UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGY OF DAM SITES ON THE UPPER TRIBUTARIES OF THE COLUMBIA RIVER IN IDAHO AND MONTANA

Part 2. HUNGRY HORSE DAM AND RESERVOIR SITE SOUTH FORK FLATHEAD RIVER FLATHEAD COUNTY, MONTANA

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 866-B

UNITED STATES DEPARTMENT OF THE INTERIOR
Harold L. Ickes, Secretary

GEOLOGICAL SURVEY
W. E. Wrather, Director

Water-Supply Paper 866-B

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Part 2. HUNGRY HORSE DAM AND RESERVOIR SITE SOUTH FORK FLATHEAD RIVER FLATHEAD COUNTY, MONTANA

By
C. E. ERDMANN

WITH A SECTION ON GEOPHYSICAL INVESTIGATIONS

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SUMMARY AND CONCLUSIONS

The Hungry Horse dam site, in Flathead County, Mont., is suitable for a high concrete dam, and leakage from the reservoir area appears to be improbable. Geologic conditions at the dam site are relatively simple. A low saddle in the drainage divide of the reservoir site limits the maximum height of a dam to 630 feet above the foundation, but other considerations limit the practical height to 500 feet (high-water flow line 3,540 feet). The critical area is in the vicinity of the saddle near the west quarter corner of sec. 24, T. 30 N., R. 19 W.

GENERAL FEATURES

Location and topography.—The South Fork of Flathead River is one of the three important affluents of the upper Flathead River, which it joins at the head of Bad Rock Canyon. The total length of the South Fork is about 105 miles, and the direction of flow is to the northwest (fig. 2). The gradient of the lower part is about 12 feet per mile.

The dam site is in sec. 21, T. 30 N., R. 19 W. (fig. 2). It is rectangular and covers about 110 acres. Its center is about 750 feet northeast of the center of sec. 21.

The reservoir area extends upstream from the dam site for 40 miles and will have an area of a little more than 40 square miles. The area of the catchment basin above the dam site is about 1,725 square miles. The average annual runoff from this basin is about 2,000,000 acre-feet, but the stream shows great seasonal fluctuation in flow.

The dam and reservoir sites are within the Flathead National Forest.

Accessibility.—At present the dam site can be reached only by walking or riding 3½ miles up the South Side Trail from South Fork Bridge, or from the west end of the Geological Survey gaging cable. The bridge is on United States Highway No. 2, 5 miles east of Columbia Falls and 22 miles northeast of Kalispell. The town of Coram, on the Great Northern Railway about 4 miles northeast of the bridge and about 5 miles from the dam site by the most direct route, is the nearest shipping point.

The east side of the reservoir area is easily accessible by the Forest Service road from Coram to the Spotted Bear ranger station. There is no road on the west side between the dam site and Elk Park.

Utility of the proposed dam.—The proposed dam will serve the purposes of power, stream regulation, flood control, and, possibly, irrigation. Preliminary studies of the feasibility of the project have been made by the Geological Survey, and by the Corps of Engineers, United States Army.

Climate.—The mean annual temperature of the region is about 41° F. The pool would probably contain ice for about 4 months of each year, but the shape of the reservoir just above the dam would be such that the structure would be protected from wave action and ice thrust.

The west (left) wall of the valley at the dam site is high and steep and not immune from the danger of snow slides.

Country rock.—The rock formation at the dam site is the Siyeh limestone of the Belt series. It is of pre-Cambrian age, has a thickness of about 4,500 feet, and is rather homogenous. Petrologically it is an incipiently metamorphosed, impure, siliceous magnesian limestone, well bedded and thoroughly jointed. The formation is strong and rigid. Its crushing strength is estimated at about 10,000 pounds per square inch. The strength of the weathered rock is thought to be about half that of the fresh material. Chemical tests have indicated that the rock, though fairly soft, is relatively insoluble, and that the passage of water through it will not cause weakness during the useful life of a dam.

Dip.—The average dip of the rock at the dam site is 25°, and the direction of dip ranges from N. 40° E. to N. 60° E. The trend of the South Fork through the dam-site area is about N. 36° W., nearly at right angles to the direction of dip.

Joints.—There are two systems of master joints in the dam-site area, one striking N. 40°–45° W. and dipping 51°–63° W., the other striking N. 67°–80° E. and dipping 60°–75° S. Other joint systems are present, but they do not influence the direction of the stream flow (fig. 5). The thorough jointing of the rock is an element of weakness. A further weakness is the present tendency of the rock in the west (left) wall of the gorge to slip down dip.

Faults.—The abutments and foundations of the dam site are free from faulting and related disturbances, but great faults of several types are present in the region and near the dam site (fig. 4). There has probably been no movement on the overthrust faults since late Eocene time. The high-angle thrust faults, which blocked out the mountain ranges, must still be considered potentially active.

The water load of the Hungry Horse Reservoir may total more than 4,500,000,000 short tons. The center of gravity of this mass will lie near the Flathead fault. Although the load may cause a slight elastic yielding of the earth's crust, this subsidence should not produce movement along the fault or act as a "trigger" to an earthquake.

Earthquake hazard.—The hazard of occurrence of a destructive earthquake in any year is 1:11,200, according to Freeman. Intensity of a shock may be about that of the Montana earthquakes of 1935.

Permeability.—The Siyeh limestone is considered to be moderately permeable through sheet openings—joints and bedding surfaces—but the permeability through the rock fabric is negligible. Under a head of 500 feet, leakage through the foundation and abutments of the dam might be considerable but could probably be controlled in large part by pressure-grouting.

DAM SITE

Form of valley.—The valley of the South Fork at the dam site is symmetrical, the form being a modified or rounded "V". The slopes between altitudes 3,540 and 3,130 feet are considered as belonging to the abutments, the surface below altitude 3,130 feet to the foundation (fig. 4 and pl. 9).

Abutments.—The right bank forms the east abutment and the left bank the west. Conditions in each are uniform throughout the site. However, because of the attitude of the strata, the bearing power of the abutments is probably not quite equal. The east abutment is stronger in a structural sense, but it is possible that percolation will be greater through it than through the west abutment. Both abutments are suitable for an arch dam.

Foundation.—Foundation conditions are essentially equal throughout the dam site. In the present river channel there is very little gravel or fill, but the valley contains a series of buried channels. Fill in these older channels apparently does not exceed 80 feet. The partly buried rock ridges are probably more weathered and permeable than is the other rock of the foundation or abutments.

The foundation is suitable for a dam of any type, and will support a high dam without crushing or sliding. Ground-water conditions are not troublesome.

Height of dam.—The site is adequate for a dam about 630 feet high, but probable leakage from the reservoir limits the practicable height to about 500 feet. The maximum altitude of bedrock in the lowest divide of the reservoir is about 3,585 feet. A dam 500 feet high (flow line 3,540 feet) will raise water to a level near this limit without incurring danger of uncontrolled drainage from the reservoir.

Comparison of dam sections.—Four sections at close intervals were studied in detail and compared for dams of various height (pls. 8, 9 and fig. 6). Section D–D′ appears to be the most economical, insofar as comparative area and length of crest-line in relation to height of dam are concerned. It is closely seconded by section B–B′, through the Devil's Elbow. All sections are equal with respect to abutments and foundations.

Choice of section.—Choice of section for construction will involve consideration of the cross-sectional area of the partly buried ridges and the possibility of their incorporation in the dam; the probable amount of rock excavation; the amount of gravel to be excavated in the buried channels and the possible use of these channels for stream diversion during construction; and the location of construction plant, powerhouse, and other appurtenant works.

Appurtenant works.—If the full potentiality of the project is utilized, appurtenant works will include spillways, a powerhouse, and possible canals.

The spillways may require rock tunnels, and tunnels may be necessary for stream diversion during construction. Tunnels in the west bank may be expected to have heavy roof conditions, and some water probably will be encountered. Those in the east bank probably will not encounter these conditions.

If irrigation canals are to be built, the rock structure favors canals along the east bank, where they would be safer from falling rock and snowslides than along the west bank, but the route to the point of utilization probably would be longer. Tunnels and canals will require concrete linings.

RESERVOIR SITE

Geology.—The reservoir area is underlain by rocks of the Missoula group of pre-Cambrian age, which rest comformably upon the Siyeh limestone. The strata consist chiefly of thin, gray-green argillites, with minor reddish argillites, and some dolomitic limestone. They are overlain uncomformably by Tertiary lake beds, glacial boulder clays, and Recent alluvium. The argillites dip to the northeast as at the dam site. The Tertiary strata also have been deformed but less intensely.

Capacity.—The maximum capacity of the reservoir at 3,540 feet is approximately 3,300,000 acre-feet.

Floor.—The floor supports a fairly dense forest, parts of which have been burned. There are a few small meadows but no cultivated land.

Ground water.—The reservoir and catchment areas are enclosed by a high ground-water divide. All streams and springs are tributary to the reservoir. The springs that have been observed flow from the glacial drift, and reversal of flow can have no serious consequences.

Silting of reservoir.—Silting of the reservoir is negligible under present conditions.

Leakage from reservoir.—Preliminary reconnaissance indicates that buried glacial gorges enter the reservoir area at low altitudes (fig. 8 and pl. 10). Geological and geophysical investigations indicate that these gorges limit the practicable height of a dam to about 500 feet, but within this limit, Hungry Horse Reservoir appears to be safe from subsurface leakage.

Mineral deposits.—Deposits of lignite coal occur in the Tertiary lake beds. The thickest beds seen did not exceed 6 feet, but there may be thicker beds. The great abundance of wood in the region and the distance to market render these coal deposits unimportant at present.

The probability that valuable deposits of oil or metals may occur is negligible.

Materials for construction.—Materials for construction are not present at the site. Material for aggregate and sand occur nearby, but it would have to be crushed or washed.

Recommendations for exploratory work.—Recommendations for exploration were first made in 1937, and it was suggested that it would be advisable to test the leakage possibilities of the Lion Hill and Abbott Gorges by drilling before investigating the dam foundation. This procedure was not followed, and preliminary exploratory drilling was carried out at the dam site in the fall of 1939 by the Corps of Engineers. Eleven borings were put down on a profile corresponding approximately to the line of cross section D–D′ (pl. 8). The results obtained are essentially those outlined in pl. 9, D. However, this does not obviate the necessity for the exploration of the buried gorges, and at least one hole should be put down over the probable location of the bedrock divides in Lion Hill Gorge and Abbott Gorge so that positive control may be available for checking the geophysical depth determinations in these areas.

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By C. E. Erdmann

INTRODUCTION

LOCATION AND ACCESSIBILITY OF THE PROJECT

This report describes the geological conditions that may affect the construction of a high dam at the Hungry Horse site on the South Fork Flathead River and the leakage from the reservoir. The relationships of the dam and reservoir sites and the catchment area are shown in figure 2.

The map of the dam site (pl. 8) covers an area of about 110 acres. The center of this tract is on the stream, 250 feet above the famous Devil's Elbow bend and about 750 feet northeast of the center of sec. 21, T. 30 N., R. 19 W., Flathead County, Mont. This locality is about 4 miles downstream from the mouth of Hungry Horse Creek, from which the name for the dam and reservoir site has been taken.

With a high-water flow line at an altitude of 3,540 feet the reservoir will extend up the South Fork for approximately 40 miles and will have an area of about 41.5 square miles. Geologic work relative to leakage from the reservoir covered a strip northeast of the river that averaged 3 miles in width and extended from the river's mouth up to Fire Creek, a distance of about 10 miles.

The principal point of departure to reach the dam site is the bridge over the South Fork on United States Highway No. 2. This locality is about 5 miles by road from the town of Columbia Falls and about 22 miles from Kalispell. The west side of the site may be reached from the bridge by walking or riding up the South Side Trail (No. 263) for 3½ miles. About a mile may be saved by driving to the Geological Survey stream-gaging station on the east or right bank, and then crossing over to the South Side Trail on the gaging cable. The Lion Lake Hillside Trail (No. 612) departs from the roadhead at the gaging

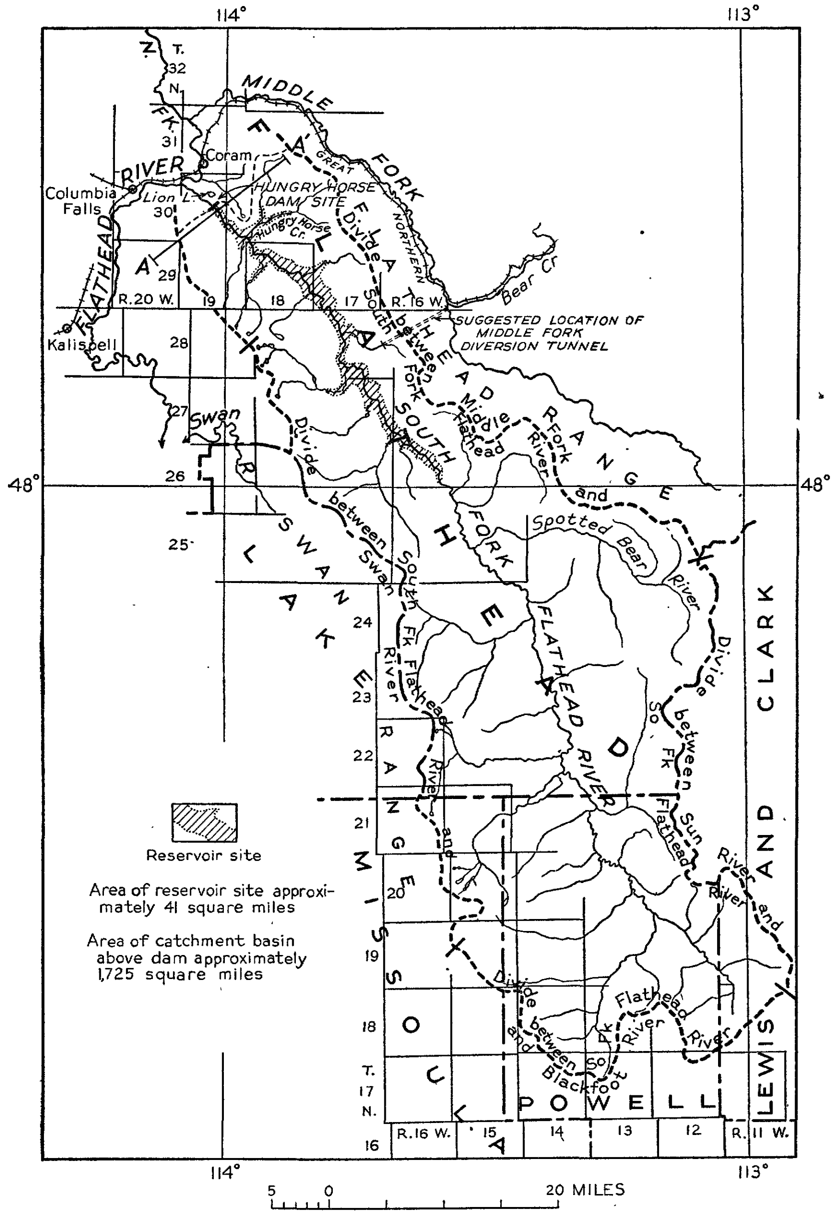

FIGURE 2.—Index map showing Hungry Horse dam and reservoir site in their relation to the drainage area of South Fork of Flathead River, Flathead County, Mont. For diagrammatic section along line *A—A′*, see figure 4.

station and follows up the right bank of the river. Along this trail from the gaging cable to the dam site is about 2 miles and to the point where this trail meets the South Fork road is an additional 2½ miles.

The lower part of the trail, near Whelp Creek, has not been kept open during recent years and is obscure and not easy to traverse on account of many windfalls.

The South Fork road is about 2½ miles east of the river at the point where it is nearest the dam site. If a road were to be built to the site, the most direct route would be south from the junction of the South Fork road with United States Highway No. 2, east of Lion Lake. This route is approximately 5 miles from Coram, a small station on the Great Northern Railway and the nearest shipping point. The construction of about 3 miles of road would be necessary, and the route would terminate on the rim of the gorge far above the river. An enlargement of the South Side Trail could be made at the expense of some rock work, but it would terminate in the gorge at the dam site. This alternate route to Coram would be about 7½ miles long.

With favorable water conditions it is possible to navigate the South Fork with small boats and powerful outboard motors from its mouth on the main Flathead River, at the head of Bad Rock Canyon, up to the Devil's Elbow, but this route is seldom used except by fishermen. The rapids above the Devil's Elbow, especially those near the mouth of Fawn Creek, make it impracticable to bring boats downstream to the dam site.

The South Fork road is maintained by the United States Forest Service from United States Highway No. 2 near Coram up the east side of the river to the Spotted Bear ranger station. This good road provides easy access to the east side of the Hungry Horse Reservoir. Access to the west side may be gained by car over the bridge near Elk Park, the road continuing up the left bank to Spotted Bear. Downstream from Elk Park the river can be crossed by wading or by boat, but these methods are advisable only during low-water stages.

PREVIOUS INVESTIGATIONS

The pioneer investigation of the Hungry Horse project was made in 1921 by B. E. Jones, of the Geological Survey. He located the reservoir site by study of the Geological Survey's topographic map of the Nyack quadrangle and visited the river to look for a possible dam site. In his report, dated July 15, 1922, Mr. Jones wrote:[1] "There is a feasible dam site on South Fork of Flathead River about 4 miles above the mouth and about 1 mile below the edge of the area shown on the Nyack quadrangle."

During the summer of 1923, E. E. Jones, of the Geological Survey, visited the area "for the purpose of locating a feasible dam site on South Fork of Flathead River at some point between Hungry Horse

[1] Jones, B. E., Preliminary report of power site reconnaissance of South Fork of Flathead River, 1922: U. S. Geol. Survey, unpublished report.

ranger station in sec. 31, T. 30 N., R. 18 W., and its junction with Flathead River in sec. 1, T. 30 N., R. 20 W., M. M., Montana."[2] This work included the preparation of a reconnaissance topographic map of the South Fork from its mouth to the north margin of the Nyack sheet and a reconnaissance hydrographic survey of the river. In his report he states that "a very good location for a dam was found in unsurveyed sec. 21, T. 30 N., R. 19 W., M. M., at a point on the river about 700 feet upstream from the Devil's Elbow." Maps and photographs of this site were furnished to M. R. Campbell, of the Geological Survey, who prepared a brief memorandum on the apparent geological conditions, which is included in Mr. Jones' report.

Within the period August 7–17, 1927, a reconnaissance geologic examination of the dam site was made by J. T. Pardee, of the Geological Survey, who used the topographic maps prepared by E. E. Jones as a base.[3] Other than this, no detailed geologic work has been done in the valley of the South Fork.

The areal geology of the valley and adjoining regions is shown on a small-scale regional map prepared for the Montana Bureau of Mines and Geology.[4]

The Geological Survey's topographic map of the Nyack quadrangle, published in 1914, does not include the dam-site area but shows practically all of the reservoir area.

PRESENT INVESTIGATION

The investigation covered by this report was carried on during the field seasons of 1934, 1935, and 1936 by engineers and geologists of the Geological Survey. It consists of three distinct phases—topographic, geologic, and geophysical.

TOPOGRAPHY

Most of Flathead River has been mapped on a scale of 1:31,680 (1 inch=½ mile) as part of a comprehensive plan of Montana river surveys. The status of the project and maps has been described in detail recently by Johnson.[5]

The special river survey maps of South Fork Flathead River[6] show land contours at 20-foot intervals up to elevations 200 feet above

[2] Jones, E. E., Reconnaissance report of South Fork of Flathead River: U. S. Geol. Survey, unpublished report, Jan. 1924.

[3] Pardee, J. T., Geology of dam sites on South Fork of Flathead River below Hungry Horse Creek, Flathead County, Mont.: U. S. Geol. Survey, unpublished report, 1928.

[4] Clapp, C. H., Geology of a portion of the Rocky Mountains of northwestern Montana: Montana School of Mines Mem. 4, pl. 1, Dec. 1932.

[5] Johnson, Arthur. Summary of Investigations on Flathead River and Tributaries, Montana. U. S. Department of the Interior, Geological Survey. Press notice 120052. 18 pp. June 1940.

[6] U. S. Geological Survey. Plan and Profile of South Fork Flathead River, Montana, from mouth to Mile 44, with Dam Site. Two plan sheets, 1 profile sheet, 1 profile sheet with dam site and cross-section. Washington, D. C. 1937. Plan and Profile of South Fork Flathead River, Montana, above Mile 44, and Tributaries. Three plan sheets and three profile sheets. Washington, D. C. 1939.

stream level. On the water surface 5-foot contours were shown. Possible dam sites were mapped on a scale of 400 feet to the inch, with a land-contour interval of 10 feet and a water-contour interval of 1 foot. Topographic contouring at dam sites was carried well above the altitude of the probable crest of a dam, and in reservoir areas the contour of the highest possible pool level was mapped. This work was directed in 1934 by W. C. G. Senkpiel and in 1935, 1936, 1938, and 1939, by Arthur Johnson.

The maps showing South Fork from the mouth to mile 44 cover the Hungry Horse project. In addition, a special map was made of the area involved in the problem of leakage from the reservoir; this map is on the same scale as the river survey and shows the area that extends along the South Fork from Hungry Horse Creek to the main Flathead River, covering about 8 square miles. Among the important topographic features shown are Lion Hill, Abbott Ridge, and the valley of South Abbott Creek.

GEOLOGY

The geological investigation of the project consisted of two distinct parts—a study of the dam site, where conditions are relatively simple, and an inquiry into the possibility of leakage from the storage reservoir, which at the beginning of the investigation appeared to be such that it would seriously limit the potentialities of the project for river regulation and flood control and considerably reduce potentialities for power.

Field work on the dam site was carried out during the period July 14–24, 1934, before the topographic survey was completed. The accompanying map (pl. 8) shows only the bare outline of the dam-site topography as traced from 100-foot contours. Profiles of the cross sections (pl. 9) are taken from the 10-foot contour map shown on sheet D of the river survey map. Because of the dense vegetation, geologic observations were located by means of tape and compass traverses from bench marks. In some places the ground was surveyed by means of traverses parallel to the probable dam axis and spaced at 100-foot intervals.

Investigation of the reservoir site and associated problems was begun October 12–14, 1934, when a rapid reconnaissance was made along South Abbott Creek and up the South Fork as far as Spotted Bear ranger station. Finished river maps were not available at this time, and the Nyack quadrangle sheet and the Flathead Forest map were used as bases. Following this, recommendations were made for the topographic mapping of South Abbott Creek and surrounding country and for geologic mapping of the east side of the South Fork Flathead River from Fire Creek to the main Flathead River.

This mapping was started in September 1935 and continued until late October. Geologic work was resumed on June 20, 1936, and was completed on July 4. Later, September 18–21, 1936, a reconnaissance was made of the upper part of the South Fork between Spotted Bear and Big Prairie.

As a result of the work in 1934 and 1935 two preliminary reports were prepared. The first described the dam-site geology in considerable detail and outlined some of the possibilities of leakage from the reservoir area.[7] The second summarized general geologic conditions and the geology at the dam site and included a revised discussion of the possibilities of leakage.[8]

GEOPHYSICS

A geophysical investigation to determine the depth of bedrock was made at the Hungry Horse dam site during July 1934 by B. E. Jones and R. K. Thies using the standard Gish-Rooney electrical resistivity method.

Resistivity work was resumed in August 1935, by Mr. Jones, who was assisted again by Mr. Thies and by A. F. Bateman, Jr. General supervision of this work was assumed by the writer early in October upon Mr. Jones' departure for Washington, D. C. The investigations were confined to the leakage problem of the reservoir. Separate interpretations of the data were made by Jones and Thies. Their reports failed to show complete agreement in one rather critical area. Some of the resistivity work there was checked during September 1936 with a portable refraction seismograph loaned by the United States Bureau of Public Roads. This investigation was carried out by E. R. Shepard and R. W. Moore, of the Bureau of Public Roads, in cooperation with the Geological Survey, which was represented by the writer. A short memorandum describing the work accomplished was prepared promptly after its completion, and a complete report giving all field data and interpretations was prepared by Mr. Shepard.[9]

All significant features related to the Hungry Horse project have been seen. The time spent at the dam site, in connection with the geophysical work is believed to have been adequate for the investiga-

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[7] Erdmann, C. E., Preliminary report on the geology of the Hungry Horse dam and reservoir site, South Fork of Flathead River, Flathead County, Mont.: U. S. Geol. Survey, unpublished report, March 1935.

[8] Erdmann, C. E., Progress report, 1935, Geology of Hungry Horse dam and reservoir site, South Fork of Flathead River, Flathead County, Mont., U. S. Geol. Survey, unpublished report, May 29, 1936.

[9] Shepard, E. R., Seismic exploration of Hungry Horse reservoir project, Montana, U. S. Geol. Survey, unpublished report, January 1937.

tion of all geologic features that might affect the construction of a high dam. These data have been incorporated into a report intended primarily for the engineer rather than the geologist; quantitative expression has been attempted, and special applications have been pointed out wherever possible. During the fall of 1939, with an advance manuscript copy of this report as a guide, preliminary exploratory drilling was carried out at the dam site by the Corps of Engineers. Eleven borings were put down along a profile corresponding approximately to the line of cross section D–D′, pl. 8. The results obtained confirm the essential accuracy of pl. 9, D. However, at the request of the Corps of Engineers, pending completion of their own report to Congress, this new information has not been incorporated in this report.

In the investigation of reservoir leakage problems equal detail cannot be maintained. The area is too large, and significant exposures are too few to establish more than generalizations. Where numerical expressions are used, they are for illustrative purposes only, to indicate orders of magnitude, and should not be taken literally. Furthermore, because of the urgency for compilation, an exhaustive study of many of the purely geologic problems of the region has been omitted.

VEGETATION

All field work was greatly retarded by the dense, sometimes almost impenetrable, vegetation. This consists chiefly of forest trees, but there are numerous thickets of snowbrush in areas where the ground is moist. In the forest during July the visibility never was more than 100 feet and sometimes was as low as 30 feet.

The only places where any considerable view may be had are along the river and in the burned areas. An occasional view from a high point on the canyon walls gives a general idea of the profile of the valley, but nothing can be seen below the level of the treetops.

CLIMATE

The brief discussion of climate that follows is based upon the records of the United States Weather Bureau stations at Columbia Falls and Belton, Mont., from the time of their establishment to 1921, inclusive, or 7 and 26 years, respectively. The altitude at Columbia Falls is 3,100 feet and that at Belton is 3,213 feet. The general altitude at the Hungry Horse dam site is about the same, but because of the direction of the valley and its narrowness and depth the dam site is more sheltered, and because of its comparatively late sunrise and early sunset it probably is cooler.

Summary of climate at localities adjacent to Hungry Horse dam site [10]

	Columbia Falls	Belton
Annual precipitation ... inches	22.37	26.46
Annual snowfall ... do	67.8	122.20
Mean temperature ... °F	42.8	41.0
Mean maximum temperature ... °F	55.2	53.9
Mean minimum temperature ... °F	28.1	30.3
Highest temperature ... °F	102.0	100.0
Lowest temperature ... °F	-35.0	-34.0

[10] Summary of climatological data for the United States, section 28, Western Montana: U. S. Weather Bureau, 1925.

Recent stream-gaging records [11] indicate an average annual runoff from South Fork Valley of about 26 inches. This corresponds closely to the average annual precipitation at Belton. Mean-temperature records indicate that ice conditions will prevail for about 4 months a year, December to March, particularly in quiet water. This factor should not be overlooked in designing the dam. However, the shape of the valley just above the dam appears to be such that the dam will be protected from wave action and ice thrust from the main reservoir area.

UTILITY OF THE HUNGRY HORSE PROJECT

A high dam at the Hungry Horse site would create storage that would be of value for stream regulation and flood control, for power, and perhaps for irrigation. The utility of this site for power, affording an increase in the power capacity of the Flathead River below Flathead Lake, was first pointed out by B. E. Jones,[12] who estimated that an additional 150,000 horsepower at a series of sites could be made available through its development.

More recently the Corps of Engineers, United States Army, has investigated the project in connection with studies for the utilization of the minor tributaries of the Columbia River.[13] The information on which their estimates are based has been compiled from the report of E. E. Jones to which reference has been made.

PROPOSED ACCESSORY DIVERSIONS

As an accessory to the Hungry Horse project the Army engineers [14] have suggested the diversion of a part of the flow of the Middle Fork of Flathead River into South Fork.

[11] Surface water supply of the United States, part 12, North Pacific slope basins; U. S. Geol. Survey, Water Supply Papers 692, 707, 722, 737, and later issues.

[12] Jones, B. E., op. cit., pp. 1–5.

[13] Columbia River and minor tributaries: Reports of the district engineers at Seattle, Wash., part 2, and Portland, Oreg., part 3, 73d Cong., 1st sess., H. Doc. 103, vol. II, p. 607–608; 802–803; 1934.

[14] Idem, p. 802.

765. From a study of the Nyack quadrangle map of the United States Geological Survey, there appears to be a possible dam site on the Middle Fork of Flathead River just above Bear Creek. The entire flow of the stream above this point could be diverted from the forebay so created, elevation 4,000 feet, to the South Fork of Flathead through an 8-mile tunnel and conduit. A powerhouse to use this water could be located at the upper regulated limit of the Hungry Horse Reservoir (about elevation 3,435 feet) thus providing an operating head of about 500 feet.

The supplementary projects suggested in paragraph 765 were made the subject of a brief reconnaissance during August 1937 to determine whether dam sites capable of fulfilling the requirements outlined exist on the Middle Fork Flathead River. The results indicate that the proposed dam site would not be satisfactory and that reconnaissance of the tunnel route is not necessary at this time.[15]

In summary, a good topographic site for a dam was found on the Middle Fork of Flathead River in the southeast corner of sec. 1, T. 28 N., R. 16 W., Flathead County, or 1.8 miles upstream from Bear Creek. At this place the gorge is about 95 feet deep, and the width from rim to rim at altitude 4,000 is only 250 feet. The country rocks are dense dull maroon and greenish-gray quartzites and argillites that probably belong to the Grinnell argillite. The entire right abutment and the stream bed are in rock, and rock extends up the left abutment for 50 or 60 feet. The strike is toward the southeast, and the dip is about 25°. An alluvium-covered terrace about 600 feet wide lies behind (west of) the left abutment.

With respect to dam-site utility this locality has two important defects: (1) a 100-foot dam would create little storage, and the section for a higher dam is not economical; (2) the Roosevelt fault, a high-angle upthrust, passes through the valley and probably is behind the left abutment, where it is concealed by alluvium.

Although evidence is not at hand to evaluate the state of activity of the Roosevelt fault at this place, the fault is one of a group, the other members of which have been active in Recent geologic time, and it also should be regarded as potentially active. The presence at this locality of a fault of this character creates a serious problem. Its position is probably such that if a low dam (100 feet) were built, the inlet of the diversion tunnel would lie in or just east of the fault. A high dam (200 feet) would require excavation but would have the advantage of making it possible to place the tunnel inlet west of the fault in the Flathead Range block. Diversion at the higher level (4,100 feet) would also develop greater storage in the Middle Fork

[15] Erdmann, C. E., Dam-site reconnaissance of Middle Fork of Flathead River, for 4 miles upstream from mouth of Bear Creek, U. S. Geol. Survey, unpublished memorandum, Sept. 17, 1937.

and would increase the available head for power at the tunnel outlet to about 550 feet. The tunnel might also be slightly shorter.

The tunnel outlet unquestionably will fall east of the Flathead fault, which cuts the west base of the Flathead Range. Smaller intermediate faults may also cut the strata of the range, but their presence has not been determined. The direction of movement upon either the Flathead or Roosevelt fault is probably nearly vertical and such that, if either became active, there would be a tendency for change in the tunnel gradient through eastward tilting of the Flathead Range block.

Movement upon the Roosevelt fault might seriously affect any type of dam built at this locality, the probable results being a shear in the left abutment and eastward tilting of the dam.

These probabilities seriously restrict the type of dam suitable for this site, and they should be subjected to further investigation before a decision is made to construct a dam here. The obvious choices are a full-gravity section, if it can be placed without crossing the fault, or a rock-fill dam if it must cross the fault. Either one should be so designed as to accommodate the maximum discharge of the river in case flow through the tunnel should be interrupted.

In my opinion, the general situation for the development of these supplementary projects is so unfavorable that they need be given no further consideration at this time. Should restriction of the Middle Fork of Flathead River ever prove desirable, other localities not directly affected by faulting and giving a greater measure of storage and control of the river can be suggested.[16] They could not, however, be incorporated in the Hungry Horse project.

ACKNOWLEDGMENTS

Many thanks are due the members of the Geological Survey with whom the writer was associated in the field. B. E. Jones, chief, Water and Power Division, has given the fullest cooperation in connection with the geophysical investigations. W. C. G. Senkpiel and Arthur Johnson, under whose supervision the river, dam site, and special surveys were made, have at all times aided and encouraged the topographers in the painstaking task of making maps that represent adequately the relationships between the land forms and the geology. Roland K. Thies assisted with the geophysical work in 1934 and 1935. Allan Sollid and his party contributed to the seismic work in 1936. A. F. Bateman, Jr., assisted with geophysics and geology in 1935. John S. James was the writer's personal assistant in 1934, and Garvin Hurwitz was geologic assistant in 1935. J. G. Crawford made and

[16] Erdmann, C. E., Alternative plan for control of Middle Fork of Flathead River and recommendations for additional river surveys upon that stream, Flathead County, Mont. U. S. Geol. Survey, unpublished memorandum, Sept. 17, 1937.

reported on analyses of the river waters and of the fresh and weathered rock from the dam site. He has assisted also in experiments on the solubility of the foundation rock. W. S. Burbank kindly allowed the use of petrographic equipment for the microscopic examination of these rocks. Miss Ninetta Davis assisted in the preparation of the illustrations.

GEOLOGY

STRATIGRAPHY

The rock formations of the lower part of the valley of South Fork Flathead River show great contrast in age and lithology. The bedrock consists of a thick assemblage of very ancient (pre-Cambrian) sedimentary rocks called the Belt series. Exposures of these rocks are abundant in the mountain ridges and flanks, but in the valleys the old rocks are partly covered by much younger and softer formations—Tertiary lake beds, glacial deposits of several kinds, and Recent alluvium. The general descriptions given below afford a background for discussion of the structural features and for consideration of some of the special characteristics that are involved in the geologic problems of the dam and reservoir sites.

BELT SERIES

The rocks of the Belt series are divisible into several mappable units or formations. (See fig. 4.) The oldest of these in South Fork Valley is the Grinnell argillite; it is overlain conformably by the Siyeh limestone, which, in turn, is overlain by the Missoula group. Their boundaries are transitional in this district. Formation identification is difficult in small exposures because, with few exceptions, the lithologic variation within any formation may duplicate practically all facies of the inclosing formations.

GRINNELL ARGILLITE

The Grinnell argillite consists of more than 2,000 feet of thinly laminated, massive, dull-reddish and greenish-gray argillite. It does not directly affect conditions in the Hungry Horse dam and reservoir site. According to Clapp [17] it crops out just east of the Flathead fault and makes the base of the west escarpment of the Flathead Range. This investigation, however, has shown that the Siyeh limestone forms the base of the north end of the range. (See fig. 4.) Strata equivalent to the Grinnell argillite are exposed in Bad Rock Canyon on the main Flathead River. These strata are called Ravalli argillite. Clapp [18] states that the Ravalli is equivalent to the Grinnell and the underlying Appekunny argillites.

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[17] Clapp, C. H., op. cit.
[18] Clapp, C. H., op. cit., p. 22.

SIYEH LIMESTONE

The sequence of rocks here designated the Siyeh limestone has been described by Clapp and Deiss.[19] It consists of two thick, massive bodies of impure limestone or dolomite, separated by a thinner westward-lensing body of reddish argillite. The upper member is known in various localities as the Upper Siyeh limestone, the Blackfoot limestone, the Helena limestone, or the Wallace limestone. The middle member has been called the red band in the Siyeh or, where more fully developed, the Spokane formation. The lower member has been called the Lower Siyeh or Newland limestone. The Spokane formation has not been recognized in the Hungry Horse reservoir area. The undivided formation in the area described in this report will be called the Siyeh limestone. Daly[20] has applied this name to equivalent strata in the MacDonald and Galton Ranges of British Columbia, which are the northwestern extension of the Swan and Whitefish Ranges of Montana.

THICKNESS

The Siyeh limestone lies conformably upon the Grinnell argillite and is transitional into the overlying Missoula group. The thickness of the formation in Glacier Park, including the red band, is about 6,100 feet. Daly reports a thickness of 4,000 feet in the Galton Range in British Columbia. A series of estimates made by the writer along the valley of the main Flathead, on the southeast face of Teakettle Mountain, indicate a thickness of 4,550 feet, and this figure is believed to be correct within 5 percent, or about 225 feet.

LITHOLOGY

The Siyeh forms the east flank of Columbia Mountain and is the only hard-rock formation present at the Hungry Horse dam site (fig. 4), where the gorge has been eroded into it to a horizon about 4,000 feet below the top.

In general the formation consists of dense, massive layers that range in thickness from about 1 foot to 14 feet and alternate with thin, irregularly-bedded splintery rock. Some of the thin-bedded rock is platy. Most samples of the rock effervesce feebly in cold dilute hydrochloric acid. The color of the massive layers and of the formation as a whole is a dull bluish or leaden gray. Thin individual beds, especially the argillaceous facies, show greenish tones. Some thin layers of very fine material are light gray and finely

[19] Clapp, C. H., and Deiss, C. F., Correlation of Montana Algonkian formations: Geol. Soc. America Bull., vol. 42, pp. 673–696, 1931.

[20] Daly, R. A., Geology of the North American Cordillera at the Forty-Ninth Parallel: Canada Geol. Survey, Mem. 38, pt. 1, p. 104, 1912.

striped with thin buff laminae. The weathered rock is commonly grayish buff or brown, varying from light to dark. Some of the dark appearance in the field is due to lichens.

A partial section, much generalized, is given in connection with the description of the dam site on page 90. The section given below was measured on fresh exposures on the north side of the road cut on United States Highway No. 2, southeast corner of sec. 5, T. 30 N., R. 19 W. It occurs near the top of the formation and appears to be typical although its thickness is but a fraction of the total. The excellence of the exposure makes it worth recording.

Partial section of the Siyeh limestone in cut on United States Highway No. 2, southeast corner sec. 5, T. 30 N., R. 19 W., Flathead County, Mont.

	Ft.	In.
Top of section not exposed.		
Limestone, shaly, silty, light gray, weathering drab; layers ¼ to ½ inch thick	6±	
Gouge zone, clay; fresh material, light gray; weathered clay, red and orange		10
Limestone, nodular; upper 6 to 8 in. massive. Nodular rock contains lentils of dense bluish-gray limestone ¼ to ½ inch thick and ½ to 4 inches long in lighter-gray, buff-weathering limestone	3	3
Limestone, dense, massive	7	5
Limestone, nodular type	2	10
Gouge zone, clay; fresh material, gray, weathering to red and orange		6
Limestone, "crinkly," dense, massive, dark bluish-gray, weathering buff. Cut by many short, thin, irregular veinlets of dark calcite; the presence of these veinlets gives the rock its crinkled appearance	14	6
Limestone, nodular	1	6
Limestone, dense, massive layer, somewhat crinkly	3	10
Limestone, thin-bedded, crinkly; some shear along upper surface	3	9
Limestone, nodular, massive	2	6
Limestone, gray, platy; beds ⅛ to ¼ inch thick		6
Gouge zone, gray clay		1½
Limestone, sandy, gray, thin-bedded		6½
Gouge zone, crushed rock weathered red at base		2–3
Limestone, nodular	2	
Limestone, dense, crinkly	5	6
Limestone, nodular	1	1
Limestone, soft, greenish-gray splotched with dull red; layers ¼ inch thick		4
Limestone, shaly; gouge zone of weathered clay and crushed limestone at base		4
Limestone, crinkly	2	
Limestone, dense, massive, thinly laminated, grading upward into crinkly type	4	6

Partial section of the Siyeh limestone in cut, etc.—Continued

	Ft.	In.
Limestone, dense, massive, gray; lower part nodular, with small lentils and blebs of bluish-gray limestone marking stratification. Lower bedding surface marked sharply by a ½-inch zone of weathered rock	13	
Limestone, dense, massive	3	
Limestone, nodular type	4	5
Limestone, massive, crinkly type	3	
Limestone, dense, massive, not nodular	3	
Limestone, massive; thinly laminated nodular type; stratification well marked by lentils of bluish-gray in drab limestone	6	
Limestone, dense, bluish-gray, crinkly type, grading up into noncrinkly evenly bedded limestone	1	
Limestone, massive, dense bluish-gray, crinkly veinlets	10	5
Gouge zone, red clay		¼-2
Limestone, bluish-gray, thinly laminated and bedded; locally weathers dull maroon to drab	4	7
Limestone, gnarly	1	
Limestone, dense, dark bluish-gray, crinkly	4	6
Limestone, dark bluish-gray, dense; in layers ¼ to ½ inch thick, alternating with brownish dolomitic layers 1 inch thick	1	6
Limestone, dense, massive, dark bluish-gray; upper part crinkly, with small dark veinlets	13	6
Limestone, gray, thin-bedded, nodular; grades upward	1	
Limestone, dense, massive, dark bluish-gray, with numerous short, irregular crinkly veinlets; upper surface sharp and distinct	11	6
Limestone, shaly, light gray, thinly laminated; upper surface ripple-marked		4
Gouge zone; limestone crushed and weathered; fresh material light bluish gray, weathering reddish or orange		3
Limestone, shaly, thinly laminated, drab bluish-gray, weathering drab		6
Limestone, massive, thinly laminated; dark crinkly veinlets ⅛ inch thick cut the bedding	6	3
Limestone, thin-bedded, light gray; layers ¼ inch to 2 inches thick. Grades upward	2	
Limestone, crushed zone		6
Limestone, massive, dense, dark bluish-gray, weathering buff. Laminations of ¼ to ½ inch marked by variations in gray color	4	6
Limestone, gray, thin-bedded, with gently undulating surfaces; nodular type; layers 2 to 10 inches thick	2	4
Gouge zone; reddish and yellow clay, with small angular fragments of limestone not more than ¾ inch long		1
Limestone, dense, light bluish-gray, weathering light ash-gray; layers ⅛ inch to 4 inches thick	1	

Partial section of the Siyeh limestone in cut, etc.—Continued

	Ft.	In.
Limestone, massive, contorted, gnarly. Dark bluish-gray dense limestone, sugary light-gray limestone, and buff to yellow-brown dolomite in various arrangements. Underlying strata show some evidence of shearing	3	10
Limestone, sandy, grayish-buff; upper part has a ¼-inch layer of finer-grained, lighter-gray rock that is weathered out in some places		2
Limestone, buff, weathered; vestiges of crinkly structure remain		2
Limestone, light gray, soft, chalky; slightly gritty; weathered yellow brown		1
Limestone, dense, massive, bluish-gray; top and base show a few thin, dark, crinkly veinlets that pinch out within 4 inches	7	10
Limestone, dense, massive, gray		1
Limestone, soft, more soluble than inclosing beds; contorted bedding; mud cracks		2
Limestone, soft, dense, massive; bluish-gray, weathering buff; breaks irregularly where not cut by joints; upper 6 to 8 inches weathers light buff; feels slightly sandy; top smooth, but undulates slightly	4	
Base concealed.	179	

Bedding in the Siyeh limestone is by more or less regular, persistent surfaces that separate differences of color, texture, and sedimentary structure. As all of the rock is medium hard, differences in hardness are not conspicuous. Color variations are due to mineralogical or chemical composition. Bluish gray indicating limestone and buff indicating dolomite are probably primary; shades of green suggesting the development of chlorite and sericite are secondary. Textural differences are expressed by thin layers, lentils, and laminae. The thickness of the laminae ranges from 0.5 to 5.25 millimeters. Each is distinctly clastic, with a marked variation in size of grain from top to bottom. The largest grains are 0.08 millimeter in diameter, but the average size is 0.02 to 0.03 millimeter. Concentrations of the hard minerals at the base of the laminae appear in thin, knifelike edges on the weathered surfaces of the rock. The surfaces of some beds are characterized by ripple marks and mud cracks, and others contain intraformational conglomerates. Nodular layers are common and occur in zones 1 foot to 4 feet thick, which seem to have a rhythmic succession. These beds are characterized by lentils of dense bluish-gray limestone ¼ to ½ inch thick and ½ inch to 4 inches long, in lighter-gray, buff-weathering stone. Some layers exhibit a peculiar internal, "molar tooth" structure, named from its resemblance to the grinding surface of an elephant's molar. Daly[21] has given careful attention to these special features.

The oldest primary feature in the massive rock is the bedding. In some places smooth surfaces show that the original mass has been cut by subaqueous injections of material that also shows bedding. These injections are due to slump or compaction of the sediment before induration. Subsequently, both bedding and injected tongues were cut by veinlets of medium dark limestone half an inch wide, whose boundaries are gradational. The veinlets also probably were formed during an early stage in the history of the rock. A later event now discernable is the injection of breccia veinlets and masses of light and dark gray-green limestone. Their pattern is complicated and shows sinuous flow lines along the bedding as well as across it. This material contains pyrite in stringers and irregular masses. Pyrite of the same appearance and probably of the same generation has replaced some of the sandy lentils, which show no connection with these veinlets. Metacrysts of pyrite and arsenopyrite also are present in the massive rock. The contacts of these breccia veins are well healed, and they probably record the first period of deformation to which the limestone was subjected after its induration. They do not appear to be related in any way to the structural features that were developed in the formation as it assumed its present attitude.

The mineralogic composition of the fresh rock is approximately as given below. The estimates were made by eye after a study of thin sections, with the exception of the carbonates, which were estimated from chemical analyses:

Composition of Siyeh limestone

	Percent
Quartz	25
Sericite	25
Feldspar	5
Calcite	10
Dolomite	33
Magnetite and pyrite	2
Total	100

The limestone can be scratched with a pin or a knife blade and is between 3 and 4 in hardness on the mineralogical scale. Its compactness permits it to be eroded into many irregular forms along the stream and to break sharp and clean along most joint directions. The formation is strong and rigid and will stand without confining pressure in

[21] Daly, R. A., op. cit., pp. 73–74, 104–105.

precipices thousands of feet high. Crushing tests of the rock are not available, but there need be no concern as to its strength; field evidence shows that the strength is in excess of 5,000 pounds per square inch for fresh rock, and the actual crushing strength of flawless specimens is probably 10,000 to 12,000 pounds per square inch. The average specific gravity of the Siyeh limestone is about 2.7, and, where highly magnesian, it may be a little more. Field tests with a refraction seismograph show that the speed of a sound pulse through the formation is 13,000 to 14,000 feet per second. A series of resistivity tests on the upper part of the formation near the southeast corner of sec. 6, T. 29 N., R. 18 W., where the dip is 54° NE., gave variable results, depending upon the orientation of the traverse with respect to the beds and whether they were dry or wet. For readings parallel to the strike, average values were: Dry, 143,916 ohm-cm; wet, 68,000 ohm-cm. For readings normal to the strike, average values were: Dry, 75,350 ohm-cm; wet, 54,950 ohm-cm.

The weathered rock is softer than the fresh, and there has been solution and redeposition of calcite, together with a loss of other soluble constituents, and some residual increases. The weathered rock is of finer grain, and bedding is broken and obscure.

CHEMICAL NATURE

The chemical nature of the Siyeh limestone is shown in the table following. Analysis A is of fresh rock from Hungry Horse dam site. Comparison with analysis F, which is probably typical of the formation along the international boundary, shows that the rock at the dam site has the same general character, but that it is decidedly more siliceous and aluminous. This is of definite advantage because it renders the rock more insoluble than ordinary limestone. Comparison of the average Siyeh, analysis G, with that of an ordinary limestone, H, and a typical dolomite, I, reveals some interesting differences. Most conspicuous are the much greater quantities of SiO_2, Al_2O_3, K_2O, and H_2O. This shows that the Siyeh limestone contains a hydrous potassium aluminum silicate, probably sericite. In its original form this material was probably some sort of clay. Analysis B is from the same bed as A, but the rock has been weathered. (See pl. 17).

Analyses of Siyeh limestone

	A	B	C	D	E	F	G	H	I
SiO_2	42.80	48.62	35.58	36.64	36.97	36.80	36.39	14.09	3.24
TiO_2	.22	.27	------	------	------	------	------	.08	------
Al_2O_3	6.40	9.90	3.40	4.24	7.59	5.92	5.07	1.75	.17
Fe_2O_3	1.76	3.16	1.56	.99	1.82	1.40	1.45 }	} .77	{ .17
FeO	------	------	.87	.57	1.12	.85	.85 }		{ .06
MnO	.03	.05	------	------	------	------	------	.03	------
MgO	6.03	5.96	10.09	4.38	8.38	6.38	7.61	4.49	20.84
CaO	23.78	16.93	19.72	25.79	16.28	21.03	20.59	40.60	29.58
Na_2O	.04	.03	.51	.49	1.04	.76	.68	.62	------
K_2O	.07	.04	1.21	.88	2.48	1.68	1.52	.58	------
Li_2O	------	------	------	------	------	------	------	Trace	------
H_2O-	.08	.04	.17	.22	.24	.23	.21	.30 }	} .30
H_2O+	.07	.04	2.93	1.87	3.11	2.49	2.63	[a].88 }	
P_2O_5	.03	.01	------	------	------	------	------	.42	------
C	------	------	.03	------	.08	.08	.03	------	------
CO_2	18.74	14.87	23.80	24.31	21.11	22.71	23.07	35.58	45.54
S	------	------	------	------	------	------	------	.07	------
SO_3	.19	.04	------	------	------	------	------	.07	------
	100.24	99.96	99.87	100.38	100.22	100.33	100.10	100.33	99.90
Sp. gr	------	------	2.741	2.748	------	------	------	------	------

[a] Includes organic matter.

A. Siyeh limestone. Left bank of South Fork of Flathead River. Fresh rock, 50 feet above water; 800 feet upstream from small rock island. Hungry Horse dam site. Analysis by J. G. Crawford.

B. Siyeh limestone. Left bank just below water surface on September 5, 1935. Same bed as A, but weathered; 800 feet upstream from small rock island. Hungry Horse dam site. Analysis by J. G. Crawford.

C. Siyeh limestone. Specimen from cliffs of Sawtooth Ridge, 1.5 miles east of Lower Kintla Lake. Daly, R. A., Canada Geol. Survey, Mem. 38, p. 75, 1912.

D. Siyeh limestone. Specimen from molar-tooth rock just west of Phillips Creek cascade, near Roosville post office. Daly, R. A., op. cit., p. 106. Analysis A.

E. Part of same specimen as analysis D, this report. Daly, R. A., op. cit., p. 106, analysis B.

F. Mean of analyses D and E.

G. Mean of analyses C, D, and E.

H. Composite analysis of 498 limestones used for building purposes. U. S. Geol. Survey Bull. 770, p. 564, analysis H.

I. Knox dolomite. A nearly pure dolomite from Ala. Analysis by W. F. Hillebrand, U. S. Geol. Survey Bull. 770, p. 579, analysis B. Described by I. C. Russell in Bull. 52, pp. 21, 24–25, 1889.

METAMORPHISM

The metamorphism to which the formation has been subjected is largely static. It has been just sufficient to cause recrystallization of the extremely fine-grained calcareous and dolomitic mud. Sericite has developed, and there has been incipient replacement of quartz and feldspar by the carbonates. Indeed, the feldspar itself may be a product of metamorphism. In some of the rock replacement has developed discontinuity in laminae 0.05 millimeter thick, but it has not been able to obliterate evidence of stratification between thicker laminae.

NOMENCLATURE

The rock of the Siyeh formation is difficult to classify. To all outward appearances it is a limestone; on the basis of mineralogy it may be called an impure dolomite; and chemical analysis indicates the presence of silica and alumina, substances not typical of the more usual limestones or dolomites. Insofar as field classification is concerned, no objection can be offered to describing the formation as a limestone, and this has been done. However, a more precise definition is desirable for engineering purposes, and in this report the Siyeh at the Hungry Horse dam site is defined as an incipiently metamorphosed, siliceous, magnesian limestone.

TRANSITION FACIES

The transition from the Siyeh limestone into the Missoula group is accomplished through a zone of variable lithology about 260 feet thick. On the south side of Lion Hill the change from the main body of dull bluish-gray rock begins with the appearance of gray-green limestone interbedded with greenish sandstones. The middle part of the zone consists of impure limestone with beds of green argillite and buff to green sandstone. The upper part of this transition is marked by the disappearance of the limestones, the greater abundance of green argillite with green to gray-black sandstone, and, finally, by the appearance of dull red or maroon argillites.

MISSOULA GROUP

The Missoula group forms the upper division of the Belt series and rests conformably upon the Siyeh limestone. The top of the group is everywhere truncated by faulting and has not been observed by the writer. Its thickness in the lower part of South Fork Valley is unknown but is very great, as indicated in fig. 4. Local variations in dip make a numerical statement impractical. In the basin of the North Fork of the Flathead, however, from Nicola Creek to Glacier View dam site along Big Creek, the partial thickness of the Missoula group from the top of the Siyeh limestone to the lower diabase sill is about 22,200 feet, and, if the strata in Huckleberry Mountain (north end of Apgar Mountain) are included, the total is about 25,000 feet.

The strata consist of thin-bedded, platy, reddish, greenish-gray and varicolored argillites and metargillites and thick, massive reddish and light-colored quartzites. All of the rock is clastic and bears evidence of shallow-water deposition. The sequence is unvaried, with the exception of the thin zone of dolomitic argillite and limestone described on pages 57–61, and subdivision into formations in this area has not been attempted.

The argillites are strong, tough, and elastic. Some of the thin quartzites have shattered under stress, but most of the rock is less fractured than the Siyeh limestone. Sound pulses through these strata have an average velocity of about 10,000 feet per second. The variations in apparent resistivity are considerable.

Average resistivity of rocks of Missoula group, in ohm-cm.

	Parallel to strike		Normal to strike	
	Dry	Wet	Dry	Wet
Red argillite	45, 400	35, 500	29, 500	34, 300
Green argillite	108, 400	29, 075	52, 850	36, 460

The lower part of the Missoula group forms the bedrock floor of most of the Hungry Horse Reservoir area and is present below the buried gorges, which were investigated for leakage possibilities. The following section was measured along the river in Flathead County.

Generalized partial section of lower part of Missoula group of Belt series on South Fork of Flathead River, in secs. 4, 5, 8, and 9, T. 29 N., R. 18 W., Flathead County, Mont.

	Feet
Top of section concealed.	
Argillite thin, irregularly bedded, and platy; predominantly dull red and maroon with some variegated dull-green rock and thin gray quartzites; ripple marks; thin films of red mud on the bedding surfaces of coarser mudstones and siltstones	1,500±
Argillite, predominantly dull green; thin, irregular beds ¼ inch to 2 inches thick. Some layers of medium-grained, gray-green sandstone	825
Dolomite, top concealed. Base of zone consists of very fine-grained, dense gray-green argillite; thin-laminated and thin-bedded gray limestone in small lentils and small irregular masses "intergrown" with buff dolomite. The rock appears rough and hackly and weathers a dull gray. The intergrowths of limestone and dolomite are much contorted and suggest molar-tooth structure. The thickness of these beds varies from 6 to 20 feet. This rock type continues, interbedded with greenish argillites of equal or greater thickness and occasionally a thin, irregular layer of pure gray limestone or sandy green limestone. There is much in the lithology of this zone to suggest the Siyeh limestone. The total thickness of the zone is believed to be about 500 feet	500
Argillite, green to grayish-green, with some thin layers of quartzitic sandstone; thin-bedded, platy	290
Argillite, dull red to maroon, with a few thin layers of dull green rock and some reddish-brown quartzitic sandstone. Argillite is ripple-marked and mud-cracked and shows clastic mica on bedding surfaces. Sandstones and quartzites are better jointed than is the argillite. This unit is more resistant than the green argillite, owing to the presence of quartzite, and makes a ridge. Tends to lens out to the southeast into the gray-green argillite	240

Generalized partial section of lower part of Missoula group, etc.—Continued

	Feet
Argillite, gray-green, with some brown bands of quartzitic sandstone. Argillite shows mud cracks and ripple marks. Rock is somewhat more massive (heavier bedded) than beds above	1,200
Argillite, dull red and maroon, with a few thin layers of green and some buff sandy bands; ripple-marked, mud-cracked, and contains mud lumps	165
Argillite, dull green, with a few thin limestone beds and some thin sandstones; well-bedded; surfaces wavy. Some beds are contorted. Argillite is mud-cracked, and some of the cracks are filled with sandstone. Sandy layers contain clay galls and blebs parallel to bedding	170
Argillite, dull red and maroon, like red zones above. Red apparently lenses out to northwest	70
Argillite, gray-green massive rock, like beds above, with some sandstone (quartzite) and limestone layers	160
Transitional zone from Siyeh limestone: An alternation of beds about 1 inch thick of gray limestone, greenish-gray argillite, gray quartzite, and buff-weathering dolomite. The whole is sprinkled with medium to coarse sand, which occurs in individual grains and lenses. Some of the lenses contain mud lumps. All beds are thinly laminated, and the succession of rock types is repeated over and over again. As the sequence reaches the upper part of the zone, the amount of dolomite and limestone decreases and is replaced with green argillite; near the top some faint red colors appear. This zone varies in thickness and character from place to place	260
Top of Siyeh limestone.	
	5,380

The section at Solander Creek is of interest because it is the only part of the Missoula group on the lower South Fork that has been noted as possessing distinctive characteristics. Presumably it represents a temporary recurrence of a shallow-water marine environment, whereas the greater part of the group in this neighborhood is probably littoral (strand flat) in origin. Some facies, notably the gnarly layers, strongly resemble some parts of the Siyeh limestone and, in small exposures, might be misidentified for that limestone. The position of this zone with reference to the top of the Siyeh limestone and its general character are represented by the dolomite unit in the above stratigraphic section of the lower part of the Missoula group. The following section gives further details.

Detailed section of dolomitic argillite and limestone exposed on right bank of South Fork of Flathead River at Solander Creek, south center sec. 5, T. 29 N., R. 18 W., Flathead County, Mont.

[Section measured August 25 and 28, 1937]

	Ft.	in.
Top concealed.		
An assemblage of beds similar to those below but poorly exposed. Thin gray quartzite, thin limestone, and thicker masses of buff dolomitic argillite, with nodules and lentils of bluish-gray limestone	60+	
Quartzite, dense, hard, thin, irregular layers; beds 2 to 6 inches thick; a deeper buff color than the bed below	6	
Quartzite, dense, gray, hard and sharp; beds 2 to 6 inches thick; finely laminated	4	
Quartzite, greenish, weathering buff; thin, dense, massive layers	7	
Quartzite, greenish-gray to gray; hard, dense, massive layers	6	3
Quartzite, dull greenish; layers 6 inches thick at base but thinning and becoming less massive at top	3	7
Limestone, dense, bluish-gray, weathering buff. Some dolomite	1	8
Quartzite, dull green, dense, massive	1	7
Argillite, weathering buff, and thin layers of lenticular limestone	4	
Limestone, bluish, weathering buff, and dolomite, with course gnarly texture	2	
Argillite, dolomitic, and thin, irregular, lenticular and nodular limestone in layers ½ inch to 2 inches thick	3	1
Quartzite, dull green, weathering dark; fine-grained, dense, massive, micaceous. Forms a ledge	6	
Argillite, dense, irregular beds ranging in thickness from ⅛ inch to 4 inches; some are finely laminated. Many thin lentils of dark-green argillite in olive-green rock, producing a ribbon structure. Layers of reddish argillite 1 inch to 2 inches thick are occasionally present	77	6
Limestone, gray, dense, massive, with a peculiar oolitic texture	1	
Limestone, with poorly developed gnarly texture	3	4
Argillite, greenish-gray, dense, massive, thinly laminated	1	
Limestone, in thin, wavy, contorted beds; gnarly structure poorly developed	2	4
Argillite, thin, dense regular beds; greenish-gray to buff, giving the rock a banded appearance	39	
Argillite, greenish, weathering buff; beds 4 to 10 inches thick. Surfaces finely marked with ripple marks averaging ¾ inch from crest to crest	4	
Argillite and limestone in thin wavy layers	3	7

Detailed section of dolomitic argillite and limestone exposed, etc.—Continued

	Ft.	in.
Argillite (quartzite) massive; top ripple-marked		2½
Argillite (quartzite) massive; top ripple-marked		7
Argillite (quartzite), in finely laminated 2-inch layers; upper surface marked with ripples 1½ inches from crest to crest		9
Argillite, gray-green, weathering buff; dense, massive	1	3
Argillite, thin, irregular platy layers		9
Argillite, dense, massive		9
Limestone, intraformational breccia	1	5
Argillite, gray-green, weathering buff; thin, dense layers; surface irregular and mud-cracked	3	6
Limestone, gnarly	1	
Argillite, dolomite, and limestone (40 percent), thin interbedded. Top current-marked	5	
Argillite, dolomitic, with about 15 percent limestone in thin lentils. Dense, massive, predominantly buff	2	11
Argillite, dolomitic, thin, platy layers	1	5
Limestone, gnarly	1	6
Argillite, greenish-gray, dense; interbedded with bluish-gray lenticular limestone	2	6
Argillite, greenish-gray, dense, massive. Top shows current ripples	2	2
Argillite, greenish-gray, dense; interbedded with bluish-gray lenticular limestone	6	
Argillite, greenish-gray, dense, thin, platy beds	1	6
Argillite, greenish-gray; in a layer about 6 inches thick that grades upward into a medium-textured, gnarly mixture of limestone and dolomite	1	
Argillite, dolomitic, and limestone in thin wavy beds ½ inch to 4 inches thick, with an occasional layer showing intraformational limestone breccia	5	
Limestone and dolomitic argillite in coarse-textured gnarly structure. Limestone lentils are much contorted. Rude suggestions of bedding in the massive layer	1	3
Argillite and limestone, interbedded. Thin (¼ to 1-inch), wavy layers with a few lentils and nodules of limestone. Top is marked by a 4-inch layer of finely laminated gray argillite	1	7
Limestone and dolomitic argillite, interbedded; thin, massive, persistent layers. Some nodular limestone	1	2
Argillite, greenish-gray, massive		4
Limestone and dolomitic argillite, interbedded; thin, massive, persistent layers. Some nodular limestone	2	6
Limestone and dolomitic argillite in coarse-textured, gnarly structure. Limestone lentils are much contorted. Rude suggestions of bedding in the massive layer	2	6
Limestone, nodular; small lenticular nodules in a matrix of greenish dolomitic argillite		5

Detailed section of dolomitic argillite and limestone exposed, etc.—Continued

	Ft.	*in.*
Argillite, greenish, with a few thin limestone lentils (¼ inch by 6 inches) at top		6
Limestone, nodular, small lenticular nodules (¼ inch by 1 inch to ½ inch by 3 inches) in matrix of greenish dolomitic argillite		7
Limestone, bluish-gray, and buff-weathering, greenish-gray dolomitic argillite, in thin (¼ inch to 4 inches), platy, alternate layers. Limestone makes up about 25 percent of unit, and the layers are fairly persistent, but some show irregularities on their upper surfaces and some are lenticular. Bedding surfaces generally smooth, but a few are mud-cracked, and some show oscillation ripples	24	6
Limestone, coarse-textured, gnarly structure; massive, heavy layers. Outcrop partly concealed by sand	21	7
Limestone, dolomitic, dense, massive; single layer	1	
Limestone, dolomitic, weathering buff; thin, dense, platy layers; effervesces feebly with dilute HCl	2	
Limestone, coarse-textured gnarly structure; massive, heavy-bedded layers 1½ to 4 feet thick. Blue limestone makes about 40 percent of mixture, and buff-weathering dolomite the remainder	5	6
Argillite, dolomitic, gray-green, weathering khaki-colored, with a small amount of bluish limestone in short lentils; thin, platy, finely laminated layers	17	4
Argillite, dolomitic, irregularly bedded with moderate amount of gnarly rock that contains more bluish-gray limestone than unit below	5	2
Argillite, dolomitic, gray-green, weathering buff, with occasional thin, short, lentils of dense bluish-gray limestone; bedding thin and regular. Outcrop largely concealed by sand	18	6
Limestone, dolomitic. Irregular nodules and lumps of dense, bluish-gray limestone, apparently once plastic and perhaps lenticular (1 inch by 3 inches), are in a matrix of dense khaki dolomite, which forms lenticular layers that pinch and swell along the strike. The layers probably average 18 inches in thickness. In some of them intraformational deformation has gone so far as to produce gnarly zones, in which the mixture of bluish-gray limestone and buff dolomite has a graphic texture. These layers are separated by equal thicknesses of massive buff dolomite	27	3
Dolomite, brownish-gray, dense		1½
Dolomite, calcareous, khaki-colored, with an occasional lentil of bluish-gray limestone. Effervesces feebly	1	
Argillite, light greenish-gray, weathering buff, with some faint shades of purplish-gray toward the top; thinly and irregularly bedded, becoming more massive toward the top	14	

Detailed section of dolomitic argillite and limestone exposed, etc.—Continued

	Ft.	*in.*
Argillite, dolomitic, less calcareous than beds below; bedding massive, regular, dense, resistant	2	
Limestone, dolomitic, dull greenish-gray, weathering buff. Effervesces feebly in cold dilute HCl	3	8
Limestone, dull gray-green, weathering yellow-buff in lower 2 feet. Thin, irregular, hackly layers 1/16 to 1/2 inch thick. Effervesces feebly in cold dilute HCl. A 1-inch layer of bluish-gray intraformational limestone conglomerate occurs 3 feet above base of unit	4	6
Limestone, gray, finely granular		2
Siltstone, calcareous, gray-green, weathering buff to reddish-brown; layers 1 inch to 4 inches thick with gently undulating surfaces showing ripple and current markings	2	10
Argillite, gray-green, weathering buff; dense, massive, indistinctly laminated layers about 2 inches thick	5	
Argillite, like unit above; units separated by rather distinct breaks	5	6
Argillite, as above	5	
Argillite, as above	6	
Argillite, as above	6	
Quartzite, light-gray to dove-gray; layers 1 inch to 6 inches thick, with occasional layers of gray-green argillite 1/2 to 1 inch thick	5	
Argillite, gray-green, weathering buff; thin, wavy beds conforming to undulations of the algal heads below		10
Algal bed, calcareous. Thinly laminated, rounded, domelike forms, about 18 inches in diameter and about 9 inches in height. The heads consist of thin (1/8- to 1/10-inch) hard brownish layers, standing in relief and separated by equal layers of bluish-gray limestone. Locally there is some calcite		9
	471	5
[The base of the algal bed is arbitrarily assumed to be the base of the dolomitic limestone section at Solander Creek, described on p. 56 as the third unit of the generalized section of the Missoula group in this vicinity. The two units described below are at the top of the greenish-gray argillite listed as the fourth unit of the general Missoula section.]		
Argillite, probably dolomitic, grayish-green; weathering buff, dense, massive. Bedding marked by lentils (1/4 inch by 6 inches) of hard, dense rock that does not weather buff. Top bed slightly irregular	4	
Argillite, gray-green, dense, irregularly bedded; surface rough and hackly. Less resistant than enclosing members	12+	
Grand total	487+	

TERTIARY

OLIGOCENE (?) AND MIOCENE (?)

The floor of the Hungry Horse reservoir site above the mouth of Fire Creek is covered with an unknown thickness of soft, partly indurated, nonfossiliferous sediments of Tertiary age. Their exact horizon within the Tertiary is unknown, but by analogy to similar formations near Missoula, Mont., which are assigned to the Miocene and later, and on structural grounds, they are here referred tentatively to the Oligocene and Miocene. A similar formation that crops out in the valley of the North Fork of Flathead River upstream from Huckleberry Mountain has been named by Daly [22] the Kishenehn formation.

South Fork Valley, as originally formed, was probably a separate structural basin, with its own temporary base level and system of internal or centripetal drainage. A similar basin probably occupied the present valley of North Fork of Flathead River upstream from Glacier View Canyon and north of the Camas Creek-Fish Creek divide in Glacier National Park; and an extension of this basin, or perhaps another basin, occupied the valley of the main Flathead River in the vicinity of Coram. Streams tributary to these basins began to aggrade their floors, and, as time went on, the thickness of the deposits became so great as to fill the basins and overlap the rims or divides, resulting in an integration of drainage.

The sediments laid down in South Fork Valley were dominantly lacustrine, with an occasional paludal or swamp phase, during which coal-forming materials were deposited. Neither the top nor the bottom of the series has been observed. In the vicinity of Coalbank in the northeast corner of sec. 3, T. 27 N., R. 17 W., the strata consist of thin-bedded clays, siltstone, sandstones, and lignites. Fossils were not found. Detailed descriptions of the coal-bearing rocks are given in the section of this report describing the economic geology of the Hungry Horse reservoir (pp. 111–114).

In the valley of the North Fork and on the Middle Fork of the Flathead River the coal-bearing rocks are overlain by red beds also of Tertiary age. The important localities at which the red beds have been observed are on the forks of McGee and Camas Creeks, SE¼SE¼ sec. 7, T. 33 N., R. 19 W., Glacier National Park; NW¼NW¼ sec. 20, T. 31 N., R. 19 W.; and on the Middle Fork of the Flathead in NE¼NE¼ sec. 7, T. 30 N., R. 16 W. At the last-mentioned locality the beds dip northeastward into the Roosevelt fault and appear to contain short, thin trains of coarse, angular outwash, suggesting a climate more arid than that prevailing during the deposition of the coal-bearing rocks. Evidence of an arid epoch at about the time these beds are believed to

[22] Daly, R. A., op. cit., pp. 86–88.

have been deposited has been observed by Bradley[23] in south-central Wyoming, and the same climatic conditions may have prevailed in northern Montana, where physiographic conditions were probably somewhat similar. There has, as yet, been no opportunity to study these little-known formations with the detail they merit, but, unquestionably, such investigations will yield much information on the middle and late Tertiary history of the upper Flathead country.

The constructional surface upon which the integration of the drainage was accomplished must have been of rather great linear extent, perhaps as much as 150 miles, but the width was comparatively narrow, probably not exceeding 10 or 12 miles; and it must have attained such a relatively high level that the relief of the inclosing hills appeared low. Indeed, it is possible that some of the erosion surfaces upon the surrounding mountains may have contributed sediments to the basins. Remnants of these soft strata have been noted at altitudes as high as 3,900 feet, 600 to 800 feet above present stream level, but in all probability the surface of integration stood even higher.

At the end of the period of stream integration downcutting began, and the master streams entrenched themselves into the poorly consolidated sediments as fast as the hard rock of the spillway over the barrier range could be reduced. At some places entrenchment was so deep that the rivers were soon superimposed upon the hard pre-Cambrian terrain, wholly out of adjustment with the attitude of its rocks and buried topography. Presumably superimposition was well established prior to the recurrence of movement on the Flathead and Roosevelt faults, which deformed the Tertiary lake beds and developed the present mountain topography. This process of superimposition was responsible for the initiation of the course of the South Fork of Flathead River between Columbia Mountain and Lion Hill and enabled the stream to maintain itself there during the tilting of the Swan Range block, and to erode the gorge in which Hungry Horse dam site is situated.

PLEISTOCENE

Geologic mapping in the Flathead River Basin in the neighborhood of Hungry Horse dam site has revealed at least two, perhaps three distinct sheets of till or boulder clay, interglacial and postglacial river deposits, and glacial lake beds.

The routes of the most ancient glaciers are not certainly known, but from observations of their deposits at scattered localities it seems probable that they followed the same paths as the most recent or Wis-

[23] Bradley, W. H., Geomorphology of the North Flank of the Uinta Mountains: U. S. Geol. Survey Prof. Paper 185–I, pp. 176, 184, 1936.

consin ice. The courses of the Wisconsin glaciers can be outlined in considerable detail by means of their deposits and their influence upon the present day topography. The South Fork glacier originated in local ice fields in the mountains to the south of the Hungry Horse project, and, protected by high valley walls and the arrangement of the mountainous topography at the mouth of the valley, moved down valley to the northwest. This direction of flow was opposed to the general trend of movement of the main body of the Wisconsin Cordilleran ice that came southward from Canada through the Rocky Mountain Trench to the west of the Swan and Whitefish Ranges. A smaller lobe descended North Fork Valley and united with the South Fork glacier near the mouth of Abbott Creek, whence it was deflected through Bad Rock Canyon of the Flathead River, uniting with the main ice lobe just east of Columbia Falls. Thus, except for the probably brief period when the glacier in the Rocky Mountain Trench pushed over the summit of Teakettle Mountain (barometric altitude 5,940 feet), there was no opportunity for contamination of the South Fork till with drift from the north.

Glacial deposits, stream-borne materials and lake beds related to the ice sheets bury the bedrock floors of the principal river valleys to depths of 200 feet or more and obscure the earlier drainage patterns. They may thus conceal ancient gorges leading from basins now contemplated for use as storage reservoirs, and their arrangement, composition and permeability will determine the amount of leakage through these gorges. Furthermore, they have been deformed by comparatively late movements on the great faults that block out the mountain ranges, some of which may still be active with possible future harmful effect on dams in their vicinity. It is evident, therefore, that the glacial deposits of the region merit detailed study.

On the main Flathead River the common relationship of the older boulder clays to the younger deposits is illustrated by the partial sections that follow:

Partial section of glacial and interglacial deposits on left bank of Flathead River, center of NE 1/4 SE 1/4 sec. 5, T. 30, N., R. 19 W., Flathead County, Mont.

Top of bank.	
Wisconsin till:	*Feet*
Stiff, buff-colored boulder clay; grades into drift below	20
Stratified drift; layers of unsorted grayish-buff silty clays and gravels in beds 2 to 3 feet thick, that dip downstream at low angles. The silt beds commonly contain a scattering of small, rounded stream pebbles. The gravels are concentrated in separate layers	12
Bed of rounded boulders, some of which are as much as 12 inches in diameter. Marks base of zone	2–3

Partial section of glacial and interglacial deposits on left bank of Flathead River, etc.—Continued

	Feet
Interglacial stream gravels of Sangamon (?) age:	
Smooth, rounded pebbles and cobbles of hard, dense argillite and quartzite in a sand matrix cemented by lime; some shingle. Extensive springs of water, high in lime content, flow from the base of the overlying drift, and where the face of this deposit is well washed, the gravels appear to predominate. This deposit is evidently related to an interglacial stage of Flathead River	66
Boulder clay. Age unknown, but probably Kansan:	
A much weathered, unsorted, heterogeneous mass of rounded to subrounded pebbles and cobbles of argillite, siltstone, and quartzite of Belt age, in a matrix of sand and clay. In the coarser grades the fragments range in size from 1/8 inch to 10 inches. Angular fragments are not common, and there is a noticeable absence of limestone. Some of the argillaceous pebbles show glacial striae on smooth faces; others are crushed and fractured. The general color of the exposure is buff, owing to an overwash of calcareous tufa from the springs above. The matrix is variable; it shows masses of light-gray and blue clay and brownish sand. The original greenish and reddish colors of the gravels are much subdued. This material is soft and sticky and is thoroughly saturated with water at this locality. The cement of the argillite and quartzite is removed to such a degree that these normally hard rocks cut like cheese with a knife or pick, or crumble between the fingers. The top of this deposit is regular and locally shows no relief. The base is not exposed	48±
Recent alluvial cone:	
The foregoing deposits are partly masked in the bluff by a postglacial alluvial cone composed of a loose, unconsolidated mass of boulders derived from the formations exposed above, with local incrustations of calcareous tufa. Its base is marked by the river. The main body of the cone stands 15 feet above river surface, and the apex rises 30 feet above the river	15±
River surface as of Sept. 24, 1935.	
	164±

Since the preceding section was measured, a small landslide about 200 feet downstream has created a new exposure of the old glacial deposits. Its top is essentially at the same elevation above river level as the top of the weathered boulder clay in the measured section. However, instead of being overlain by fresh, cemented gravel, the upper part of the till grades into a 4-foot lens of soft, medium- to fine-grained gray-white sandstone that carries a few scattered cobbles and pebbles. The upper surface of the lens shows slight irregularity and evidence of erosion. Resting upon it is about 4 feet of homogeneous sandy brick red clay. This red clay overlaps the gray pebbly sandstone and rests upon the boulder clay at the west (downstream) end of the exposure. The base of the clay bed is nearly a plane but in some places a short, thin tongue projects into the sandstone, and small lentils of clay occur within the sandstone just below the top. The boundary between the red clay and gray sandstone has a visible dip component of 13° N. 20° E., that carries it below the base of the adjacent measured section, but at intermediate distances the contact with both the overlying and underlying boulder clay may be seen. This dip may be because of slumping, but more or less widely separated deposits of equivalent or lesser age show dips of approximately the same direction and amount. For example, near the forks of McGee and Camas Creeks, SE¼SE¼ sec. 7, T. 33 N., R. 20 W., a similar boulder clay has a dip component of 13° N. 75° E.; near NW¼NW¼NE¼ sec. 20, T. 31 N., R. 19 W., deposits of the earlier interglacial gravels have a visible dip component of 18° N. 10° W. The dip of the red clay bed may, therefore, be considered as authentic. This conclusion is significant in that it points to Pleistocene deformation and shows that there is a thickness of more than 100 feet of highly weathered boulder clay.

Farther upstream, the following section was observed.

Generalized section of glacial deposits on left bank of Flathead River, secs. 17 and 20, T. 31 N., R. 19 W. Flathead County, Mont.

	Feet
Top of bank.	
Wisconsin till.	
Not examined in detail	50±
Interglacial deposits of Yarmouth (?) age	
Clay (silt) and gravels. Stratified clays and interbedded gravels. Colors vary; dull brick red, dull gray green, gray and very light gray or white; locally banded and variegated. Carbonaceous streaks. Upper part, which locally has been prospected for coal, consists of reddish-gray silt containing logs of carbonized wood. Age unknown, but it probably antedates the interglacial Sangamon (?) river gravels. Relations are difficult to determine because of slumping. Thickness at least 50 feet, but may be 100 feet or more	50±
Gravel, containing lenses of brick-red silt, grading upward into red clay and silt banded with thin (6-inch) layers of gray-white, medium-grained sandstone that contain stringers of fine stream gravels at their base. Coarse gravel predominantly of stream origin, well shingled. Hard fresh, retaining original colors. Not cut by joints. Contains large, irregular lumps of an old boulder clay with soft, crushed pebbles in a moderately indurated matrix, with some secondary calcite	10±
Silt and clay, red, with thin layers of white sandstone, as above. Base not seen. Thickness unknown, but probably not great	15±5

Generalized section of glacial deposits on left bank of Flathead River, etc—Con.

	Feet
Boulder clay and stratified drift. Age unknown, but probably Kansan.	
Boulder clay. Matrix of brick-red sandy clay containing a few small pebbles	5
Boulder clay. Chiefly pebbles. Grades into bed above	2–3
Sandstone. Dull pinkish gray; grayish white on weathered surfaces and along joints. Hard, well lithified; sharp, harsh to the touch, fine- to medium-grained; dense and massive; 2-foot layer of conglomerate at base. Upper part shows neither bedding nor lamination, but an occasional pebble is irregularly oriented, as on end. Average size of rounded quartz pebbles is about 1 inch. Argillite pebbles leached a gray-white color. Cut by three well-defined sets of joints, all of whose surfaces are sharp and clean and frequently cut the pebbles. Fracture between joints rough and irregular	5–7
Boulder clay	2
Sandstone, fine-grained. Dull pinkish gray	3
Cobble layer. Concentration of coarser material suggests reworking of upper part of underlying bed by stream action. Boulders are as large as 1 foot by 2 feet; angular to subround; a few medium-sized round pebbles. No definite arrangement. Rocks all of Belt series, softened; colors, dull; matrix sand, silt, and gravel, dull reddish gray	1
Boulder clay. Unsorted, hetergeneous mass of stream-worn pebbles, rounded to subangular, of Belt sedimentary rocks, in a matrix of dull reddish and pinkish gray sand and silt with some gravel; matrix weathers to a dark reddish gray. Formation as a whole dark in color. Rude stratification marked by thin breaks of reddish sand. Boulders usually do not exceed 4 by 6 inches in size; in layers that show no sorting or other arrangement. Material weathered and softened, especially where under water. Surface rough and hackly, because of closely spaced, nonpersistent joints, of which three sets are present	2–3
Pebble clay. Matrix as above, but contains no cobbles and relatively few pebbles. Base concealed in river	2+
	150±

Study of these sections and supplementary information from other localities indicates a fairly continuous sequence of events that is believed to extend over most of the Pleistocene epoch. The following tentative assignments have been made in a preliminary effort to systematize the glacial geology of the region. Considerable revision may be anticipated as the investigation of these deposits proceeds.

580023—44——6

KANSAN (?) TILL

The boulder till at the base of the foregoing sections is tentatively classed as the earliest known Pleistocene deposit in this region because of its basal position in the most nearly complete stratigraphic sections so far obtained, its high degree of induration and weathering, the presence of deformed pebbles as well as structural deformation, and the incorporation of typical lumps of this till in younger interglacial stream deposits. Lithification appears to be local and to have affected chiefly the beds of sand rather than the clayey matrix of the till. Weathering also is variable and seems to be most complete where the deposits are washed continually by the water of springs or by the river. It is doubtful, however, if the initial softening of the argillite pebbles was due to present conditions.

The mechanical composition of a specimen of the Kansan (?) till from the left bank of Flathead River near the center of the NE¼ SE¼ sec. 5, T. 30 N., R. 19 W., is given in figure 3 and in the table on page 76. All of the material appears to be of Belt origin. Measurements of the resistivity of the formation were made at this locality. The surface of the exposure was wet and partly covered with travertine. The free surface gave a value of 10,650 ohm-cm. for a 20-foot interval, and the travertine-covered surface gave 8,615 ohm-cm. for a 30-foot interval. The difference is probably due to the greater amount of mineralized water pouring over the travertine. (See fig. 7, analysis 4.)

INTERGLACIAL DEPOSITS OF YARMOUTH (?) AGE

An early Pleistocene interglacial stage is believed to be recorded by the fluviatile gravels and lacustrine clay and silt that occurs between probable Kansan (?) and known Wisconsin drift on the left bank of Flathead River in sec. 20, T. 31 N., R. 19 W. The character of these beds suggests that they were laid down in an arm of a ponded body of water, which may have been an interglacial predecessor of the late Wisconsin glacial Lake Missoula.

The top of the formation has not been observed, and the total thickness is unknown. Deposits of a soft, unlithified red till, that may be Illinoian, crop out just across the river in SE¼ SW¼ sec. 17, T. 31 N., R. 19 W., and general structural relations suggest that this till overlies greenish, reddish, and lignite-bearing silts. The relationships of the formations are obscured by land slides, but the impression received from going over the ground is that the ice that deposited the red till reworked the upper part of the lacustrine silts. Another indication of the age of the silt is the presence of carbonized wood and thin noncommercial beds of lignite, the development of which requires considerable time.

ILLINOIAN (?) TILL

Deposits of reddish boulder clay, definitely older than the Wisconsin stratified drift but of unknown relationship to the old, deeply weathered till and the red till on the main Flathead between the head of Coram Canyon and the mouth of the Middle Fork, are exposed at a number of localities in the valley of the South Fork or in its lower tributaries, as Hungry Horse Creek, Fire Creek, and Riverside Creek. The last-named localities are separated by several miles, and it has not been possible to correlate the reddish till in each of them by direct tracing. On the basis of their relationship to the young buff Wisconsin drift, their situation in limited areas protected from the principal erosive effect of the last glacier, and their composition and color, the reddish tills on Riverside, Fire, and Hungry Horse Creeks are believed to belong to the same till sheet. As these deposits and deposits of Kansan (?) till have not been found together, there is as yet no structural basis for determining their relative age. They are differentiated chiefly on the basis of weathering, the difference being so great that there can be little hesitation in concluding that the reddish till is very much younger than the Kansan (?) till.

Because of identical relationships with the younger buff drift, and similarity in color and weathering, this reddish till is correlated tentatively with the brick-red boulder clay on the main Flathead River in SE¼ SW¼ sec. 17, T. 31 N., R. 19 W., that occurs between probable Kansan (?) and known Wisconsin till sheets. This assignment indicates that the reddish till probably belongs to the Illinoian ice stage. In this report it will be referred to as the Illinoian (?) till.

The most accessible locality in which the relations to the younger glacial deposits are illustrated is in the vicinity of Riverside Creek bridge near the center of the SW¼ sec. 13, T. 29 N., R. 18 W. Here the Illinoian (?) till is well exposed on the left bank of the creek upstream from the bridge and in the road cut south of the bridge. Fresh, silty, buff drift of Wisconsin age rests upon the reddish till, the contact showing some evidence of minor channeling. Both drifts were trenched by Riverside Creek following the Wisconsin ice stage; and later, during the Lake Missoula epoch, the newly cut stream valley was filled with silt to such depth that both the red drift and the gray and buff Wisconsin were overlapped.

The Illinoian (?) till near Riverside Creek bridge is a dense, well-compacted boulder clay ranging in color from pinkish brown to dull maroon. The general appearance is that of a massive, earthy deposit, but when the loose soil is removed, textural differences and minor color variations appear. Stratification is developed locally. The coarsest material is of gravel size, and its amount and distribution are variable. Some of the gravel is rounded and of stream origin; the remainder is angular to subangular and has been derived from the bedrock by plucking. Movement of the clayey matrix, probably while being compacted by the load of Wisconsin ice, has polished some of the smoother rounded pebbles. Most of the pebbles, however, have slightly roughened surfaces and show a slight amount of weathering, so that knife-blade scratches make a thin incised line. The smaller pebbles crumble under a light blow of a hammer.

The matrix has a waxy or soapy feel when dry, and a hardness of about 1. Small blocks show spheroidal weathering. The fresh surface has a warm, pinkish tone and a finely granular or silty texture. This appears to advantage when the surface is slightly moistened. Most of the material is too fine-grained to identify with the unaided eye. There is, however, about 3 percent of a white, amorphous substance that appears as irregular specks. It does not react to dilute hydrochloric acid. Probably it is related to the superficial weathering of the mass. Also present are a few tabular flakes of white and black mica. Other minute black specks seem to be bits of coal, indicating partial derivation of the deposit from the Tertiary lake beds. The material is porous and absorbs about half its own volume of water, swelling rapidly until the saturation point is reached, when it breaks down to a flocculent, fluid mass. With lesser amounts of water the material works down to a plastic mass that has a tendency to crack in thin layers.

The resistivity of this material is next to the lowest encountered, probably because of its large content of clay and the abundance of iron oxide. Measurement on a 3-foot layer of clayey till gave an average value of 2,207 ohm-cm., and determinations on deposits containing more gravel range from 2,462 to 2,906 ohm–cm.

On the northwest bank of Fire Creek in the NW¼SW¼ sec. 3, T. 29 N., R. 18 W., a similar red boulder clay is exposed in a cut 40 feet high and 25 feet wide. Small rounded and angular rock fragments are embedded in a matrix of silty clay. The material resembles that exposed on Hungry Horse Creek but contains more rock. A short distance downstream the Wisconsin till is exposed in bluffs 100 feet high. This arrangement indicates that the Wisconsin till was deposited in a valley cut in the red till and confirms the age relations observed at other places.

The most extensive exposures of the Illinoian (?) till yet discovered are outcrops in bluffs 250 feet high on Hungry Horse Creek in sec. 29, T. 30 N., R. 18 W. The specimen taken for mechanical analysis (see fig. 3 and table, p. 76) came from the base of the bluff on the left bank of the creek in the NE¼SE¼ sec. 30. Larger outcrops occur on the right bank, 500 to 600 feet downstream from the fork with Emery Creek, in the NW¼NW¼ sec. 29. Except that they are on a

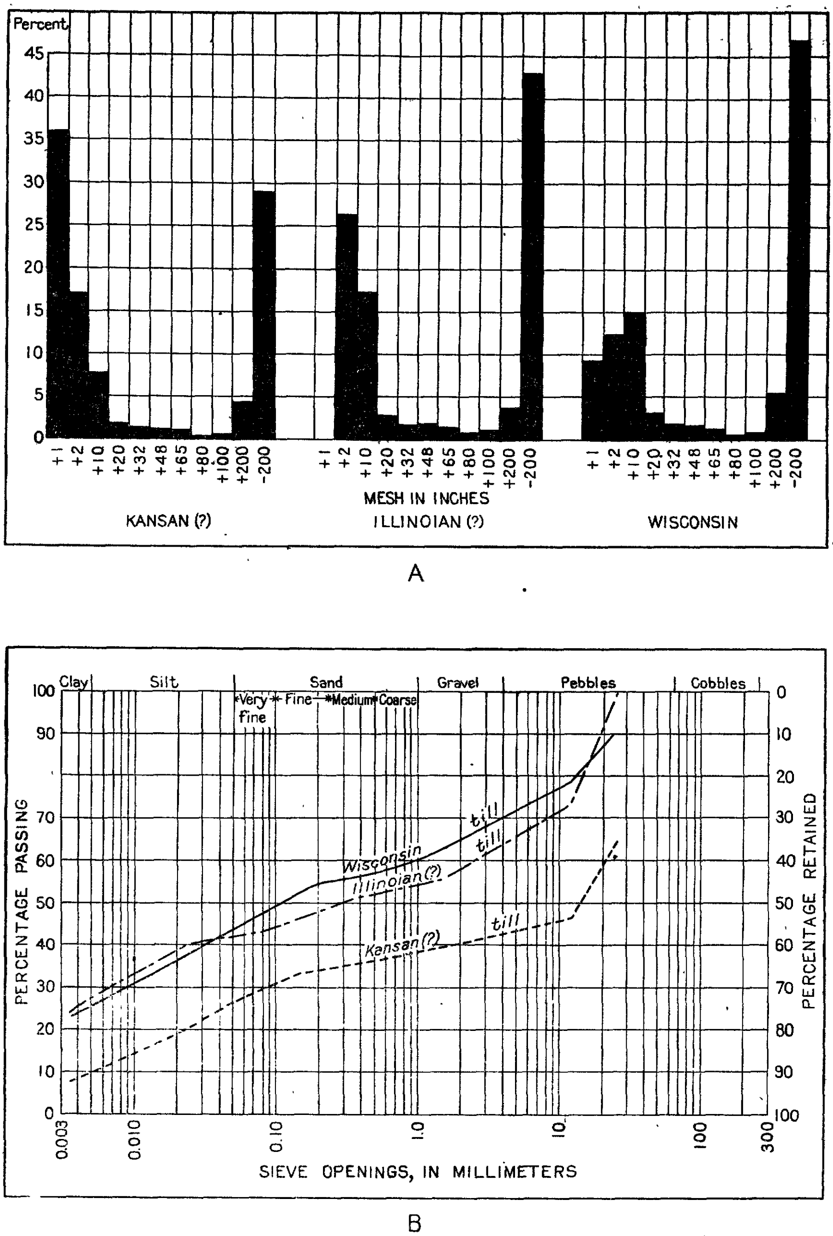

FIGURE 3.—Mechanical composition of glacial boulder clays: *A*, Histograms; *B*, Cumulative curves.

larger scale, the relations to the young buff till are the same as at Fire Creek. The valley of Hungry Horse Creek is straight and narrow from the mouth of Emery Creek for about 0.7 mile, below which it widens out into the broad valley occupied by the South Fork glacier in Wisconsin time. The reddish boulder clay does not appear in Hungry Horse Creek below this intersection.

The till on Hungry Horse Creek is unlike that on Riverside Creek in that it is lighter in color, more silty and stony, and has a harsh, gritty feel. Locally, it has the appearance of concrete aggregate, and the pebbles are so firmly embedded that they can be broken from the matrix only with difficulty. There is also less evidence of weathering in the pebbles, which are both rounded and angular and as hard and fresh as those occurring in the buff till. Resistivity measurements are not available, but the values would probably correspond to those from the stony red till on Riverside Creek.

INTERGLACIAL DEPOSITS OF SANGAMON (?) AGE

Extensive deposits of gravels of probable Sangamon age are well exposed on the left bank of the main Flathead River from the vicinity of the mouth of Abbott Creek upstream beyond the town of Coram. A stratigraphic section describing these gravels and indicating their relations to the older and younger glacial deposits has been given on pages 64–65.

A thick section of these deposits, overlain by buff drift, crops out on the right bank of the Flathead River in the southwest corner of sec. 8, T. 31 N., R. 19 W., about a mile below the mouth of the Middle Fork, and extensive exposures occur on both sides of the river in the neighborhood of the east quarter corner of sec. 19. The gravels rest unconformably upon the old weathered drift and the lignite-bearing silt. The size, form, and arrangement of the material are such that it must have been laid down by a westward flowing stream equivalent in power to the present-day Flathead River. The degree of sorting and the position of the beds with respect to the overlying stratified till suggest strongly that the stream had not yet been enlarged by the increased flow incident to the initiation of the Wisconsin ice stage.

On the exposures at the center of the NE¼ SE¼ sec. 5, T. 30 N., R. 19 W., resistivity measurements on the wet face of this gravel gave a value of 34,250 ohm-cm. for an interval of 24 feet. Seismic velocities, measured through a cover of Wisconsin drift, average about 10,000 feet per second, practically the same as for argillite of the Missoula group. This value is unusually high for a gravel deposit and is probably due to predominance of fresh argillite pebbles, cobbles, and boulders in a tight matrix of calcareous sand.

WISCONSIN DRIFT

The last of the great Pleistocene ice invasions took place during the Wisconsin stage, which may be subdivided into several substages. Numerous kinds of deposits were formed, some abundantly, and each defines clearly a specific phase. From their relationships a rather complete record may be reconstructed.

The Wisconsin stage began with an increase in vigor of the main streams, which were enlarged temporarily by melt water from the snouts of the advancing valley glaciers. With increased effectiveness of ice erosion the detrital load of the rivers increased, and deposition of fluvioglacial beds or stratified drift began. These deposits were eventually overridden and usually destroyed by the advancing ice, which probably made many local advances and retreats as the epoch moved toward culmination. Glacial scour occurred on a great scale, and heavy deposits of boulder clay were developed. The boulder clay covers most of the surface near the Hungry Horse project and is the principal substance choking the buried gorges east of the dam site. During the melting period of the glaciers there was fluvioglacial action similar to that accompanying their advance. These reworked materials and fresh deposits from the small tributary glaciers on the adjacent mountain slopes were piled upon the new surface. After the main South Fork glacier had retreated far up the valley, there was a short interval of intensive cutting by tributary streams. At the same time, far downstream, an enormous ice blockade was developing in the valley of the Clark Fork just above the present Lake Coeur d'Alene, in Idaho. As this barrier backed up the waters a lacustrine phase began, which culminated in the great Lake Missoula. The rising base level of this temporary lake reduced the gradient of the tributary streams, resulting in constructional terraces along them; and finally typical lacustrine silts began to be laid down. Their remnants have been noted at altitudes as high as 4,250 feet on the southeast flank of Teakettle Mountain. With the reduction of the lake level, stream action again predominated, and the country rapidly assumed its presence appearance.

The Wisconsin boulder clay rests indiscriminately on all older formations. Like the other tills it is a moderately graded mixture of coarse and fine material. Because of the thorough jointing and stratification of the bedrock from which they were plucked, the boulders are not large, and they are not common except near the bedrock surface. Perhaps the most noticeable occurrence of Belt erratics is on the Flathead River in the SE¼ sec. 32, T. 31 N., R. 19 W. At this locality several large boulder trains that were apparently derived from a lateral moraine on the right bank of the South Fork glacier have been washed by the stream, and there is a concentration of blocks too large for transport by normal river flow. Ordinarily the diameter of the boulders does not exceed 2 feet. In the unmodified boulder clay the total amount of coarse material, ranging in size down to fine gravel, is about 40 percent. An impression of larger amounts is produced in some places by surface concentration due to frost action. The larger pieces are angular; the intermediate sizes, the cobbles to coarse gravel, are subangular to subrounded and include considerable quantities of gravels from streams and some from the older glacial deposits; the fine gravel is distinctly angular. The specimen of Wisconsin clay selected for mechanical analysis came from a cut on United States Highway No. 2 near the center of NE¼SE¼ sec. 5, T. 30 N., R. 19 W., and its composition is given in figure 3 and in the table on page 76. Lithologically 65 to 70 percent of the coarse material is gray to gray-green argillite and quartzite; 15 to 20 percent, red argillite and quartzite; and 5 to 10 percent, limestone and dolomite. These amounts may vary widely, depending upon the proximity and character of bedrock. The quantity of limestone is less than might be expected. This condition is probably due to solution and weathering, which is responsible for the prevailing gray-buff color of the till. In a few localities on Hungry Horse Creek, fresh scars reveal a compact bluish-gray boulder clay, which is believed to be typical of the unweathered till.

The matrix consists of sand, silt, and clay. The sand, which makes up about 20 percent, consists chiefly of angular rock particles rather than mineral grains. The real binding material is the grayish-buff silt and clay, which may amount to 40 or 45 percent. When wet, it is moderately plastic and sticky. Occasionally it is present in thin, boulder-free, noncontinuous layers within the unstratified drift. Locally these beds may show considerable dip, as if they had been deformed by ice thrust. Usually, however, the fine material is packed tightly around the angular coarse material, and the deposit has a high degree of cohesiveness and internal friction. This fine material also allows much compaction, and the heavy loads of ice in their passage over the soft, yielding mixture have produced a very firm deposit. Sound pulses travel through it with an average velocity of about 7,000 feet per second, whereas unconsolidated gravels and sands give velocities of only 2,000 to 3,000 feet per second. The resistivity of the Wisconsin till varies within limits that embrace practically all other materials encountered, and truly diagnostic values cannot be given. A number of special tests have been made, and the results range from 12,200 to 248,000 ohm-cm. The variation is largely a function of the amount of moisture in the till, but the amount of clay and the composition of the included rock fragments also are important. Local tests are always a necessity during work on this formation.

DEPOSITS OF GLACIAL LAKE MISSOULA

Deposits of glacial Lake Missoula are fragmentary and scattered in the area covered by this report. The are surficial in character and are not involved in the problem of leakage from the Hungry Horse reservoir. For this reason detailed descriptions are not given. In general, the beds consist of thin, unconsolidated layers of fine sand and silt, varved clay, light-gray calcareous siltstone that may grade toward marl, and minor bar and beach deposits. Occasional ice-rafted pebbles are present in the finer sediments. The most extensive occurrence of interbedded silt and clay is in the W½SW¼NW¼ sec. 4, T. 29 N., R. 18 W., the top standing at an altitude of about 3,500 feet. A tough structureless body of marly silt crops out at Riverside Creek bridge in the center of the SW¼ sec. 13, T. 29 N., R. 18 W. Resistivity tests at this locality gave values of only 1,433 ohm-cm. for a 20-foot interval, the lowest encountered in this investigation.

The highest known remnant of these beds is on the southeast flank of Teakettle Mountain at an altitude of 4,250 feet, in the northwest corner of sec. 31, T. 31 N., R. 19 W. The deposit consists of fine, unconsolidated sand and silt and was evidently a bar or spit during the highest stage of the lake. The purer marls seem to be near-shore deposits in the vicinity of springs that issue from the Siyeh limestone. One such bed is on the right bank of the South Fork Flathead River. (See pl. 9, A–A′.) Another has developed in sec. 1, T. 30 N., R. 20 W., near the trackwalkers house in Bad Rock Canyon.

One other group of lake beds has been noted on the left bank of of Hungry Horse Creek, near the old Hungry Horse Ranger station, about 650 feet downstream from B. M. 3311, in sec. 31, T. 30 N., R. 18 W. The exact relations of these beds have not been determined. They do not resemble the deposits of glacial Lake Missoula and may be related to local ponding of Hungry Horse Creek.

MECHANICAL COMPOSITION OF GLACIAL BOULDER CLAYS

In the foregoing description of the Kansan (?) till, the Illinoian (?) till and the Wisconsin drift, reference has been made to composition, as determined by mechanical analysis. The specimens selected for study are not true samples because time and facilities precluded the examination of hundreds of pounds of material, but they are believed to be representative of the finer parts of the deposits. The histograms of figure 3, *A* present the data obtained by sieve analysis down to −200 mesh, and cumulative diagrams of figure 3, *B.* show the same information and also the composition of the −200 mesh material as obtained by hydrometer analysis. The two forms supplement one another, the former being of interest to the geologist and the latter to the engineer.

Comparison of figure 3, *B* with other curves [24] show that the Wisconsin and Illinoian (?) tills fall well within proposed limits in mechanical analysis for both graded and ungraded materials suitable for impervious sections of roll-filled earth dams and that the Kansan (?) till falls near the lower limit for graded material and partly below the limit for ungraded material. This is of importance in connection with the effectiveness of the boulder clay in preventing seepage through buried glacial gorges.

The percentage of particles of different sizes taken from figure 3, *B* is given in the table below. Cobbles and the next larger size, boulders, are present in the formations, but are not included in the tabulation.

Particle size in glacial boulder clays

	Wisconsin clay	Illinoian (?) clay	Kansan (?) clay
	Percent	*Percent*	*Percent*
Clay	25.5	27.5	10.0
Silt	18.0	15.5	16.5
Very fine sand	5.5	2.5	4.0
Fine sand	6.0	4.5	4.0
Medium sand	2.5	3.0	2.0
Coarse sand	3.0	2.5	1.5
Gravels	9.5	9.0	4.5
Pebbles	30.0	35.5	57.5
Total	100.0	100.0	100.0

With regard to grading, the curves on figure 3 all show some evidence of regular proportion by size, as is demonstrated by the tendency of the curves to be concave upward, to flatten toward the fine sizes, to steepen toward the coarse. According to grade the specimens rank as follows: Illinoian (?), Wisconsin, Kansan (?). Reference to figure 3,*A* and the table above shows that all are particularly deficient in sand sizes. However, compensation for this lack is supplied by the relatively large amounts of silt and clay. These groups contain the "effective sizes" that control the rate of movement of water through the material and the compactibility. According to Lee: [25]

> * * * the statement can be made that regularly graded material having a degree of fineness sufficient to include at least 3 percent of clay, or ungraded material containing at least 25 percent of clay, when thoroughly compacted, is practically watertight.

Review of the data shows that the Illinoian (?) and Wisconsin boulder clays are partly graded, with a clay content of more than 25 percent; in consequence, large masses, as valley fill, should have a

[24] Lee, C. H., Selection of materials for rolled-fill earth dams: Am. Soc. Civil Eng. Proc., vol. 62, No. 7, pp. 1025–1042, 1936.

[25] Lee, C. H., Idem, p. 1037.

high degree of compaction and impermeability and should effectively block seepage. The Kansan (?) till is less compactible and more permeable, owing to the high percentage of pebbles and cobbles. With the exception of the lacustrine silts, all the other glacial deposits are permeable, and their presence in valley fill would probably contribute to leakage if any considerable head of water were raised against the fill.

RECENT DEPOSITS

POST-LAKE MISSOULA GRAVELS

These beds are chiefly of stream origin. They cap river terraces 75 to 80 feet above the present stream levels and block the minor gorges in the dam-site area. They consist mainly of gravels reworked from the older deposits and are cemented by sand, tan silt, and lime, which is secondary and frequently confined to the upper part of the bed. In consequence, the softer underlying parts weather away, and large blocks of conglomerate break down. These gravels bear some resemblance to the interglacial river gravels, but are not so compact.

ALLUVIUM

Deposits of active alluvium, sand, and gravel are not abundant at the dam site because of the vigor with which the river sweeps through the gorge. Such deposits occur, however, at the head of the gorge in secs. 26 and 27, T. 30 N., R. 19 W., about 1½ miles above the dam site and are abundant from this point on upstream. They are loose and unindurated, and gravels and cobbles of fresh Belt rocks are more common than sand.

STRUCTURE

MOUNTAIN STRUCTURE

The mountain structure of this part of Montana consists of an alternating series of depressed areas and uplifted and tilted blocks, rectangular in pattern and having a general trend to the northwest. The apparent simplicity of this arrangement is misleading. The present mountain structure is the result not of one orogenic event but of a number of related movements that occurred at intervals throughout the Tertiary period. The youthfulness or height of the great ranges intimate that the mountain-building process may not be complete.

The following generalized sequence of orogenesis is based upon the Tertiary geologic history of northwestern Montana. The mountains adjacent to South Fork Valley must have been involved in one way or another. The antecedent events are omitted, and the account begins with the first positive movement in the development of the present ranges. This was probably a regional uplift that originated toward the close of Cretaceous time. Locally it may have been domal in character. The intensity of the folding increased with probable overfolding from the west, and the movement culminated in the great Lewis overthrust fault. This overthrust developed in early Eocene (post-Fort Union) time, and constituted the second important step in the building of the ranges. Accumulating evidence suggests that in the vicinity of the international boundary in Glacier National Park both the Lewis and the Livingston Ranges are underlain by the Lewis fault and that its displacement has a magnitude of not less than 40 miles. If this is true, it is conceivable that the Lewis overthrust may also underlie the Flathead Range and possibly South Fork Valley. The third mountain-building movement probably took place in middle Oligocene time. The deformation seems to have been characterized first by the warping of the Lewis overthrust and later by high-angle thrust faulting or upthrusting. The later movements resulted in the development of the structural valleys and the relative uplift of the mountain blocks. The important faults that date from this time are the Flathead, Swan, and Roosevelt faults, to mention only those in the region here considered. According to Clapp [26] these faults are older than the low-angle thrusts typified by the Lewis. In some places, however, as in North Fork Valley above Apgar Mountain, there seems to be evidence that they are younger. If Clapp's conclusions are correct, the age assignments of the second and third series of orogenic movements should be reversed. The fourth and last important orogenic event occurred probably in middle or late Miocene time, when there was renewal of movement along the margins of the structural valleys and deformation of the Tertiary lake beds. Evidence of minor uplift and tilting since the close of the Pleistocene demonstrates that crustal forces are still mildly active.

The Flathead fault lies at the base of the Flathead Range, passing a few miles east of Hungry Horse dam site (see fig. 4) and along the east side of the reservoir area. Its situation thus causes more concern than any other fault in the region, although the dam site lies in a block controlled chiefly by the Swan fault. The Flathead fault can be traced with considerable accuracy from the vicinity of Belton Point in sec. 24, T. 31 N., R. 19 W., southeastward to the southeast corner of T. 18 N., R. 10 W., beyond which it appears to die out. Among the localities at which the fault or its effects can be observed are the lower end of Dry Parks, near the northeast corner of sec. 10, T. 26 N., R. 16 W., the mouth of Black Bear Creek, southeast corner of sec. 16, T. 23 N., R. 14 W.; east of Mud Lake, sec. 25, T. 22 N., R.

[26] Clapp, C. H., Geology of a portion of the Rocky Mountains of Northwestern Montana: Montana School of Mines Mem. 4, p. 24, Dec. 1932.

14 W.; and at White River Butte, sec. 29, T. 21 N., R. 13 W. Northwest of Belton Point there is indirect evidence of the fault at least as far as Coal Creek, about 20 miles, making the total distance over which the effects of the fault can be recognized about 110 miles. Clapp [27] describes the fault as a steeply dipping, longitudinal strike fault of the upthrust type. In the structure section nearest the dam site the dip is about 75° to the northeast, the amount decreasing somewhat down dip. The upward movement is indicated as having occurred on the east side (hanging wall) of the fault. The stratigraphic displacement of the Flathead fault, as well as the others, is great. East of the dam site the Siyeh limestone has been thrown against rocks of the Missoula group, and farther to the southeast the Grinnell argillite has been brought up. This variable displacement probably ranges between 5,000 and 15,000 feet. Other less important faults are associated with these great fractures. Some of them are transverse and appear to be normal faults; others are parallel to the great upthrusts and may have the same general character.

Pardee [28] has mentioned the presence of a zone of faults in Wilson Valley (South Abbott Creek), and Campbell [29], on geomorphic grounds, has suggested the presence of a fault striking through the old location of the Hungry Horse ranger station and another at the west base of Pioneer Ridge, between sec. 16, T. 28 N., R. 18 W., and sec. 5, T. 27 N., R. 17 W. The present investigation has failed to show an important fault striking through the valley of the South Fork of Abbott Creek, and there is no fault at Hungry Horse dam site. There is, however, a wide shear zone just below the top of the Siyeh limestone in the west flank of Abbott Ridge and east flank of Lion Hill, about 5,000 feet east of the dam site.

The shear zone is well exposed in cross section in the new cut on the South Fork road near the north center of sec. 36. T, 30 N., R. 19 W. It begins just below the top of the Siyeh limestone and extends downward stratigraphically for at least 1,400 feet. This situation suggests that its position has been localized by the difference in elasticity between the brittle limestone and the more yielding argillite. Shearing is not uniformly distributed throughout this zone, and where it is absent there is usually intense jointing. At the above locality there is minor shearing just below the top of the limestone, but the most intense movement is confined to a layer about 200 feet thick beginning about 1,100 feet below the top of the limestone. Six distinct shears are visible, with gouge zones ranging in width from 1 or 2 inches to 6 feet.

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[27] Clapp, C. H., op. cit., plate 1.

[28] Pardee, J. T., Geology of dam sites on South Fork of Flathead River below Hungry Horse Creek, Flathead County, Mont.; U. S. Geol. Survey, unpublished report, 1928.

[29] Campbell, M. R., in Jones, E. E., Reconnaissance report of South Fork of Flathead River: U. S. Geol. Survey, unpublished report, Jan. 1924.

Their strike corresponds to that of the beds inclosing them, but they dip in the opposite direction at angles of 35° to 80°. Along a horizontal surface, such as the road grade, they appear at intervals of 15 to 125 feet. Between them the strata are closely jointed, many of the intervals being as little as 6 inches. Several distinct movements can be identified, the principal thrust component being from the southwest. In one system, generally striking N. 70° E. and dipping about 80° NW., the shears are spaced at intervals of 6 to 10 feet, and each shows an inch or two of gouge clay. Along some of them where the gouge is thin, the overriding block is brecciated to a depth of a foot or more. Indications are that the block northwest of the fracture has moved toward the northeast. In another system, less common, the strike is N. 14° E. and the dip is 40° W. The overlying block has moved eastward and upward, with the development of a gouge layer 2½ feet thick. The most intensive movement, as suggested by the number and width of the slips, has taken place along a series of joints that range in strike from N. 20° to 82° W. and in dip from 40° to 55° SW. The gouge zones are as much as 6 feet thick, and some include a jumble of limestone blocks that are as much as 5 by 10 feet in exposed dimensions, indicating considerable grinding or displacement. Some of the fractures of this zone are exposed in the road cut in the southeast corner of sec. 5, T. 30 N., R. 19 W., where they strike N. 45° W. and dip 53° SW. They usually occur in groups spaced 1 to 3 feet apart. Each consists of three fractures, the movement occurring along the middle one. The displacement is small, seldom more than 1 foot, and there is a correspondingly small amount of gouge. These fractures cut bedding surfaces along which there has been considerable slippage and development of gouge clay as much as 6 inches thick.

Another shear zone, about which little is known, crosses Hungry Horse Creek 1,300 feet west and 2,150 feet north of the southeast corner of sec. 30, T. 30 N., R. 18 W. It apparently separates an area of low dips from a more thoroughly compressed zone toward the Flathead fault. There has been some movement and brecciation. Small drag folds just downstream indicate strong compression from the west.

PROBABILITY OF MOVEMENT ALONG FAULTS

The planning of high dams in situations where their failure would entail loss of life and large property damage necessitates careful attention to every factor pertinent to their safety. When such structures are located on or in the vicinity of geologic faults, an inquiry into the probability of movements along these faults must be included, so that, if there is evidence of activity, special precautions may be included in the design to make the structure as nearly proof against earthquakes as possible.

An evaluation of the probabilities of future activity along a fault is not always a simple matter. Different types of faults may require different sets of criteria. One of the most comprehensive outlines for reaching conclusions as to the status of activity of a fault is that suggested recently by Louderback:[30]

> The criteria for arriving at a judgment that a fault is active are geological, historical, and seismological.
>
> The best geological criterion is based on evidence of recent displacement along the fault, and especially on evidence of a series of displacements, running through a long period of time and coming down close to the present, as is definitely shown, for example, along the San Andreas and Hayward faults. If a fault shows evidence of repeated movements during Quaternary time, up to and including very recent offsets, as, for example, in very young alluvium, it is not likely that it died but yesterday, and we must believe that future movements are practically certain. The actual observational evidence includes fresh or youthful nonerosional scarps, offset streams and alluvial fans, longitudinal depressions and sag ponds, deformed and displaced recent deposits, and similar phenomena along the fault or shear zone.
>
> Historical evidence lies in the records of earthquakes the descriptive accounts of which permit reasonable reference to a particular fault.
>
> A seismographic method of learning what faults in a region are active is that of determining the locations of centers of origin of recurring small earthquakes. These earthquakes, although they cause no damage and are often too small to be felt, give definite records on seismographic instruments and indicate that the faults along which they are generated are unstable and subject to repeated adjustments.

The fault movements and shears described in the preceding section are not old in a geologic sense. Even so, it seems safe to regard the Lewis overthrust fault as inactive because the antecedent conditions that culminated in its development no longer exist. The same is probably true of the reverse or upthrust movement along the Swan and Flathead faults during Oligocene and Miocene time. Deformed glacial deposits referable to the Kansan (?) and to the Illinoian (?) ice stages furnish evidence that movement of some sort has persisted along the Flathead fault until late Pleistocene time. Actual scarps have not been observed, but a number of widespread observations suggest that an eastward tilt movement has continued until the Sangamon (?) interglacial stage. Deformation has not been observed in gravels of this age, but not all of the localities where they may be expected to occur have been visited. Consequently, the apparent recent quiescence of the Flathead fault and the lack of a historic record of seriously destructive earthquake shocks do not guarantee future immunity from faulting.

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[30] Louderback, G. D., Characteristics of active faults in the central Coast Ranges of California, with application to the safety of dams: Seismol. Soc. America Bull., vol. 27, p. 9, 1937.

Present knowledge is insufficient to determine if the Pleistocene fault movements were normal or not. Farther west in Montana, postglacial faulting illustrates reversal of movement on high-angle thrust faults similar to the Flathead fault. Under these circumstances it seems best to assume that there has been renewal of movement on the Flathead fault, and to assume further that there may be future settling of the basin floors.

The tendency to settle may be mitigated regionally, however, by the gentle southerly crustal tilt due to the recoil of the northern country from its load of glacial ice. Some local compensation is probably afforded by the fact that the basins are now being degraded, that is, the streams are removing the overload rather than adding material. As long as this erosion continues, local subsidence of the basins by movements along the bounding faults is less likely to occur.

Obviously the construction of a dam at the Hungry Horse site will reverse the load conditions for the lower part of the South Fork Basin. The crust below the floor, particularly in the vicinity of the reservoir area will be subjected rapidly to the weight of the impounded water, and, as time passes, this load will be increased somewhat by sedimentation. The specific problem is whether or not this loading will cause subsidence of the lower South Fork Basin and activate the Flathead fault, thereby creating local earthquake conditions.

The area of the Hungry Horse reservoir site at the 3,540-foot contour is about 41.5 square miles. (See fig. 2.) Maximum capacity at this level is roughly 3,300,000 acre-feet. This volume of water would weigh about 4,487,000,000 short tons, and the average load per square mile would be approximately 108,000,000 tons.

Owing to the shape and profile of the proposed Hungry Horse reservoir, the center of gravity of its water mass will probably lie within a few miles of the Flathead fault. The possibility of the area being underlain by the Lewis thrust fault has been mentioned; if this is so, it is conceivable that the great faults that break the thrust plate at the surface may diminish, decrease in dip, or be partially absorbed in the overridden mass, thereby reducing direct transmission of any superimposed load to the granitic crust. In the absence of detailed knowledge of the fault pattern, of isostatic conditions, and of other fundamental constants of the earth in this region, it is impossible to calculate how much the surface would be depressed by the additional load of the reservoir. My opinion is that the amount would be very small.

Glacial studies in South Fork Valley have shown that at least three times during the Pleistocene the surface supported a load of ice and water enormously greater than any artificial load that can ever be created there now. Each time the ice was widespread and accumulated and diminished very gradually. The Wisconsin stage of glaciation was relatively recent, probably closing only 15,000 to 20,000 years ago. There is no known evidence of crustal adjustment by faulting during subsequent years. Observation of the well-jointed, overhanging limestone cliffs on the west side of the South Fork at Hungry Horse dam site suggests that the area has not been greatly disturbed since their development, dating from the end of the Wisconsin stage. The absence of recognized postglacial faulting also supports the conclusion that the crust adjusted itself to the Pleistocene ice loading and deglaciation without fracture deformation.

POSSIBLE INFLUENCE OF EARTHQUAKES

Testimony to the stability of the Flathead and associated faults is supplied by their failure to respond to the fairly strong earthquake waves that swept through South Fork Valley several times during October 1935. These shocks originated with an intensity of about 9 in the neighborhood of Helena, Mont., 157 miles southeast of Hungry Horse dam site, through which they passed with an intensity of between 4 and 4½ on the Rossi-Forel scale.[31] There was no disturbance of the Flathead fault along its entire length, so far as known, even though this fault strikes to the southeast into areas that were shaken with an intensity of between 5 and 6. Therefore, it seems probable that the faults in the vicinity of Hungry Horse dam site will not be activated by shocks originating in adjacent basins, such as the North Fork Basin between the Flathead and Roosevelt faults north of Belton, or in the Rocky Mountain Trench west of the Swan and Mission Ranges.

The earthquake frequency of the Rocky Mountain region has been investigated recently by Freeman,[32] who states:

> By reason of the scant records and the rugged topography, notwithstanding the distance from the ocean, it seems only prudent for an insurance company to base its premium rates for this Rocky Mountain-Wasatch region on the basis of expecting that at one place or another there may be an average of four serious earthquakes per century within this vast area of 1,120,000 square miles.

Freeman also predicts that the four earthquakes will be of intensity 9 or 10, the intensity of the Montana earthquakes of 1925 and 1935, and that—

> the resulting hazard of an occurrence of a destructive earthquake at any one city or area of 25 x 100 miles in any particular year is 1 : 11,200.[33]

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[31] Scott, H. W., The Montana earthquake of 1935; Montana Bur. Mines and Geol., Mem. 16, pl. 3, Butte, Mont., 1936. Newmann, Frank, United States earthquakes, 1935, The Helena, Mont., earthquake of October and November 1935: U. S. Coast and Geodetic Survey, serial No. 600, figs. 6 and 7, 1937.

[32] Freeman, J. R., Earthquake damage and earthquake insurance, p. 150, New York, McGraw-Hill Book Co. 1932.

[33] Idem, p. 630.

After the destructive earthquakes at Helena in October 1935, a thorough investigation of conditions there, as well as of Montana earthquake history, was made by Scott,[34] who writes:

From the historical record of earthquakes in Montana it is quite apparent that any of the above-mentioned areas may experience a moderate earthquake at any time. From the geological evidence and the historical record we may conclude that:

(1) Earthquakes of damaging intensity will continue to occur in the western half of the state.

(2) Earthquakes, comparable in intensity to the Manhattan and Helena earthquakes, may occur.

(3) The risk of damage and loss of life is not the same throughout western Montana; that is, serious earthquakes are more apt to occur in some areas than in others.

It therefore seems reasonable to conclude that the water load of the Hungry Horse reservoir will not be sufficient to cause appreciable deformation of the earth's crust below its floor. Such deformation as may occur probably will be absorbed elastically by the crust without activation of the Flathead fault. If any adjustments are engendered their effects may not be apparent for a great many years. In other words, there is no danger that the loading of the Hungry Horse reservoir will act as a trigger to an earthquake. If movement along any of the master faults should be resumed it probably will be in connection with subsidence of the floor of some adjacent structural basin. Conditions favoring renewed movement are now opposed by other strong forces but should displacement occur it would likely result in earthquakes of intensity 9 or 10 on the Rossi-Forel scale at the epicenter. Finally, although the probability of earthquakes in South Fork Valley is much less than that in Prickly Pear Valley at Helena, the Hungry Horse dam should be designed to withstand the acceleration of shocks of the intensities mentioned.

GEOPHYSICAL INVESTIGATIONS

By B. E. Jones

Electrical resistivity measurements were made at the Hungry Horse dam site just above Devil's Elbow to determine the depth of overburden in the old channels. Measurements were made also on the divide between Lion Hill Gorge and Abbott Gorge about 2½ miles above the dam site to determine the depth to rock at the divide and in Abbott Gorge, as the topography indicates that Abbott Gorge might have been occupied by the river at an earlier time. Measurements were made up Lion Hill Gorge as far as the summit, in Abbott Gorge at the divide, and at the upper end of Abbott Gorge around Hungry

[34] Scott, H. W., op. cit., pp. 2–6.

Horse Ranger Station. A few seismic measurements also were made by E. R. Shepard, of the United States Bureau of Public Roads, at the divide between Lion Hill Gorge and Abbott Gorge.

RESISTIVITY MEASUREMENTS

HUNGRY HORSE DAM SITE

Resistivity measurements were made at the Hungry Horse dam site on the right bank below Devil's Elbow, on the left bank just above the elbow, and one measurement in the old channel on the left bank about 1,000 feet above the elbow. These measurements indicate that the old channels are not so deep as the present channel except possibly on the right bank. On the left bank the old channel 1,000 feet above the elbow was the least eroded.

On the bench on the left bank just above the elbow it was difficult to obtain good results because of limited space on the surface. Measurements were made along diagonal lines, but these were liable to extend in one direction or the other beyond the banks of the old buried channel. The depth to rock varies considerably, but no indication was found that the old channel extends below the water surface of the present river, which was at an elevation of about 3,040 feet at the time the measurements were made. The maximum depth of this old channel just above the elbow was estimated to be 48 feet, although possibly a narrow canyon reaches to a greater depth. The old channel at this point offers no serious obstacles to the building of a dam. The cross-sectional area would be only slightly greater than for a dam 800 feet upstream.

The measurements on the right bank are consistent and should be reliable. Measurements along a line on the right bank near the trail indicated a depth of 76 feet. A few readings taken about 150 feet from this line toward the hillside indicated a depth of about 100 feet but were not sufficient to define a curve. The cross-sectional area at this site (sec. A–A′, pls. 8 and 9), however, is greater than at either of the sites upstream, and unless geologic complications develop at the upper site, this lower one can be disregarded.

On the left bank the measurements in the valley 1,000 feet above the elbow indicate a variation either in the apparent resistivity of the overburden or a variation in depth. Possibly the line crosses a narrow gorge, or the small stream may flow on top of clay with a bed of dry gravel below; the first explanation seems the more probable. However, the depth to rock at this point is not so great. The only depth determination made here indicated 35 feet. A cross section (D–D′, pls. 8 and 9) indicates that this site would require a minimum amount of material for a masonry dam.

LION HILL GORGE AND ABBOTT GORGE

The topography of Hungry Horse reservoir site seems to indicate that Abbott Gorge is a continuation of the valley of the South Fork of Flathead River. To verify this and to determine, if possible, the depth to rock in Lion Hill Gorge and Abbott Gorge, resistivity measurements were undertaken in the fall of 1935 and continued in 1936. Measurements were made up the valley of Lion Hill Gorge and also at points along what appeared to be the principal old channel of the river, which has been called Abbott Gorge. The bedrock at the mouth of Lion Hill Gorge is the Siyeh limestone with a high resistivity, but a few hundred feet up the valley the rock changes gradually to an argillite with a comparatively low resistivity. The low resistivity in the underlying rock renders more difficult the determination of depth to the rock and predictions as to the character of the overburden. Measurements in the Lion Hill gorge indicated that the rock slopes gradually up the hill with about 100 feet or more of overburden (sec. C–C′, pl. 11). The high point reached was slightly in excess of 3,500 feet and was just a short distance downstream or west of the surface divide. From this point the rock dropped off slightly to the east to a depth of about 140 feet in Abbott Gorge. The underlying rock is assumed to be argillite. If the prediction be based entirely on geophysics, a layer of glacial till about 500 feet thick would be presumed to exist in Abbott Gorge.

SEISMIC OBSERVATIONS

A few seismic observations were made at the top of the divide between Lion Hill Gorge and Abbott Gorge divide at the request of the Geological Survey by E. R. Shepard, research engineer of the Bureau of Public Roads, during the period September 10–15, 1936.

In order to facilitate the interpretation of the data, calibration tests were made at several locations where the character of the subsurface material was in evidence. The first test was made on a gravel bank along the highway on the left bank of Flathead River at the mouth of Bad Rock Canyon. The exposed cut showed 1 to 2 feet of topsoil under which was fresh gravel grading from earth and fine gravel to clean coarse gravel at a depth of about 5 feet. The observations showed a top-soil velocity of 1,600 feet per second and a depth of 5.6 feet to a material with a fairly uniform velocity of 3,200 feet per second. This is evidently the characteristic velocity in the partly cemented gravel. The second observation was made along the left bank of the river in sec. 33, T. 31 N., R. 19 W., where glacial till, cemented gravel, and weathered boulder clay were present. The face of the bank along the river at this point rises 80 to 100 feet above the level of the river. Tests were made on the high level about 40 feet back from the face of the cliff. The results show the top layer to be similar to that at the first location, but longer shots indicate that material at a depth of 52.8 feet has a velocity of 10,200 feet per second.

This depth would extend 29 feet into a layer of interglacial stream gravels in a matrix of light-brown sand and clayey sand. The velocity of 10,200 feet per second is about that for argillite in place, but it is difficult to account for bedrock in this location. A possible explanation is that the interglacial stream gravels, being 90 percent fresh argillite, gave a velocity about the same as that for argillite.

The first observation on the Lion Hill Gorge-Abbott Gorge divide was made at station 39 and the shots were from the southwest. (See pl. 10.) The velocity in the underlying material was 11,800 feet per second, and the estimated depth to the high-velocity material 99 feet. Other shots from the northeast and southeast gave a depth of 36.5 feet to the high-velocity material and a velocity of 10,400 feet per second. At station 39 the seismic observations indicated an overlying material extending from a depth of about 4 feet below the surface to bedrock and having a velocity of 6,000 to 7,500 feet per second. Test pits dug at this point and at station 12 disclosed a top layer of humus and at a depth of 4 to 6 feet a dense blue clay mixed with gravel, a glacial till. Some of the gravel was highly weathered, some fresh.

The next observation was made at a point about 500 feet southeast of station 39, and the first shots were taken from the northeast. The depth of overburden was estimated to be 45 feet, and the velocity was 10,700 feet per second. A second observation (No. 5) was made at the same point, the line of test being due south, and a depth of 63.2 feet was obtained with a velocity of 10,500 feet per second in the underlying material. The next observations (Nos. 6 and 7) were made at station 12, where a depth of 35 feet was obtained. Shots taken from both southeast and northeast indicated a dip in the underground strata from northwest to southeast, causing the indicated velocity to vary from 9,000 to 17,000 feet per second. The next observations were made at a point 370 feet east of station 12 in Abbott Gorge. A depth of 6.2 feet of topsoil was obtained, but below that the velocity was uniform at 6,700 feet per second. The maximum shooting distance was 470 feet, and the line of shots was from the southwest and northeast (Nos. 8 and 9). The last test was made at a point 270 feet north of station 47 on the line between 47 and 48. The line of test was northwest and southeast along Abbott Gorge. A depth of 30.5 feet was obtained through a material with a velocity of 5,000 feet per second, and below that was a material giving a velocity of 7,000 to 8,000 feet per second to the northwest and 8,000 feet per second to the southeast at a maximum shooting distance of 520 feet.

Both the seismic records and the electrical measurements indicate a high divide between Abbott Gorge and Lion Hill Gorge. The measurements at stations 47 and 48, where velocities of 7,000 to 8,000 feet per second were obtained at shooting distances of more than 400 feet, indicate a glacial till, and the comparatively high velocity is due to its compactness and induration. Test measurements described previously suggest that well-cemented gravels of a fresh rock will have the average velocity of the rock in place. The rewashed till (stratified drift or aqueo-glacial deposits) below the Wisconsin till and above the interglacial Sangamon (?) river gravels might have a velocity of 7,000 to 8,000 feet per second.

A test pit 6 feet deep at station 48 showed a brownish clay mixed with gravel. There was more sand and gravel than in glacial till found at stations 12 and 39, and possibly this may account for the slightly higher velocity. In any event this material must be well consolidated to give a velocity as great as 7,000 feet per second.

HUNGRY HORSE DAM SITE

The general profile of the valley of South Fork of Flathead River at the Hungry Horse dam site is a wide, rounded V in the gentle back slope of Columbia Mountain. (See fig. 4.) The symmetry of the upper slopes extends downward from the shoulders of the V to an altitude of about 3,130, where there are remnants of a rock bench. The slopes between 3,130 and 3,600 feet are typical of a glaciated valley, but there is a complete absence of glacial drift. (See pl. 9.) The benches at 3,130 feet probably formed the floor of the valley at the close of the Wisconsin glaciation. This old floor has been trenched by the river, and the altitude of the base of the channel through the dam site is between 2,980 and 3,020 feet. The slopes between these altitudes and 3,130 feet are less regular than those above. For convenience in discussion, the slopes between 3,130 and 3,540 feet will be considered as the abutments, and the surfaces below 3,130 feet as the foundation.

The general geology and the individual formations and deposits have been discussed in the preceding sections of the report. Only the features that are directly related to the utility of the dam site will be considered further here.

BEDROCK

The bedrock at the dam site is the Siyeh limestone, which has been fully described in the section on geology. (See pp. 48–55.) The part exposed is dull bluish gray, massive, homogeneous, well bedded and thoroughly jointed. Petrologically it is an incipiently metamorphosed, highly aluminous, siliceous, magnesian limestone. Chemical tests have indicated that it is relatively insoluble, and that the seepage of water through it will not cause weakness during the useful life of a dam. The hardness is about 4 on Mohs' scale, and the

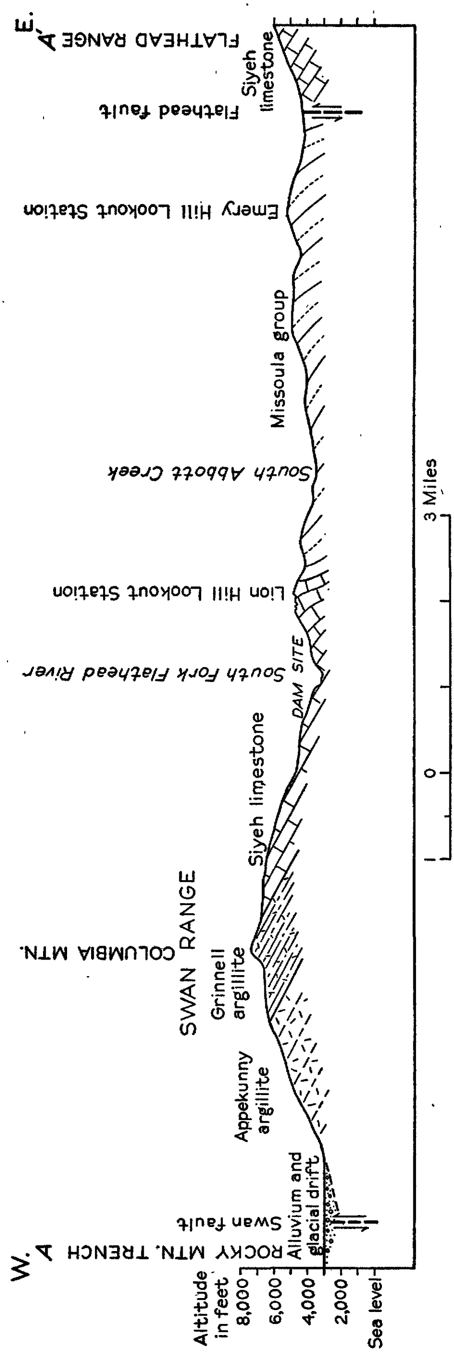

FIGURE 4.—Diagrammatic section showing regional geologic setting of Hungry Horse dam site. Section taken along line *A–A'*, figure 2.

rock yields readily to river corrasion. Clear water discharging from a spillway or overflowing the top of a dam will have little scouring effect, but the dynamic flow of such discharge would eventually quarry out joint blocks. All of the Siyeh formation is strong and rigid. The crushing strength of flawless pieces is estimated at more than 10,000 pounds per square inch. The strength of the weathered rock is thought to be about half that of the fresh material. The formation as a whole transmits sound pulses at an average velocity of 14,000 feet per second. The resistivity is high and ranges from 55,000 to 145,000 ohm-cm., depending upon the amount of ground water and the direction of the measurements with respect to the attitude of the beds.

The much-generalized partial section given below has been compiled from observations at the dam site. The base of the section is in the bottom of the river gorge and is believed to be about 4,000 feet below the top of the formation.

Generalized section of Siyeh limestone at Hungry Horse dam site on South Fork Flathead River

	Feet
Top not seen.	
4. Limestone, thin-bedded, dense, splintery, bluish to dull greenish gray, weathering to brownish shades; with occasional thin zones of massive beds, as below	1,000
3. Limestone, dull bluish-gray, in dense, massive heavy beds	80
2. Limestone, bluish and greenish gray, thin and irregularly bedded, and platy and thinly laminated	40
1. Limestone, bluish gray, sometimes greenish, occasionally weathers buff. Thick, dense, massive beds, which exhibit locally probable intraformational structures	60

DIP

The regional dip of the limestone is northeast at an average inclination of 25°. Locally the range in dip is from 21° to 30°. The range in direction is from N. 40° E. to N. 60° E., the corresponding directions of strike being from N. 50° W. to N. 30° W. The bedding surfaces upon which these observations were made are smooth, regular, and clean in the massive rock but less perfect in the thin-layered rock. Reverse or westward dips are unknown at the dam site, but they occur in small areas some distance east.

The amount of dip increases as the shear zone 5,000 feet east of the dam site is approached. There dips as high as 57° have been noted, but the variation in strike is small. The development of dip was accompanied by gliding along the major bedding surfaces. Evidence of this movement is not observed easily in outcrops parallel to the strike, but it is well shown in the road cut on United States Highway No. 2 at the southeast corner of sec. 5, T. 30 N., R. 19 W., where gouge zones ranging in thickness from 2 to 10 inches occur about every 20 feet in the section of limestone exposed. Gliding with gouge is characteristic of the major bedding surfaces in the Siyeh limestone, whereas development of fracture cleavage or small drag folds due to greater tenacity of the bedding surfaces is more typical of the argillites.

Strike and dip symbols at 13 localities at the dam site are shown on plate 8, and these data are shown diagrammatically in relation to direction of jointing and river flow in figure 5.

JOINTS

One of the most important mechanical features of the Siyeh limestone is the jointing, that is, the tendency of the rock to fracture or crack in more or less definite directions, usually at steep angles to the bedding surfaces. Thorough studies of the jointing were made in the dam-site area for estimates of permeability, and notes were made at many other localities in connection with observations of structure.

Twenty-six determinations of joint directions and dip were made at 11 different localities at the dam site. At each place the rock is broken by at least two and sometimes by four sets of fractures. There are, however, more than four sets of joints in the area. (See fig. 5.) On the basis of strike alone most of the fractures can be placed in four groups: N. 40°–45° W.; N. 20°–30° W.; N. 35°–45° E.; N. 67°–80° E. Six other directions of strike were noted, but only two are established upon more than one observation. When classification is based upon direction and degree of dip as well as strike, only two groups stand out: Strike N. 40°–45° W., dip 51°–63° W.; and strike N. 67°–80° E., dip 60°–75° S. These two sets may be called the master joints of the dam-site area. From this dual basis of classification 10 other sets appear, but not more than three separate observations can be referred to any one group. Further effort at classification or attempts to relate specific joint sets to different stress epochs will not be made here, as they lead to considerations not pertinent to this report. It is sufficient to note that there were at least three stages of jointing, and that the master joints at the dam site correspond to those of the region.

In general, the master joints are strong, clean and persistent; but an occasional one has a rough, irregular surface. The joints that trend northwest all show evidence of movement, some in considerable amount. Only a few of the joints that trend a little east of north show movement.

The spacing of the joints appears to have some relationship to the lithology of the stratum in which they occur. In thin, irregularly bedded, splintery limestone the joints of a set are closely spaced, sometimes only an inch apart; but more commonly the interval is

2 to 6 inches. In the heavy-bedded, massive layers the spacing is not uniform and may be from 6 inches to 20 feet. Ordinarily, there is a group of closely spaced fractures and then a wide, unbroken interval.

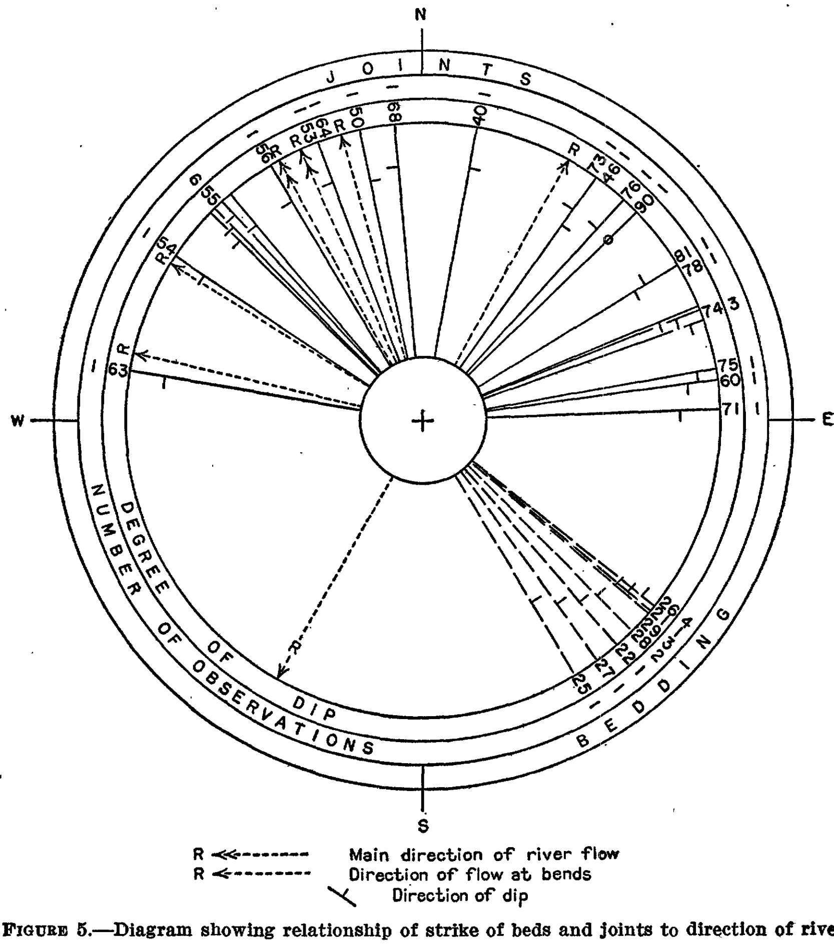

FIGURE 5.—Diagram showing relationship of strike of beds and joints to direction of river flow at Hungry Horse dam site.

FAULTS

Faulting has not been recognized in the dam-site area.

PERMEABILITY

Permeability in a rock formation implies the existence of connected passages, the minimum diameter of which is at least several times the diameter of the percolating fluid molecule. Dam-site investigations require consideration of permeability from two points of view—percolation through the fabric or texture of the rock and movement of water through tabular or sheet openings, such as bedding surfaces, faults, and joints.

Because of metamorphism and incipient recrystallization, the texture of the rock at Hungry Horse dam site is much like that of a slate. Thus, for all practicable purposes, percolation through the rock fabric is negligible and it will not be considered further. Whatever seepage occurs will take place through sheet openings, but estimation of such flow is very difficult, because it is almost impossible to evaluate properly the number and width of cracks in any unit volume of rock in place.

The Siyeh limestone is well bedded and thoroughly jointed. The bedding surfaces are probably the most persistent sheet openings, and gliding or adjustment along them makes them relatively permeable. As the valley is approximately parallel to the strike, the rock attitude favors leakage along the bedding around any dam that may be built. This attitude, however, also favors underdrainage of the dam, thus tending to reduce uplift. (See also p. 97.) A conservative estimate would allow one major bedding surface for each 5 feet of rock, and on this basis there would be about 200 surfaces below the highest pool level at the dam site. Actually the total number of laminae, fissile surfaces, and minor beds is countless.

It is even more difficult to guess at the number of joints. Probably only the master joints extend through both the massive and the thin-bedded rocks. The thin-bedded rocks are the most excessively jointed, some layers being cut by at least four sets, two of which usually are closely spaced. In some rock of this type a unit of 1 cubic foot may be cut by at least 25 sheet openings. The massive layers are less jointed, but probably are cut by at least 1 crack per cubic foot. Massive rock does not make up more than 25 percent of the stratigraphic section at the dam site. Considering this section as a whole, it is probable that it will average at least 10 sheet openings per cubic foot.

The width of the openings varies greatly. Some gape open for an inch or so at the surface but are probably very narrow where under 50 feet or more of cover. The shear zones range in width from a fraction of an inch to several feet. Commonly, they are packed tightly with gouge clay and appear to be impermeable, but oxidation of the margins of the clay bodies indicates that the bounding surfaces are permeable. Joint cracks 0.01 inch wide will readily pass large volumes of water. Cracks of width less than 0.005 inch are approximately at the lower limit of field observation, unless the surfaces they traverse are especially smooth and polished. Cracks less than 0.01 inch are too thin to grout, yet water will move freely through openings many times smaller. Obviously, cracks below grouting size form important leakage channels, and, since the percolation factor varies as the cube of their width those between 0.001 and 0.0001 foot are especially important.

Measurements were made on some of the cracks on a polished surface of weathered limestone. Limonitic stains on the wall rock indicated that solutions had moved along them. The range was from 0.000032 foot (0.01 mm.) to 0.00032 foot (0.10 mm.), and the linear extent of the wider cracks was greater. There was no evidence of limonite stain in cracks less than 0.000032 foot wide, slight evidence between 0.000032 foot and 0.00008 foot (0.025 mm.), and much evidence between 0.00008 foot and 0.00032 foot (0.10 mm.). All of these cracks are in the capillary range, below the limits of grouting and too minute for ordinary field observation. Under normal heads they obviously have passed considerable amounts of water, and great heads, such as that created by a high dam, would increase this flow and would stimulate flow through thinner cracks. Owing to the small probability of silting in the Hungry Horse reservoir, cracks in the rock are not likely to be closed by clay.

For illustrative purposes only, the foregoing approximations may be used to estimate the quantity of seepage through a unit volume of rock at the dam site by means of the Slichter formula:

$$Q=K\frac{H}{L}A$$

In order to show the relationship of the size of the crack to the amount of seepage, calculations have been made for three widths on the assumption that (1) ten cracks pass through each cubic foot of rock; (2) L=1 foot; (3) A=1 square foot; and (4) H=300 feet and 525 feet. The results are shown below:

Discharge per unit area

Width of crack		K	K x 10	Q	
Mm.	Foot			H=300	H=525
0. 03	0. 0001	6×10^{-8}	6×10^{-7}	$\frac{1,800}{10^7}$	$\frac{3,150}{10^7}$
0. 10	0. 0003+	210×10^{-8}	210×10^{-7}	$\frac{63,000}{10^7}$	$\frac{110,250}{10^7}$
0. 304	0. 001	6000×10^{-8}	6000×10^{-7}	$\frac{1,800,000}{10^7}$	$\frac{3,150,000}{10^7}$

Since, with the possible exception of height, the dimensions of a prospective dam are not available, the Q values cannot be applied to the dam site without making further assumptions. In plate 9, section D–D′, consider the area A–B–C which is 26,665 square feet.

Assume the path of percolation to be 1,000 feet and the average width of crack to be 0.001 foot. Then, for a head of 525 feet, the maximum allowable for Hungry Horse dam site, the discharge would be:

$$\frac{31.5\times10^5}{10^7}\times\frac{26,665}{10^3}=\frac{839,947.5}{10^5}=8.39 \text{ cu. ft. per second.}$$

The total permeable area around a 525-foot dam would be about five times the area used in the above estimate, therefore the total discharge might be about 42 cubic feet per second. This figure is probably near the maximum, since it would hardly be reasonable to allow cracks of a greater width or a dam of greater height. This volume of water is about one-fifth the flow of the river during the lowest water stages. The estimates for thinner cracks would be smaller in proportion to the value of the constant, K. Grouting will greatly reduce seepage around the dam.

ABUTMENTS

Any normal section of the valley at the Hungry Horse dam site strikes about N. 68° E. The east and west walls of the valley would form the east and west abutments of the dam. Below 3,130 feet the east wall includes stratigraphic units 1, 2, and 3 (see p. 90), and above 3,130 feet unit 4 is present. The west wall consists of units 1, 2, and 3. Thus, except in its lower part, the east abutment involves more thin-bedded and jointed rock than does the west abutment.

The combination of joint systems and bedding have outlined rhombohedral blocks of rock whose size is dependent upon the spacing of the joints and the thickness of the beds. This variation is great, consequently the dimensions of the blocks range from a few inches to several feet. As these blocks are loosened and detached by weathering they have a tendency to move down dip under the influence of gravity. Owing to the attitude of the rock, this tendency is effective only upon the west side of the valley. The west side is characterized by talus slopes that contain fairly large angular blocks and by the short, overhanging cliffs from which they have been detached. On the east side the beds dip into the wall, and the face of the east wall is controlled by the steep west-dipping master joints. The loosened joint blocks are thus supported in place until they are thoroughly shattered. For these reasons the east wall is a fairly uniform slope, lightly mantled with a litter of small rock fragments. Since the rock is held in place longer, it is more thoroughly weathered than are the cliffy slopes of the west wall.

The east wall or abutment is the strongest structurally, but the rock there is more thinly bedded, more throughly jointed, and more weathered than that on the opposite wall. Presumably, percolation would be greater around the east abutment than around the west. The rock of the west abutment is more massive, less jointed, and less weathered, but because it dips into the dam site its structural situation is weak and it may be less well adapted to take up an arch thrust. Slight down-dip movement of the rock in the west wall might result in considerable pressure on the west end of a dam, and this might become great enough to crack the concrete before the rock was materially weakened. Resistance to this potential stress can perhaps be offered best by a dam of the straight gravity type. Down-dip movement would also widen some of the joints in the massive rock, permitting leakage. In case of an earthquake shock such movement might become dangerous, for in addition to the general tendency of the beds to slip down dip, large blocks might be detached from the higher slopes and tumble down on the dam. Their impact on the dam might be sufficient to injure the dam or its appurtenant works.

The high steep slopes on each side are not immune to snowslides, and, if possible, this contingency should be provided for. The danger would be greatly accentuated if the forests on the higher slopes should ever burn off.

In summary: The bearing power of the two abutments is not quite equal, the east being the stronger. On the other hand, percolation through the east abutment possibly would be greater than that through the west.

FOUNDATION

During late Pleistocene and Recent time the old floor of the valley at 3,130 feet was eroded vigorously by South Fork Flathead River, was reburied by alluvial and lacustrine deposits, and later partially reexcavated and eroded through a new channel.

The present channel is a narrow, rugged gorge whose local features are the result of the structural control of the stream, which has attained this course after flowing in at least three and possibly four or five temporary channels within the narrow confines of the valley. Earlier courses are indicated by the topography of the valley floor. This floor consists of a series of partly exposed, midvalley rock ridges, which strike in a direction parallel to that of the valley and which are separated in places from the adjacent side walls of the main valley by linear areas of gravel or by the present stream gorge. The rock ridges and filled channels are shown in plan on plate 8 and in section on plate 9.

The character of the fill is best determined from a section of the abandoned channel on the 3,100-foot contour north of the letter W in "Devils Elbow" on plate 8. The upper part consists of a conglomerate of smooth water-worn pebbles of Belt rocks, usually not more than 6 inches in diameter, in a matrix of tan silt cemented by porous gray-white marl. The upper 8 or 10 feet of the fill is so well indurated by the marl that it breaks off in large blocks, which remain unshattered as they roll down to stream level. At the top of the conglomerate are superficial deposits of creamy white, fluffy marl, without sand or gravel, which may be either lacustrine or spring deposits. The material below the cemented rock is a normal fluvio-glacial fill, and is relatively soft and easily eroded. The silt is easily washed away, and the surface is so well mantled with pebbles that exposures are uncommon.

The depth of the fill below the comparatively level gravel surfaces has been made the object of a special geophysical study by B. E. Jones. The location of the geophysical determinations is shown on plate 8, and cross sections are shown on plate 9.

The measurements indicate that there is a marked variation in depth in the ancient channel along the west (left) side of the valley. As this abandoned course appears to be even straighter than the present channel, one would expect it to be graded and not to show abrupt changes in floor level. The explanation seems to be that during its regimen the stream has occupied, abandoned, and then reoccupied various separate segments of its pre-Lake Missoula channel, and that the present topography emphasizes the early course rather than the temporary channels that preceded the establishment of the present course. The dam-site area is too small to determine the exact sequence of the changes, but their result was to produce the series of parallel rock ridges on the floor of the valley.

It is clear that the greatest quantities of fill are in the abandoned channels rather than in the present courses. It is conceivable that these old channels might be used for stream diversion during the construction of a dam in order to avoid the necessity of diversion tunnels through the rock.

The rock of the foundation ridges consists chiefly of units 1, 2, and 3 of the stratigraphic section given on page 90. It is mostly massive, but because of its great surface of exposure it is likely to be thoroughly weathered. The joints and bedding surfaces are probably more open than in the rock of the present stream floor. For this reason, if any of the ridges were to be incorporated in a dam foundation, they might prove to be more permeable than the abutment rock.

Under great head of water, percolation through these foundation ridges might tend to produce a considerable amount of uplift. This contingency is favored by the relatively low dip of the strata, which gives a large component of horizontal surface against which the pressure could work. However, the attitude of these strata and the jointing are favorable to fairly rapid drainage of these ridges if their upstream sections are protected from percolation by adequate cut-off walls.

The attitude of the strata with respect to the strike of the dam axis gives security against sliding of the beds of the foundation upon one another. The security against sliding of the dam on its foundation is not so great as if the beds dipped upstream, but the irregularity of the foundation profile will help to prevent against this sliding. The initial strength of the foundation rock is ample to support a dam of maximum height. Its principal lithologic defect is its low hardness, about 4, and its susceptibility to corrasion. The rock has been shown to be relatively insoluble and will not soften under the influence of water. The dam foundation is good except in one respect—permeability through bedding and joint surfaces. Structural and lithologic conditions are uniform throughout the dam site. The chief differences are in the cross-sectional area of the gravel fill and the rock ridges.

COMPARISON OF SECTIONS

Plate 8 gives the location of the four representative sections at the Hungry Horse dam site shown in plate 9. The table on plate 9 gives a statistical comparison by areas, and figure 6 gives a graphic summary and comparison of some of the data. Section A–A′, represents the area from line of section to within 200 feet of Section B–B′. Section B–B′ represents the area 200 feet north and about 400 feet south of the line of the section. Section C–C′ represents the area 100 feet north and 300 feet south of the line of the section. A profile 300 feet south of this line, through the small rock island, would be very similar if the rock area A–B–C were removed. Section D–D′ represents the area 400 feet north and 400 feet south of the line of the section.

The minimum area of open valley below an altitude of 3,540 feet is in section D–D′, and is 492,120 square feet. The minimum crest length for any pool level is also in this section and is 1,705 feet at altitude 3,540. The minimum cross-sectional areas of gravel fill and rock ridge are in section D–D′, and are, respectively, 2,420 and 4,240 square feet.

Inspection of figure 6 reveals some interesting features. The parallelism of the lines representing the four sections is indicative of the symmetry of the valley. The first comparison, "Area of open valley," shows that for any possible height of dam the cross-sectional area of section D–D′ is less than for any other profile but it is not greatly exceeded by section A–A′. The second comparison, "Total area," includes the area of open valley plus the area of buried valley

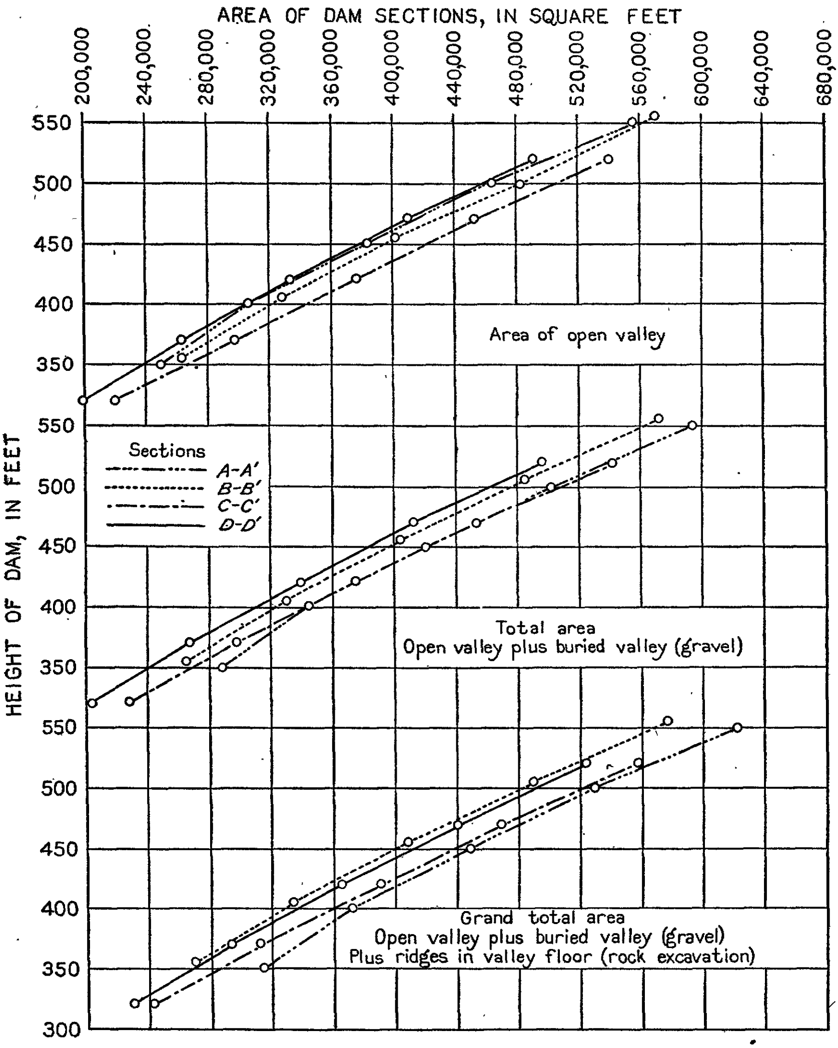

FIGURE 6.—Graphic comparison of dam sections, Hungry Horse site, Flathead County, Mont.

or gravel fill. Here also section D–D′ maintains its favorable position. However, in the third comparison, "Grand total area," which includes area of open valley plus area of buried valley plus cross-sectional area of partly buried rock ridges in the valley floor, which may be excavated in some places, section D–D′ proves to be slightly inferior to section B–B′.

Since the four sections are equal with respect to abutment and foundation and approximately equal with respect to area of open valley, selection of the dam section must be made after consideration of cross-sectional area of the partly buried ridges with respect to their incorporation in dam design, possible rock excavation, and percolation, and after consideration of the buried channel sections with respect to gravel excavation, possible use for stream diversion during construction, and for appurtenant works.

APPURTENANT WORKS

If the duty of the contemplated dam at the Hungry Horse site involves power, stream regulation and flood control, and irrigation, the appurtenant works, in addition to the spillway, will be canal or flume sections and a powerhouse site.

Spillway tunnels.—Spillways may require rock tunnels, or tunnels may be necessary for stream diversion during construction. The geologic and topographic conditions outlined indicate that any tunnel at the dam site must be driven essentially along the strike of the beds. A tunnel on the west side of the valley may be expected to go through well-bedded massive rock. Owing to the attitude of the rock, a tunnel on this side would have heavy roof conditions and might encounter some water. A tunnel along the east side of the valley would be in thin-bedded, less massive rock, which might be a little more weathered and softer than that on the other side. The roof would probably not be so heavy, and the probabilities are that no serious water conditions would be encountered.

If the spillway were to discharge near the toe of the dam, it is possible that the dynamic flow of flood discharge might quarry out joint blocks and weaken the foundation. If an overflow type were to be adopted paving of the foundation at the toe of the dam would be desirable. Such construction, however, might retard drainage from below the dam and increase the tendency toward uplift.

Canals.—If an open irrigation canal were to be built, the rock structure on the east side of the valley would be more favorable for its construction. However, the most direct route to irrigable areas would be along the west side of the valley. Such a canal would have to be paved to prevent leakage and would have to be protected from snowslides and windfalls along the mountainous slopes.

Powerhouse site.—Powerhouses or other buildings would be in danger of damage from snowslides and falling rock, as has been mentioned.

HUNGRY HORSE RESERVOIR SITE

TOPOGRAPHIC FEATURES

The proposed Hungry Horse Reservoir will occupy the lower part of the valley of South Fork Flathead River. At maximum level of 3,540 feet the pool will cover an area of approximately 41 square miles and will extend from the dam at mile 4 to mile 44, just downstream from Ranger View. Over this distance the width of the pool surface varies from about 0.35 mile to about 3.0 miles, where it extends up tributary valleys. The average stream gradient is about 12 feet per mile. The catchment basin above the dam site includes 1,725 square miles, practically the entire drainage area of the South Fork Flathead River. Both areas are long and narrow, and their relationships are shown in figure 2. The topography of the reservoir site is shown in detail on sheets A and B, Plan and profile of South Fork of Flathead River, Mont., from the mouth to mile 44, United States Geological Survey, 1937; and the catchment area is shown on the map of Flathead National Forest published by the United States Forest Service.

In the lower few miles the reservoir will be deep and narrow, but it will begin to open up near the mouth of Fire Creek. An abrupt bend just below the mouth of Wounded Buck Creek will separate the riverlike stretch just above the dam from the open lake. This condition will protect the dam from ice thrust from the reservoir. The mean annual temperature being about 41° F., there will be ice in the lake for 4 or 5 months of each year, and conditions will probably be similar to those in the nearby mountain lakes, such as Lake McDonald at Belton.

The floor of the reservoir is well covered with a dense growth of brush and small trees. Aside from the burned areas, the only naturally open tracts are some small meadows along the river or its abandoned courses, as at Trout Lake. Clearing the reservoir will be a major problem.

CAPACITY OF RESERVOIR

The average annual runoff from the basin of South Fork Flathead River is about 2,000,000 acre-feet. The capacity of the reservoir for different altitudes of water surface is given in the following table:

Capacity of Hungry Horse Reservoir at various altitudes of water surface

Altitude, feet	Capacity, acre-feet	Altitude, feet	Capacity, acre-feet
3,060	0	3,300	332,000
3,080	300	3,320	427,000
3,100	1,500	3,340	535,000
3,120	4,200	3,360	661,000
3,140	9,350	3,380	810,000
3,160	17,900	3,400	983,000
3,180	31,100	3,420	1,181,000
3,200	52,300	3,440	1,408,000
3,220	83,800	3,460	1,664,000
3,240	127,000	3,480	1,957,000
3,260	184,000	3,500	2,290,000
3,280	252,000	3,540	3,800,000

COMPOSITION OF RIVER WATER

The chemical character of the water of South Fork Flathead River is shown in the table below by three analyses of samples taken in spring, summer and fall. The water is a very dilute normal-carbonate river water and shows slight seasonal variation. During spring and early in the summer months, when snow water is coming down, the volume of the stream is large and the mineral concentration greatly diluted (analysis 3). Late in summer and in autumn ground water appears that has been in contact with the rocks or overburden for long periods of time, and the concentration increases (analysis 1). A partial analysis run only for calcium and magnesium on a sample collected August 25, 1934, showed 50 and 5 parts per million, respectively. This condition probably represents the maximum concentration. The sample taken in November (analysis 2) shows less calcium and magnesium in solution, but this may have been somewhat dilute, as the water was bailed from a hole in the ice. Analyses 4 and 5 are typical of the springs tributary to the river. The spring represented by No. 4 issues from the base of the Wisconsin till, and its water is actively depositing travertine. There are also some lime-secreting algae in the rivulet flowing from it. The spring represented by analysis 5 is one of a series of 40 or more flowing from the right bank at the Columbia Falls dam site on the main Flathead River. The water emerges from a sheet-like deposit of glacial outwash and probably represents the reappearance of Cedar Creek, which sinks into the drift just north of the town of Columbia Falls. This water is not depositing lime, although its calcium content is about the same as that of the other spring. A graphic comparison of these waters in reacting values in parts per million is given in figure 7.

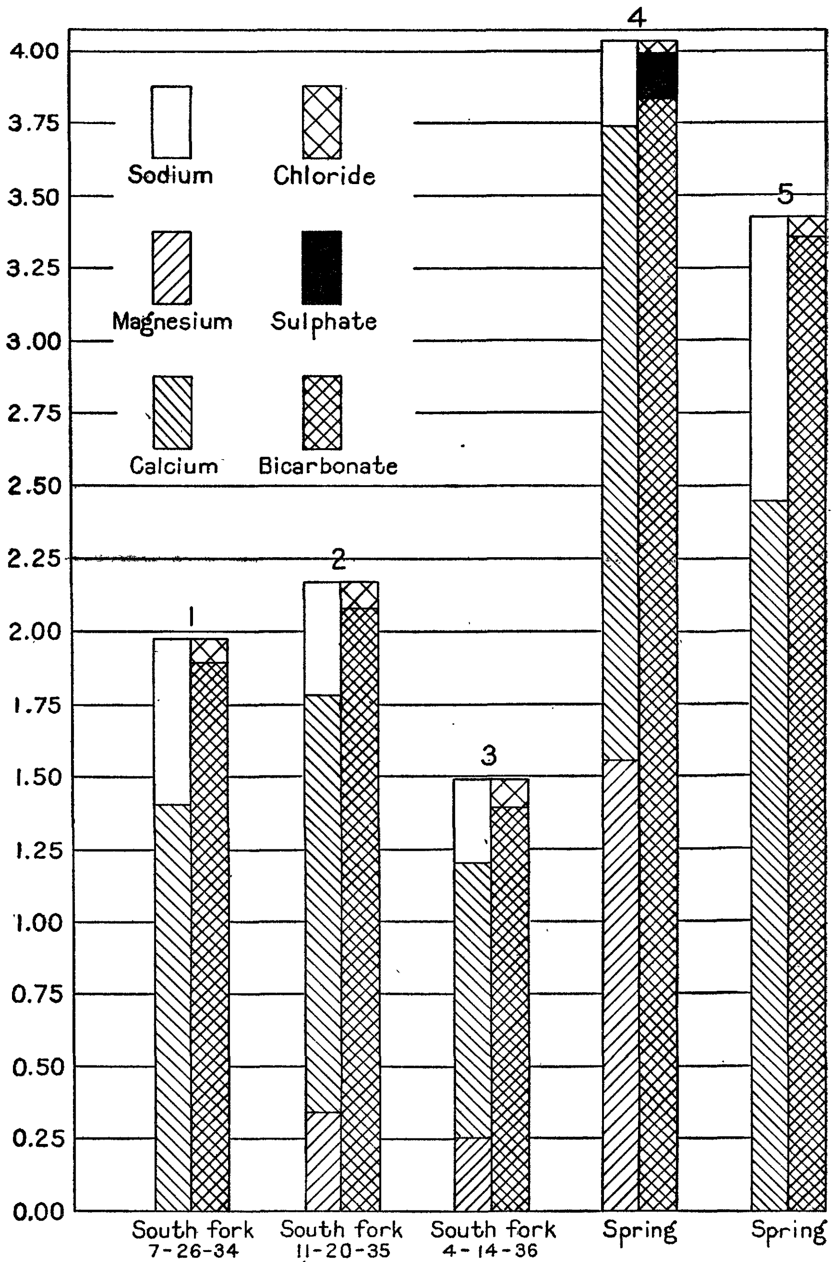

FIGURE 7.—Typical analyses of river and spring waters, giving reacting values in parts per million. Hungry Horse project, Flathead County, Mont.

Typical analyses of river and spring waters, Hungry Horse project, Flathead County, Mont.

[Analyses by J. G. Crawford, U. S. Geological Survey Laboratory, Casper, Wyo.]

	1	2	3	4	5
Parts per million					
Sodium (Na)	13	9	6	6	22
Calcium (Ca)	28	29	19	45	49
Magnesium (Mg)	Trace	4	3	19	Trace
Sulphate (SO_4)				7	
Chloride (Cl)	3	3	3	3	3
Bicarbonate (HCO_3)	115	127	85	234	203
Reacting values, in parts per million					
Sodium (Na)	0.57	0.38	0.28	0.27	0.96
Calcium (Ca)	1.40	1.45	.95	2.25	2.45
Magnesium (Mg)		.33	.25	1.56	
Sulphate (SO_4)				.15	
Chloride (Cl)	.08	.08	.09	.09	.09
Bicarbonate (HCO_3)	1.89	2.08	1.39	3.84	3.33
Reacting values, in percent					
Sodium (Na)	14.47	8.80	9.46	3.31	14.08
Calcium (Ca)	35.53	33.56	32.09	27.57	35.92
Magnesium (Mg)		7.64	8.45	19.12	
Sulphate (SO_4)				1.84	
Chloride (Cl)	2.03	1.85	3.04	1.10	1.17
Bicarbonate (HCO_3)	47.97	48.15	46.96	47.06	48.83
Properties of reaction					
Primary salinity	4.06	3.70	6.08	5.88	2.34
Secondary salinity	0	0	0	0	0
Primary alkalinity	24.88	13.90	12.84	.74	25.82
Secondary alkalinity	71.06	82.40	81.08	93.38	71.84
Chloride salinity	100.00	100.00	100.00	37.51	100.00

1, 2, 3. South Fork Flathead River. Samples taken just above South Fork Bridge, Highway No. 2. 1, July 26, 1934; 2, Nov. 20, 1935; 3, Apr. 14, 1936.
4. Spring in center of NE¼ SE¼ sec. 5, T. 30 N., R. 19 W. Base of Wisconsin till.
5. Spring in south-central part of sec. 17, T. 30 N., R. 20 W. Wisconsin outwash gravel.

SILTING

The turbidity of the water of the South Fork of Flathead River is very low. Quiet water has a deep green color, and bottom can be seen easily at depths of 30 feet. Owing to the heavy forest cover of the catchment area and to the fact that most of the soft, unindurated, silt-yielding formations occupy the valley floor and not the higher slopes, the river is fairly clear even during the high-water season of April, May, and June. Additional evidence that the stream carries little silt is furnished by the small size of the delta at the inlet of Flathead River into Flathead Lake.[35] Under present conditions silting will not be a problem in the Hungry Horse Reservoir. If the catchment area should be burned over the equilibrium may be destroyed and the rate of runoff and silting increased. Even so, the harder rocks of the higher hills will contribute little fine-rock debris.

[35] Topographic map of Flathead Lake project, Montana, south half, scale 1:12,000, U. S. Geol. Survey, 1929.

GEOLOGIC CONDITIONS

The geology has not been mapped in detail over the entire area of the reservoir, but some of the salient features have been determined by reconnaissance. The general structural conditions have been outlined briefly in the section on Structure. Strata of the Missoula group constitute the bedrock floor and are overlain by Tertiary lake beds, glacial drift, and alluvium.

LEAKAGE FROM HUNGRY HORSE RESERVOIR

The chief geologic problem of this reservoir is that of leakage. High surface and ground-water divides inclose the basin, except at the north end. All known springs issue from glacial drift, and their reversal of flow or flooding-out can have no important consequence. Conditions appear to be ideal.

The north or open end of South Fork Valley lies between the back (east) slope of Columbia Mountain and the west flank of Emery Ridge, both being parts of the Swan Range tectonic block. It is diversified by several topographic features parallel to the general course of the valley, which have an important bearing on the problem. From west to east these features are the active gorge of the South Fork of Flathead River, the line of hills trending southward from Lion Hill through Abbott Ridge, and a long, narrow strip of lowland extending northwest from the mouth of Solander Creek (southeast corner of sec. 5, T. 29 N., R. 18 W.) to the valley of the main Flathead south of the Coram Ranger station (southwest corner of sec. 34, T. 31 N., R. 19 W.). (See fig. 8.)

On the topographic map this low belt gives a strong impression of continuity, and although it is occupied by portions of several distinct streams it appears definitely to be the prolongation of the course of South Fork Flathead River above the mouth of Solander Creek. These relations were recognized by Pardee who described them as follows:

> East of the canyon and parallel to it is a wide valley, called Wilson Valley, that is not now occupied by a stream but forms a depression continuous with the upper valley of the South Fork. The floor of Wilson Valley descends both ways from a divide that is about 500 feet higher than South Fork in the canyon opposite.
>
> * * * * * * *
>
> Wilson Valley, which lies about 2 miles east of the South Fork Canyon and is parallel to it, is a depression from 1 to 2 miles wide with a rather flat floor and moderately abrupt sides. At the south it joins the valley of the South Fork and is, in fact, seen to be the continuation of that depression northward beyond Hungry Horse Creek.[36]

Casual inspection of these relationships suggests that the low strip or depression is a former course of the South Fork of Flathead River

[36] Pardee, J. T., op. cit., pp. 2–4.

and gives rise to a working hypothesis that an older, presumably Tertiary, outlet of the South Fork Basin lay between Lion Hill and Abbott Ridge. This hypothetical valley is designated in this report as Abbott Gorge.[37]

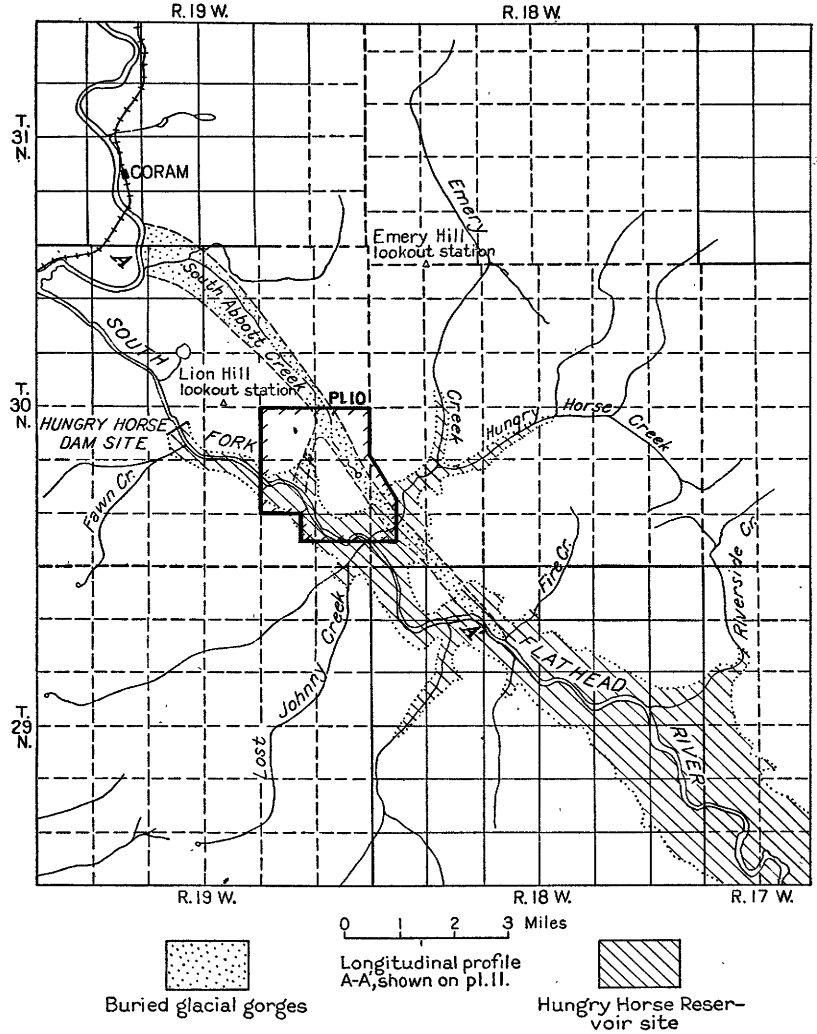

FIGURE 8.—Index map showing relation of buried glacial gorges to the South Fork of Flathead River and Hungry Horse Reservoir, Flathead County, Mont.

The supposition as to the existence of this gorge, with its many implications, has been fundamental to the course of the investigation of leakage from the reservoir. A subsidiary hypothesis of high-

[37] The geographic names used herein are taken from the map of the Flathead National Forest, United States Forest Service, 1933.

level river diversion is required to account for the present superimposed course of South Fork Flathead River on the steep east flank of Columbia Mountain. An important corollary is that the Tertiary outlet, now so thoroughly covered by later deposits, must have been more than equal in width and depth to the present outlet, because the period during which the former was supposed to have been carved by the stream far exceeds the time that can be allotted for the excavation of the latter if initiated by high-level glacial diversion. Consideration of the late geologic history of the region suggests that Abbott Gorge may have been occupied successively, and in variable amounts, by basal stream gravels, Tertiary lake beds, and glacial and interglacial deposits. Unless the later glaciers scoured its sides and bottom clean and refilled it with boulder clay, it seems possible that remnants of permeable deposits might serve as conduits for large volumes of water to escape from the reservoir if the impounded flood were raised against cross sections of the fill.

Hungry Horse Creek intersects Abbott Gorge at the center of the north line of sec. 31, T. 30 N., R. 18 W., the location of the old Hungry Horse Ranger Station, where there is a widening of the creek valley and a small park or clearing of a few acres. (See pl. 10.) Abbott Gorge south of the creek is not involved in the leakage problem, but some localities in it are of importance in connection with the study of the origin of the gorge. The part of the gorge north of the creek is occupied by Hungry Horse Lake meadows and South Abbott Creek. The meadows lie east of Abbott Ridge at an altitude just over 3,600 feet. (See pl. 11, sec. G–G′.) The flat treeless floor surrounding the small central pond, called Hungry Horse Lake, is firm and covered with wild hay, but the forest is encroaching upon the open land. The land surface at the south end of the meadows descends steeply to Hungry Horse Creek. Northward it rises gradually to a divide that lies just north of the south quarter corner of sec. 24, T. 30 N., R. 19 W. The altitude on the divide is 3,695 feet, and the pass is so narrow that on the map the 3,700-foot contour girdling Abbott Ridge almost touches the same contour on the southwest end of Emery Ridge. (See secs. A–A′, and F–F′, pl. 10.) South Abbott Creek heads against the north slope of this divide. The drainage is not well developed, and the ground is soft and marshy. The stream flows northwest with increasing gradient and better definition of valley to its junction with Abbott Creek in the center of the NE¼ sec. 4, T. 30 N., R. 19 W. The confluence with the main Flathead River is three-fourths of a mile west of the junction.

South Abbott Creek forks near the center of the west line of sec. 24, T. 30 N., R. 19 W., an intermittent stream entering from the southwest. This small tributary heads in an obscure, marshy divide, a little south of the west quarter corner of sec. 24, which separates it from the river. This divide, altitude 3,650 feet, is the controlling elevation of Hungry Horse Reservoir. The ground to the northeast is nearly level, and the drainage channel toward South Abbott Creek is ill-defined. Drainage toward the river passes through a deep ravine that separates Lion Hill from Abbott Ridge. (See pl. 10, sec. C–C′; pl. 11, sec. E–E′.) The depth and width of this ravine suggest that it once extended from the river northeastward into Abbott Gorge. It is designated here as the Lion Hill Gorge.

The distance from the mouth of Abbott Creek to the supposed head of Abbott Gorge, near the mouth of Solander Creek, is about 9 miles. The shortest route for seepage through this gorge is from the old Hungry Horse Ranger Station, a path of about 6 miles. This distance is so considerable that it seems impossible for seepage to occur along it, but the length of the zero gradient along this course, that is, the distance from the 3,540-foot contour on the reservoir face of the fill to the same contour in South Abbott Creek, is only 2.4 miles. If the South Fork Flathead River once occupied this gorge, a subterranean drainage course might exist below the fill and leakage might occur if reservoir water found access to this passage. Conditions illustrative of those possibly extant in the gorge are found on the left bank of the main Flathead River in the center of the NE¼ SE¼ sec. 5, T. 30 N., R. 19 W., near the mouth of Abbott Creek. A series of springs issue from the contact between the interglacial Sangamon (?) stream gravels and the Wisconsin drift, and although the discharge of each is less than half a cubic foot per second, the total discharge is considerable because of their great number over a distance of about 2 miles. These highly permeable glacial deposits fill in the lower part of Abbott Creek Valley. They appear to be related to the main Flathead River, but if they persist southward toward Hungry Horse Reservoir leakage might develop. Another striking example of the permeability of stratified glacial deposits has been described in connection with the Columbia Falls dam site on the main Flathead River.[38]

The deep ravine at Lion Hill gorge seems to provide opportunity for nearly the full head of the reservoir to be brought near Abbott Gorge at a point only 4 miles from its mouth. Furthermore, the distance between the 3,540 contour in Lion Hill Gorge and the same

[38] Erdmann, C. E., Geology of dam sites on the upper tributaries of the Columbia River in Idaho and Montana, pt. 3, Miscellaneous dam sites on the Flathead River and tributaries upstream from Columbia Falls, Mont.: U. S. Geol. Survey Water-Supply Paper 866–C (in preparation).

contour in South Abbott Creek is only 1.2 miles. Consideration of seepage through this gorge shows the following possibilities:

A. If there were no rock divide between the two gorges, water might percolate through the fill from Lion Hill Gorge to the bottom of Abbott Gorge, where it might find an existing drainage course. Under this assumption, owing to the thickness of the Wisconsin till in Lion Hill Gorge and its low permeability, the danger of seepage is not great, but it is not entirely absent. The same reasoning applies if there were a thin intergorge divide deeply buried.

B. If a wide bedrock divide between the two gorges were covered with a thin till mantle, the danger of leakage would also be slight.

C. If a narrow bedrock divide were present, water seeping through a thin till mantle might find its way into shear openings in the hard rock and so make its way to the floor of Abbott Gorge, and thence probably to the main river.

In order to test seepage contingencies for both gorges, it was necessary to determine in the field the following conditions:

(1) Whether these gorges exist as postulated, and if so—

(2) Their origin, fluviatile or glacial, or both, and especially whether the ancient South Fork river had ever flowed through them.

(3) Their width, depth, and character of floor.

(4) The location and character of their junction, or the nature of the bedrock divide between them.

(5) The character and arrangement of their filling.

The method consisted chiefly of an inquiry into the origin and development of the drainage system of South Fork Valley and a study of its glacial history. This work indicated the critical localities (pl. 10), and obscure points in them were checked by use of geophysical methods.

Without entering into a detailed discussion of each of the above points, the following conclusions may be stated:

The Abbott and Lion Hill Gorges exist as postulated (fig. 8 and pl. 10).

They originated as minor tributaries to the Flathead River and South Fork Flathead River.

Any occupancy of either gorge by the main river has been temporary and, owing to glacial blocking and diversion, at a much higher level than that of the present stream. The present form of each is due to glacial scour. The floor of Abbott Gorge is ungraded and has considerable relief (pl. 11, A–A′). It appears not to be a continuous gorge. Cross sections (pl. 11, B–B′, F–F′, G–G′) show that it has neither great width nor depth. A peculiar feature is that, with the single exception of Hungry Horse Creek, it has no important tributaries throughout its length of about 9 miles; whereas the river valley has at least six large tributaries over the same distance. Furthermore, if the river had once occupied the gorge for a long period, one would expect to find some evidence of wind gaps where the streams flowing down the back slope of the Swan Range passed over Abbott Ridge and Lion Hill, but there are no wind gaps. These conditions differ from those of the characteristic glaciated stream valleys in this region and are sufficient grounds on which to reject the hypothesis that Abbott Gorge was in Tertiary time the outlet of the South Fork Basin. The associated hypothesis of high-level Pleistocene diversion of the South Fork River is also rejected.

Therefore, it seems highly probable that the present valley of the South Fork Flathead River has been the sole outlet from the basin since late Tertiary time.

A bedrock divide appears to stand above the floor of Abbott Gorge near the south quarter corner of sec. 24, T. 30 N., R. 19 W., and probably rises above the high-water flow line of the reservoir, effectively blocking drainage. It is expressed at the surface by the drainage divide between Hungry Horse Lake meadows and South Abbott Creek. Should this conjecture be in error, an adequate factor of safety is provided by the length of filled section of the gorge (pl. 11, A–A′).

The longitudinal profile of Lion Hill Gorge is regular and slopes toward the river from a broad bedrock divide that separates it from Abbott Gorge (pl. 11, C–C′, D–D′, E–E′).

The surface junction of Lion Hill and Abbott Gorges is in the west center of sec. 24, T. 30 N., R. 19 W. (fig. 8 and pl. 10). There is no subsurface connection. The width of the bedrock divide separating the gorges varies from about 3,300 feet at the base (3,450 feet) to about 1,900 feet at the high-water flow line of the reservoir (3,540 feet). The rock surface is believed to rise at least 45 feet above this level, or to 3,585 feet. The top is thus rather flat, and the high point is on the east side, near the rim of Abbott Gorge. The cover is shallow and ranges from 35 feet to about 100 feet below the surface divide. The conditions represented by this interpretation are essentially those of the second seepage possibility, that is, a wide bedrock divide between two gorges covered with a thin till mantle, and under such conditions the danger of leakage is slight.

Acceptance of the conclusion that the gorges are chiefly of glacial origin and relatively shallow greatly simplifies interpretations of the character and arrangement of the fill. Geologic evidence, as well as seismograph and resistivity data, indicate that the fill is glacial boulder clay of Wisconsin age. Seismograph data show that it is compact and therefore of low porosity. Mechanical analyses indicate a partially graded material, high in silt and clay and of low permeability.

The general conclusion from the conditions outlined above is that the Hungry Horse Reservoir is safe from leakage through buried glacial gorges, as such drainage is blocked effectively by bedrock divides that rise above the high-water flow line and by an impermeable covering and fill of glacial boulder clay over and on both sides of them.

DRILLING EXPLORATION

In a project of this magnitude some risk is involved in accepting geologic appearances at face value. Actual test of the conditions is always advisable. In this project preliminary drilling has already been done at the dam site in the fall of 1939 by the Corps of Engineers (p. 43), but the gorges have not yet been explored. Preferably, the gorges should have been drilled first, because, if conditions in them prove unsatisfactory or irremediable within reasonable expenditure, there might have been no occasion to drill the dam site.

Suggestions are here offered with regard to exploratory drilling in the gorges, although it is recognized that a complete schedule cannot be planned in advance. The bedrock divide separating Lion Hill Gorge from Abbott Gorge should be explored by drilling on 200-foot centers along a line trending N. 40° W. through resistivity location 39, plate 10. One hole should be put down at location 39, another 200 feet northwest, and at least three to the southeast. Other holes should be drilled at locations 12 and 38. This arrangement would give the bedrock profile of the upper part of Lion Hill Gorge, show whether or not a bedrock divide separates it from Abbott Gorge, and provide information on the depth and character of the fill. Seven holes would be required, and the total footage should not exceed 600 feet if the findings of this preliminary investigation are correct.

A good test of the presence or absence of the bedrock divide in Abbott Gorge would be to drill one hole on the surface divide at B. M. 3695 (pl. 10). If conditions are found to be as represented in plate 11, A—A′, sufficient proof of a bedrock divide in Abbott Gorge will have been obtained. However, if other conditions are found, it may be advisable to extend drilling northeastward from locality 12 toward locality 46, with a test at the latter as well as an intermediate locality.

MINERAL DEPOSITS OF THE HUNGRY HORSE RESERVOIR AREA

COAL

Lignite coal occurs in the Tertiary lake beds in the Hungry Horse Reservoir area and will be submerged by waters in the reservoir. For this reason knowledge of the nature and extent of the deposits is desirable. The general character of the enclosing formation has been described on pages 62 and 63.

The presence of coal in the area has long been known, as the beds crop out along the South Fork Flathead River at several localities. A few of these were visited, and the detailed measurements made give a general idea of the probable character of the entire deposit. Its extent and areal distribution must remain unknown until further field work has been done. Likewise unknown are the total thickness of the enclosing formation, the nature and extent of its deformation, the thickness of the coal-bearing zone and the number of seams, the position of this zone in the formation, and whether it is possible to correlate the beds at the various localities or to use a given seam as a key bed for structural mapping.

The reconnaissance work suggests that the coal-bearing zone is of considerable thickness, possibly 200 to 300 feet, and that there are many thin seams, only a few of which are of commercial thickness. The habit of the seams appears to be lenticular, and it is doubtful if any bed of commercial value persists throughout the area. The largest seams observed range from 3 to 6 feet in thickness. Search should be made for a bed equivalent to that mined at the North Fork Coal mine, which has a total thickness of 25 feet.

So far as is known, no mines have been opened on the exposed beds, probably because of the great distance of the area from a market and the abundance of wood for local fuel.

From the brief examination made, it is my tentative opinion that the entire deposit is not valuable and that the loss occasioned by covering it with water will be small.

Measurements of coal beds along South Fork Flathead River

1. Outcrop in low cut on east side of road 0.1 mile north of Logan Creek bridge, NW¼, sec. 2, T. 27 N., R. 17 W.

	Ft.	in.
Roof: Siltstone, soft buff.		
Coal: Lignite, black, woody	1	6
Floor: Clay, gray, carbonaceous.		

2. At Coalbank, east side of South Fork Flathead River below road, in southwest corner of sec. 35, T. 28 N., R. 17 W., near north end of Elk Park. Strata dip 12° S. 43° E. Beds on west side of river not examined.

	Ft.	in.
Top of section.		
Stream gravel	30±	
Lignite, black		9
Siltstone, buff, slightly carbonaceous	1	2
Lignite, black	1	5
Clay and siltstone, gray and brownish; 3-inch layer of sandstone near base	2	3
Lignite, black	4	10
Clay, brownish	1	4
Lignite, black	1	10
Clay, brown		6
Lignite		1
Clay, brown		2
Lignite		2
Clay, carbonaceous		8
Lignite, black		9
Clay, carbonaceous		2
Lignite, bony, black		8
Clay, carbonaceous		6
Clay, gray		3
Clay, carbonaceous		3
Clay, gray		3
Bone		3
Lignite		2
Clay		1
Lignite, black		3
Clay		3
Lignite, bony, black		6
Clay		2
Lignite, black		3
Clay, gray		2
Lignite, black		5
Siltstone, light gray	5	1

2. Coalbank, east side of river below road—Continued.

	Ft.	in.
Lignite, bony, black		9
Clay, carbonaceous, brown		8
Lignite, bony	1	
Siltstone and brownish clay		11
Lignite		1
Clay, carbonaceous, brown		4
Siltstone, gray	4	6
Lignite, small lentil		3
Siltstone, gray		2
Clay, carbonaceous and lignite		7
Siltstone, light gray		8
Lignite, clean, bright, black; lentil about 3 feet long		1
Siltstone, light gray		8
Lignite		4
Siltstone, light gray		6
Clay, carbonaceous, and lignite		9
Siltstone, light brownish-gray		11
Shale, carbonaceous		8
Mudstone, brownish; irregular thin layers of yellowish-brown sandstone at top		11
Clay, gray, carbonaceous, and lignite		2
Lignite		2
Siltstone, gray		4
Siltstone, light brown, carbonaceous, and carbonaceous clay		7
Lignite, black		3
Clay, gray, carbonaceous		10
Siltstone, light gray; nodular sandstone near middle 1 inch thick	6	5
Clay, carbonaceous, with fragmentary lignite at base at angles to bedding		5
Siltstone, light gray	2	1
Clay, carbonaceous, brown		4
Siltstone, light gray		2
Clay, carbonaceous; locally lignite lentils 4 to 6 inches thick appear in this bed; maximum thickness of the bed may be 14 inches		4
Lignite, black		2
Clay, carbonaceous, dark brown		6
Siltstone, gritty, light gray; dry weathered surface white, adheres to tongue	2	5
Clay, carbonaceous, dark brown to black		2
Siltstone, gritty, light gray; dry weathered surface white, adheres to tongue	4	6
Sandstone, pink, hard		8-10
Clay, sandy, pink	4±	
	95±	

3. East bank of river below Devils Corkscrew Creek, southwest corner of sec. 12, T. 27 N., R. 17 W. Beds dip 21°, N. 50° E. This locality would have to be examined at very low-water stage to determine character of the submerged bed.

	Ft.	in.
Stream conglomerate in matrix of red sandy clay. Bank caving	10±	
Lignite, bony. Concealed by slump	2±	
Siltstone, buff	4	
Siltstone, gray, carbonaceous at base	1	6
Lignite, black	1	2
Siltstone, buff	1½–2	
Lignite (?), submerged; outcrop on bank concealed by slump	6 (?)	
Siltstone, buff	5±	
	31±	

4. About 100 feet downstream from locality 3, at water's edge.

	Ft.	in.
Siltstone, massive, buff, overlain locally by stream conglomerate with matrix of pink clay.		
Lignite, black, dirty, woody structure; slacks easily; contains an occasional thin seam of bright coal	3+	
Sandstone, gray		6
Lignite, black, as above	1	6
Siltstone, buff		
	5+	

5. Wheeler Creek. Good exposures of coal have been reported from the mouth of this creek in secs. 14, 15, and 22 and possibly farther upstream in T. 29 N., R. 17 W., but it was not possible to visit them.

OIL

Seeps of oil have not been reported from Hungry Horse Reservoir area. Some of the conditions of their occurrence in the North Fork Valley are duplicated, and it is possible, if the Flathead Range overlies the Lewis overthrust fault, that small seeps might occur in the Belt formations along the Flathead or related faults, but if such exist the probability of their being of commercial importance is extremely remote.

Deposits of asphaltite in dikes have been reported from near the mouth of Mid Creek, sec. 3, T. 23 N., R. 14 W., about 17 miles upstream from the head of prospective backwater from Hungry Horse dam. The geology of these deposits is unknown, but they may be related in origin to oil seeps from younger strata that have been overridden by faulted masses of Belt rocks.

METALLIFEROUS DEPOSITS

A few bodies of intrusive basic igneous rock, probably dikes and sills, cut the Missoula group near the south end of the reservoir area, and some may occur within that area. Some of these may have caused sparse mineralization by pyrite and chalcopyrite or may have given rise to quartz-carbonate veins. The reservoir area and surrounding country can hardly be regarded as a mineral region.

MATERIALS FOR CONSTRUCTION

The vicinity of the Hungry Horse dam site is not favored with a wealth of materials suitable for the construction of a high dam.

GLACIAL DRIFT

Morainal material or valley till is not abundant in the vicinity of the dam site. The chief constituents are apparently silt and clay from the unconsolidated formations and small rock fragments. Boulders are uncommon, but stream cobbles from ancient terraces have been incorporated locally. Sand makes only a small portion of the mass. It is so heterogeneous, however, that careful search might reveal local deposits that upon washing would yield useful materials.

SAND

Most material of sand size consists of small particles of rock rather than of mineral grains. Deposits suitable for cement probably exist in some of the glacial outwash along the Flathead River in the vicinity of Columbia Falls, or in high constructional terraces on the Middle Fork Flathead River near Nimrod, sec. 31, T. 29 N., R. 16 W.

CEMENT

The Siyeh limestone in general is too high in magnesium for use in manufacture of Portland cement. Detailed sampling might yield a suitable ledge, but this would be a considerable task, and, since the other ingredients are also lacking the most practicable procedure would be to import the cement.

POZZUOLANIC MATERIALS

No pozzuolanic materials occur in the region.

CONCRETE AGGREGATE

The Siyeh limestone would probably make good aggregate if it were not so thoroughly jointed. If used for this purpose, it should be crushed to dimensions lower than the smallest joint blocks to avoid planes of weakness. The Ravalli argillite would make good aggregate, as it is hard, tough, massive, and insoluble. The rocks of the Missoula group are usually thin-bedded and micaceous, and where quartzites occur they are generally well shattered. Igneous rocks are not present in the vicinity. If the river gravels were washed for sand, the stream pebbles and cobbles or argillite could be used for aggregate. They are hard, smoothly rounded, and impervious.

MASONRY

Some of the considerations that apply to concrete aggregate apply to rock for masonry. The Missoula group consists of thin-bedded argillites, unsuitable for masonry. The Ravalli argillite has suitable beds, but their outcrop is at some distance from the dam site. The Siyeh limestone has some massive ledges suitable for masonry, but the material would have to be selected carefully to avoid faulty, jointed blocks.

TIMBER

Ample supplies of timber for concrete forms and other rough lumber are available. Sawmills could be set up locally.

COAL

The beds examined in the vicinity of Coalbank are thin and unsuitable. The bed exposed in the river just below Devils Corkscrew Creek might be stripped and mined, also the bed on Wheeler Creek. The nearest local source of coal is the mine on North Fork Flathead River about 25 miles by road from Columbia Falls.

WATER SUPPLY

The water supply is abundant and of good quality.

ELECTRIC POWER

The Mountain States Power Co. has a small plant at Big Fork, and their nearest trunk line is at Columbia Falls. The Montana Power Co.'s plant at Kerr dam on Flathead River, below Polson, makes available large amounts of power. A special trunk line will have to be built to bring the power to Hungry Horse dam site.

NATURAL GAS

The nearest source of natural gas for fuel or power is at Cut Bank. The distance from Cut Bank to the dam site by way of the Great Northern Railway is about 105 miles.

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