs roads in the NW. cor. sec. 15, T. 4 S., R. 25 E. In lithologic appearance it is like much of the type-area Browns Park material; we agreed that in all probability it is part of the Browns Park formation and that the conglomerate is its basal conglomerate—such as is seen, for example, near Vermilion Creek.

POSSIBLE BROWNS PARK MATERIAL WEST OF LODORE CANYON

The Untermanns (1954, p. 180) record the following occurrences:

> The writers have observed a small deposit of white chalky sandstone resembling the Browns Park formation on Diamond Mountain, south of the Pot Creek area and west of Lodore Canyon, in the vicinity of Diamond Springs, at an elevation of 7500 feet. In addition to this exposure, other remnants lithologically similar to the Browns Park have been observed along Pot Creek and on Wild Mountain by J. L. Kay (personal communication). These deposits have not been carefully studied and their significance is not yet fully understood.

In a statement which includes references to the aforesaid occurrences or to others apparently similar nearby, Kinney (1955, p. 115–116) independently wrote:

> On Pole Mountain, Mosby Mountain, and Lake Mountain, the lower bed of the Bishop is a characteristic basal conglomerate, 25 to 40 feet thick, composed of well-rounded boulders of limestone, chert, and sandstone in a matrix of medium- to coarse-grained sand. Overlying this basal conglomerate is a chalky-white tuffaceous sandstone, 25 to 100 feet thick, which, in turn is overlain by light-tan to buff conglomerate with a sand matrix. * * * in the escarpment formed by equivalent beds on Diamond Mountain, the conglomerate appears as streaks or thin beds, and medium-grained, partly tuffaceous, light-gray sandstone comprises most of the formation. * * * As mapped along the south flank of the Uinta Mountains, the Bishop conglomerate grades eastward from very coarse-grained quartzitic conglomerate to medium-grained tuffaceous sandstone with lenses and thin beds of boulders. At intermediate positions, and near the base of the formation, beds of chalky-white tuffaceous sandstone are found interbedded with conglomerate, thus suggesting an interfingering of facies. The tuffaceous sandstone superficially resembles the Browns Park formation of northwestern Colorado.

These occurrences, with a basal conglomerate (heretofore identified as Bishop) intertongued with or overlain by grayish-white sandstone, in part tuffaceous, seem quite like the already described deposits on Harpers Corner.

In view of these outcrops described by the Untermanns and Kinney, we spent several days in June 1959 in reconnaissance of numerous drainage courses high in the Uintas, from the vicinity of Lodore Canyon westward for more than 25 miles. At many places we noted, but did not map, exposures of a grayish-white sandstone that is partly tuffaceous, resembles lithologically the sands of the Browns Park formation, and occurs under conditions like those of the similar outcrops observed previously on Douglas Mountain.

SUMMARY

As thus outlined, the area of the present Yampa Canyon is immediately adjoined at its east end, on both sides of the river, by parts of the continuous, mapped Browns Park formation and is virtually surrounded elsewhere by patches of material that, because of its lithologic character, may well belong to that formation.

These observed conditions were felt to warrant the deduction that "at one time the site of the present Yampa Canyon * * * was buried at an unknown altitude and to an unknown thickness by deposits of the Browns Park formation." Inasmuch as the Untermanns have now found material similar to the Browns Park at four places between Yampa River and the main Yampa fault, this view will be assumed correct, as a basic factor in the hypothesis of canyon development that follows.

POSSIBLE DEVELOPMENT OF THE CANYON—A CHRONOLOGICAL OUTLINE

Thus far this report has consisted chiefly of descriptions of the features observed in and near Yampa Canyon. Possible explanations of some of the features have been given or implied. There remains to be offered a more orderly chronologic outline of the processes and events by which the canyon may have originated and developed to its present form. Dating by periods and epochs is recognized as only approximate; the sequence and nature of events are regarded as of more significance in this study. A number of the suggestions are not susceptible of proof; and some of them may not be acceptable to all. Certainly the suggestions are made with varying degrees of conviction. Some of the problems remain problems, and possible explanations are offered only tentatively.

FIRST STEP

Major uplift of the Uinta Mountain arch as a part of the Laramide orogeny had been followed during the Eocene by extensive erosion of the mountains, and by deposition of much of the resulting material in the Uinta and Green River Basins to the south and north and also lapping around the eastern end of the arch over the site of the later Axial Basin anticline. Concurrently, there had been repeated but presumably small further uplifts of the main arch, for the mountainward edges of the formations of Eocene age in the basins show varying amounts of tilting and overlap as well as local deposits of coarser material.

In late Eocene or early Oligocene time, possibly after an interval of quiescence, uplift was renewed—this time extending far southeastward, so as to cause arching of the Axial Basin anticline and, then or later, the sharper localized upthrusts at Cross and Juniper Mountains.

During these times of uplift there may have been the beginning of the Yampa, Red Rock, and Mitten Park faults and some movement on them; but I do not know of any positive evidence that proves or disproves this possibility.

SECOND STEP

During middle Tertiary time—perhaps extending from early Oligocene into the Miocene—uplift largely or even completely ceased. Erosion of the Uinta Mountain arch went on actively, however, until at last the mountain mass (though presumably still well above sea level) was reduced to mature topography. The erosion surface was regarded by the Atwoods (1938, p. 964) as a part of the very widespread "Rocky Mountain Peneplain."

Bradley (1936) described and analyzed in detail the processes and their topographic and geologic results along the crest and on the north flank of the Uinta Mountains. He pictured a great erosion surface, a pediment formed under arid or semiarid conditions, which sloped gently northward and northeastward for many miles out into the Green River Basin and rose in the other direction, with increasing gradient, to the foot of the high residual mountain peaks, between which at places it passed in flatter, narrow strips and began a gentle southward slope on the opposite flank. Bradley named this widespread subsummit surface the Gilbert Peak surface, and described it as now covered at many places by remnants of the Bishop conglomerate. Hundreds of feet below the Gilbert Peak surface, according to Bradley's concept, was the later Bear Mountain erosion surface, of less areal extent, also developed under arid or semiarid conditions. Part of this surface, he thought, formed the floor of Browns Park, which, as a wide, rather flat bottomed, eastward-draining valley, was eroded below the Gilbert Peak surface in the quartzitic sandstone of the Uinta Mountain group at the same time as the higher, shallower "Summit Valley" of Powell. The Bear Mountain surface, Bradley believed, was later buried under the Browns Park formation, including at places a basal conglomerate that resembles the Bishop conglomerate.

Later field studies by Kinney (1955) on the south flank of the mountains near Vernal and by Hansen

(1955, 1957) along the upper Green River, together with their observations during our reconnaissance trip (already mentioned) in the spring of 1959, have brought into question (Kinney, Hansen, and Good, 1959) some phases of Bradley's concept, particularly certain relations between the Gilbert Peak and Bear Mountain surfaces and between the Bishop conglomerate and the Browns Park formation. I have seen too little of the region as a whole to pass judgment on their questions and wish to emphasize that the picture offered in this suggested outline is not intended to be a broader judgment but merely my own views as to conditions and development in the area above and adjoining the site of Yampa Canyon. More specifically, I feel that the evidence now available indicates that in this Yampa Canyon area there was only a single pediment erosion surface (whether it be identified as the Gilbert Peak or the Bear Mountain) and a single covering deposit, the Browns Park formation, as described in the paragraphs that follow. If in this area there was once a second surface, covered with a separate Bishop conglomerate, all evidence for it seems to have been destroyed.

My concept of the erosion surface on the south side of this part of the Uintas accords essentially with the pattern discussed by several authors and described more fully by Howard (1942). No attempt is made herein to give a general summary of Howard's very complete analysis of the processes suggested by others and his conclusions reached from that analysis and from his own observations; but a few points are emphasized. Because of some existing ambiguities, he proposed (op. cit., p. 11) "the term 'pediplane' as a general term for all degradational piedmont surfaces produced in arid climates which are either exposed or covered by a veneer of contemporary alluvium no thicker than that which can be moved during floods." To the inner or mountainward zone of the pediplane, underlain by upland rocks and hence formed in consequence of the retreat of the upland front, he applied the unmodified term "pediment." For the outer, peripheral zone of the pediplane, beveling the younger, less consolidated materials deposited in a flanking basin during previous aggradation, he suggested the term "peripediment." In describing the mountainous parts of his pediments, Howard quoted Davis (1933) as saying that "a two-sided mountain mass retreating * * * will, after first acquiring more or less indented and embayed margins and later narrowing to an irregular ridge with a serrate crest, be worn through in graded passes * * *." For the "graded passes" of Davis, Howard used Sauer's term "pediment passes."

Applying the pattern thus described by Howard, I picture the erosion surface developed during the second step in this area as a *pediplane* sloping southward from the crest of Douglas Mountain and from the still higher crest west of the present Lodore Canyon, to an unknown distance out into the Uinta Basin. Along those crests were the rather flat *pediment passes* that lay between higher residual hills and ridges and that connected with the northward-sloping pediplane on the opposite flank of the range. (These pediment passes seem to correspond to the passes farther west where, as described by Bradley (1936, p. 171), "* * * smooth portions of the Gilbert Peak surface cross the range and slope southward, being the headward remnants of that surface which once flanked the south side of the range.") Southward these *pediment passes* opened into the wider and more sloping embayments which, in turn, opened further and merged into the main part of the pediment. This pediment truncated the older southward-dipping rocks of the Uinta arch at an angle much less than that of their dip; it also cut across the incipient Yampa, Red Rock, and Mitten Park faults if by that time they had come into existence. The surface of this main part of the pediment is pictured as rather smooth at places and gently undulating, with perhaps a few low residual hills, at other places.

Presumably the pediment reached the contact between the older, "upland" rocks and the Eocene deposits in the Uinta Basin. Presumably, also, a flanking *peripediment* beveled those Eocene deposits and extended for an unknown distance out over them. However, no trace of that surface is now known in the Uinta Basin, possibly for reasons mentioned by Bradley (1936, p. 169) in comparing the Uinta and Green River Basins.

The pediment is visualized as also extending eastward and wrapping around the southeast end of Douglas Mountain and of the Uinta Mountain arch; for the surface on which lies the Browns Park formation bevels sharply the steeply dipping older beds in Lily Park on both sides of Little Snake River.

In appearance, the pediplane on the south and east sides of the mountains presumably resembled the Gilbert Peak surface on the north flank as pictured by Bradley (1936, pl. 38*A*).

THIRD STEP

During the Miocene(?) there was laid down the widespread and varied material known as the Browns Park formation. Bradley (1936, p. 178, 184) ascribed the deposition of the Bishop conglomerate on the Gilbert Peak surface and of the Browns Park formation on the Bear Mountain surface to a moderate increase in aridity, and gave several reasons for that view. I have no new evidence to offer on this explanation.

The varied composition and the source of these beds in the western part of Browns Park were concisely described by Hansen (1957) as follows:

This formation contains rocks of diverse textures and lithologies including finely laminated olive-drab clays; pale orange, friable, poorly sorted siltstones and sandstone; chalky white, loose to compact bedded tuffs and tuffaceous sandstones; and variously sorted loosely cemented conglomerates, some exceedingly coarse and bouldery. The source of the tuffs is unknown, but most of the remaining material—at least the coarser fraction—was locally derived. Broad fans, consisting chiefly of pebbles and cobbles of red quartzite derived from the Uinta Mountain group but containing also Paleozoic limestone and older Precambrian metamorphic rocks, built out intermittently from the highlands enclosing Browns Park. From time to time the fans were buried by falls of vitric volcanic ash, some of which was reworked into tuffaceous sandstone. Periodically, much of Browns Park was flooded by lake waters that deposited blankets of sand and clay. The result is a complex interbedding of conglomerate, sand, tuff, and clay. The tuffs and clays retain remarkable uniformity over considerable distances, but the sands and conglomerates thin markedly from the sides toward the axis of the valley.

According to my concept, the Browns Park formation in and near the eastern part of the Uinta Mountains was deposited on the previously developed pediplane, including the Browns Park valley and the "Summit Valley" of Powell. On pages I–17–20 are listed a number of observations about the Browns Park formation and about unmapped outcrops of material lithologically resembling it. The observations are there described in support of my belief that at one time the site of the present Yampa Canyon * * * was buried at an unknown altitude and to an unknown thickness by deposits of the Browns Park formation.

More specifically, in this particular region I believe—

1. That the thickest part of the formation occurred in the eastern part of the Browns Park valley by filling of this deep valley of erosion.
2. That the sedimentary material of the formation was derived chiefly from the exposed core of the Uinta Mountains, but that it was greatly augmented by tuff from an unknown outside source. (Hansen has informed me that in this area tuff, tuffaceous sandstone, and montmorillonite clays make up 50 to 55 percent of the exposed stratigraphic section.)
3. That variations in the kinds of rock in the basal conglomerate where present were determined by the lithologic nature of those formations exposed where serving as local sources of the detritus. Thus, boulders of light-colored quartzite and related rocks from the locally exposed Red Creek quartzite are common in the western end of Browns Park; the basal conglomerate in the rest of Browns Park eastward to Little Snake River and on the north side of Cold Spring Mountain near Vermilion Creek is mostly composed of reddish quartzitic sandstone derived from the Uinta Mountain group exposed on and north of the crest of the range; and boulders of gray limestone predominate on the east end and south flank of the arch because of the continuous outcrop of limestone of Mississippian age from Lone Mountain southward and thence far to the west.
4. That, as valley filling progressed, the sandy major upper part of the formation (augmented by the wind-borne volcanic tuffs) overlapped westward up the Browns Park valley and also laterally high up against the valley walls—for example, high against the Uinta Mountain group on the north flank of Douglas Mountain.
5. That, simultaneously, sand derived from the Uinta Mountain group in local residual peaks and ridges along the crest washed down into the pediment passes, and then some of it was carried down the north flank, presumably meeting and mingling with that part of the formation rising in the valley.
6. That sand and scattered cobbles from part of the crest and the retreating mountain mass moved down the south flank and, augmented by tuffs, came to rest as a blanket filling hollows and covering the beveling surface of the pediplane to some unknown distance southward. The thickness of this blanket also is unknown; but it is surmised to have been of the order of several hundred feet on the outer part of the pediment, above the site of the present canyon.

FOURTH STEP

The ensuing collapse of the eastern part of the Uinta Mountain arch has been repeatedly and rather fully described. Apparently it was first noted and announced by Powell (1876) who, however, left some room for uncertainty as to just when he thought it happened. At one place (p. 201) he stated:

The Uinta uplift in the region of Brown's Park was at one time several thousand feet greater than we have represented it to be, but after the deposition of the Brown's Park beds it fell down that much * * *.

At three other places (p. 169, 206, 207) he at least implied the same time for the movement. Yet at a fifth place (p. 208–209) he wrote:

Let us now consider the effect which the reverse throw along the great Uinta fault and the throw along the Yampa fault has had on this valley. * * * Thus it is seen that the great block between these two faults has fallen down from

> 1,000 to 5,000 feet in its different portions. Prior to this downthrow there was a great elevated valley drained into the Green River. When the downthrow commenced it is probable that the Brown's Park beds were not yet deposited, but after it had continued for some time the region was so depressed that the waters of the stream were ponded and a lake formed. In this lake, then, the Brown's Park beds were accumulated.
>
> We know that the Brown's Park beds were involved in a part at least of this downthrow, and hence were deposited before the downthrow was accomplished, because the beds themselves were involved in the displacement; they are severed by faults and bent by fractures where they are seen to overlap or extend beyond the area of downthrow.
>
> Hence it is seen that Brown's Park is not a valley of displacement or of subsidence, but was originally formed as a valley of degradation—an elevated valley in a mountain region. It subsided or fell down as a part of a greater block.

Pre-Browns Park faulting in the Uinta Mountains was widespread. However, I lean toward the view that Powell's collapse or graben movement of the arch (whether by new faults or by reversal of throw on earlier faults) did not start *before* deposition of the Browns Park formation began. Field evidence for some graben movement *during* Browns Park time has been presented (Sears, 1924a, p. 296 and fig. 8); in 1921–22 we observed additional but somewhat less clear evidence of the same kind on Spring Creek in T. 7 N., R. 95 W., northeast of Maybell. But I believe that by far the greater part of the graben movement took place *after* deposition of the Browns Park formation was complete.

Powell's wording also left some room for uncertainty whether he pictured the collapse as virtually a single rapid movement or as caused by many small movements over a long period. I think however that he held, and intended to express, the latter concept. A postulate of intermittent, cumulative graben movement seems to be more logical, though in this area not susceptible of clear proof; collapse of such magnitude in a single movement or a very few movements would be well-nigh incredible.

The aggregate effect of the sinking in the southern part of the graben, above the site of the present Yampa Canyon and its environs, is pictured as follows:

1. In a narrow zone along the Yampa fault, rather steep northward dips in the Browns Park formation (as well as in the underlying truncated older beds that previously had dipped to the south) were caused by drag. Where the Red Rock fault branches northwestward this zone of steep dips is repeated.
2. North of and flanking the narrow drag zone was a wider zone (perhaps ranging in width from 4 to 9 miles) in which the surface of the Browns Park formation was essentially horizontal in a north-south direction but, because of tilt, sloped gently toward the west-northwest.
3. Still farther north, extending to the crest of the ridge, was a zone in which the depositional southward slope of the Browns Park formation had remained undisturbed because the broad central part of the graben had gone down almost vertically.

My picture, then, is of a trough on the surface of the Browns Park formation, some 4 to 9 miles wide, essentially flat in a transverse north-south direction but extending with gentle slope in a direction about N. 80° W. This trough was bounded on its south side by a rather steep northward slope and on its north side by a gentler though perceptible southward slope.

This trough, however, was not restricted to the area of the present Yampa Canyon. On the contrary it continued, with gently rising floor, far to the east and northeast above and north of the Axial Basin anticline. The graben movement had extended in that direction, though with force and effect diminishing eastward; this was deduced from the present attitude of the Browns Park formation (a flat-bottomed, steep-edged syncline lying unconformably above an anticline) and from the faults and flexures observed along the present margins of that formation. (See Sears, 1924a, p. 287–288, 291–292.)

It is only fair to point out a present-day structural anomaly near the mouth of Little Snake River which, if not due to some later warping or fault movement, lays open to question my picture of a continuous trough passing that vicinity. The south side of the graben and of the trough here conforms to the general pattern; south of Yampa River (opposite the mouth of the Little Snake) the beds of the Browns Park form a gentle topographic half-bowl that slopes toward the Yampa and that, east and west of Elk Springs, is rimmed on the south by a crude hogback of the basal conglomerate rising to a higher altitude and dipping more steeply northward. (See Sears 1924b, pl. 35.) The north side of the major graben (op. cit., pl. 35) lies along the north edge of the Browns Park outcrops in T. 8 N., Rs. 97–99 W. The north side of the inner trough, with dips approximately southward, might here be expected somewhat farther south; this would make Yampa River in its course from the canyon through Cross Mountain to Yampa Canyon follow the floor of the trough. However, as shown by the northward dips west of the Little Snake in Lily Park (op. cit., pl. 35) and as observed by Kinney, Hansen, Good, and me during our reconnaissance in the spring of 1959, the pre-Browns Park beveling surface and the basal conglomerate and overlying sandy beds of the Browns Park formation not only rise toward Douglas and Cross Mountains but also rise from the bridge across the Little Snake in sec. 20, T. 7 N., R. 98 W., southward toward the Yampa. This apparent anomaly requires further study and consideration. Unfortunately, large-scale topographic maps are not available (the locality is just east of the Dinosaur National Monument topographic sheet); and in this neighborhood our field work in 1922 consisted only of a few pace traverses without the carrying of elevations. But because of the very large fault on the west side of Cross Mountain and the steep dips of the truncated older beds forming a sharp, plunging syncline between that fault and the southeast end of the Uinta Mountain arch, it is not difficult to imagine that, perhaps long after its creation, the trough was here somewhat warped and dislocated by a little renewed movement.

FIFTH STEP

It seems probable that the fifth step overlapped the fourth to some unknown amount. If the collapse took place by a series of small movements over a prolonged period, and if the resulting trough began to take form at some time during that period, then the incipient trough—long before its full development—should have started to affect the location and direction of drainage.

Also, perhaps during the fifth step or perhaps after its close, the amount of drainage increased greatly. Both Blackwelder (1934, p. 561–562) and the Atwoods (1938, p. 968–969) have postulated that late in Tertiary time there began a very widespread and very great uplift of the entire Rocky Mountain region and adjacent provinces, which gradually brought about much augmented rainfall and runoff.

But regardless of these problems of timing, the effect of the trough may be deduced.

Therefore I suggest that streams flowing westward and southwestward from the Continental Divide down the depositional slope of the Browns Park formation began to be influenced by the graben, perhaps in the general vicinity of Cedar Mountain, and gathered into a new Yampa River. Joined successively by other streams farther west, this growing river was guided down the trough. It was restrained from major deflections to the north or south by the steeper dips on the edges, but was relatively free to swing laterally within the zone in which the floor of the trough was essentially level in a crosswise direction. Presumably its course was at first fairly straight, but by lateral erosion the initial irregularities were cut, enlarged, and smoothed into incipient meanders.

As long as the river was flowing on or in the soft cover of the Browns Park formation it was in no way affected by the structure or varying lithology of the buried older rocks, and thus it had no cause to depart from uniformity. Hence the slow development from irregularities to incipient meanders should have proceeded at about the same rate throughout, so that in shape and gradient all parts of the river's course at any one time would resemble each other. Surely there was no pronounced and striking difference in pattern from place to place such as characterizes the river's course today.

During this period, lateral erosion was accompanied by a certain amount of downcutting. Through combination of the two processes, presumably there was shallow incision with long low slipoff slopes on the ends and downstream sides of spurs and with low cutbanks on the outside of curves and the upstream sides of spurs. But because the Browns Park formation in this area was relatively thin—perhaps a few hundred feet at most—incision in it and further enlargement and smoothing of incipient meanders could not go on indefinitely. When this fifth step came to a close, the river had not yet widened its valley floor to the point of free swinging and the creation of flood-plain scrolls, and had accomplished little down-valley sweep.

In plan, the river at the close of this period is visualized as having a very different shape or pattern from that developed later, and as occupying a different geographic position.

In the part corresponding to what is herein called the middle section of the canyon, except for the stretch through the "half-turn district," the river is pictured as then following the course marked by the dashed line in figure 8. Comparison of this figure with the map, plate 1, shows that the dashed line is drawn along the outer edges of those later features that are herein interpreted as meander-migration scars. If this position was correct, the river distance between points B and C would then have been about 26½ miles instead of 19⅔ miles as at present; and if the difference in altitude, 333 feet, between those two points has remained unchanged, the average gradient of the river from point B to point C was then about 12.5 feet to the mile instead of the present 16.9 feet.

In the part corresponding to what is herein called the lower section of the canyon, a meander is pictured as extending northward to the north end of the site of the Warm Springs scar. Through the rest of this part the river's course is thought to have been similar in pattern to that in the middle part—that is, in more angular incipient meanders as contrasted with the intricate dovetail meanders of today. For the

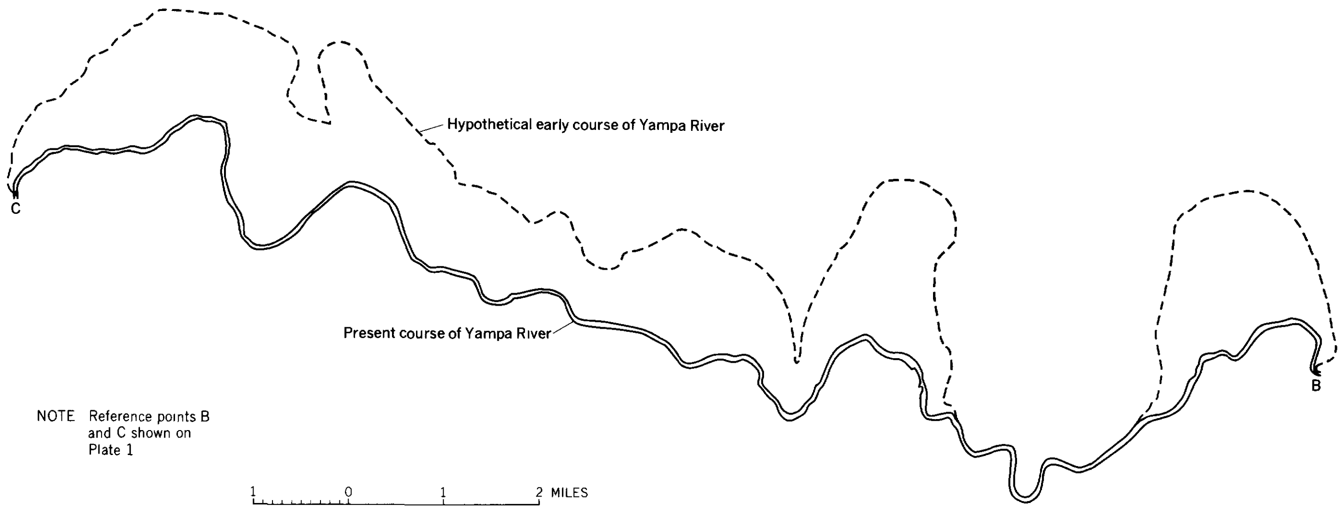

FIGURE 8.—Hypothetical course of Yampa River between points B and C just before cutting through Browns Park formation.

reason given in the fourth paragraph above, uniformity of pattern at that time in the several parts of the river seems logical. Moreover, in this lower part the shape and location of the spurs and upper walls of the present canyon (as seen on the aerial photographs and on the Dinosaur National Monument topographic sheet) indicate ample leeway for the type of course just described. However, subsequent erosion of the canyon brought such great modifications that the drawing of a hypothetical course would not be justified. But I am confident that the river distance from point C to point D was then substantially less than the present 23⅚ miles, hence that the gradient between those points was steeper than the present averaged 7.4 feet per mile—perhaps of the order of the 12.5 feet per mile suggested for the middle part.

The fifth step came to an end when at some point the river first cut through the Browns Park formation to the underlying older rocks.

SIXTH STEP

Change from the fifth step to the sixth step is seen as involving not a change in process but a differing effect on the river's course through differences in structure and lithology from the covering Browns Park formation to the underlying rocks. Superposition and its attendant phenomena began. The forces that had led to downcutting, lateral cutting, and a small amount of downstream sweep continued to operate, but with varying results.

It has been suggested that, when the river cut through the Browns Park formation to the more resistant older rocks, further downward erosion would have depended on rejuvenation, perhaps through uplift (with or without some tilting). Such uplift should have left some local physiographic traces; if so, none have come to my attention, though perhaps because they were destroyed by subsequent erosion. However, I am inclined to believe that there was no uplift at this time, and that the river still had ample power for further downcutting.

The point at which the river first cut through the Browns Park formation to the older rocks in this area is not known and is not thought to be susceptible of proof. But several clues afford grounds for speculation and a tentative conclusion.

1. The pediment (pre-Browns Park surface) was described as sloping gently southward at an angle definitely less than the angle of southward dip of the older beds that it truncated.
2. The Browns Park formation was pictured as thickening slightly southward, its basal beds of course having a dip that corresponded to the slope of the pediment surface and its upper beds having a somewhat smaller southward dip.
3. During the graben movement, the zone that became the crosswise flat floor of the trough was tilted slightly northward, thereby decreasing a little the southward dip of the basal beds of the Browns Park and the southward slope of the buried pediment surface.

If these seemingly plausible conditions were true, then the northern ends of the incipient meanders had a somewhat lesser thickness of the Browns Park formation to penetrate than the rest of the river, though the difference was probably very small. In the absence of a more tangible or more verifiable hypothesis, this picture is tentatively assumed to be correct. On this basis, I would suggest that the river first cut through the Browns Park formation at the mountainward ends of the meanders curving around the sites of the present Anderson Hole and Warm Springs scars. (A line drawn between those two places lies north of, or updip from, the ends of the other assumed meanders.)

The immediate effect of reaching the older, more resistant rocks should be some decrease in the rate of downward erosion at those points and the creation of temporary or local baselevels upstream from them. However, if the thickness of the soft Browns Park cover then remaining elsewhere along the river was as small as pictured, only a relatively short time should be required to reach the undermass throughout.

Because the strike of the older rocks was a little north of west, and their dip was predominantly about 6° S.W., the intersection of the Weber-Morgan boundary with the old truncating pediment surface was roughly parallel to that strike; the younger formation (the Weber sandstone) lay south of that boundary intersection and the older (the Morgan formation) lay north of it. As soon as the river cut through the Browns Park cover, it ran on those two formations. In the middle part of the river (between points B and C) its course was on the upper beds of the Morgan, except for the stretch through what is herein called the "half-turn district" where it ran on Weber sandstone. In the lower part of the river (between points C and D) its course was on Weber sandstone except for that northward-extending meander around the site of the Warm Springs scar, where it was again on the upper beds of the Morgan.

Inasmuch as the attitude (strikes and dips) of the Morgan and Weber was essentially uniform throughout the middle and lower parts of the river (from point B to point D), it seems obvious that the further development, which brought the conspicuous differences in river pattern from place to place, must have been influenced chiefly by differences in the way those two formations affected erosion.

RIVER DEVELOPMENT IN MORGAN FORMATION

The alternating sandstone and limestone beds of the upper one-half or two-thirds of the Morgan formation were more resistant than the soft material of the Browns Park. Where and while the river was running in those upper beds of the Morgan its course is pictured as not shifting widely. Lateral erosion was retarded somewhat by greater rock resistance in the banks but was sufficient to cut those banks into cliffs whose height increased during continued downcutting.

After incision had progressed to a further depth of perhaps 200 feet, the river at the north ends of its meanders reached the even more resistant limestones in the lower part of the Morgan while elsewhere it was still in the upper beds. Direct vertical erosion practically ceased at those points of greatest stratigraphic penetration; the river as a whole continued its tendency to slowly cut down its altitude, but at those points found less obstacle in a gradual southward, downdip shifting on top of the still more resistant beds.

Such a process of meander shifting bears little relation to that by which the well-known slipoff slopes are formed on the convex ends and downstream sides of alternating spurs in one type of more normally incised meanders. On the other hand, the suggested process would seem to be closely related to that which was early (and perhaps first) described by Salisbury (1898, p. 146) as follows:

"Flowing along the strike of dipping beds, streams do not usually sink their channels vertically, but shift them down dip at the same time that they are deepened. This process is known as monoclinal shifting."

This process was described also by Tarr (1914, p. 547), by Dake and Brown (1925, p. 106), and by Von Engeln (1942, p. 142) under the same name; by Cotton (1949, p. 89–90) and by Thornbury (1954, p. 112) under the name "homoclinal shifting"; by Wooldridge and Morgan (1937, p. 159) and by Lobeck (1939, p. 191) under the name "uniclinal shifting"; and by Worcester (1948, p. 187) without name. I think that in all these cited descriptions the authors had specifically in mind only the lateral, downdip shifting of *first-cycle* strike-valley streams with concurrent shifting of divides—a well-known phenomenon. However, their names and the process itself appear to be applicable also to the lateral, downdip shifting of incised meanders herein postulated under unusual conditions favoring such a shift.

The initial effect of the shifting was to straighten and flatten the arcuate north ends of the meanders to a shape more nearly in accord with the strike of the beds. This effect is recorded in the present pattern of contour lines (see particularly those in the Anderson Hole, Tepee Hole, and Warm Springs scars on pl. 1). Then, as more and more of the river cut down to the more resistant lower beds, increasingly large parts of the meanders shifted bodily southward down the dip, to ever lower altitudes. As the river thus shifted its position, its progressively abandoned channel became the growing, southward-sloping meander-migration scars. The shape of the scar floors indicates continuous cutting and shift; no traces of cutoffs and meander cores are seen. On their sides the scars are rimmed with cliffs whose bases are in general at progressively lower altitudes southward. At the north ends of the longer scars, however, such rimming cliffs as may once have existed have been essentially obliterated through erosion by the intermittent streams that came from Douglas Mountain to the early meanders; these streams were extended southward during the migration and have since cut into and modified the floors of the scars.

By some lateral erosion and spur trimming, the rimming cliffs on the west side of the Tepee Hole scar and the east side of the Browns Hole scar were cut back to form a southward-pointing, conspicuously sharpened spur (fig. 3).

As part of the river migration thus postulated, the meanders grew smaller (though not more rounded), the river was shortened, and presumably its gradient was increased.

On its southern side the shifting river was constantly encroaching against and eroding or even undermining the updip edges of the higher beds. Through this relation and process the south wall was kept steep and narrow throughout, and its top was kept in close conformity with every bend and turn of the river. In this way, too, the boundary between the Morgan and the overlying Weber sandstone came to lie almost continuously high along the south wall.

In time the spurs between the meanders, as well as the interstream divides forming the uplands on both sides of the river, were stripped of all or almost all their earlier Browns Park cover, and also were somewhat further lowered by erosion. Maintenance of a sharp angle between the top of the cliffs and the upland surface was perhaps the result of aridity.

RIVER DEVELOPMENT IN WEBER SANDSTONE

In its lower part (except for the meander around the present Warm Springs scar), and presumably also in the "half-turn district" of the middle part, the river is visualized as cutting through the Browns Park cover to the Weber sandstone rather than to the Morgan formation.

Reasons have already been given why the river is thought to have had a uniform pattern of incipient meanders throughout its middle and lower parts just before passing through the Browns Park formation. Yet wherever superposition began on the Weber sandstone the river now has a general pattern of rounder and more intricate meanders, many of which form what are often called "goosenecks." Furthermore, in those portions the present canyon has asymmetric cross sections and interlocking spurs with distinct slipoff slopes. (See pl. 1.)

Inheritance of the present curving intricate pattern through uplift and rejuvenation is ruled out because, as indicated above, such a pattern presumably did not exist here on the Browns Park formation. My belief that uplift did not accompany the beginning of superposition has already been stated. Early writers seemed to take for granted that incised meanders could result only through inheritance of such a course established during a previous cycle; but, perhaps first influenced by Winslow (1893), many writers have pointed out that incised meanders may form within a first cycle through lateral erosion during incision.

The conclusion seems to me inescapable that the present pattern of incised meanders was developed after superposition began, and that the conspicuous differences of pattern between the parts of the canyon cut in the Weber and the parts cut in the Morgan reflect directly the different ways in which those two formations affect erosion.

In their description of the Weber sandstone the Untermanns (1954, p. 36) said: "The poorly cemented and highly jointed nature of the Weber accelerates its erosion, producing characteristic deep, steep-walled gorges and resulting in extremely rough topography." The joints in the Weber, particularly those approximately parallel to the strike, show very plainly on the aerial photographs.

With a high degree of confidence, therefore, I postulate that during incision in the Weber many incipient meanders were more and more eroded laterally to complex, rounded meanders, with concurrent growth of slipoff slopes on the spurs. During this development there may have been some quick, local shifts in the position of the channel, for here and there on the north side of the river are features that somewhat resemble high-level cutoffs and meander cores; but these are uncertain because the topography has been so greatly modified through later erosion by side streams.

With much less confidence, I suggest the possibility that during incision there may also have been some larger scale, more general changes of the river's course to positions farther south. However, if such changes actually happened, their cause and results were very different from those of the gradual shift that brought about the meander-migration scars in the Morgan. The possibility is mentioned here for three reasons: the shape of the sloping land north of the river as visualized from the topographic map; the fact that sheer or even sharply undercut cliffs of Weber sandstone (see fig. 4) are much more numerous on the south side of the river; and (approached through a still different line of thought) the suggestion made in the closing section of this report that such changes in canyon channel may have taken place around and east of Steamboat Rock.

But regardless of whether such larger scale changes in position were or were not possible, the development of much more intricate meanders during incision is pictured as having considerably lengthened the river between points C and D, thereby proportionately reducing its gradient.

SEVENTH STEP

Some rejuvenation probably took place at a fairly late time in the incision.

On page I–8 the southward-sloping meander-migration scars in the middle section of the canyon are described as terminated near the river by a break to a steeper slope, which causes an upward convexity. If, as I believe, the floors of the scars were cut during migration of the river down southward-dipping more resistant beds in the lower part of the Morgan, then an explanation must be sought as to why those beds were at last breached and why the canyon was eroded below them.

The breaching of these more resistant beds, and the appearance of the steeper slope as the north side of a valley-in-valley, together seem to be most logically attributed to rejuvenation that led to the cutting of a V-shaped inner gorge. Such rejuvenation may have been the result of uplift, with or without some tilting; of increase in stream flow; or of some other cause. Von Engeln (1942, p. 176) has stressed the very great increase in cutting power that can result from a very small increase in velocity of flow.

The somewhat anomalous vertical and horizontal position of the present break in slope can perhaps be explained as follows. When the river had come virtually to its present location, rejuvenation caused more vigorous downcutting. At first the northern part of each meander was still flowing on the more resistant lower beds of the Morgan; hence the inner gorge there began at once to be cut into those beds. On the other hand, because of the southward dip the southern part of each meander was still flowing on somewhat higher and less resistant beds of the Morgan; hence the upper part of the inner gorge was there cut first into those less resistant beds, and the river did not reach and cut down into the more resistant lower beds until progressively later; after that, the beds above them were eroded away.

On page I–12 the slipoff slopes on the interlocking spurs in the lower section of the canyon are described as interrupted part way down by crude "treads" of somewhat less slope. Below these "treads" the banks are steep. It would be natural to assume that the steep banks below are a continuation of the valley-in-valley postulated for the middle section and therefore were cut at the same time and by the same process. Of that continuity, time, and process, however, no clear evidence is seen on either the topographic map or the aerial photographs.

The "treads" lie at successively lower altitudes toward the south, without regard to whether that direction is upstream or downstream on the several meanders. This fits the picture of their relation to lithology and dip. Perhaps they were formed when and where downcutting of any slipoff slope was slowed by locally reaching a slightly more resistant bed; and then, when downward and lateral erosion cut through that bed in its particular meander, cutting of a steeper bank below it was resumed.

EFFECT OF MITTEN PARK AND RED ROCK FAULTS

The foregoing chronologic outline presents the seven steps that may have led up to and caused the development of the winding, deeply incised Yampa Canyon in the Uinta Mountains. The outlined steps bring the river and the canyon to the point of their junction with the Green. (No discussion is here given about possible later regional uplift that may have brought mountains and rivers to present altitudes.)

But no explanation has yet been suggested for a problem relating partly to Yampa Canyon and partly to the course and development of Green River downstream from the junction, although the problem was briefly mentioned on page I–6:

> Because of the later and more detailed mapping by the Untermanns * * * I wish to emphasize that in its lower course Yampa River runs into, and joins Green River within, the added depression or triangular graben between the Red Rock and Mitten Park faults—a complicating problem to be discussed under the last heading of this report.

The problem includes chiefly two puzzling questions: (a) What is the origin of the spectacular hairpin-shaped meander of Green River around Steamboat Rock? (b) How did the combined rivers get out of the extra depression and across the Mitten Park fault with its large downthrow on the upstream side?

If the Mitten Park fault came into existence and if all or much of the movement on it was accomplished prior to the cutting of the pediment, to the deposition of beds of the Browns Park, and to the forming of the graben and the trough—that is, prior to the second, third, and fourth steps of the chronologic outline—then I find it difficult to account for the great difference in present altitudes of the conglomerate and material similar to the Browns Park high on Harpers Corner ridge and of the material similar to the Browns Park found by the Untermanns low in the graben between the Yampa fault and the Yampa River.

On the other hand, if all or most of the movement on the Mitten Park fault happened as part of the general graben movement and trough formation, then the upthrow (northwest) side of the Mitten Park fault would apparently have formed a barrier to the river flowing down the trough. In that case it would be natural to infer that water from the two rivers would be ponded on the upstream side of the barrier until it grew deep enough to overflow that barrier and begin to cut a channel through and west of it. Such ponding *may* have taken place; but, if it did, no traces of it seem to remain and it would be out of harmony with some other steps in my hypothesis.

An alternative is here suggested as a possible way out of the dilemma; as a possible explanation for the course of the Green around Steamboat Rock; and also as a possible explanation of three features that are yet to be described.

The alternative suggestion is that early in the canyon cutting, at a higher level, the last few miles of Yampa River (west of the southern part of the meander in the Warm Springs scar) may have been somewhat farther north than at present; that the Yampa may have joined the Green at or near the east end of the Mitten Park fault; and that the enlarged Green River may have flowed for more than 1 mile westward along the fault (whose throw increases in that direction) until it firmly established its course and was able to leave the fault plane and continue farther west on the upthrow side.

The features that give rise to that suggestion are as follows:

1. East and west of the north end of Steamboat Rock are two nearly straight stretches of Green River, one of which is about 0.6 mile long, and the other about 0.3 mile. If those two stretches are extended and connected by an imaginary line that is slightly arcuate northward, the line thus extended intersects the north end of Steamboat Rock at its present lowest spot (seen on the Dinosaur National Monument topographic map to be at an altitude between 5,750 and 5,800 feet).
2. The greatly curving Mitten Park fault, after passing Harpers Corner and crossing Green River, cuts across the north end of Steamboat Rock at or very near the lowest spot. Thence it reaches Green River again and, low in the canyon, extends along the upstream straight stretch. However, its throw here diminishes so sharply that the fault itself apparently ends in the east wall of the curving canyon and passes eastward into a flexure. On special large-scale (1:17,000), very detailed aerial photographs, that flexure is indicated rather clearly for about 2 miles by a locally increased southward dip of some lighter colored beds of the Weber exposed at the surface (see also the more closely crowded topographic contours on pl. 1, just south of the altitude marked "6962"); but the flexure is only faintly visible and seems to be almost gone in the southern part of the floor of the Warm Springs scar.
3. The slope between the flexure just described and Yampa River from Warm Springs to point D is now greatly dissected by short streams that drain to the Yampa. But within that small district are three higher hills still capped with patches of the southward-dipping Park City formation. From the eastern (largest) and the middle patches the ground slopes northward until, about 0.3 mile from each patch, it forms a smooth concave curve and then merges with and starts to rise as the slope of the southward-dipping flexure. At the low point of each of those curves the present altitude is between 6,240 and 6,280 feet as shown on the Canyon of Lodore South sheet (which, being newer and of larger scale, brings out the topography more clearly for this study). On each side these curving surfaces have been encroached upon and eroded into by the heads of young streams. But as seen on topographic maps and on aerial photographs and as later viewed from Harpers Corner (see fig. 9), these two smooth concave curves look like remnants of an old high-level round-bottomed channel. Moreover, if these curves do indicate an old channel, its course in both directions can be deduced. Upstream, its floor may be represented by a crude "shelf" shown by contours farther apart; if so, its north wall here also is the steeper south slope of the flexure, but its south wall has now been entirely cut away. Downstream, the possible channel might have been along a line which, if drawn between the low points of the two concave curves and extended northwestward with a gentle swing, would cross the present rim of Lodore Canyon through a comparably low gap and meet Green River near the east end of the fault.

Taken separately, any one of the three features described may seem to be either due to chance or without significance. Taken together, each strengthens the others and makes coincidence more improbable.

If this alternative suggestion seems to explain plausibly these features and the passing of the Mitten Park fault, a corollary appears: subsequently, because of southward dip and of jointing in the Weber sandstone, the erosion of new deeper channels cut Green River southward to form its narrow, elongated canyon around Steamboat Rock and also diverted the lower part of Yampa River to the present junction at point D.

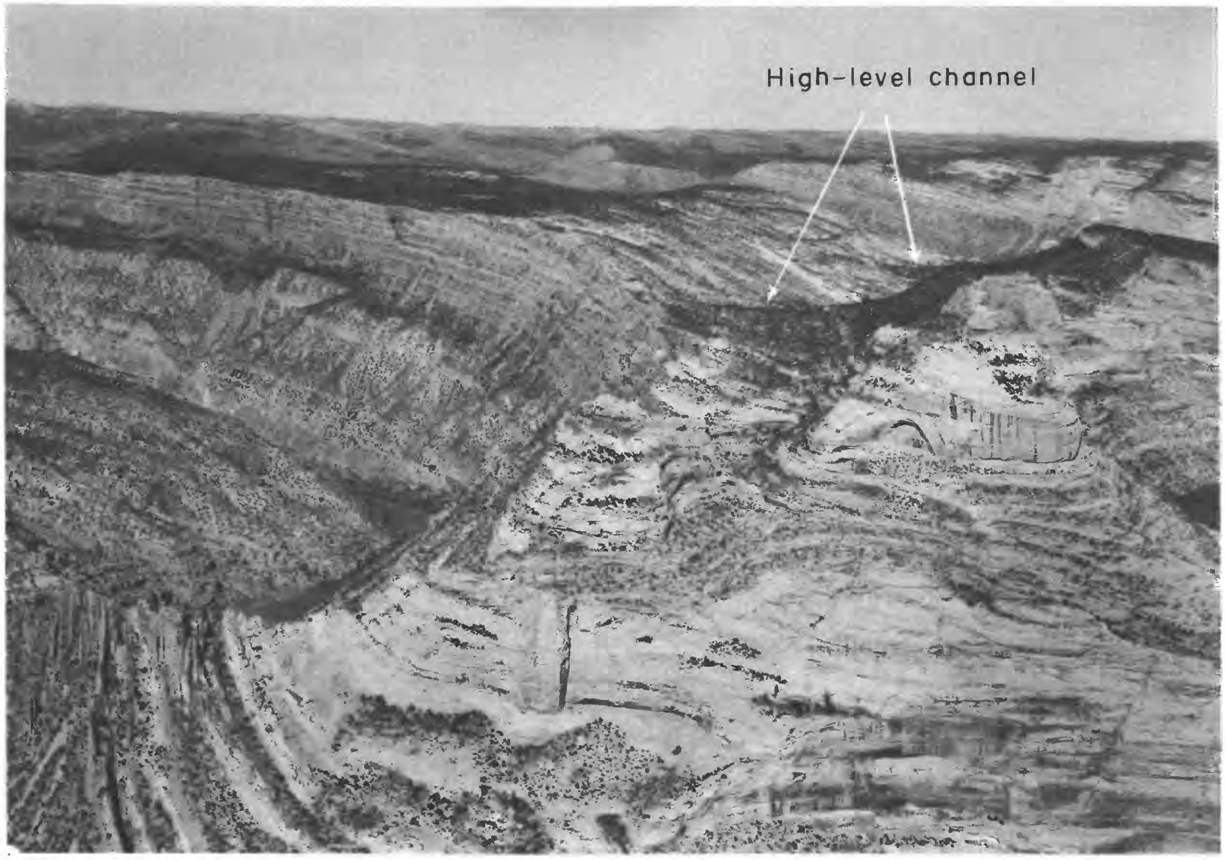

FIGURE 9.—Possible former high-level channel of lower part of Yampa River. View eastward from Harpers Corner. At right, eastern and middle hills capped with Park City formation. Green River at left, Yampa River at extreme right. (National Park Service photograph.)

SELECTED BIBLIOGRAPHY

Atwood, W. W., and Atwood, W. W., Jr., 1938, Working hypothesis for the physiographic history of the Rocky Mountain region: Geol. Soc. America Bull., v. 49, no. 6, p. 957–980.

Bates, R. E., 1939, Geomorphic history of the Kickapoo region, Wisconsin: Geol. Soc. America Bull., v. 50, p. 819–880.

Blackwelder, Eliot, 1934, Origin of the Colorado River: Geol. Soc. America Bull., v. 45, no. 3, p. 551–566.

Bradley, W. H., 1936, Geomorphology of the north flank of the Uinta Mountains: U.S. Geol. Survey Prof. Paper 185–I, p. 163–199, pls. 34–45.

Carey, B. D., Jr., 1955, A review of the Browns Park formation, *in* Intermountain Assoc. Petroleum Geologists, Guidebook, 6th Ann. Field Conf. 1955, p. 47–49.

Cotton, C. A., 1949, Geomorphology: 5th ed., revised, New York, John Wiley & Sons, 505 p.

Dake, C. L., and Brown, J. S., 1925, Interpretation of topographic and geologic maps: New York, McGraw-Hill Book Co., 355 p.

Davis, W. M., 1914, Meandering valleys and underfit rivers: Assoc. American Geographers Annals, v. 3, p. 3–28.

——— 1933, Granitic domes of the Mohave Desert, California: San Diego Soc. Nat. Hist. Trans., v. 7, p. 211–258.

Emmons, S. F., 1877, Descriptive geology: U.S. Geol. Explor. 40th Parallel (King), v. 2, p. 191–206, 222–227, 271–290.

Engeln, O. D. von, 1942, Geomorphology, systematic and regional: New York, The Macmillan Co., 655 p.

Forrester, J. Donald, 1937, Structure of the Uinta Mountains: Geol. Soc. America Bull., v. 48, p. 631–666, 4 pls., 1 fig.

Hancock, E. T., 1915, The history of a portion of Yampa River, Colorado, and its possible bearing on that of Green River: U.S. Geol. Survey Prof. Paper 90–K, p. 183–189, pls. 20–21.

Hansen, W. R., 1955, Geology of the Flaming Gorge quadrangle, Utah-Wyoming: U.S. Geol. Survey Geol. Quad. Map GQ–75.

——— 1957, Geology of the Clay Basin quadrangle, Utah: U.S. Geol. Survey Geol. Quad. Map GQ–101.

Howard, A. D., 1942, Pediment passes and the pediment problem: Jour. Geomorphology, v. 5, no. 1, p. 3–31; no. 2, p. 95–136.

Johnson, Douglas, 1932, Streams and their significance: Jour. Geology, v. 40, no. 6, p. 481–497.

Kinney, D. M., 1955, Geology of the Uinta River–Brush Creek area, Duchesne and Uintah Counties, Utah: U.S. Geol. Survey Bull. 1007, 185 p.

Kinney, D. M., Hansen, W. R., and Good, J. M., 1959, Distribution of Browns Park formation in eastern Uinta Mountains, northeastern Utah and northwestern Colorado [abs.]: Geol. Soc. America Bull., v. 70, no. 12, p. 1630.

Lobeck, A. K., 1939, Geomorphology, an introduction to the study of landscapes: New York, McGraw-Hill Book Co., 731 p.

Mahard, R. H., 1942, The origin and significance of intrenched meanders: Jour. Geomorphology, v. 5, no. 1, p. 32–44.

Moore, R. C., 1926a, Origin of inclosed meanders on streams of the Colorado Plateau: Jour. Geology, v. 34, no. 1, p. 29–57.

——— 1926b, Significance of inclosed meanders in the physiographic history of the Colorado Plateau country: Jour. Geology, v. 34, no. 2, p. 97–130.

Powell, J. W., 1876, Report on the geology of the eastern portion of the Uinta Mountains: U.S. Geol. and Geog. Survey Terr., 218 p., atlas.

Rich, J. L., 1910, The physiography of the Bishop conglomerate, southwestern Wyoming: Jour. Geology, v. 18, no. 7, p. 601–632.

——— 1911, Gravel as a resistant rock: Jour. Geology, v. 19, no. 6, p. 492–506.

——— 1914, Certain types of stream valleys and their meaning: Jour. Geology, v. 22, no. 5, p. 469–497.

Salisbury, R. D., 1898, The physical geography of New Jersey: New Jersey Geol. Survey, Final Rept. 4, p. 1–187.

Sears, J. D., 1924a, Relations of the Browns Park formation and the Bishop conglomerate and their rôle in the origin of Green and Yampa Rivers: Geol. Soc. America Bull., v. 35, p. 279–304, 11 figs., 1 pl.

Sears, J. D., 1924b, Geology and oil and gas prospects of part of Moffat County, Colorado, and southern Sweetwater County, Wyoming: U.S. Geol. Survey Bull. 751–G, p. 269–319, pls. 35–37.

Tarr, R. S., and Martin, Lawrence, 1914, College physiography: New York, The Macmillan Co., 837 p.

Tarr, W. A., 1924, Intrenched and incised meanders of some streams on the northern slope of the Ozark Plateau in Missouri: Jour. Geology, v. 32, no. 7, p. 583–600.

Thornbury, W. D., 1954, Principles of geomorphology: New York, John Wiley & Sons, 618 p.

Untermann, G. E., and Untermann, B. R., 1954, Geology of Dinosaur National Monument and vicinity, Utah-Colorado: Utah Geol. and Mineralog. Survey Bull. 42, p. 1–221, pls. 1–3.

Winslow, Arthur, 1893, The Osage River and its meanders: Science, v. 22, p. 31–32.

Wooldridge, S. W., and Morgan, R. S., 1937, The physical basis of geography: New York, Longmans, Green & Co., 445 p.

Worcester, P. G., 1948, A textbook of geomorphology: 2d ed., New York, D. Van Nostrand Co., 584 p.

INDEX

Page

Acknowledgments 5
Aerial photographs, as sources of information 4, 11, 13, 14, 29
Anderson Hole scar 10, 27
Axial Basin anticline 20

Basal conglomerate, Browns Park formation 22
Bishop conglomerate 20
Bower Draw scar 11
Browns Hole scar 11, 27
Browns Park formation, discoveries in area 17–20
drilling data 5
erosion surface below 20
Miocene deposition of 21–22
recent extensions of area 16
stripping of 24, 25, 26, 27
superposition of drainage pattern from 15, 16

Canyon walls, topography and geomorphology of 7

Douglas Mountain 8–9

Five Springs Draw scar 11

Geologic map, discussion 4–5
Geology, lower section 14
middle section 9
upper section 6
Geomorphology 7, 8, 9
Graben between Mitten Park and Red Rock faults, formation of 22–23
influence on late Tertiary drainage 23
relation to river course 6, 15
Green River, course below mouth of Yampa River 28–29

Half-Turn district 7, 9, 11–12, 24, 27
Harper's Corner ridge, Browns Park formation 29

Incised, definition 3–4

Mancos shale 7
Meander, definition 3
Meander-migration scars 3
definition and description 9–12
in Morgan formation 28
Meanders, in Browns Park deposits 24
in Morgan formation 26–27
in older rocks 24–26
in Weber sandstone 27–28
shifting of 26–27
Middle Eocene erosion 20
Mitten Park fault 3, 4, 6, 19, 20, 21
effect on river development 28–29
position 4
relation to Yampa River 3
Morgan formation 6, 7, 9, 14
boundaries 4–5
meander-migration scars in 28
river development in 26–27, 28

Page

Park City formation 14
Pediment, erosion in 25–26
Pediment passes 21
Pediplane 21
Peripediment 21
Previous work 4

Red Rock fault 3, 4, 5, 20, 21
effect on river development 28–29
position 4
relation to Yampa River 3

Slipoff slopes and treads 9, 12, 28
Steamboat Rock, river flexure at 27–28, 29
Structure, upper section 6–7
Superposition, relation to river course 15, 16, 24, 27

Tepee Hole scar 10–11, 27
Topographic maps, as sources of information 4
Topography, canyon walls 7–8
lower section 12
middle section 12
uplands 7, 8–9
upper section 6

Uinta Mountain arch 6, 7, 15, 20, 21
collapse of 22–23
Uplands, topography 13–14
Uplift, late Eocene–Oligocene 20
late Tertiary 24

Warm Springs scar 24, 26, 27, 29
Weber sandstone 6, 7, 9, 14
boundaries 4–5
river development in 26, 27–28

Yampa Canyon 6, 7, 12, 13
development above junction with Green River 19–28
explanation of features 15–29
location and extent 5
lower section 12–14
late Tertiary river course 24
middle section 7–12
geology 9
late Tertiary river course 24, 26
location and structure 6
meander-migration scars 10
river pattern and direction 7
three-fold character 3, 6
upper section 6–7

Yampa fault 3, 4, 5, 7, 9, 19, 20, 21
position 4
relation to Yampa River 3
Yampa River, middle course 5
migration 26–27
pattern and direction 6, 7, 12
rejuvenation of 28
relation to faults 3