STATE OF MONTANA
Tim Babcock, Governor

BUREAU OF MINES AND GEOLOGY
E. G. Koch, Director

BULLETIN 47
July 1965

GEOLOGY AND GROUND-WATER RESOURCES OF THE MISSOULA BASIN, MONTANA

by

R. G. McMurtrey, R. L. Konizeski, and
Alex Brietkrietz

MONTANA BUREAU
of
MINES AND GEOLOGY

Butte, Montana

STATE OF MONTANA
BUREAU OF MINES AND GEOLOGY
E. K. Koch, Director

Bulletin 47

GEOLOGY AND GROUND-WATER RESOURCES OF THE MISSOULA BASIN, MONTANA

by
R. G. McMurtrey, R. L. Konizeski, and
Alex Brietkrietz

This bulletin has been prepared by the U. S. Geological Survey, Water Resources Division, under a cooperative agreement with the Montana Bureau of Mines and Geology.

MONTANA COLLEGE OF MINERAL SCIENCE AND TECHNOLOGY
Butte, Montana
July 1965

McKEE PRINT.

For Sale by

Montana Bureau of Mines and Geology

Room 203-B, Main Hall

Montana College of
Mineral Science and Technology

Butte, Montana

Price $1.00

CONTENTS

ILLUSTRATIONS

[All plates in pocket]

TABLES

GEOLOGY AND GROUND-WATER RESOURCES OF THE MISSOULA BASIN, MONTANA

by

R. G. McMurtrey, R. L. Konizeski, and
Alex Brietkrietz

ABSTRACT

The Missoula Basin, a wedge-shaped intermontane depression in west-central Montana, includes the Missoula and Ninemile Valleys. It has an area of about 180 square miles, and is drained by the Clark Fork of the Columbia River, Ninemile Creek, and their tributaries. The climate is semiarid, annual precipitation being about 13 inches. The economy is dependent mainly on forest-product industries and on agriculture maintained by irrigation.

The basin was formed during Late Cretaceous or early Tertiary time in a Precambrian sedimentary rock terrane. It was downdropped on the northeast side, overthrust on the southwest side, and subject to recurrent movement until late Tertiary time. During middle Tertiary, Oligocene(?), time the basin was partly filled with perhaps as much as 13,000 feet of erosional detritus from the marginal highlands, interbedded with minor amounts of volcanic ejecta. The detritus accumulated in environments that alternated from boggy meadow-marshland and pond to outwash fan. The resultant deposits of interbedded shale and conglomerate were subsequently mantled by a few hundred feet of well-sorted channel gravel and sand of Pliocene(?) age. Recurrent late Pliocene movement around the margins of the basin tilted the Tertiary strata to the northeast. The basin was flooded and drained during successive glaciations and interglaciations of the Pleistocene Epoch. More than 200 feet of unconsolidated glaciolacustrine gravel, sand, and clay was deposited. The present drainage system is eroded into these deposits. The principal topographic features are of a composite depositional and erosional origin. The Clark Fork flood plain and low fringing terraces and the Ninemile flood plain are mantled by recent erosional debris. High terraces in the Missoula Valley are formed mostly on sediments that were deposited in ancient glacial Lake Missoula. Upland areas on the northeast side of the basin are erosional features formed mostly on Tertiary strata.

Three gravity profiles and a gravity map were drawn for the Missoula Valley. They indicate a maximum depth of fill of about 3,000 feet in the central part, and a total volume of fill of about 25 cubic miles.

More than 3¾ million acre-feet of water flows through the basin each year. The Clark Fork, draining an area of about 6,000 square miles, discharges about 2 million acre-feet into the basin each year; the Bitterroot River, which has a drainage area of about 3,000 square miles, discharges about 1¾ million acre-feet. The discharge from other streams is unknown but is relatively insignificant.

Of about 30 million acre-feet of ground water in storage in the Missoula Valley, about 8 million acre-feet is available to wells. Use of ground water increased from about 6,500 acre-feet per year in 1957 to about 24,000 acre-feet per year in 1963. The principal source of ground water is the upper 200 feet of the unconsolidated sediments of the basin fill. Water levels in wells range from a few feet above land surface (in artesian wells) to 290 feet below land surface, but most are less than 50 feet. Seasonal fluctuation of the water level averages about 8 feet. Yields of the wells range from a few to 5,000 gallons per minute.

A generalized map of the water table in the Missoula Valley indicates that the general direction of movement of ground water is toward the Clark Fork, but locally the direction of movement varies. The rate of movement is generally less than 3 feet per day.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

In 1955 the U. S. Geological Survey and the Montana Bureau of Mines and Geology began a cooperative program of ground-water studies in Montana to provide data for planning the use and conservation of the ground-water resources of the state (Fig. 1). The investigation of the geology and water resources of the Missoula Basin, begun in July 1961 and completed in May 1964, is a part of the statewide program.

Use of ground water in the Missoula Basin for municipal, industrial, irrigation, domestic, and other supplies probably exceeded 20 million gallons per day during the peak pumping period in the summer of 1961. Because most of the water was pumped from two small areas in the basin and the use of ground water was increasing rapidly, a comprehensive investigation of the ground-water resources became essential to the orderly planning of future water supplies.

The investigation was made in order to appraise ground-water conditions and resources in the Missoula Basin with particular reference to (1) thickness, character, and areal extent of water-bearing beds underlying the valley; (2) occurrence, source, and direction of movement of ground water; (3) availability and quantity of ground water; (4) seasonal, annual, and long-term changes in ground-water storage; and (5) chemical character of the water.

The investigation was planned in cooperation with Dr. E. G. Koch, the director of the Montana Bureau of Mines and Geology. It was made under the direct supervision of Frank A. Swenson and Charles W. Lane, successive district geologists of the U. S. Geological Survey.

ACKNOWLEDGMENTS

The authors express their appreciation to all who aided this study. Thanks are extended to those individuals who willingly supplied information about their wells and permitted access to their property. Special thanks are due those who permitted repeated access to their wells for water-level measurements. Well drillers, especially Glen

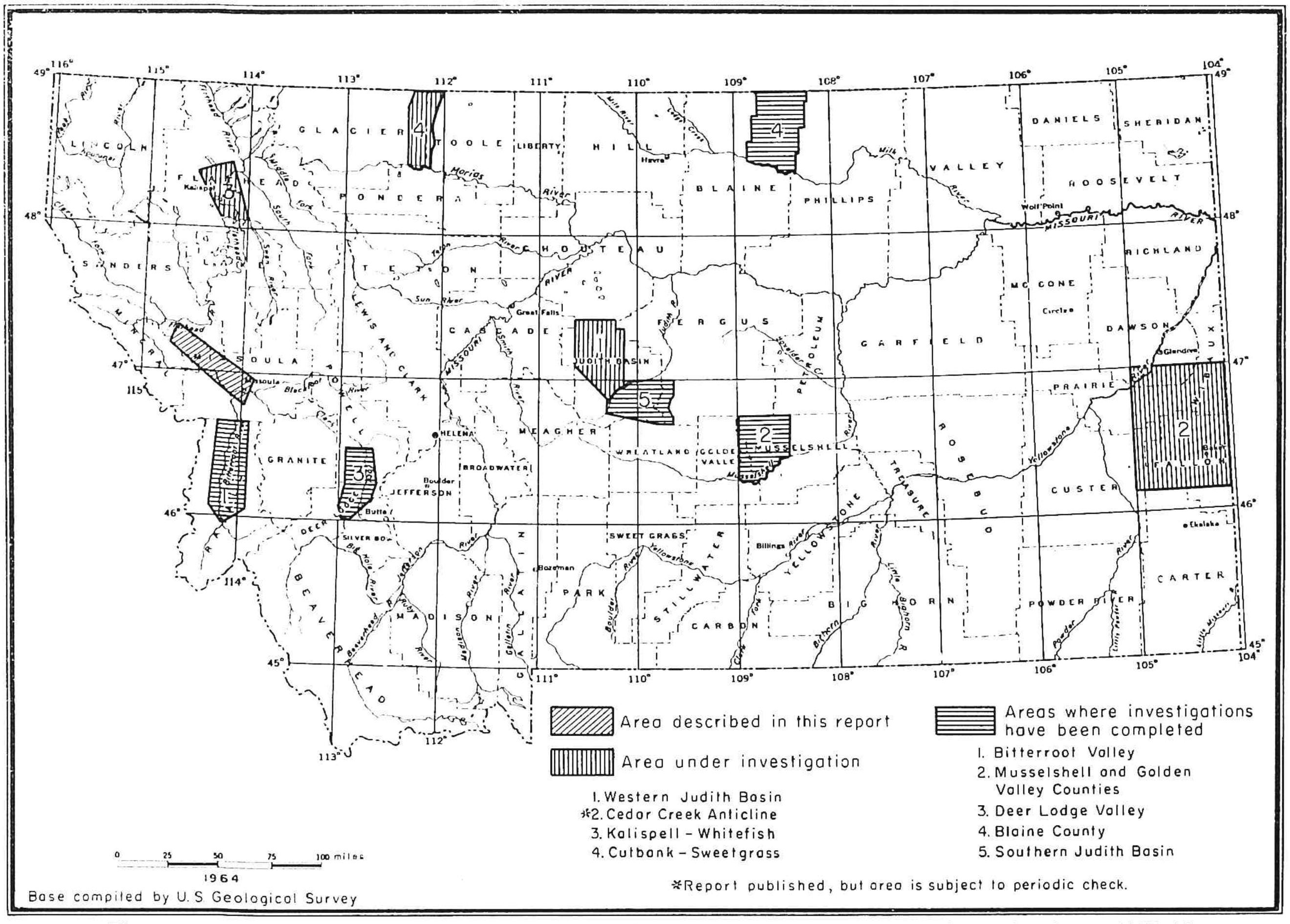

Figure 1.—Map of Montana showing location of cooperative ground-water investigations, 1955-64.

Camp and William F. Osborne, were helpful in providing well logs and other useful information. The following organizations contributed to the progress of the investigation: U.S. Forest Service; U.S. Geological Survey, Topographic Branch; U.S. Soil Conservation Service; Montana State Highway Commission; and Montana Power Company. The Missoula County Surveyor and the City of Missoula Engineer supplied valuable bench-mark data.

Special thanks are due Professor John Hower of Montana State University for his capable aid and direction during the gravimetric study. Professor William E. Bonini of Princeton University supplied unpublished gravity data to check the regional gradient.

PREVIOUS INVESTIGATIONS

Douglass (1899, p. 10, 11) described "***ancient shore lines***" formed by "***dashing of waves against the mountain sides***" and "***soft laminated clays***" in the Missoula Valley. Later (1902) he identified Oligocene "***White River or John Day***" beds in an area about 1½ miles north of Missoula. Rowe (1903, p. 21) described a geologic section in the same area, and Jennings (1920) described fossil plants collected from this area. Pardee (1910; 1942; 1950, p. 390) presented a detailed discussion of the ancient glacial Lake Missoula, discussed evidence of unusual currents in the lake, and described structural relationships within the Missoula Basin in connection with the hypothesis of its late Cenozoic block-fault origin. Eakins and Honkala (1952) summarized the Cenozoic history of the Missoula Valley. Alden (1953) described many geomorphic, stratigraphic, structural, and glacial aspects of the basin.

Perry (1933, p. 1-4) investigated the possibilities of shallow wells as a source of irrigation water in the Frenchtown area. The Montana State Engineer (1960) described the history of land and water use on irrigated areas in Missoula County.

Rowe (1906), Schrader (1911), Pardee (1913), Sieja (1959), Sahinen (1957), and Sahinen and others (1958, 1960, 1962) have written many papers on specialized phases of the geology of the basin that are not specifically relevant to this report.

METHODS OF INVESTIGATION

The geologic relationships pertinent to this report were studied in the field and mapped on aerial photographs. The resulting geologic map includes not only the basin but also a border zone that shows the structural and stratigraphic relations of the valley fill to the consolidated rocks of the marginal highlands. During the summer of 1962 a gravimetric survey of the Missoula Valley was made in order to obtain information on the depth of valley fill and to interpret subsurface structural features and bedrock configuration.

A well inventory was made and data were compiled for 281 wells in the area. Measurement of the water level was made periodically in 39 wells to determine the nature and amount of water-level fluctuations. The altitudes at 154 wells were determined by instrument leveling for use in the preparation of a water-table contour map that shows the general shape and slope of the water table in part of the basin. Information obtained from the well inventory and the water-level measurements are given in a report by Brietkrietz (1964). The hydrologic properties of water-bearing materials were determined in the field by means of five aquifer tests. The chemical characteristics of the water in the basin were determined from chemical analysis of water from 21 wells and 9 stream locations.

SYSTEM OF NUMBERING WELLS

The wells described in this report are assigned numbers that are based on their location within the system of land subdivision used by the U.S. Bureau of Land Management. The well number shows the location of the well by quadrant, township, range, section, and position within the section. A graphic illustration of this method of well numbering is shown in Figure 2. The first letter of the well number gives the quadrant of the meridian and baseline system in which the well is located. The first numeral indicates the township, the second the range, and the third the section in which the well is located. Lower-case letters that follow the section number show the location of the well within the quarter section (160-acre tract) and the quarter-quarter section (40-acre tract). These subdivisions are designated a, b, c, and d in a counterclockwise direction, beginning in the northeast quadrant. If two or more wells are located within the same 40-acre tract, consecutive digits beginning with 1 are added to the well number. For example, well B-13-20-9ba3 is in the NE¼NW¼ sec. 9, T. 13 N., R. 20 W., and is the third well inventoried in that tract.

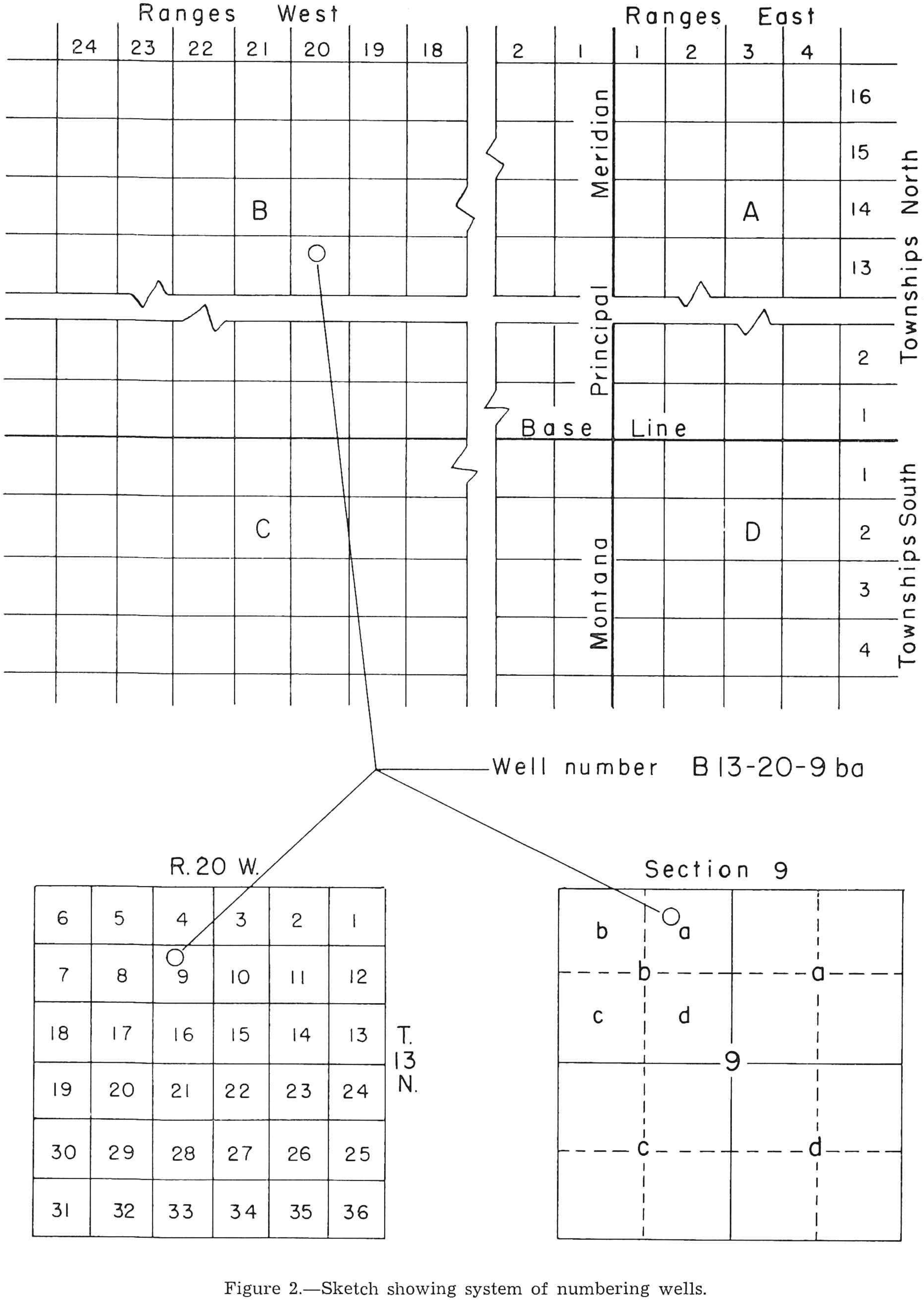

Figure 2.—Sketch showing system of numbering wells.

GEOGRAPHY

LOCATION AND EXTENT OF BASIN

The Missoula Basin (Pardee, 1950, p. 390) lies entirely within Missoula County in west-central Montana. It is a 180-square-mile wedge-shaped intermontane depression consisting of two segments, the Missoula and Ninemile Valleys. Its base near Missoula is about 8½ miles wide, and it trends N. 55° W. for about 50 miles (Fig. 3).

PHYSIOGRAPHY

The Missoula Basin is bounded by deeply dissected mountains whose summits are mostly below 6,500 feet, but whose higher peaks attain altitudes above 7,000 feet. Some of the higher mountains to the northeast are glaciated, and bedrock is exposed over much of their area. The steeply rising, valleyward slopes of the surrounding highlands form rugged 2,000- to 4,000-foot walls about the basin. The remarkably straight northeastern wall consists of a succession of triangular spur-end facets. It is interrupted by a narrow pass at the head of O'Keefe Creek (Fig. 4). The equally straight southwestern wall of Ninemile Valley is formed mostly by a succession of relatively low foothill benches. It cuts off abruptly near the middle of the basin at the mouth of a great westward-trending gorge, the Alberton Narrows. The southwestern wall of the Missoula Valley is formed by a succession of cliffs and steeply rising mountain slopes. It is roughly arcuate from the Alberton Narrows to Sherman Gulch. From Sherman Gulch it extends southeastward to a wide gap at the mouth of the Bitterroot Valley in the southern corner of the basin.

The valleyward slopes of Mount Jumbo and Mount Sentinel form steep triangular facets across the southeast end of the basin on each side of a 1,500-foot-deep V-shaped gorge known locally as the Hells Gate. The uniform upper slope of Mount Jumbo is interrupted by two small hanging valleys whose lower rims are about 4,200 feet above sea level. The uniformity of the lower slopes below 4,200 feet is interrupted by multiple horizontal benches, which may be traced for many miles around the Missoula Valley and which occur locally in the Ninemile Valley. They range from

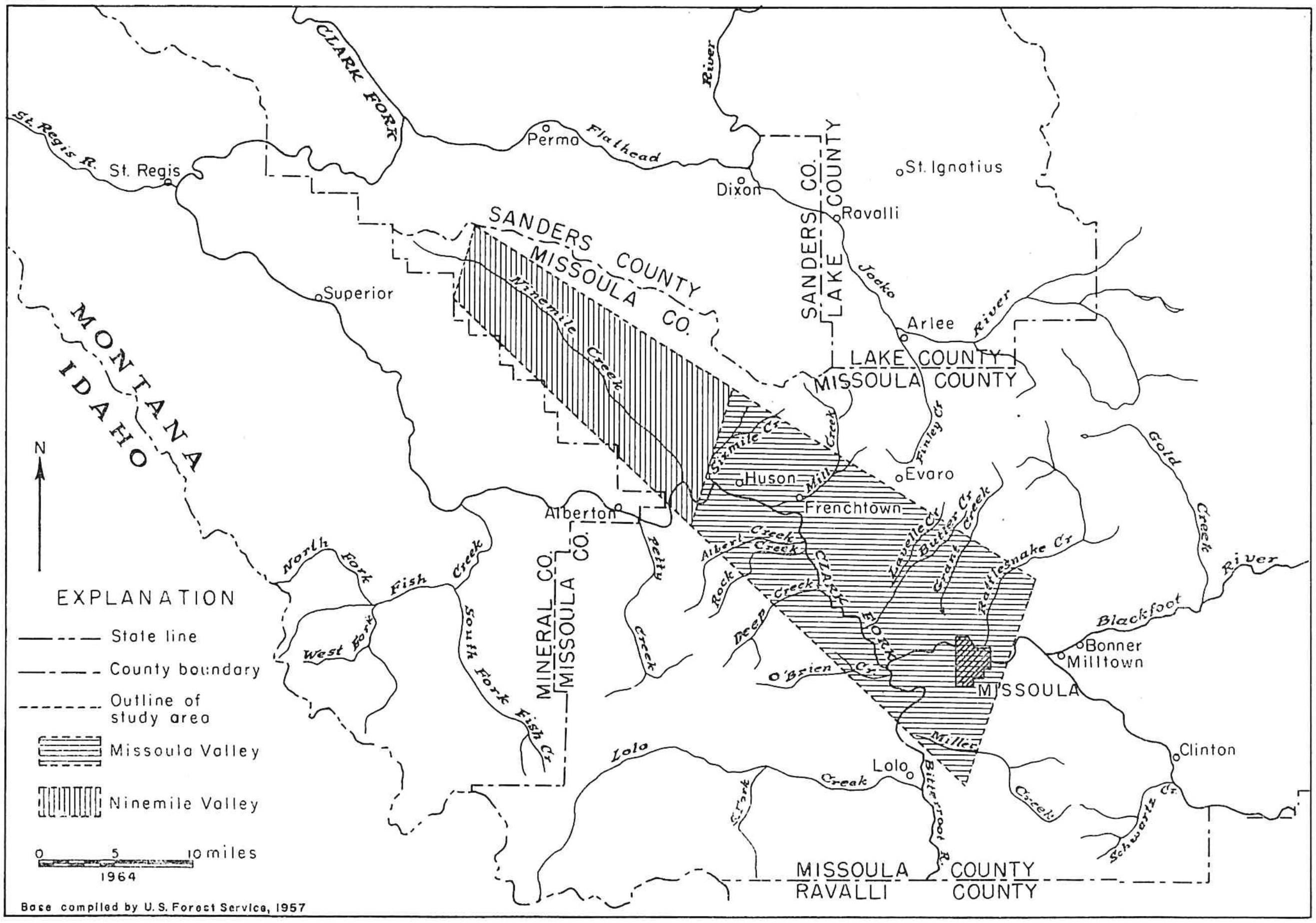

Figure 3.—Map of the Missoula area showing outline of Missoula Basin and principal drainage features.

delicate scorings, so faint as to be almost invisible, to several tens of feet in width.

The floor of the Missoula Valley is dominated by four principal topographic units. These are (1) the Clark Fork flood plain bounded by (2) low fringing terraces, which are bordered in turn by (3) high terraces which, on the northeast side of the valley, slope gently upward to (4) a deeply dissected "north-side" ridge parallel to the valley wall. Numerous subterraces occur locally at various levels within the valley (Fig. 5).

The Clark Fork flood plain trends westward for 6 miles from the mouth of the Hells Gate to the Bitterroot River and then abuts against the base of the mountains along the southwest side of the valley for 17 miles to the Alberton Narrows. The flood plain is very narrow at each end of the Missoula Valley but within the valley attains a maximum width of more than 2 miles. It is a relatively flat swampy area and includes many sloughs and cut-off oxbows.

The low fringing terraces, which are as much as 2 miles wide near Missoula, are generally separated from the flood plain by 10- to 20-foot scarps. Their relatively flat surfaces are interrupted by unique topography. Many shallow, arcuate erosion scars mark the ancient sites and attitudes of the Clark Fork and its tributaries. McCauley's Butte (Fig. 4) rises abruptly above the flood plain a few miles west of Missoula near the junction of the Clark Fork and the Bitterroot River. It is a steep-sided, 200-foot-high, 100-acre erosional remnant that is perhaps the most striking topographic feature in the valley.

The high terraces, which are as much as 4 miles wide in the central part of the valley, are generally separated from the low terraces by 50- to 100-foot scarps and they slope gently upward to-

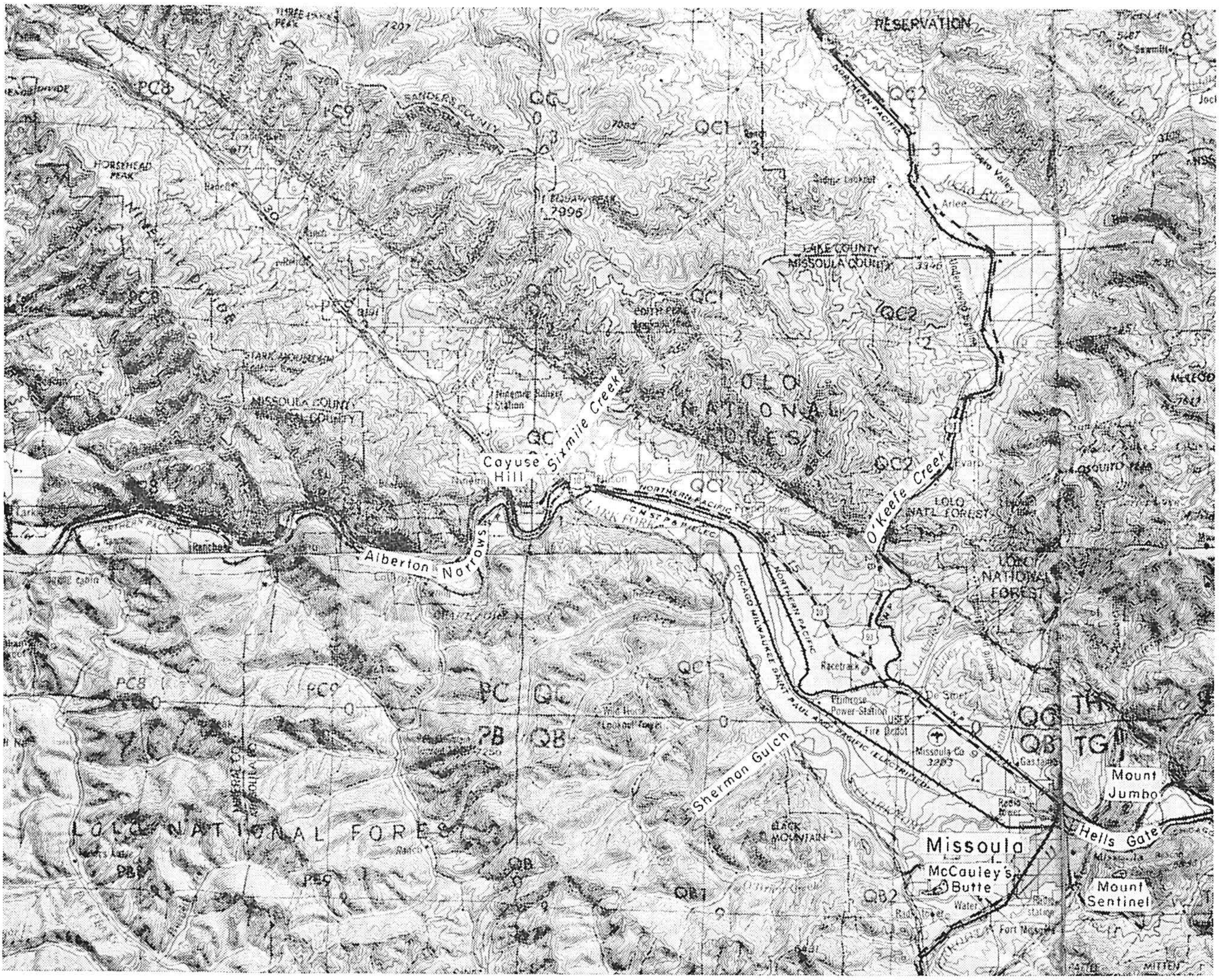

Figure 4.—Photograph of U. S. Army relief maps of western Montana (1958) showing topography of Missoula Basin.

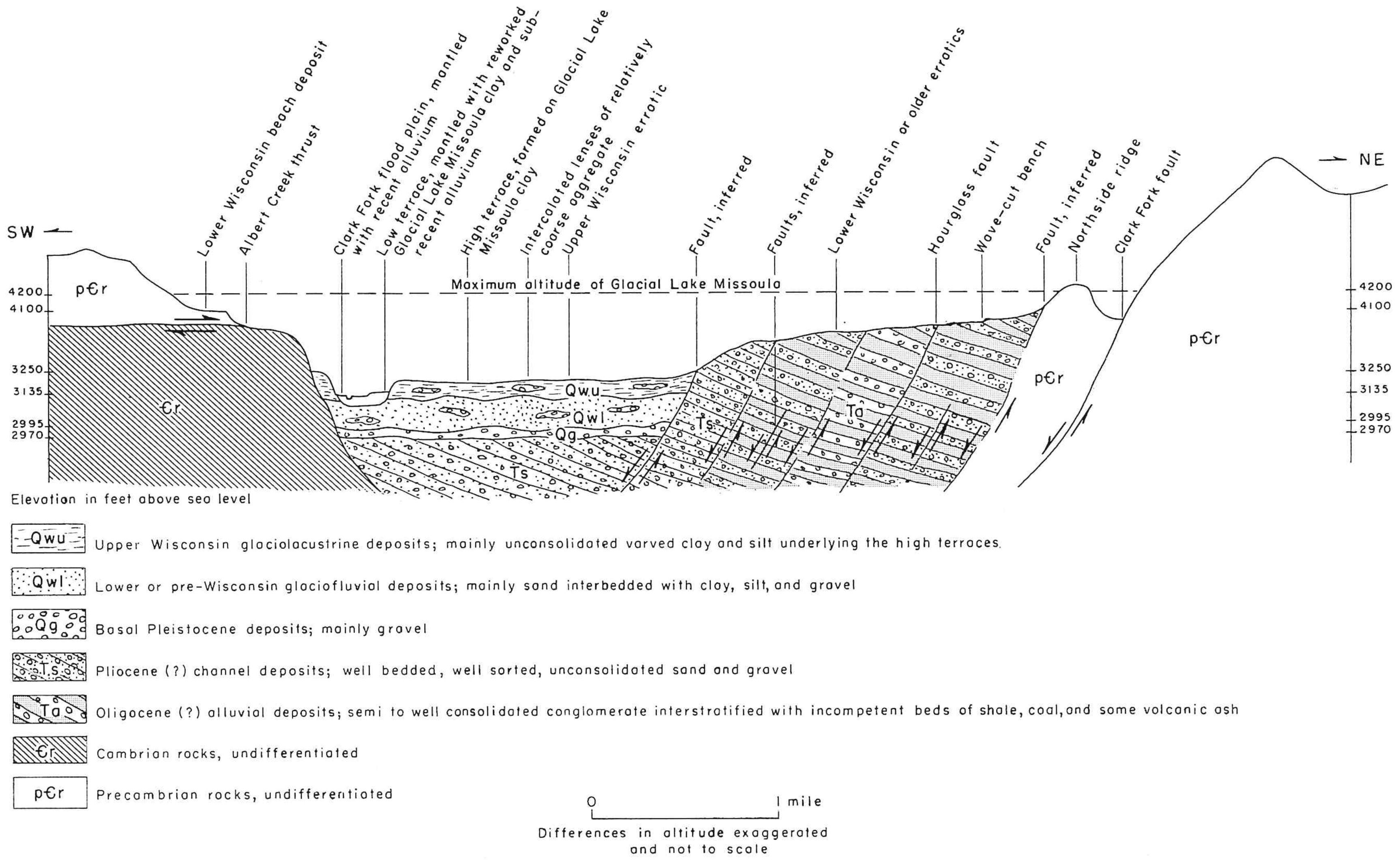

Figure 5.—Diagrammatic section across Missoula Valley showing topographic, structural, stratigraphic, and sedimentologic relationships.

ward the mountains to a maximum altitude of about 3,250 feet. In some places along the northeast side of the valley they merge with the lower slopes of the grossly uniform northside ridge, but in other places they are separated from the ridge by a scarp. The ridge extends the full length of the valley and is dissected at right angles by the narrow flat-bottomed valleys of the six major tributaries entering the Missoula Valley from the northeast. The crest of the northside ridge is 600 to 800 feet above the Clark Fork and for much of its length is separated from the mountain front by a narrow gorge. The gorge diminishes to the northwest, however, and the ridge broadens so that it abuts the mountain front.

In contradistinction to the Missoula Valley, the floor of the Ninemile Valley is dominated by only two principal topographic units, the Ninemile flood plain and a belt of low flat-topped hills on the north side. The flood plain, in fashion similar to the Clark Fork flood plain, abuts the highlands to the southwest. Its average width is about three-quarters of a mile. The belt of hills on the north side tapers from about 5 miles in width at the mouth of the valley to ultimate extinction near the upper end of the valley. The individual hills rise a few hundred feet above the flood plain and extend northeastward to the mountain front. One of them, Cayuse Hill, forms a topographic divide between Ninemile and Missoula Valleys.

DRAINAGE

The Clark Fork emerges from the narrow confines of the Hells Gate, flows peacefully across its broad alluvial fan for 6 miles to a junction with the Bitterroot River, winds down the length of the Missoula Valley for 17 miles to the mouth of Ninemile Creek, and finally exits to the west between the great rock walls of the Alberton Narrows. From the Hells Gate to the Bitterroot River the Clark Fork drops from an altitude of 3,160 feet to 3,088 feet, an average gradient of 12 feet per mile. From the Bitterroot to the Alberton Narrows, which is at an altitude of 2,980 feet, it has an average gradient of 6 feet per mile. Ninemile Creek is about 25 miles long and has an average gradient of 39 feet per mile.

Ninemile Creek and the Clark Fork are joined by numerous small corrading tributaries that have steep gradients through narrow V-shaped canyons in the mountains and relatively gentle gradients through flat-bottom valleys within the basin. The lower courses of many of the tributaries are entrenched 10 to 20 feet below their flood plains. Most of the tributaries flowing from the northeast are perennial, but most of those flowing from the southwest are intermittent.

CLIMATE

The climate in the basin is semiarid; summers are dry with moderate temperatures and cool nights; winters are damp and cloudy with periods of cold.

The long-term annual precipitation at Missoula for the period 1931-62 was 12.89 inches. May and June are the wettest months, averaging 1.84 and 1.96 inches respectively; March is the driest month, averaging 0.68 inch (Fig. 6). Slightly more than half the precipitation occurs during May through September, which is the principal growing season.

The average annual temperature for the period 1931-62 at Missoula is 45.5°F. The average temperature in January, the coldest month, is 22.4°F, and in July, the warmest month, 68.3°F. The average July maximum temperature is 87.0°F and the minimum is 49.6°F.

HISTORY

The first record of white man entering the Missoula area was that made by the Lewis and Clark Expedition. A hunting party from the group entered the area from the south on September 10, 1805, and Lewis and a small party went through the area on July 3 and 4, 1806. Only a few trappers and traders traversed the area between 1806 and 1850. Hellgate was established in 1860 and Frenchtown in 1864. Missoula was started in 1865 and became the county seat in 1866. The Northern Pacific Railway reached Missoula in 1883, and the Chicago, Milwaukee, St. Paul, and Pacific Railroad in 1906.

The impetus for settlement of the Missoula Valley was the rich farming lands rather than mining. The first irrigation was started in 1865. According to the Montana State Engineer (1960), an area of about 17,000 acres of land within the basin now is irrigated. Water for irrigation of 12,000 acres is obtained from the Clark Fork; water for 1,000 acres is obtained from the Bitterroot; and water for 4,000 acres is obtained from tributary streams, sloughs, and springs.

ECONOMY AND RESOURCES

The economy of the Missoula area is dependent mainly on the forest-product industries and on agriculture maintained by irrigation. The chief agricultural enterprise is raising livestock. The

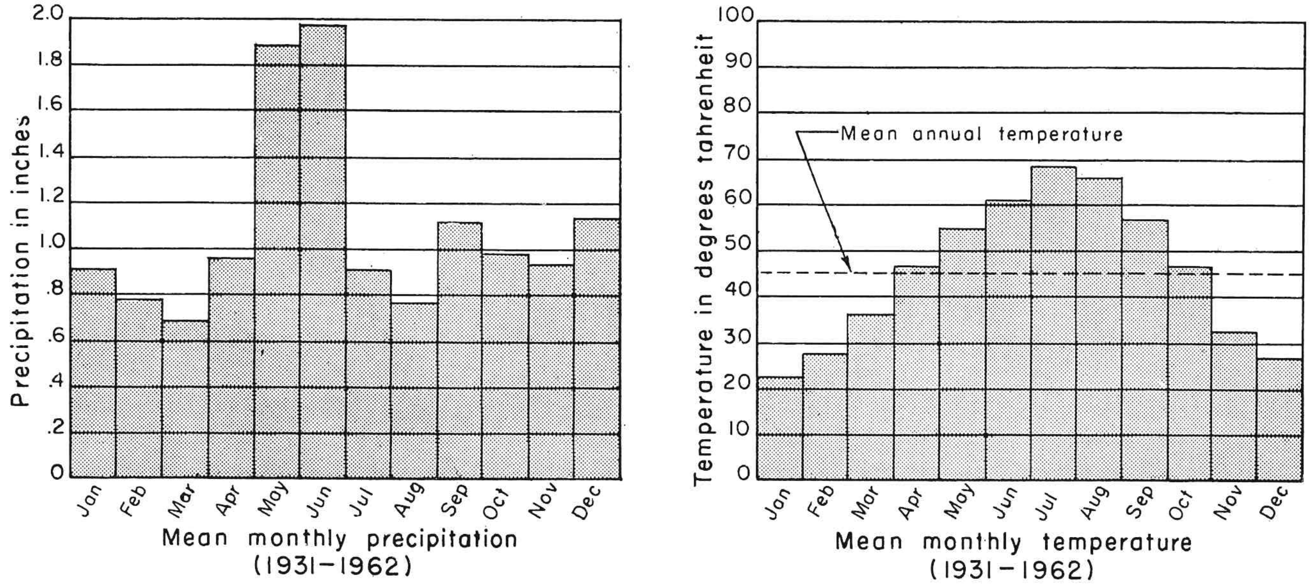

Figure 6.—Graphs showing climatological data for Missoula. (From records of the U.S. Weather Bureau.)

principal irrigated crops are alfalfa, small grains, and sugar beets.

The forest products of the region are a renewable resource and contribute greatly to the economy. According to the U. S. Forest Service, the national forest lands within 60 miles of Missoula have a sustained annual yield of more than 50 million board feet. The annual sawmill capacity in Missoula reportedly is about 300 million board feet. Some of the logs and rough lumber are shipped several hundred miles to be finished in the Missoula mills. More than 20 percent of the labor force in Missoula County is engaged in the manufacture of wood products (oral communication, Montana State Unemployment Compensation Commission).

Mining of gold, copper, silver, lead, zinc, and coal was of some importance in the past, but there is now (1964) very little metal mining in the area. There is some mining of nonmetallic minerals such as sand, gravel, and barite.

The tourist industry is important to the economy of the Missoula area. The regional headquarters of the U.S. Forest Service in Missoula employs more than 600 people and provides contractual work for many others.

GEOLOGY

REGIONAL STRATIGRAPHY

Rocks underlying the three major drainage areas above the Missoula Basin (upper Clark Fork, Blackfoot, Bitterroot) range in age from Precambrian to Recent. Precambrian sedimentary rocks and Cenozoic valley fill are found in all three areas. Mesozoic and Cenozoic extrusive rocks are present in the upper Clark Fork and the Blackfoot drainages. Mesozoic and Cenozoic intrusive rocks are present in the upper Clark Fork and Bitterroot drainages.

Only Precambrian sedimentary rocks are present along the lower Clark Fork drainage for a distance of about 150 miles below the Alberton Narrows.

LOCAL STRATIGRAPHY

ROCKS OF PRE-MESOZOIC AGE

The hard rocks marginal to and underlying the the Missoula Basin are referred to in this report as basement rocks (Pl. 1). Because they are relatively impermeable and are not regarded as potential aquifers, they were not examined in detail. A generalized description is presented here, and the basement rocks are alluded to briefly elsewhere in the text in order to implement discussions of the geology of the valley fill and the ground-water regimen. The information is mostly from detailed descriptions by Lindgren (1904); Emmons and Calkins (1913); Clapp (1932); Langton (1935); Hanson (1952); Ross and Rezak (1959); and Kauffman (1963).

The highlands marginal to the Missoula Basin are formed mostly on rocks belonging to the Belt Series (Precambrian). In speaking of the Belt rocks, Ross (1963, p. 31) states that most of them "***lack features of color or texture that are striking enough to be readily recognized. Recognition of stratigraphic units, in consequence, has had to depend largely on the personal predilections of each observer, including his past experience with the series***. Nearly all available descriptions are expressed in such nonquantitative terms as to be of limited use."

More than 10,000 feet of Belt quartzite, argillite, and carbonate rocks crop out around the Missoula Basin. Belt rocks also underlie large areas of the northside ridge, and small inliers occur in the Grant Creek drainage, along the high terrace near Primrose, at McCauleys Butte, and near the mouth of Miller Creek.

Some of the foothills southwest of the Missoula Valley and the low hills in the lower part of the Ninemile Valley are formed on carbonate and argillaceous rocks of Cambrian age. Similar rocks crop out through clay of Lake Missoula in the Primrose area. From exposures south of the Chicago, Milwaukee, St. Paul, and Pacific Railroad tracks in the NE¼ sec. 31, T. 14 N., R. 20 W., Professor Donald Winston, Department of Geology, Montana State University, and one of the authors (R. L. Konizeski) collected a Middle Cambrian (Silver Hill Formation) fauna.

ROCKS OF MESOZOIC AGE

In 1956 Mr. Turley Robertson of Missoula discovered in the Grant Creek drainage a specimen identified by W. A. Cobban, Paleontology and Stratigraphy Branch, U. S. Geological Survey, as the cephalopod *Placenticeras meeki.* The species is very common in the marine Bearpaw Shale (Upper Cretaceous) of central and eastern Montana. The specimen from the Grant Creek drainage is a large segment of the chambered part and has very sharp fragile processes that are especially subject to erosional damage. Therefore, it must have been either transported to the basin by human agency, or buried and preserved in place as indicated by Mr. Robertson.

Mr. Robertson was killed in an auto accident before the location of the find was determined. If the discovery was valid, it follows that the ancient Bearpaw sea extended farther west than was formerly supposed. The entire Grant Creek drainage was searched rigorously, however, and no Bearpaw Shale was found.

ROCKS OF TERTIARY AGE

Volcanic rocks. — Volcanic rocks crop out on the highlands marginal to the northwest end of the Missoula Valley and the southwest corner of the Ninemile Valley, and in a borrow pit near the mouth of Butler Creek in the Ninemile Valley. They cap older (Belt) rocks but otherwise display few characteristics that might aid in determining their total thickness. These volcanic rocks, or similar rocks, reportedly were penetrated at a depth of 180 feet beneath unconsolidated Cenozoic fill in a drill hole in the NE¼ sec. 31, T. 15 N., R. 21 W., a mile southeast of Huson (oral communication, W. F. Osborn, drilling contractor).

Sedimentary rocks. — Overlying the basement rocks and partly filling the Missoula Basin is a great mass of erosional debris interbedded locally with lenses of volcanic ash. The deepest recorded well in the basin was drilled in valley fill near the fault line at the mouth of Pattee Canyon in the SW¼ NW¼ sec. 34, T. 13 N., R. 19 W. The well reportedly was completed in bedrock at a depth of 550 feet (oral communication, Glen Camp, drilling contractor). Another well, 3 miles southeast of Frenchtown in the SE¼ sec. 7, T. 14 N., R. 20 W., was still in valley fill at its total depth of 438 feet. Gravimetric data indicate a maximum depth of fill in the Missoula Valley of about 3,000 feet and a total volume of about 25 cubic miles.

By far the greatest volume of the valley fill is of Tertiary age. Tertiary sediments crop out over an area of about 55 square miles, or about one-third of the basin. Their character, orientation, and distribution are directly related to the lithology, structure, and distribution of the source (basement) rocks; to the ancient environments of erosion and deposition; and to the character and degree of volcanic activity. It was estimated that as much as 13,000 feet of strata might occur in the Butler-LaValle Creek area and by extrapolation for many miles along the northeast side of the Missoula Basin. Tertiary beds exposed in any single outcrop measure no more than a few hundred feet in thickness. Furthermore, the Tertiary strata have been greatly deformed, and the area is transected by several known, and perhaps numerous hidden, faults. Thus, because of repetition of beds by faulting, the true thickness may be much less than indicated.

The oldest exposed Teritary strata crop out sporadically along the northeast side of the Missoula Basin from Rattlesnake Creek, near Missoula, to Kennedy Creek, half way up the Ninemile Valley. Douglass (1902), identifies Tertiary strata about 1½ miles northwest of Missoula as either White River (Oligocene) or John Day (Miocene) age. Jennings (1920, p. 396, 425) accepted Douglass' Oligocene age determination. Chaney

(1950, p. 229, 232) described *Sequoia affinis* from beds in the Missoula Valley as of Oligocene age. Alden (1953, p. 21) stated that coal in the Tertiary "lake beds" near Missoula is "***said to be in the lower part of the Oligocene***" and "The beds composing the foothills north of the Pleistocene terraces in the Missoula Valley are certainly erosion remnants of a great valley fill deposited during Oligocene and Miocene time." Becker (1961, p. 31) referred to the Missoula Valley Oligocene flora.

Despite the unanimity of most subsequent workers in accepting Douglass' shrewd and very likely correct guess, there is no firm basis for assigning an Oligocene age to these strata. Douglass' original conclusion was evidently based on lithologic similarity to the White River beds of the High Plains hundreds of miles to the east; a risky correlation at best. Fossil flora such as described by Jennings are invaluable as guides for interpreting ancient environments but are less reliable as stratigraphic indices. During the course of this investigation, the exposed Tertiary strata were carefully searched for stratigraphically definitive fossils (especially vertebrate) but none were found. In the absence of contradictory evidence, the basal exposed strata are provisionally described as of Oligocene (?) age.

The Oligocene (?) strata consist of relatively competent beds of conglomerate and sandstone interstratified with relatively incompetent beds of shale, coal, and some volcanic ash. The conglomerate and sandstone is poorly bedded and is generally semiconsolidated. Most of it is composed of erosional debris derived from Belt rocks in the valley walls, but some, on the east side of Grant Creek, in the NW¼ sec. 5, T. 13 N., R. 19 W., includes large amounts of erosional detritus derived from a diorite dike 4 miles upstream. Oligocene (?) deposits near the mouth of Stony Creek in the NE¼ sec. 7, T. 15 N., R. 22 W., and on the valley wall 1½ miles south of Frenchtown near the center of sec. 4, T. 14 N., R. 21 W., include erosional detritus from local outcrops of rhyolite.

Most of the conglomerate is composed of well-rounded grains, some as much as 12 inches in diameter but most less than 4 inches, which are cemented with rusty mud that is slightly calcareous at some places. Typical conglomerate crops out on the banks of an irrigation ditch in the SE¼ sec. 10, T. 13 N., R. 19 W.; on the east side of the Butler Creek road in the SW¼ sec. 24, T. 14 N., R. 20 W.; and in a borrow pit on the north side of the road about 2 miles east from the Ninemile Ranger Station in the NW¼ sec. 14, T. 15 N., R. 22 W. The percentage of mud becomes progressively greater toward the upper end of the Ninemile Valley. Schrader (1911, p. 62) erroneously described Oligocene conglomerate northwest of the Ninemile Ranger Station as morainal debris and judged it to be an important placer deposit, but it proved uneconomical to work because of the excessive clay content. In a few places, proximal to basement rocks near the Clark Fork fault, the conglomerate is composed of angular fragments of rock and might be more properly described as a breccia.

The interstratified shale, coal, and volcanic ash are easily erodible relative to the conglomerate and sandstone. Thus there are but few exposures, mostly in artificial cuts. About 30 feet of semiconsolidated gray to black shale crops out in a borrow pit three-quarters of a mile northeast of the Ninemile Ranger Station in the NW¼ sec. 9, T. 15 N., R. 22 W. Five feet of plant-bearing shale was exposed (1963) in a basement excavation 2 miles northeast of Huson in the SE¼ sec. 18, T. 15 N., R. 21 W. A small flora was collected from this locality. J. A. Wolfe of the Paleontology and Stratigraphy Branch, U. S. Geological Survey (written communication), states, "There is nothing in your flora not also found in Jennings' collections, but, on the basis of your collection, an absolute age equivalency cannot be established. It is noteworthy, however, that *Sequoia* and *Alnus* are very abundant in both your collection and Jennings', and a similar ecologic situation is therefore indicated."

More than 20 feet of plant-bearing volcanic ash (probable collecting site of Douglass and Jennings) is exposed about 1½ miles north of Missoula in the NE¼ sec. 9, T. 13 N., R. 19 W. Rowe (1903, p. 21) describes 100 feet of plant-bearing ash, sandstone, coal, fire clay, and "soapstone" in the same area. Pardee (1913, p. 234) gives the following description of Tertiary strata exposed north of Missoula.

Clay, gray to cream colored, and volcanic ash containing one or more coal beds	200± feet
Sandstone, light gray, micaceous	40± feet
Coal	7± feet
Clay, greasy, gray	50± feet
Clay, brown to red	
	297± feet

These exposures and numerous abandoned coal mines in Tertiary sediment along the northeast side of the Missoula Basin are now covered by slumpage.

Because the exposed Oligocene (?) sediments are either fine grained or mud cemented so that they have relatively low permeability, all known wells drilled in them were either dry or of relatively low yield. Some supplied water of undesirable quality. Oligocene or older Tertiary strata of greater permeability may occur at depth in the southwest side of the basin, however. If so, they are a potential source of large supplies of ground water.

Valleyward from and apparently underlying the Oligocene (?) strata in the Butler Creek area, there is exposed in a borrow pit east of the road in the NW¼ sec. 26, T. 14 N., R. 20 W., about 120 feet of light-gray unconsolidated sand and gravel. Lensing out and truncation of the beds is common. This material is well-sorted and consists mostly of well-rounded Belt debris, considerable mica, and a small percentage of igneous rock fragments. These properties are related to stream transport from multiple sources, including local valley-wall basement rocks for the Belt detritus, and probably the nearby easily erodible border-zone gneiss and Idaho batholith west of the Bitterroot Valley for the mica and igneous debris (Ross, 1950, p. 138). Similar sediments are exposed in a gravel pit east of the lower Miller Creek road in the SE¼ sec. 1, T. 12 N., R. 20 W., and on the east escarpment below Council Hill in the NE¼ sec. 22, T. 13 N., R. 20 W. These two localities are near the mouth of the Bitterroot River, and the percentage of igneous rocks present is greater than in the deposits in the Butler Creek area, especially in the smaller size fractions. Alden (1953, p. 21) has indicated that the sand and gravel might be Oligocene in age; however, similar deposits in the Bitterroot Valley have yielded vertebrate fossils of Pliocene age. On the basis of these relationships and because their lithology implies an environment of deposition greatly dissimilar to that of the Oligocene (?) sediments, they are provisionally described here as of Pliocene (?) age.

The exposed Pliocene (?) deposits are well sorted and coarse grained, but because they occur in restricted interfluvial areas of relatively low recharge they are not believed to be potential sources of ground water. Pliocene (?) sediments may underlie the Quaternary alluvium in areas of maximum recharge between the mouths of Grant Creek and Miller Creek, however. If so, they are a potential source of large supplies of ground water.

ROCKS OF QUATERNARY AGE

Aggregate thickness of Quaternary alluvium in the Missoula Basin is about 400 feet but at any single locality less than 300 feet is present. Unconsolidated lacustrine deposits underlie slightly more than one-third of the basin, or about 65 square miles. Those deposits exposed between an altitude of 4,200 and 3,250 feet are probably of early Wisconsin and pre-Wisconsin ages. Those exposed below an altitude of 3,250 feet are of late Wisconsin age. Most of the exposed older rocks were deposited as a relatively thin mantle on Oligocene (?) strata in the "hill" country of the Ninemile Valley, but some erratics and shoreline deposits rest on Tertiary strata and basement rocks in the Missoula Valley.

In the Ninemile Valley the older deposits are composed of angular to subrounded glacial detritus ranging from silt size to blocks 10 feet or more in diameter. More than 100 feet of poorly bedded glaciolacustrine sand and gravel is exposed in a borrow pit east of the Stony Creek road in the NE¼ sec. 33, T. 16 N., R. 22 W. In some places large angular erratics of Belt rock seem to be weathered in place from underlying basement rocks, but local mine dumps show the substrata to be Oligocene (?) conglomerate. Thousands of early Wisconsin or pre-Wisconsin erratics derived from Belt rocks are scattered over the north-side ridge in the Missoula Valley. In several areas, notably in the Grant Creek and Sixmile Creek drainages, the erratics form arcuate concentrations around hills.

Early Wisconsin or pre-Wisconsin shoreline deposits mantle numerous wave-cut benches in the Missoula Basin. Most of the deposits are so thin that they were not mapped, but high on the valley wall about 2½ miles southwest from Primrose in the SE¼ sec. 2, T. 13 N., R. 21 W., there is a perfectly preserved beach deposit about 80 acres in extent. Its shoreline is at an altitude of 4,100 feet and the outer edge is at 4,000 feet, which is 1,000 feet above the river. About 150 feet offshore is a well-formed bar, which once sheltered a lagoon. There are no outcrops in the area; marmot mounds on the offshore bar are formed of micaceous quartzose silt and sand. Eleven miles east, in the NE¼ sec. 22, T. 13 N., R. 19 W., a large spit extends valleyward from below a basement-rock hill at the mouth of Rattlesnake Creek. The spit is about a third of a mile long and slopes from an altitude of 3,420 feet at its upper limit to 3,360 feet at the outer edge. It is composed of angular sand and gravel derived from Belt rocks.

The high terraces, which are mostly below 3,250 feet, and some equivalent areas marginal to the lower Ninemile Creek flood plain, are formed on buff-colored varved lacustrine clay of late Wisconsin age. An irrigation well in the NW¼ sec. 14, T. 13 N., R. 20 W., penetrated 115 feet of clay (oral communication, W. F. Osborn, drilling contractor), but the average thickness is about 90 feet, and the base of the clay is near river level. Well-log data indicate that the clay is underlain by 125 to 140 feet of sand interbedded with clay, silt, and gravel which, in turn, overlies 10 to 35 feet of basal Pleistocene gravel resting on Tertiary strata.

Intercalated in the clay and sand, in the Huson-Frenchtown area, are a few lenses of erosional detritus of a grain size only slightly larger than that of the enclosing sediments. From the Alberton Narrows to the mouth of the Hells Gate, the number of lenses gradually increases and the average grain size of their component materials is greater. In the broad central valley below Missoula, the lenses are a significant fraction of the Quaternary sediments. Sand and poorly sorted deltaic deposits of angular Belt detritus interfinger with the clay in local areas marginal to the mouths of various tributary canyons along the southwestern wall of the valley.

Pardee (1942, p. 1570) and Alden (1953, p. 108) supposed that the bulk of the lacustrine clay was derived from moraines in the upper Blackfoot drainage. Sieja (1959), on the basis of limited clay-mineralogy data, accepts their conclusions but notes that some material was derived from the Rattlesnake glacier and some minor amounts from the Bitterroot glaciers. Because of their geographical relations, and because both the Clark Fork and the Bitterroot River drain deeply glaciated areas underlain by rocks similar to those in the Blackfoot drainage basin, it seems paradoxical that all three streams should not have contributed relatively large amounts of material to the lacustrine deposits in the Missoula Basin. Most of the detritus from the Bitterroot glaciers was dumped directly into the lake and there was less opportunity for sorting than in the headwaters of the Clark Fork and Blackfoot drainages (McMurtrey and Konizeski, in review). As noted by Alden (1953, p. 156) the varved clay extends only a short distance into the Bitterroot Valley.

There are no published records of fossil biota from the clay deposits, but trackways of several species of annelids and an arthropod were collected during the course of this investigation (Fig. 7). They are probably related to similar modern forms from Flathead Lake and McDonald Lake, northern remnants of the ancient glacial Lake Missoula.

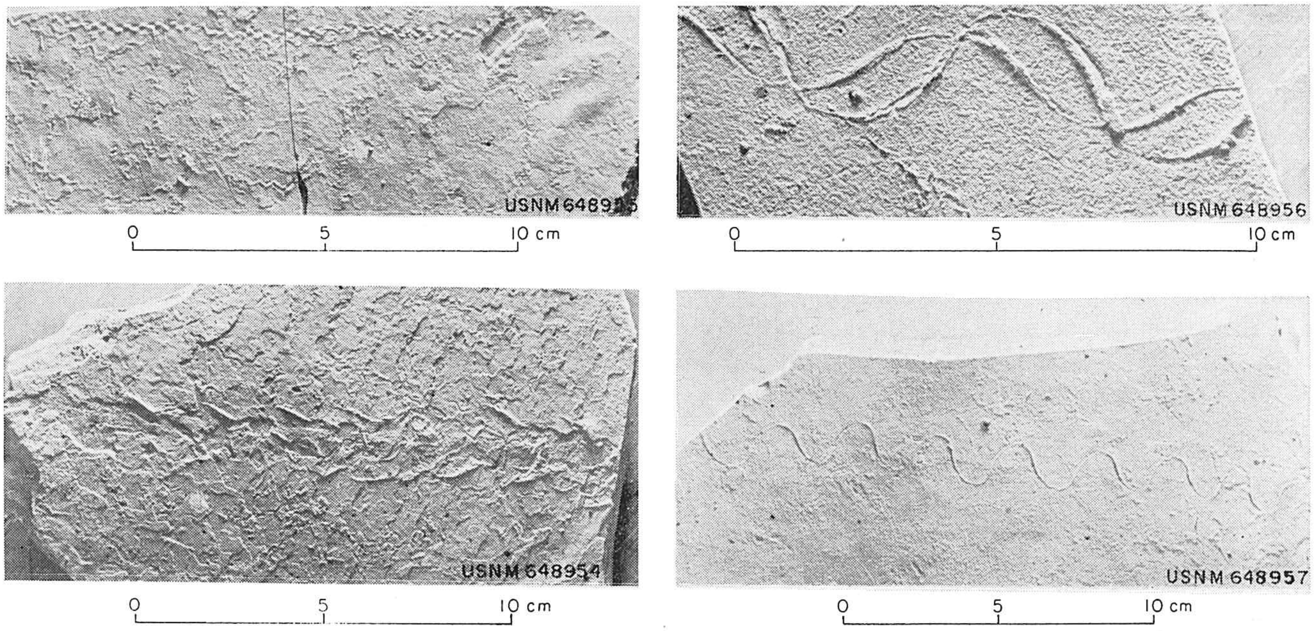

Figure 7.—Trackways of fossil species of annelids and an arthropod collected from clay of glacial Lake Missoula exposed in railroad cut in the SE corner NE¼ sec. 10, T. 13 N., R. 20 W.

About one-third of the Missoula Basin, or 55 square miles, is mantled by Recent alluvium; one-half is on the low terraces in the Missoula Valley, and the rest is on the flood plains of the Clark Fork, Ninemile Creek, and their tributaries. The low-terrace alluvium is post-Lake Missoula to pre-Recent in age (Pl. 1). It consists of reworked clay, and well-rounded sand and gravel of a wide variety of rock types. The Clark Fork flood-plain alluvium of Recent age consists of mixtures of a wide variety of well-rounded grains of igneous, metamorphic, and sedimentary rocks in accordance with its various extra- and inravalley sources. In the Ninemile drainage the flood-plain alluvium consists almost entirely of angular to well-rounded Belt detritus derived from local valley-wall sources. Some reworked Oligocene (?) and Pliocene (?) rocks border the outcrops of Tertiary rocks.

Because of the variable lithology and the similarity to underlying Pleistocene and possibly Pliocene (?) sediments, the thickness and basal configuration of the Recent alluvium are poorly known. It has been reported (oral communication, local ranchers) that gold dredges operating in Recent flood-plain alluvium in the upper Ninemile Valley above Stark encountered Tertiary coal at depths of about 20 feet. Tertiary "bedrock" (miners' terminology) generally underlies 10 to 20 feet of Recent alluvium in the Butler, Kennedy, McCormick, and Josephine Creek placers. Because the Clark Fork is presently a corrading stream, the alluvial mantle on its flood plain is presumed to be relatively thin, probably no more than a few tens of feet thick.

Because the Recent alluvium is thin and is especially subject to pollution, it is of relatively little value as a potential aquifer. The much thicker body of Pleistocene sediments is only a small percentage of the total volume of valley fill but, because of its orientation with respect to the Tertiary substrata, adequate recharge, and relatively high transmissibility, it is presently the most important aquifer in the basin. The fine-grained lacustrine clay and silt of Wisconsin age and the alluvial sand of pre-Wisconsin age have little or only moderate potential, but the many intercalated lenses of well-sorted coarse-grained material underlying the broad flat below the Hells Gate yield sufficient water to supply domestic, farm, and some irrigation requirements. The heterogeneous lacustrine deposits in the Ninemile Valley occur mostly in upland areas of minimal recharge and probably have little value as a potential aquifer. The coarse permeable material forming the basal deposits of the Pleistocene occurs in areas of maximum recharge and generally yields large supplies of water for municipal, industrial, and irrigation use.

STRUCTURE

The Missoula Basin is a closed structural depression downdropped to the northeast along the translatory Clark Fork fault, overthrust from the southwest along the Ninemile fault and Albert Creek thrust (Geology of the north half of the Missoula quadrangle, F. W. Hall, Montana State University, Ph.D. thesis), and cut off on the east by a transverse fault below Mounts Sentinel and Jumbo. The northeastern wall of the basin is the surface trace of the steep, southward-dipping Clark Fork fault (Pardee, 1950, p. 390, 392), which is tangential to an extensive system of arcuate lineaments about the margins of the Idaho batholith (Ransome and Calkins, 1908, p. 62; Wallace and Hosterman, 1956, p. 590), and intersects the north-trending Bitterroot-Flathead lineament at an angle of about 55°. The southwestern wall of the basin is mainly the surface trace of faults inherent to the system of arcuate lineaments about the Idaho batholith (Fig. 8).

The Ninemile fault is hidden beneath Quaternary alluvium but its presence is indicated by local geologic relationships, and it ties in with large-scale thrusting from the southwest along the Albert Creek thrust (Pl. 1). The transverse fault below Mounts Sentinel and Jumbo accounts for their remarkably uniform, 60-degree valleyward-dipping slopes. The presence of the fault is further substantiated by fault gouge reported in a well drilled at the base of Mount Sentinel in the SW¼ NW¼ sec. 34, T. 13 N., R. 19 W. (oral communication, Glen Camp, drilling contractor).

The Clark Fork fault cuts both Precambrian basement rocks and Oligocene (?) strata along the north side of the basin. Orientation of Oligocene (?) strata near the junction of the Clark Fork and Hourglass faults is clearly related to right lateral translatory movement, the northern block moving up and to the southeast. The surface trace of the Hourglass fault forms the narrow central stricture between the two topographic highs of Hourglass Hill (Fig. 4). With this exception, all the exposed Oligocene (?) strata on the northeast

Figure 8.—Photograph of U.S. Army relief maps of western Montana (1958) showing topographic relationships of Missoula Basin to arcuate lineaments around Idaho batholith.

side of the basin dip toward the mountains. The continuity of orientation of the Oligocene (?) strata across the Clark Fork fault, in the vicinity of LaValle and Butler Creeks, seemingly relates to parallel block faulting in the highlands north of the valley. The apparently great thickness of Oligocene (?) strata and the orientation of the Pliocene (?) strata near the mouth of Butler Creek probably relate to a system of parallel faults (Fig. 5). Several Recent northeast-trending normal faults occur in the LaValle Creek area. The exposed Oligocene (?) strata on the southwest side of the Missoula Valley are undeformed.

The glacial Lake Missoula clay exhibits very little evidence of postdepositional deformation. Folding of some central-valley interbeds has been ascribed to grounding of icebergs, deposition in shallow water (semifluid slumpage), and (or) postdepositional slipping (Eakins, 1951, p. 13; Sieja, 1959, p. 9, 12). In the SE¼ sec. 35, T. 15 N., R. 21 W., a 10-foot section of clay in glacial Lake Missoula is folded into a shallow northeast-trending monocline, downdropped toward and parallel to Mill Creek. Its presence, in consort with the similarly oriented normal faults in the LaValle Creek area, indicates that the tributary streams across the Missoula Valley north-side ridge are structurally controlled and superimposed.

SUMMARY OF GEOLOGIC HISTORY

The origin of the Missoula Basin was directly related to local deformation of the basement rocks. Its age is known only within broad limits, as inferred from the age relationships of the marginal faults and of the valley fill. The Albert Creek thrust displaces Precambrian rocks over Cambrian rocks. The Clark Fork fault cuts Precambrian rocks, and was involved in the deposition and subsequent deformation of Oligocene (?) and Pliocene (?) strata. If the specimen of *Placenticeras meeki* is valid evidence, the basin may have existed as an embayment of Late Cretaceous (Bearpaw) sea, or it may be that a much larger region was submerged than has been formerly supposed and the marine deposits have since been mostly stripped from the area. Strata as old as Paleocene are present in neighboring valleys (Lowell and Klepper, 1953; McLaughlin and Johnson, 1955). Therefore, it is reasonable to suppose that pre-Oligocene strata may also be present at great depth in the Missoula Basin fill. The cumulative inference is that a topographic low may have existed as early as Late Cretaceous (Bearpaw) time, or the basin could have been initiated in Paleocene, Eocene, or even early Oligocene time.

It has commonly been supposed that the middle Tertiary was a time of relatively low Rocky Mountain relief (Van Houten, 1952, p. 74, table 1), although floral distributions indicate that the Rockies have constituted a topographic barrier throughout Cenozoic time (Chaney, 1940, p. 480). The Missoula Basin Oligocene (?) deposits relate to moderate local relief. Extensive marshes, meadowlands, and peat bogs occurred in the northeastern areas of the basin. Here, in reducing environments under climatic conditions somewhat warmer than now prevail, there accumulated, at times, evenly bedded mud, silt, local deposits of volcanic ash, and the decaying residue of a mesic-angiosperm-dominant flora (Jennings, 1920; Becker, 1961, p.31). At other times, probably in response to regional tectonics, but perhaps in part to cyclic climatic changes, there were deposited in oxidizing environments around the northeastern margins of the subsiding basin, great overlapping fans of poorly bedded, poorly sorted gravel and sand with varying admixtures of ferruginous mud that is slightly calcareous in places; the whole transported thither by sheet-slope and gully wash from the adjacent uplands. At least 3,000 feet and perhaps as much as 13,000 feet of interbedded shale and fanglomerate was ultimately deposited.

The almost universal subrounding to well rounding of the individual grains of the fanglomerate, in conjunction with the relatively short travel distance and the ubiquitous admixture of mud, relates to deep weathering of the basement rocks by corrosive action of soil acids. The almost complete absence of igneous debris in the exposed strata, as contrasted to its universal presence in the post-Oligocene deposits, might be interpreted in several ways. First, it might be supposed that the granitic cores of the mountains upstream from the Missoula Basin had not yet been exposed to erosion. It has been shown, however, that large areas of granitic rocks were exposed in the upper Clark Fork drainage (Konizeski and others, 1961, p. 8). Second, it might be supposed that the Missoula Basin was a closed depression during Oligocene (?) time and that there were few if any outside sources of erosional detritus. However, annual rainfall was probably not less than 30 inches (Axelrod, *in* Konizeski, 1961, p. 1639) and, in the absence of through drainage, such precipitation would almost surely have resulted in extensive ponding, which is belied by the lack of lacustrine sediments in the exposed Oligocene (?) strata. A third, and more logical, explanation is that there was through drainage, but that the river was crowded against the southwestern side of the basin by accumulating erosional debris from the northeastern uplands. This hypothesis fits all known geological relationships. It accounts for the lack of igneous material in the Oligocene (?) strata exposed in the northeastern part of the basin, calls for a considerable percentage of igneous debris in the subsurface Oligocene (?) strata in the southwestern part of the basin, and implies a high-energy, stream-channel environment of deposition in that area. An academically intriguing extension of this interpretation is that of reversed drainage direction as hypothesized for the upper Clark Fork and neighboring drainages by Perry (1934, p. 3).

No records have been found of Miocene deposition in the Missoula Basin.

By Pliocene (?) time a strong through-flowing drainage had been established. Well-rounded, well-sorted gravel and sand were being transported into the basin from the Bitterroot, and probably from the upper Clark Fork Valley. The material included much detritus of Cretaceous to lower Tertiary igneous rocks, as well as erosional debris derived from Belt and Palezoic sedimentary rocks. It was mostly deposited in stream-channel environments, probably to a total depth of fill greatly in excess of the maximum of 120 feet now exposed.

Later, in middle and (or) late Pliocene (?) time, there was recurrent movement along and adjacent to the Clark Fork fault. The floor of the basin was broken into elongate northwest-trending northeastward-dipping blocks so that Pliocene (?) strata in the Butler Creek area now appear to underlie Oligocene (?) strata (Fig. 5). Some Oligocene (?) beds, within the acute angle formed by the juncture of the Clark Fork and Hourglass faults, were reoriented to the southeast (Pl. 1).

Late Pliocene (?) lowering of base level in the Alberton Narrows was accompanied by basin-wide erosion of the Tertiary fill and beginning of the present topography. Orientation of the superimposed tributary streams across the north-side ridge was perhaps partly controlled by local faulting at right angles to the Clark Fork lineament.

Post-Pliocene erosional and depositional developments within the Missoula Basin were functions of climatic rather than structural controls. The beginning of Quaternary time was marked by a general lowering of average annual temperatures, and concurrently, in the northern Rocky Mountains, by the growth of great alpine glaciers. The glaciers seemingly were formed on deeply weathered terranes from which they scoured large quantities of coarse debris. Much of this material was ultimately deposited within adjacent valleys. As much as 35 feet was deposited in the Missoula Basin (Fig. 5). Subsequent ice scour of the exposed, relatively unweathered basement rocks produced much fine-grained detritus in addition to the coarser aggregates. Most of the clay and silt-size material (glacial flour) was evidently transported through the Missoula Basin, but at least 140 feet of interbedded clay, silt, sand, and gravel remained (Fig. 5).

The former existence of a great glacial lake in northwestern Montana perhaps was suspected first by Chamberlin (1888, p. 78) who noted "***a series of parallel watermarks of the nature of exceptionally slight terraces sweeping around the sides of the [Flathead] valley [25 miles north of the Missoula Basin] and encircling the isolated hills within it, like gigantic musical staves." Professor Bailey Willis of the U.S. Geological Survey subsequently presented the idea of a Pleistocene lake dammed by a glacier (see Douglass, 1899, p. 11). Irrefutable evidence has since been cited (Pardee, 1910, 1942; Alden, 1953; Bretz and others, 1956) to show that the Clark Fork was dammed several times during the Pleistocene. Ancient wave-cut benches of the resultant glacial Lakes Missoula relate to maximum impoundages to 4,150-4,200 feet above sea level.

During one or more times of maximum impoundage, drifting icebergs accumulated all along the northeast side of the lake, perhaps as a result of persistent air currents similar to those now extant. As the icebergs gradually melted, thousands of erratics and other coarse glacial debris accumulated on the lake bottom. It seems probable that some clay and silt-size glacial outwash also must have accumulated. If so, any evidence of its former presence has been destroyed by erosion during succeeding interlacustrine (interglacial) epochs.

The last glacial lake was evidently drained as a result of intermittent downcutting of the ice dam at its outlet (Eakins and Honkala, 1952), concurrent with melting and retreat of the local glaciers. As the water receded, clay and silt (glacial flour) was carried to the lake in ever-increasing amounts. As much as 115 feet of the material was ultimately deposited in the Missoula Basin, mostly below an altitude of 3,500 feet (Fig. 5). Small populations of a few species of annelids and arthropods lived in the turbid waters of the ancient glacial lakes (Fig. 7). Related species still occur in Flathead and McDonald Lakes, lingering remnants of the last Wisconsin impoundment.

The present high-terrace, low-terrace, and flood-plain topography is mostly a post-Lake Missoula development. The high terraces are erosional remnants of the ancient lake floor. The low terraces and the Clark Fork flood plain are composite erosional-depositional features.

GRAVIMETRIC SURVEY

Gravity surveys have been useful in other intermontane basins in obtaining subsurface information. A gravity survey was made in the Missoula Valley to determine approximate depth and volume of valley fill and to help interpret subsurface features and bedrock configuration.

FIELD METHODS

About 350 gravity stations were established on an approximate half-mile grid at bench marks, water wells, and easily accessible locations. Elevations of the stations were determined to the nearest foot by instrumental leveling. The gravity readings were made with a portable temperature-compensated World-Wide gravity meter. The uncorrected readings are believed to be accurate to the nearest 0.05 milligal relative to one another.

To determine the instrumental drift, readings were made at a selected base station (U.S. Bureau of Land Management reference monument, NE cor. sec. 31, T. 13 N., R. 19 W.) at the beginning and end of each day's work, and at intervals of about 2 hours at a previously occupied station. The following data were recorded at each station: (1) station designation, (2) time of reading, (3) gravity meter reading, (4) altitude of station, and (5) description of station. Two readings were taken at each station and then averaged. The station locations were plotted on maps as an aid to station reference and description.

REDUCTION OF DATA

The observed gravity values were corrected for drift, latitude, elevation, free-air and Bouguer, terrain, and regional gradient as described by Dobrin (1960, p. 218-241). A factor of 0.061 milligal per foot, based on an assumed rock density of 2.67 grams per cubic centimeter, was used as the combined free-air and Bouguer correction. Terrain corrections using tables and chart published by Hammer (1939) were made for 19 selected stations. Interpolated values were applied to the other stations.

By comparing gravity values of stations on bedrock, a regional gravitational gradient was determined as a slab sloping to the southeast. This surface was divided into 0.10 milligal intervals and superimposed on the overall gravity map. The appropriate value was then subtracted from each station, thus leaving a residual gravity map. The residual gravity reading for each station is on file in the U. S. Geological Survey office in Missoula.

INTERPRETATION OF DATA

Dobrin (1960, p. 253) has pointed out the ambiguity inherent in the interpretation of gravity data, namely, that without other information there is no unique solution. In this gravimetric survey the number of variables has been reduced by the application of surface and subsurface geologic evidence.

RESIDUAL GRAVITY MAP

The residual gravity map of the Missoula Valley (Pl. 2) shows an elongate gravity low west of Missoula and a smaller closed low of higher gravity at Frenchtown. The two lows are separated by an area of higher gravity. The low near Missoula narrows considerably where it swings around a prominent U-shaped gravity high, which extends northeastward beneath the valley fill. The small oblong gravity low at Frenchtown has about 8 milligals of residual gravity relief relative to bedrock areas as compared with 16 milligals of residual gravity relief for the gravity low near Missoula. The lows may represent the ancient drainage of the Clark Fork. The gravity map also shows an opening into the Bitterroot Valley, suggesting a possible earlier drainage for the Bitterroot River that could possibly account for the broadness of the trough near Missoula.

The close relationship of the gravity map and the geologic map is shown particularly by the following: (1) High gravity occurs over exposures of basement rocks around the periphery of the valley, near Primrose, and west of the mouth of Rattlesnake Creek; relatively low gravity occurs over areas of low-density Tertiary and Quaternary deposits. (2) In the LaValle-Butler Creek area, the abrupt change in direction of the contours indicates some deformation, which is partly borne out by the surface expression of the Hourglass, Clark Fork, and several transverse faults. (3) In the Grant Creek area, the gravity contours are compatible with the Hourglass and Clark Fork faults. The gradient is fairly steep (6 milligals per mile) from the valley bottom up to the Hourglass fault, and relatively flat (1 milligal per mile) between the two faults. For about a mile north of the Clark Fork fault the gravity decreases. The nearly flat gradient between the faults extends from Grant Creek to Butler Creek.

GRAVITY PROFILES

Three profiles (Pl. 2) were calculated by using a graticule as described by Dobrin (1960, p. 256) to convert corrected gravity readings to depth, in feet, to basement rock. An assumed density contrast of 0.6 gram per cubic centimeter between the basement rocks and valley fill was used. The profiles were prepared especially to determine the approximate thicknesses and volume of valley fill and to help interpret the structure.

Profile A-A′ shows about 2,500 feet of sediments overlying basement rock. These sediments are probably in fault contact with basement rock along the Hourglass fault, as shown by a sharp break in profile at the fault and a steep gradient to the southwest of the fault. About 100 feet of unconsolidated material overlies basement rock northeast of the fault.

Profile B-B′ indicates that the present channel of the Clark Fork is underlain by less than 300 feet of sediments. This is substantiated by logs of wells B-13-20-9cc and B-14-20-31da. The first well encountered basement rock at an altitude of 2,974 feet and the other at 2,791 feet. Basement rock is exposed northeast of the channel at Primrose, but about 3,000 feet of sediment overlies basement rock 3½ miles northeast of Primrose. Seemingly the ancient Clark Fork channel was north of the present channel.

Profile C-C′ shows about 1,500 feet of sediment overlying basement rock. The thinning of sediment to the northwest and the bedrock outcrop in the Alberton Narrows are indicative of a closed basin.

HYDROLOGY

DEFINITIONS AND ABBREVIATIONS

The following definitions are based on those given by Meinzer (1923b). A few terms not included in the following list are defined where they are introduced in the text.

Aquifer. A formation, group of formations, or part of a formation that will yield ground water in useful quantities.

Artesian water. Ground water that rises in a well above the point at which it is encountered in an aquifer; water confined under artesian pressure.

Confining bed. A bed overlying an aquifer that, because of its impermeability or low permeability relative to the aquifer, prevents or impedes upward loss of water and pressure; a similar bed beneath an aquifer that prevents or impedes downward loss of water and pressure.

Discharge, ground-water. Water moving out of the zone of saturation.

Drawdown. Lowering of the water level in a well as a result of withdrawal of water from it or from another well in the vicinity.

Evapotranspiration. The combined discharge of water to the air by direct evaporation and plant transpiration.

Flowing well. An artesian well through which water is forced above the land surface by hydrostatic pressure in the aquifer.

Permeability. A measure of the capacity of an aquifer to transmit water.

Permeability, field coefficient of. The rate of flow of water in gallons per day under prevailing conditions, through a cross section of aquifer 1 foot high and 1 mile wide, under a hydraulic gradient of 1 foot per mile.

Porosity. The ratio of the volume of openings in a rock or soil to its total volume, usually expressed as a percentage.

Recharge, ground-water. Water moving into the zone of saturation.

Specific capacity. A measure of the productivity of a well; the rate of yield, in gallons per minute, per foot of drawdown in a well.

Storage, coefficient of. A measure of an aquifer's capacity to store and release water; the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

Transmissibility, coefficient of. The rate of flow of water, in gallons per day under prevailing conditions, across each mile strip extending the saturated thickness of the aquifer, under a hydraulic gradient of 1 foot per mile. It is equal to the field coefficient of permeability multiplied by the saturated thickness of the aquifer, in feet.

Water table. The upper surface of the zone of saturation except where that surface is formed by an impermeable layer; the water at the waer table is under atmospheric pressure.

Zone of aeration. The zone in which the open spaces in the rocks are not (except temporarily) filled with water under hydrostatic pressure.

Zone of saturation. The zone in which the open spaces in the rocks are filled with water under hydrostatic pressure.

The following abbreviations are used in this report:

acre-ft—acre-feet; the volume of water required to cover 1 acre to a depth of 1 foot; equal to 43,560 cubic feet, or 325,850 gallons.

cfs—cubic feet per second; a unit of discharge equivalent to about 449 gpm.

gpm—gallon(s) per minute

gpd—gallon(s) per day

gpd/ft—gallon(s) per day per foot

mgd—million gallons per day

ppm—part(s) per million

SURFACE WATER

Records of streamflow are collected at several gaging stations in and near the Missoula Basin (U.S. Geological Survey, 1962, p. 212, 213, 223-226; 1960, p. 220). For the period 1929-62 the Clark Fork above Missoula had a maximum flow of 31,500 cfs on May 23, 1948; a minimum flow of 115 cfs on October 25, 1943; and an average flow of 2,824 cfs—2,044,000 acre-ft per year. The drainage area above the station is 5,999 square miles. For the same period, the Clark Fork below Missoula had a maximum flow of 52,800 cfs May 23, 1948; a minimum flow of 388 cfs January 18, 1933; and an average flow of 5,181 cfs—3,751,000 acre-ft per year. The drainage area above the station is 9,003 square miles. The difference in flow between the two stations was mainly contributed by the Bitterroot River, which has a drainage area of 2,812 square miles (U.S. Geol. Survey, 1955, p. 349). Average flow of the Bitterroot River near Florence for the period 1957-62 was 2,148 cfs—1,555,000 acre-ft per year; maximum flow was 16,700 cfs on May 26, 1958; and minimum flow was 365 cfs on August 20, 1961. Two tributaries to the Bitterroot downstream from the station near Florence, Eightmile Creek and Lolo Creek, have a combined drainage area of 270.6 square miles and contribute an average flow of 222 cfs—160,700 acre-ft per year—to the Bitterroot River.

The difference in annual flow of the Clark Fork between the station below Missoula and the Alberton station for the period 1960-62 averaged 234,000 acre-ft. The difference was mainly contributed by Ninemile Creek; some was contributed by Mill Creek and other small tributaries.

Streamflow fluctuates seasonally with changes in precipitation, snowmelt, irrigation diversion, and other factors. Maximum flow occurs in the spring when the winter's accumulation of snow melts and the amount of precipitation is high. Minimum flow occurs in the fall or winter.

GROUND WATER

Throughout historical time ground-water movement has been poorly understood and subject to much speculation. It has taken many centuries to develop the science of ground-water hydrology to its present level of technical reliability. Because of the inherent advantages of ground water for many uses there has been a marked increase in its development. Along with the development has come more public interest in, and more scientific studies of, the principles of ground-water hydrology. These scientific studies have shown that (1) ground water obeys natural laws; (2) practically all ground water is derived ultimately from precipitation; (3) most usable ground water is an important component of the circulatory pattern of the hydrologic cycle (Fig. 9); and (4) the complexity of occurrence of ground water is intimately associated with the geology of the area.

PRINCIPLES OF OCCURRENCE*

The rocks that form the outer crust of the earth are seldom completely solid throughout. They contain many open spaces known as voids—interstices, pore spaces, joints, fractures, and solution channels. All ground water occurs in these

---

*For a more detailed discussion see Meinzer (1923a, p. 2-102).

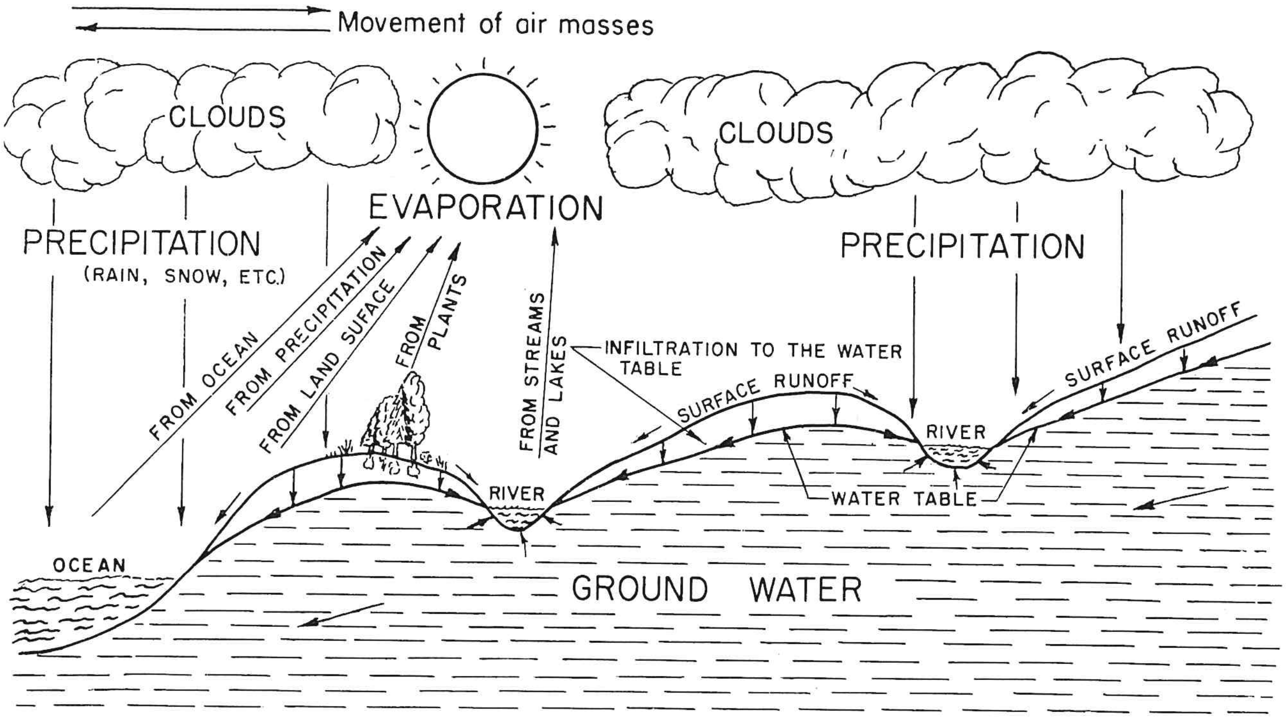

Figure 9.—Hydrologic cycle.

open spaces. Thus their size, shape, character, and distribution determine, to a great extent, the occurrence of ground water. In the Missoula Basin most of the ground water occurs in the pore spaces between the grains of the Quaternary and Tertiary sediments; some occurs in joints and fractures in the basement rocks.

Part of the water falling on, or flowing over, the ground seeps into the soil zone and percolates downward through the zone of aeration until it reaches the zone of saturation. The zone of saturation is a vast underground reservoir, which stores and transmits water. The open spaces in the rocks are generally interconnected and act as conduits through which water constantly moves. The rate of movement of ground water is much slower than that of surface water. The velocity of surface water is measured in feet per second; the velocity of ground water is measured in feet per day or feet per year. It is the slow rate of movement of ground water that makes possible the flow of surface streams during periods when there is no precipitation or runoff from snowmelt.

Water is discharged from the underground reservoir to the earth's surface through springs, wells, and effluent streams, or to the atmosphere by evaporation and plant transpiration (evapotranspiration). Under natural conditions the discharge from the underground reservoir is equal to the recharge. Man has set up unnatural conditions in the Missoula Basin, and adjustments have been or are being made in the natural pattern of ground-water recharge, movement, and discharge. Irrigation of agricultural land and development of municipal and industrial water supplies has changed the natural conditions. The change caused by irrigation occurred far enough in the past that a new balance between recharge and discharge has been fairly well established. Except for one industrial development, changes caused by municipal and industrial development have been either far enough in the past to have a new balance established or have been small enough that a noticeable change was not apparent from the data collected. One industry that recently started pumping about 10 mgd of water has noticeably changed the natural conditions; a new balance may be established (1964).

The geology of the area determines whether the water in an underground reservoir is under artesian (confined) or water-table (unconfined) conditions (Fig. 10). Most of the ground water in the Missoula Basin is unconfined, some is semiconfined for at least part of each year because the water level is in the soil zone, and some is confined. A few wells flow at the surface. The ge-

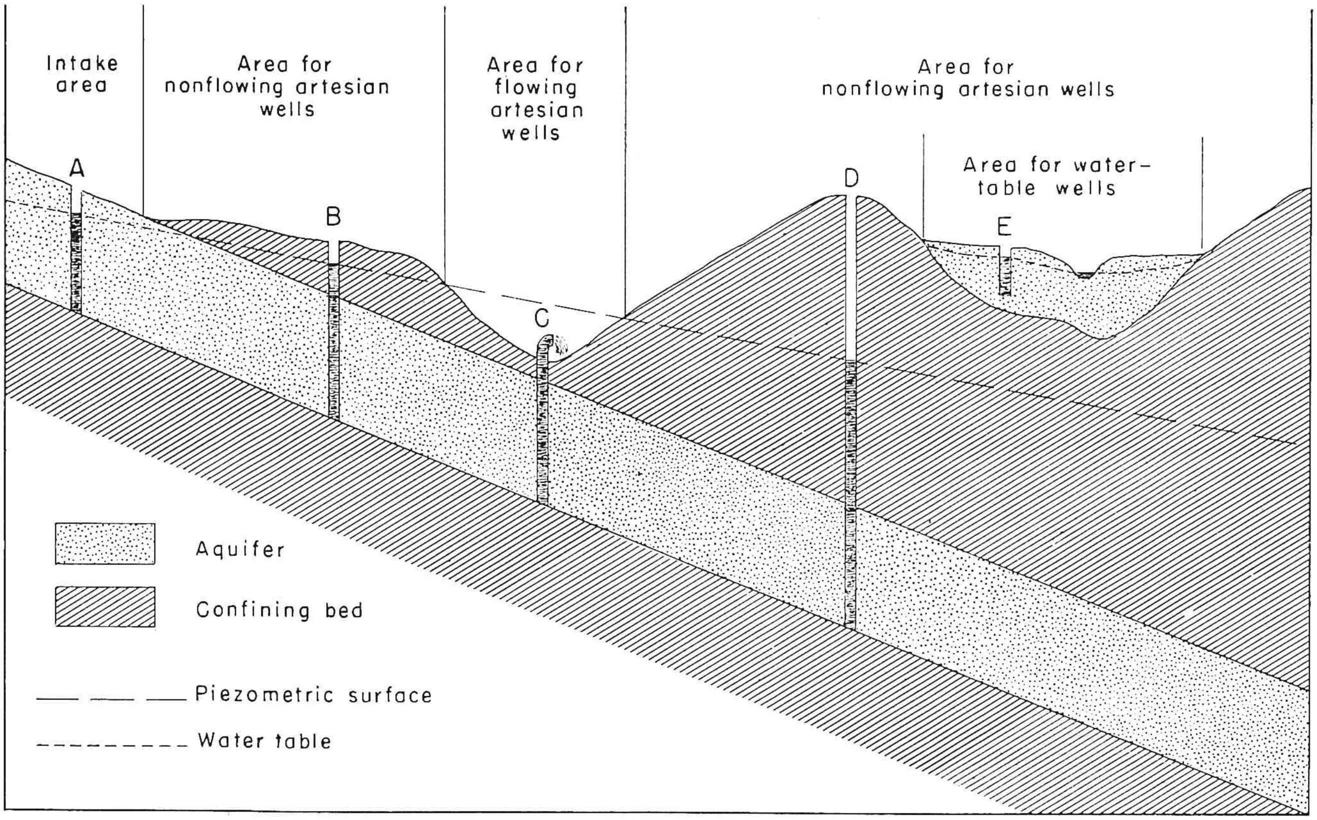

Figure 10.—Hypothetical section showing geologic conditions necessary for artesian (confined) and water-table (unconfined) aquifers. **A** and **E** are water-table wells; **B** and **D** are nonflowing artesian wells; and **C** is a flowing artesian well.

ology of the area also determines to a great extent the depth to water in the underground reservoir. In some places in the Missoula Basin, as in seeps and swamps, the water table is at land surface. In the flood-plain alluvium of the Clark Fork and some of its tributaries, the water table is within 10 feet of the land surface. Under most of the high terraces and in some of the alluvial fans, the water table generally ranges from 10 to 200 feet below land surface. Depths of wells in the area range from a few feet to 550 feet, but most are less than 175 feet.

HYDROLOGIC PROPERTIES OF WATER-BEARING MATERIALS

The quantity of ground water that an aquifer will yield to wells depends on the hydrologic properties of the material forming the aquifer. Those properties of greatest significance are the ability to store and transmit water, as measured by the porosity and by the coefficients of storage (S), permeability (P), and transmissibility (T). The porosity of a rock, which is its property of containing voids, controls the amount of water that can be stored in an aquifer. It varies with the arrangement, shape, and degree of sorting of the particles making up the aquifer. The size of particle is not an important determining factor of porosity, but it is a determining factor in the coefficient of storage, which is a measure of the ability of an aquifer to take water into, or release it from storage. Fine-grained materials, such as clay or silt, may be more porous than coarse sand or gravel but will yield very little water when subjected to gravity drainage.

The coefficient of permeability of a material is not indicated by its porosity. A fine sand may have a porosity exceeding 30 percent, but because of the small size of its pores, it offers much greater resistance to the transmission of water than does a coarse sand or gravel having the same porosity. A clay stratum may have a higher porosity than a sand or gravel stratum, but because of the minute size of its pores, it may be nearly impermeable. The difference is that in the fine-grained materials most of the water is held by molecular attraction, whereas in the coarse-grained materials the pore spaces are sufficiently large and inter-

TABLE 1.—AQUIFER TEST DATA

Well number	Geologic source	Depth of well (feet)	Pumping rate (gpm)	Drawdown in pumped well (feet)	Length of test (minutes)	Specific capacity (gpm/foot)	Coefficient of transmissibility (gpd/foot)	Remarks
B-13-19- 8cc	Alluvium	70.5	275	1.5	90	183	410,000	
-22cb1	- - do - -	116	550	....	390	.....	1,800,000	No way to measure water level in pumped well.
-27bc	- - do - -	148	1,170	5.2	250	225	620,000	
-33ad	- - do - -	117	1,090	4.1	250	266	1,200,000	
B-15-21-34-da1	- - do - -	22.3	90	.6	200	150	85,000	

connected that water can more readily move through them by gravity. A well will yield very little water from fine-grained materials. The coefficient of transmissibility relates the coefficient of permeability to the aquifer thickness. It equals the coefficient of permeability multiplied by the saturated thickness of the aquifer, in feet.

QUANTITATIVE OBSERVATIONS

Aquifer tests.—Approximate values of the coefficient of transmissibility were obtained in five places in the Mssoula Valley by a field method commonly known as a "pumping test" (Table 1).

When a well tapping a water-table aquifer is pumped, water is removed from the aquifer surrounding the well and the water level is lowered (Fig. 11). The depression formed in the water table has the shape of an inverted cone whose apex is at the water level in the well being pumped. The base of the cone is the original water surface and the height is equal to the drawdown in the well. The drawdown is proportional to the pumping rate and, other things being equal, after sufficient time of pumping it is inversely proportional to the transmissibility of the aquifer. The area affected by pumping (area of influence) is controlled by the length of time and the rate at which the well is pumped and by the transmissibility and storage properties of the aquifer. The cone of depression around a well being pumped will increase in depth and area until it intercepts enough recharge or reduces natural discharge sufficiently to supply the amount of water being dis-

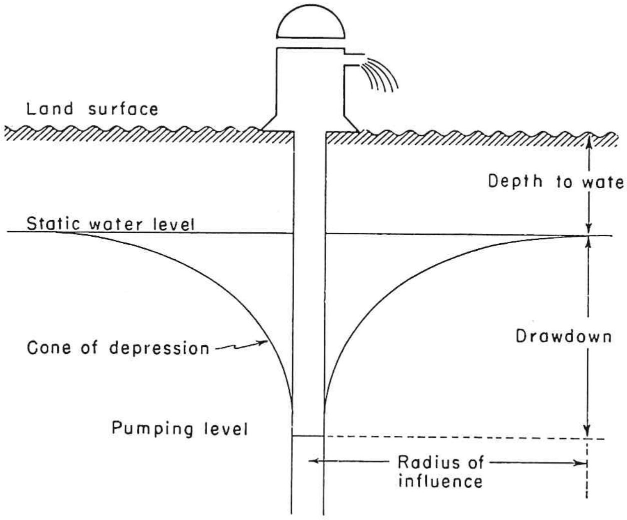

Figure 11.—Diagrammatic section of a well that is being pumped, showing its cone of depression, drawdown, and radius of influence.

charged by the well. After pumping is stopped, the water table surrounding the well will, in time, return to its original position.

By pumping a well at a known constant rate for a measured time, and by keeping a periodic record of the drawdown in the area of influence during the time of pumping and for a measured time after pumping has stopped, enough data can be collected to compute, by use of formulas developed by Theis (1935) and by Jacob (1947), the coefficients of transmissibility and of storage.

In one of the pumping tests (Table 1) made in the Missoula Valley, drawdown and recovery were measured only in an observation well; measurements could not be made in the pumped well. The test was too short to enable accurate determination of the coefficient of storage. In the other four tests, drawdown and recovery were measured only in the pumped well. No other wells within the area of influence were available for measurement. Without observation wells, the coefficient of storage could not be determined. The five tests were not made under ideal conditions, but the data obtained are significant when used with the knowledge of the conditions under which the tests were made.

The coefficient of transmissibility can be used in conjunction with other data to (1) estimate yield and drawdown for proposed wells; (2) determine the amount of ground water flowing through an area; and (3) determine the rate at which ground water is moving.

Specific capacities of wells.—The specific capacity is the relation between the discharge from a well and the drawdown in the well. At a given discharge the drawdown increases as either the coefficient of transmissibility or coefficient of storage decreases. Therefore, the specific capacity of a well should give some indication of the hydrologic properties of the producing aquifer. Theis and others (1963, p. 332) outlined a method for estimating the transmissibility of a water-table aquifer near a well of known specific capacity. He noted many limitations of the method, but he also indicated its usefulness. This method was used in the Missoula Valley to obtain values of the coefficient of transmissibility in the vicinity of 29 wells, including 4 wells on which pumping tests were made (Table 2).

The coefficients of transmissibility obtained from the specific capacities of four wells ranged from 32 percent to 109 percent of the coefficients obtained from pumping tests on the same four wells. This is not unusual, as the drawdown from which the specific capacity is determined is dependent not only on the water-yielding properties of the aquifer but also on the construction and development of the well. Actual drawdown will be greater than the theoretical drawdown even in the best designed and constructed wells and may be several times as great in poorly constructed and poorly developed wells. It has been shown by Jacob (1947, p. 1056) that the specific capacity decreases with increasing time and with increasing discharge. Therefore, using the specific capacity determined from a short test and (or) a high discharge from a small-diameter well to estimate the coefficient of transmissibility could cause some very large errors.

The coefficients of transmissibility obtained from the specific capacities of 25 wells ranged from 1,300 to 1 million gpd/ft. Most of the coefficients are probably low because of low specific capacities due to improper well completion. The coefficients determined from specific capacities of small-diameter wells with unperforated casing generally range from 10 to 50 percent of the true coefficients. Coefficients determined from larger-diameter wells that are screened or perforated and developed may be 30 to 90 percent of the true coefficients, depending on the degree of development and the rate of discharge.

Although the coefficients of transmissibility obtained from specific capacities are subject to large errors, they are useful when used in conjunction with other data in estimating yield from various water-bearing formations and from various depths within any given formation.

WATER TABLE AND MOVEMENT

The surface defined by the level at which water stands in nonpumped, tightly cased wells penetrating an unconfined aquifer is termed the water table. It is an irregular sloping surface that conforms roughly to the topography. The water table is a dynamic surface that rises and falls as the aquifer is recharged and discharged. The water table has many irregularities that are caused by local differences in the permeability of the aquifer material and local and seasonal differences in discharge from, or recharge to, the reservoir. For a given rate of ground-water flow, the water-table slope will be relatively gentle if the aquifer is coarse and permeable, such as a clean sand and

TABLE 2.—COEFFICIENTS OF TRANSMISSIBILITY ESTIMATED FROM SPECIFIC CAPACITIES

Well number	Depth (ft.)	Diameter (in.)	Specific capacity (gal./ft.)	Coefficient of transmissibility (gpd./ft.)	Geologic source*	Remarks
B-12-19-18bb1	344	6	1.5	2,500	T	
B-12-20- 2cb	105	6	.8	1,300	Pc	
-12bb1	104	6	28	46,000	Qa	
B-13-19- 7ad2	65	6	13	21,000	Qa	
- 8cc	70	8	183	270,000	Qa	Coef. of trans. from Pumping Test—110,000
- 8dd	145	10	12	17,800	Qa	
-15da	69	10	12	17,800	Qa	
-17bc	212	16	83	122,000	Qa & T	
-21cd	120	12	60	89,000	Qa	
-27bc	148	12	225	330,000	Qa	Coef. of trans. from Pumping Test—620,000
-28dc	116	12	33	49,000	Qa	
-29da2	110	14	45	67,000	Qa	
-30bd	121	12	735	1,000,000	Qa	
-31cc2	100	10	100	148,000	Qa	
-32bb	97	8	15	22,000	Qa	
-33ba	123	12	200	296,000	Qa	
-33ad	117	12	265	390,000	Qa	Coef. of trans. from Pumping Test—1,200,000
-34bb	145	12	104	154,000	Qa	
B-13-20- 1bb	215	10	89	130,000	Qa	
- 5ba2	132	4	3.3	5,400	Qa	
-12dc	58	6	10	16,400	Qa	
-14bb1	233	10	84	124,000	Qa	
B-14-19-35dd	84	6	1	1,600	Qa	
B-14-20-31da	166	6	15	25,000	Qa	
B-14-21-24ba2	172	16	52	77,000	Qa	
-24ba6	183	16	85	125,000	Qa	
B-15-21-34da1	22	120	138	93,000	Qa	Coef. of trans. from Pumping Test—85,000
-34da2	165	5	15	25,000	Qa	
B-15-22-26ab	120	10	5.5	8,000	Qa(?)	

*Geologic source: T, Tertiary rocks; Pc, Precambrian rock; Qa, Quaternary alluvium.

gravel; the slope will be relatively steep if the aquifer is fine grained and less permeable, such as a fine sand or silty sand and gravel.

The slope of the water table and the direction of movement of ground water can be determined from a water-table contour map. The water levels and altitudes of 154 wells in the Missoula Valley were determined during this investigation, and were used in making a generalized water-table contour map (Pl. 3). Water-table contours are shown for only part of the valley, because of insufficient control elsewhere. Even within the area contoured, many of the details of the shape and slope could not be shown. The contours are based on water-level measurements made in October 1962.

Ground water moves downslope perpendicular to the contours. The water-table contour map shows that ground water in the area contoured moves generally southwest. From the eastern edge of the area to the confluence of the Clark Fork and Bitterroot River, movement of ground water is parallel to the Clark Fork; in the rest of the area movement is generally toward the Clark Fork. In detail, the direction of movement varies considerably from one place to another. A noticeable cone of depression has been developed in sec. 13 and 24, T. 14 N., R. 21 W., an area of industrial use of ground water. Water moves into this area from all directions.

The rate of ground-water flow (Q) through the reservoir under Missoula and south of the Clark Fork was determined from the equation

$$Q=TIL,$$

where

T=transmissibility in gallons per day per foot,

I=slope of ground-water table in feet per mile, and

L=length of section in miles.

A 3-mile section was taken along the 3,140-foot water-table contour line southeast from the river to where the line bends southwest (Pl. 3, A-A′). The slope is about 10 feet per mile through this section, and the transmissibility (determined from a test on well B-13-19-27bd) is 620,000 gpd/ft. When these values are substituted in the equation, the rate of flow is found to be

$$Q=TIL=620{,}000 \times 10 \times 3=18{,}600{,}000 \text{ gpd}$$

$$\simeq 2{,}490{,}000 \text{ cubic feet per day}$$

The velocity at which the ground water moves through the section was estimated from the relationship

$$v=\frac{Q}{pA}$$

v = velocity in feet per day,

Q = rate of flow through section in cubic feet per day,

p = porosity, and

A = area of cross section in square feet.

The above-determined rate of flow, an estimated porosity of 40 percent, and an aquifer thickness of 150 feet are used to compute the velocity

$$v=\frac{Q}{pA}=\frac{2{,}490{,}000}{0.40 \times 5{,}280 \times 3 \times 150}=2.6 \text{ feet per day}$$

Lower values of transmissibility offset steeper gradients in other parts of the area so that the rate of movement of ground water is probably less than 3 feet per day.

FLUCTUATION OF THE WATER TABLE

The amount and rate of water-table fluctuation in the Missoula Basin depends on the aquifer characteristics and on points and amounts of recharge and discharge. There is a continual discharge of ground water by seepage into streams, by evapotranspiration (generally along streams), and by pumping from wells. The discharge causes a gradual lowering of the water table except during periods when discharge is exceeded by replenishment of the underground reservoir from snowmelt runoff, precipitation, and seepage from streams and irrigation systems. The water table fluctuates more by the recharge or discharge of a given quantity of water than does the level of a surface reservoir, because water occupies only part of the volume of the ground-water reservoir. A record of the rise and fall of the water table provides valuable information about ground-water conditions. Fluctuations of the water table in the Missoula Valley were determined by periodically measuring the water level in 39 wells.

Water-level fluctuations may be placed in three general groups—short term, seasonal, and long term. Short-term fluctuations are an indication of aquifer characteristics; seasonal fluctuations are an index of change in quantity of water in storage; and long-term fluctuations may indicate whether there is an overdraft or surplus.

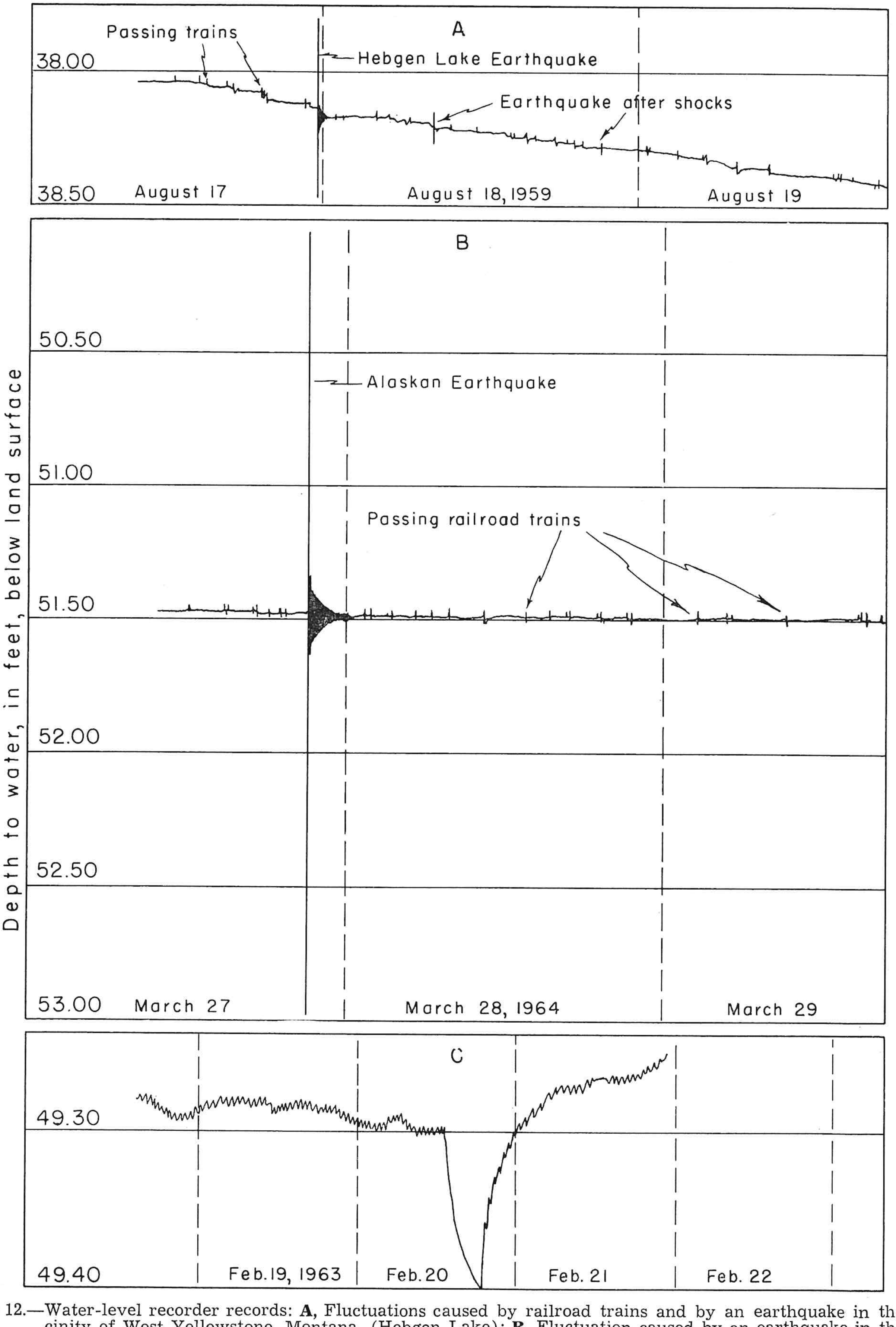

Figure 12.—Water-level recorder records: **A**, Fluctuations caused by railroad trains and by an earthquake in the vicinity of West Yellowstone, Montana, (Hebgen Lake); **B**, Fluctuation caused by an earthquake in the vicinity of Anchorage, Alaska, and by railroad trains; and **C**, Effect of pumping a nearby well.

Short-term fluctuations include (1) rapid changes in water level due to earthquakes or the imposition of heavy loads such as railroad trains; (2) daily changes due to pumping from the aquifer; and (3) changes due to variations in barometric pressure, temperature, and wind velocity. Figure 12 shows two types of short-term fluctuations. Records from well B-13-19-8cb (Fig. 12, A and B) show fluctuations caused by railroad trains and by two earthquakes—one in the vicinity of West Yellowstone, Montana, and the other in the vicinity of Anchorage, Alaska. The record from well B-13-19-22bc1 (Fig. 12, C) shows the effect of pumping a nearby well.

Seasonal fluctuations indicate the amount of water taken into and released from storage during the year. In general, the water table in the Missoula Valley declines from a summer high to a spring low. Most of the rise occurs in April, May, and June. Hydrographs and other data indicate that location, depth to water, geologic setting, and climatic variations have a noticeable effect on the seasonal fluctuations (Fig. 13). The time of the year when the high point in the annual fluctuation is reached differs with location in the valley and does not occur always at the same time of year at a given location. During the period of record, about one-third of the measured wells reached their highest annual water level in June, about one-third in July, and the other one-third in August. Water levels in most wells are lowest in February or March; in the others they are lowest in January or April.

Well B-12-19-18bb1 is in Tertiary sediments and is relatively deep. The small amount of fluctuation is due to the considerable depth to water and to the sediment size and bedding of the material between the source of recharge and the water table. Wells B-13-19-6ba and B-13-19-8cb are in Quaternary sediments, but the former is near the contact with Tertiary sediments. Both are influenced by excess water from irrigation, but less water is involved in the greater fluctuation in well B-13-19-6ba, owing to finer-grained sediment in and overlying the aquifer. The finer-grained sediment is probably the reason for the water level in the well reaching its peak later than that in well B-13-19-8cb. The hydrograph of the water level in well B-13-20-14ac is typical of many shallow wells in irrigated areas. The water level rises in the spring, owing to recharge from snowmelt runoff, precipitation, and application of irrigation water; stays fairly high during the summer, owing to continued application of irrigation water; and drains to approximately the same base level during the fall and winter. The peak water level in well B-13-20-14bb1 is reached in late June or early July even though there is 115 feet of clay overlying the aquifer and the depth from land surface to the water level is 85-90 feet. This indicates that the well is probably bottomed in sediments that are in hydraulic connection with the river or the flood-plain alluvium. Well B-14-21-13cd is near an industrial well field. The industry started using ground water in 1957, but well B-14-21-13cd showed very little effect from the use until 1961. The water level resulting from the present rate of withdrawal from the well field may now (1964) be fairly well stabilized.

RECHARGE

The Missoula Valley ground-water reservoir is recharged by infiltration from influent streams, from excess irrigation water, and from precipitation and snowmelt runoff. The Clark Fork is perched above the water table for a distance of about 4 miles after it enters the Missoula Valley. In this reach the river contributes some water to the ground-water reservoir. For the rest of its course through the valley, the Clark Fork is an effluent stream except for a short period during spring runoff when it rises high enough to contribute some water to the ground-water reservoir. Much of the water diverted from the Clark Fork to irrigate about 12,000 acres of land in the valley seeps down to the ground-water reservoir.

Most of the major tributaries to the Clark Fork in the area of investigation are influent for at least part of their course. Therefore, when all of the water is not being diverted for irrigation, they become effective sources of recharge to the underlying and adjacent sediments. During the summer, most of the water is diverted from the tributary streams to irrigate about 5,000 acres of land. Some of this water seeps down to the ground-water reservoir.

The amount of recharge from precipitation and snowmelt runoff is governed by the amount, distribution, and intensity of precipitation, the topography, the permeability and moisture-holding capacity of the surficial deposits, the consumptive use through evapotranspiration, and the capacity of the ground-water reservoir to store additional water. Probably very little direct recharge from precipitation and only a small amount from snow-

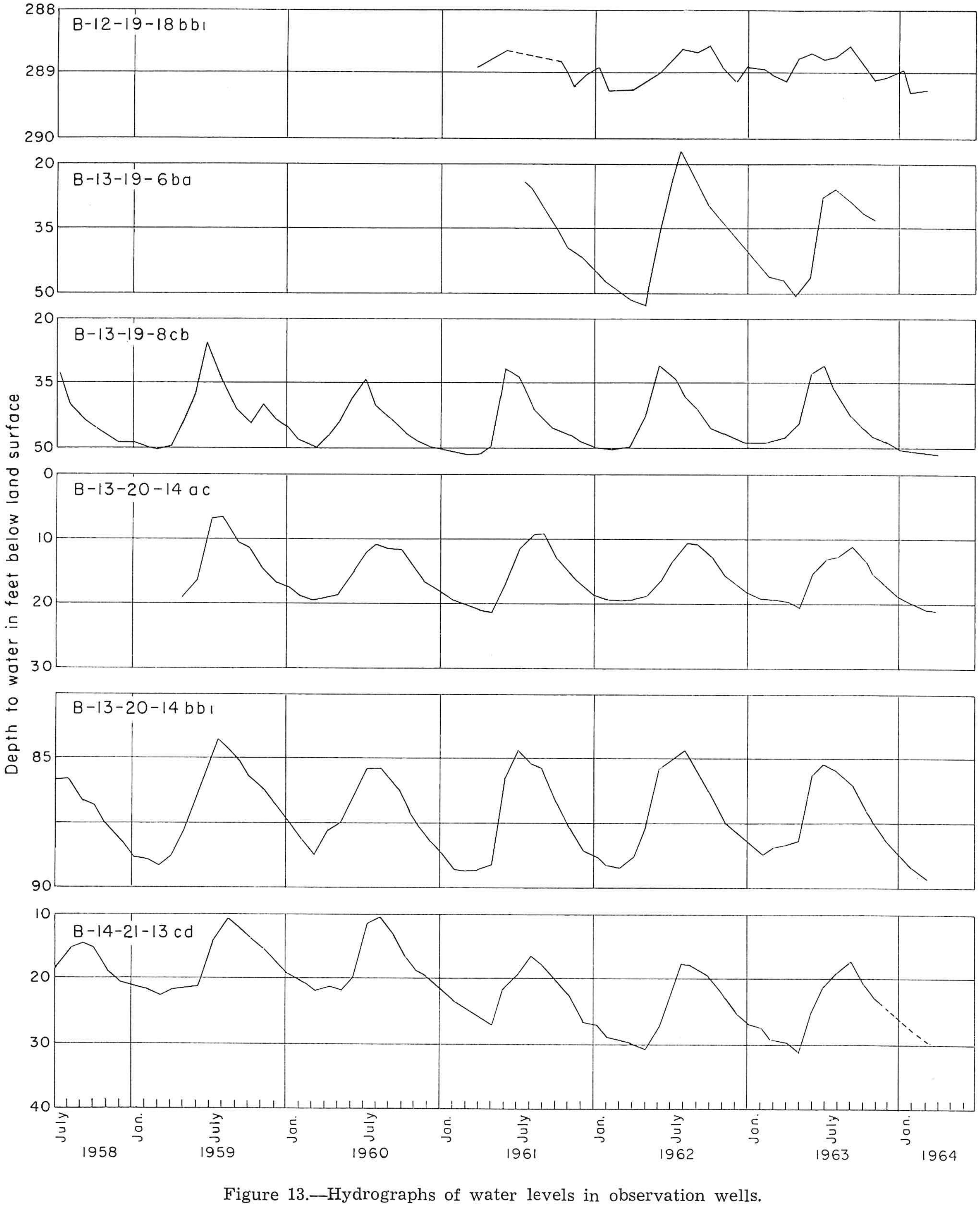

Figure 13.—Hydrographs of water levels in observation wells.

melt runoff occurs in the nonirrigated part of the valley. Some runs off, but most of the available moisture in the nonirrigated part of the valley is utilized by plants or is evaporated. The average annual precipitation on the irrigated part of the valley is about 13 inches. Almost one-third of this amount normally occurs in May and June, which are also the months of maximum recharge from influent streams and irrigation, so it is impossible to tell from the hydrographs of water levels in observation wells how much recharge occurs directly from precipitation and snowmelt runoff. It is probably small in comparison to the amount of recharge from other sources.

STORAGE

The volume of water stored in the sediments in the Missoula Basin is the product of the volume of saturated sediments and their porosity. No estimates could be made for the Ninemile Valley, but gravity data indicate the volume of saturated sediments in the Missoula Valley is about 25 cubic miles. Assuming a porosity of 40 percent, there is about 30 million acre-ft of ground water in storage. Part of the water (that represented by the coefficient of storage) is available to wells; part is held by capillarity as the water table is lowered. The storage coefficient is probably about 0.1. Therefore, about 8 million acre-ft of the water in storage in the sediments is available to wells. As the saturated thickness and the quantity of water in storage decrease, however, the yields of wells also decrease. The decrease in yield of wells and the increase in pumping lift make it impractical to recover all the "available" water in storage. The amount that would be recovered at any time depends on well construction and pumping costs in relation to economic benefits obtained from the water. It is estimated that about 1¾ million acre-ft of water is available to wells in the upper 200 feet of saturated material.

The seasonal change in the volume of ground water in storage is estimated to be 50,000 acre-ft, although the net change from year to year is small. This estimate is based on 8 feet of annual fluctuation in the water table throughout 100 square miles of the valley.

DISCHARGE

Ground water is discharged from the fill in the Missoula Valley by effluent seepage into streams, drains, springs, and seeps; by evapotranspiration; and by pumping from wells. Where the water table intersects the land surface, ground water is discharged by effluent seepage. As indicated by the water-table contour map (Pl. 3), ground water is being discharged into or near the middle and lower reaches of the Clark Fork.

During the summer the water table is high. At this time of year, seven drainage ditches, having a total length of about 6 miles, discharge an estimated 37 cfs of water into the Clark Fork through tributary stream channels (oral communciation, William Cardon, U.S. Soil Conservation Service). Ground-water discharge through springs and seeps is small in comparison to discharge by effluent streams and drains. There are only a few small springs in the basin.

Much water is discharged from the basin by evapotranspiration. There are large areas where the water table is within a few feet of land surface during much of the year, and there are many other areas (swamps) where the water table is at land surface for at least part of the year. Evaporation from the water surfaces and the soil and transpiration by various types of vegetation effectively discharge large quantities of ground water. Some water is also discharged from the basin by direct evaporation from 450 acres of industrial waste disposal ponds and from about 1,500 acres of open stream channels.

The amount of ground water discharged from wells is relatively small in comparison to the amount discharged by effluent streams and evapotranspiration. Probably less than 25,000 acre-ft of water per year is pumped from the ground-water reservoir in the basin.

DEVELOPMENT

Since 1957, when less than 6,500 acre-ft was pumped, the use of ground water has increased greatly. In 1963, about 24,000 acre-ft was pumped from 17 industrial, 9 municipal, 14 irrigation, 5 air-conditioning, and several hundred domestic and stock wells in the Missoula Valley. Peak pumping was probably more than 90 acre-ft per day for short periods during some of the hottest days in July and August. About 65 percent of the 24,000 acre-ft was pumped from 6 wells that supply one industry; less than 10 percent was pumped from the other 11 industrial and the 5 air-conditioning wells. About 20 percent was pumped from the 9 municipal wells in Missoula. Municipal use of ground water doubled from 1957 (700 million gallons) to 1963 (1.4 billion gallons).

Enough recharge is available to the sediments in the Missoula Valley so that additional withdrawals of water can be made without excessive lowering of the water table. More than 20,000 gpm, the peak pumping rate in 1963, could probably be withdrawn continuously from wells now being used without any adverse effect on the water regimen of the area. Additional wells can be installed in the Missoula Valley from which large quantities of water can be withdrawn without adversely affecting present users. Because of the great variation of water-yielding ability of the sediments in different parts of the valley, test holes should be drilled prior to the installation of industrial or irrigation wells. The most likely areas for obtaining wells are the flood plain of the Clark Fork and the low terrace bordering the flood plain. In these areas, properly constructed and developed wells commonly yield as much as 1,000 gpm, and yields of as much as 5,000 gpm can be obtained locally. Developments in which several thousand gallons per minute will be pumped continuously should be located near the Clark Fork where recharge can be induced from the river.

CHEMICAL QUALITY OF WATER

Although water obtained from wells is initially derived from rain or snow, which is nearly pure water, it always contains some dissolved constituents. These constituents include mineral matter dissolved from the soil and underlying rocks through which the ground water passes. The concentration of dissolved constitutents in the surface water of the Missoula Valley is generally less than that of the ground water. The chemical quality of the water in the Missoula Basin was determined from the analyses of 21 samples of ground water and 12 samples of surface water (Table 3).

The maximum concentration of constituents considered important by the U. S. Public Health Service (1962, p. 7) for drinking water used on common carriers preferably should not exceed the concentrations shown in the following table.

Constituent	Concentration (ppm)
Chloride (Cl)	250.
Fluoride (F)	1.5*
Iron (Fe)	0.3
Nitrate (NO_3)	45.
Sulfate (SO_4)	250.
Total Dissolved Solids	500.

The only constituent in water samples from the area of investigation that exceeded the concentrations shown above is iron, and it exceeded the maximum recommended concentration in water from only three ground-water and two surface-water sources. Excessive concentrations of iron will cause staining of laundered clothes and plumbing fixtures.

Hardness of water is caused almost entirely by calcium and magnesium. As hardness increases, soap consumption for laundering increases, and incrustations accumulate more rapidly in boilers, pipes, and heating coils. Hardness of the ground water in the area of investigation ranged from 94 to 270 ppm and the water falls into the U. S. Geological Survey classification of hard to very hard. Total hardness of the surface water ranged from 44 to 212 ppm and the water is classed as soft to very hard.

The water is generally of good chemical quality and is suitable for most domestic, irrigation, and industrial uses.

SUMMARY AND CONCLUSIONS

Quaternary deposits, which are exposed over about 120 square miles in the Missoula Basin, have an aggregate thickness of about 400 feet, but do not exceed 300 feet in any single locality. They consist of unconsolidated lacustrine deposits and Recent alluvium including heterogeneous glacial detritus, varved clay, well-sorted alluvial sand and gravel, and a basal gravel that overlies Tertiary strata. Tertiary deposits are exposed over about 55 square miles of the basin. Sediments of Tertiary age are at least 3,000 feet thick west of Missoula, and may be as much as 13,000 feet thick. They consist of interbedded clay, silt, sand, and some gravel intercalated with beds of shale, coal, and some volcanic ash.

Ground water occurs in the pore spaces between the grains of the Quaternary and Tertiary sediments; some occurs in joints and fractures of the basement rocks. Water is added to the pore spaces by infiltration from influent streams, from irrigation water, and from precipitation. It is removed from the pore spaces by effluent seepage into streams, drains, springs, and seeps; by evapotranspiration; and by pumping from wells. The general direction of movement of ground water is southwest at a rate of less than 3 feet per day.

In areas of exposure, the Tertiary sediments yield only a few gallons per minute to wells.

---

*Where the annual average of maximum daily air temperature ranges between 53.8° and 58.3° F.

TABLE 3.—CHEMICAL ANALYSES OF WATER FROM THE MISSOULA VALLEY

[All analyses by Montana State Board of Health, unless otherwise indicated. Results given in parts per million.]

Location	Date of collection	Depth of well (feet)	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Total hardness ($CaCO_3$)	pH
12-19-18bb2	9 -3-63	300	....	....	0.12	37	10	7	170	9	0	0.2	0.0	150	132	....
12-20-11ab	9- 3-63	96	....	....	.48	31	13	2	153	7	1	0	0	120	132	....
13-19- 6ba	9- 3-63	80	....	....	.12	48	27	6	280	9	2	.3	1.1	262	230	....
13-19- 7cc	9- 3-63	....	....	....	.2	35	10	0	128	1	0	0	.7	128	127	....
13-19- 8dc	(a) 4-21-60	107	....	18	0	76	64	....	....	8	2	....	....	154	140	7.4
13-19-17ac1	9- 3-63	88	....	....	.08	51	23	0	174	11	6	0	3.5	166	220	....
13-19-17bc	(b) 10-30-62	212	....	9	.05	98	56	....	157	....	7	....	....	135	154	8.4
13-19-21dc	9- 3-63	104	....	....	0	55	15	0	180	31	1	.1	.2	194	200	....
13-19-30bd	9- 3-63	122	....	....	0	55	12	2	180	36	2	.1	1.8	210	187	....
13-19-32dd1	9- 3-63	84	....	....	0	59	20	0	225	28	3	0	8.3	236	230	....
13-20- 1bb	9- 3-63	215	....	....	0	22	10	3	110	3	0	0	0	94	94	....
13-20- 9bd	9- 3-63	39	....	....	.4	59	19	0	215	35	3	0	1.2	246	225	....
13-20-14bb1	9- 3-63	233	....	....	0	44	13	0	168	16	2	0	.9	170	165	....
13-20-35ba	9- 3-63	93	....	....	.12	59	20	0	210	34	3	.1	1.1	246	230	....
14-20- 7dd	9- 3-63	202	....	....	6.94	26	11	15	160	9	1	0.5	0.9	164	110	....
14-20-28ab1	8-14-63	259	....	....	.1	31	7	0	116	7	2	.4	0	148	105	....
14-21-13cd	9- 3-63	40	....	....	0	86	13	20	277	43	4	.1	3.4	326	270	....
14-21-13dc2	8-14-63	153	....	....	0	37	12	9	180	7	3	0	0	174	143	....
15-21-29da	9- 3-63	23	....	....	0	68	18	0	238	30	1	0	8.5	270	242	....
15-21-31ba	8-14-63	251	....	....	.04	35	7	28	192	3	3	.2	0	164	115	....
15-21-34da2	8-14-63	165	....	....	0	35	8	7	155	2	2	0	0	132	121	....
Bitterroot River at Buckhouse Bridge in NE¼ sec 1, T. 12 N., R. 19 W.	4-11-63	....	48	....	.3	16	3	8	49	5	2	0	.2	66	50	7.3
- - do - -	5-13-63	....	....	....	.16	9	3	8	55	4	2	.4	.1	66	33	....

Clark Fork at East Missoula in SW¼ sec. 14, T. 13 N., R. 18 W.	4-11-63	....	44	....	.34	42	15	3	110	50	4	.2	.4	190	167	....
- - do - -	5-14-63	....	....	....	.34	26	10	10	104	37	4	.1	.4	152	105	....
Clark Fork below American Crystal Sugar Co. in SW¼ sec. 17, T. 13 N., R. 19 W.	(b)10-30-62	....	....	14	.05	158	54	....	144	....	3.4	....	....	140	212	8.5
O'Brien Creek in SE¼ sec. 27, T. 13 N., R. 20 W.	8-14-63	....	74	....	0.04	40	12	2	177	3	2	0	0	178	149	....
Grant Creek in NW¼ sec 28, T. 14 N., R. 19 W.	8-14-63	....	58	....	.04	13	0	15	73	2	3	0	0	44	33	....
Deep Creek in NE¼ sec. 35, T. 14 N., R. 21 W.	8-14-63	....	83	....	.04	16	3	2	64	2	2	0	0	58	50	....
Mill Creek in SE¼ sec. 25, T. 15 N., R. 21 W.	8-14-63	....	60	....	0	25	6	0	95	4	2	0	0	88	88	....
Sixmile Creek in NE¼ sec. 12, T. 15 N., R. 22 W.	8-14-63	....	51	....	.1	48	4	2	160	5	2	0	0	136	137	....
Ninemile Creek in SW¼ sec. 28, T. 15 N., R. 22 W.	8-14-63	....	69	....	.2	18	3	5	67	6	3	0	0	76	55	...

(a) Nalco Chemical Co.

(b) Magnus Chemical Co.

Water availability from the Tertiary sediments that underlie the Quaternary is not known with certainty but could be important in the future. The Quaternary deposits are presently (1964) the most important aquifer in the Missoula Basin. Wells in this aquifer are generally less than 175 feet deep and yield from a few to 5,000 gpm. An average of about 15,000 gpm was pumped from the Quaternary deposits during 1963. More than 20,000 gpm, the peak pumping rate in 1963, could probably be withdrawn continuously from wells now being used without adversely affecting the water regimen of the area. Additional wells that will yield more than 1,000 gpm can be installed in parts of the basin without adversely affecting present withdrawals. The most likely areas for obtaining large yields from wells are the flood plain of the Clark Fork and the low terrace bordering the flood plain. Test holes should be drilled prior to the installation of industrial or irrigation wells.

About 30 million acre-ft of water is stored in the Tertiary and Quaternary sediments; about 8 million acre-ft is available to wells. The amount of water that is removed at any time will depend on well construction and pumping costs in relation to economic benefits obtained from the water. The seasonal change in ground-water storage is about 50,000 acre-ft, although the net change from year to year is small. There is a decrease in storage from July through March and an increase in storage from April through June.

The water is generally of good chemical quality and is suitable for domestic, irrigation, and industrial use.

REFERENCES CITED

Alden, W. C., 1953, Physiography and glacial geology of western Montana and adjacent areas: U. S. Geol. Survey Prof. Paper 231, 200 p. [1954].

Becker, H. F., 1961, Oligocene plants from the upper Ruby River basin, southwestern Montana: Geol. Soc. America Mem. 82, 127 p.

Bretz, J. H., Smith, H. T. U., and Neff, G. E., 1956, Channeled scabland of Washington—new data and interpretations: Geol. Soc. America Bull., v. 67, no. 8, p. 957-1049.

Brietkrietz, Alex, 1964, Basic water data report no. 1 Missoula Valley, Montana: Montana Bur. Mines and Geology Bull. 37, 43 p.

Chamberlin, T. C., 1888, Administrative report: U.S. Geol. Survey 7th Ann. Rept., 1885-86, chap. a, p 76-85.

Chaney, R. W., 1940, Tertiary forests and continental history: Geol. Soc. America Bull., v. 51, no. 3, p. 469-488

.... 1950, A revision of fossil *Sequoia* and *Taxodium* in western North America based on the recent discovery of *Metasequoia*: Am. Philos. Soc. Trans., v. 40, pt. 3, p. 171-262.

Clapp, C. H., 1932, Geology of a portion of the Rocky Mountains of northwestern Montana: Montana Bur. Mines and Geology Mem. 4, 30 p.

Davis, W. M., 1914, Sublacustrine glacial erosion in Montana [abs.]: Geol. Soc. America Bull., v. 25, p. 86.

Dobrin, M. B., 1960, Introduction to geophysical prospecting: 2d ed., New York, McGraw-Hill, 446 p.

Douglass, Earl, 1899, The Neocene lake beds of western Montana and descriptions of some new vertebrates from the Loup Fork: Montana State Univ. M.S. thesis, 27 p.

.... 1902, Fossil Mammalia of the White River beds of Montana: Am. Philos. Soc. Trans., new ser., v. 20, p. 237-279.

Eakins, G. R., 1951, Clay mineralogy of glacial Lake Missoula varves, Missoula County, Montana: Montana Univ. thesis.

.... and Honkala, F. S., 1952, Cenozoic history of Missoula Valley, Missoula County, Montana [abs.]: Geol. Soc. America Bull., v. 63, no. 12, pt. 2, p. 1361.

Emmons, W. H., and Calkins, F. C., 1913, Geology and ore deposits of the Philipsburg quadrangle, Montana: U.S. Geol. Survey Prof. Paper 78, 271 p.

Hammer, Sigmund, 1939, Terrain corrections for gravimeter stations: Geophysics, v. 4, p. 184-194.

Hanson, A. M., 1952, Cambrian stratigraphy in southwestern Montana: Montana Bur. Mines and Geology Mem. 33, 46 p.

Jacob, C. E., 1947, Drawdown test to determine effective radius of artesian well: Am. Soc. Civil Eng. Trans., v. 112, p. 1047-1070.

Jennings, O. E., 1920, Fossil plants from the beds of volcanic ash near Missoula, western Montana: Carnegie Mus. Mem., v. 8, no. 2, p. 385-450.

Kauffman, M. E., 1963, Geology of the Garnet-Bearmouth area, western Montana: Montana Bur. Mines and Geology Mem. 39, 40 p.

Konizeski, R. L., 1958, A Pliocene vertebrate fauna from the Bitterroot Valley, Montana, and its stratigraphic significance: Geol. Soc. America Bull., v. 69, no. 3, p. 345-346.

.... 1961, Paleoecology of an early Oligocene biota from Douglass Creek basin, Montana: Geol. Soc. America Bull., v. 72, p. 1633-1642.

REFERENCES CITED—(Continued)

................................, McMurtrey, R. G., and Brietkrietz, Alex, 1961, Preliminary report on the geology and ground-water resources of the northern part of the Deer Lodge Valley, Montana: Montana Bur. Mines and Geology Bull. 21, 24 p.

Langton, C. M., 1935, Geology of the northeastern part of the Idaho batholith and adjacent region in Montana: Jour. Geology, v. 43, no. 1, p. 27-60.

Lindgren, Waldemar, 1904, A geological reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho: U.S. Geol. Survey Prof. Paper 27, 123 p.

Long, W. F., 1951, Survey report on Grass Valley Drainage Project, Missoula County Soil Conservation District in Missoula County, Montana: U.S. Dept. Agriculture Survey Rept., 22 p.

Lowell, W. R., and Klepper, M. R., 1953, Beaverhead Formation, a Laramide deposit in Beaverhead County, Montana: Geol. Soc. America Bull., v. 64, no. 2, p. 235-243.

McLaughlin, K. P., and Johnson, D. M., 1955, Upper Cretaceous and Paleocene strata in Montana west of the Continental Divide, *in* Billings Geol. Soc. Guidebook, 6th Ann. Field Conf., 1955, p. 120-123.

Meinzer, O. E., 1923a, The occurrence of ground water in the United States, with a discussion of principles: U.S. Geol. Survey Water-Supply Paper 489, 321 p.

.... 1923b, Outline of ground-water hydrology, with definitions: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

Montana State Engineer, 1960, History of land and water use on irrigated areas and maps showing irrigated areas in colors designating the source of supply, Missoula County, Montana, parts 1 and 2: Helena, Mont., State Engineer's office.

Pardee, J. T., 1910, The glacial Lake Missoula: Jour. Geology, v. 18, p. 376-386.

.... 1913, Coal in the Tertiary lake beds of southwestern Montana: U.S. Geol. Survey Bull. 531-G, p. 229-244.

.... 1942, Unusual currents in glacial Lake Missoula, Montana: Geol. Soc. America Bull., v. 53, no. 11, p. 1569-1599.

................................1950, Late Cenozoic block faulting in western Montana: Geol. Soc. America Bull., v. 61, no. 4, p. 359-406.

Perry, E. S., 1933, Shallow wells as a source of irrigation water in Frenchtown and Camas Prairie Valleys, Montana: Montana Bur. Mines and Geology, Misc. Contr. 5, 8 p.

.... 1934, Physiography and ground-water supply in the Big Hole Basin, Montana: Montana Bur. Mines and Geology Mem. 12, 18 p.

Ransome, F. L., and Calkins, F. C., 1908, The geology and ore deposits of the Coeur d'Alene district, Idaho: U. S. Geol. Survey Prof. Paper 62, 203 p.

Ross, C. P., 1950, The eastern front of the Bitterroot Range, Montana: U.S. Geol. Survey Bull. 974-E, p. 111-175. [1952].

................................, 1963, The Belt Series in Montana: U.S. Geol. Survey Prof. Paper 346, 122 p.

................................, and Rezak, Richard, 1959, The rocks and fossils of Glacier National Park: The story of their origin and history: U.S. Geol. Survey Prof. Paper 294-K, p. 401-439.

Rowe, J. P., 1903, Some volcanic ash beds of Montana: Montana State Univ. Bull. 17, 32 p.

.... 1906, Montana coal and lignite deposits: Montana State Univ. Bull. 37, 82 p.

Sahinen, U. M., 1957, Mines and mineral deposits, Missoula and Ravalli Counties, Montana: Montana Bur. Mines and Geology Bull. 8, 63 p.

................................, Smith, R. I., and Lawson, D. C., 1958, Progress report on clays of Montana: Montana Bur. Mines and Geology Inf. Circ. 23, 41 p.

.... 1960, Progress report on the clays and shales of Montana, 1958-59: Montana Bur. Mines and Geology Bull. 13, 83 p.

.... 1962, Progress report on the clays and shales of Montana, 1960-61: Montana Bur. Mines and Geology Bull. 27, 61 p.

Schrader, F. C., 1911, Gold-bearing ground moraine in northwestern Montana: U.S. Geol. Survey Bull. 470-B, p. 62-74.

Sieja, D. M., 1959, Clay mineralogy of glacial Lake Missoula varves in Missoula County, Montana: Montana Univ. thesis.

Theis, C V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., v. 16, pt. 2, p. 519-524.

................................, Brown, R. H., and Meyer, R. R., 1963, Estimating the transmissibility of aquifers from the specific capacity of wells, *in* Methods of determining permeability, transmissibility, and drawdown: U.S. Geol. Survey Water-Supply Paper 1536-I, p. 331-340.

Umpleby, J. B., and Jones, E. L., Jr., 1923, Geology and ore deposits of Shoshone County, Idaho: U.S. Geol. Survey Bull. 732, 156 p.

U. S. Geological Survey, 1955, Compilation of records of surface waters of the United States through September 1950, part 12, Pacific slope basins in Washington and upper Columbia River basin: Water-Supply Paper 1316.

.... 1960, Surface water supply of the United States, part 12, Pacific slope basins in Washington and upper Columbia River basin: Water-Supply Paper 1716.

.... 1962, Surface water records of Montana.

U.S. Public Health Service, 1962, Drinking water standards: Public Health Service Pub. 956, 61 p.

Van Houten, F. B., 1952, Sedimentary record of Cenozoic orogenic and erosional events, Big Horn Basin, Wyoming, *in* Wyoming Geol. Assoc. Guidebook 7th Ann. Field Conf., 1952, p. 74-79.

Wallace, R. E., and Hosterman, J. W., 1956, Reconnaissance geology of western Mineral County, Montana: U. S. Geol. Survey Bull. 1027-M, p. 575-612.

THE MONTANA BUREAU OF MINES AND GEOLOGY IS A PUBLIC SERVICE AGENCY FOR THE STATE OF MONTANA. ITS PURPOSE IS TO ASSIST IN DEVELOPING THE STATE'S MINERAL RESOURCES. IT CONDUCTS FIELD STUDIES OF MONTANA GEOLOGY AND MINERAL DEPOSITS, INCLUDING METALS, OIL AND GAS, COAL, AND OTHER NONMETALLIC MINERALS, AND GROUND WATER. IT ALSO CARRIES OUT RESEARCH IN MINERAL BENEFICIATION, EXTRACTIVE METALLURGY, AND ECONOMIC PROBLEMS CONNECTED WITH THE MINERAL INDUSTRY IN MONTANA. THE RESULTS OF THESE STUDIES ARE PUBLISHED IN REPORTS SUCH AS THIS.

FOR FURTHER INFORMATION, ADDRESS THE DIRECTOR, MONTANA BUREAU OF MINES AND GEOLOGY, MONTANA COLLEGE OF MINERAL SCIENCE AND TECHNOLOGY, BUTTE.

1919