UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PRELIMINARY INVESTIGATION OF GROUND-WATER OCCURRENCES IN THE WELDON SPRING AREA, ST. CHARLES COUNTY, MISSOURI

BY Claude M. Roberts

With
Further Notes on Problems
of the Weldon Spring Area,
Missouri

By C. V. Theis

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

December 1951
Open-File Report 82-1008

This is an exact transcription of the original 1951 report (except for page numbers) and has not been reviewed for conformity with current U. S. Geological Survey editorial and policy standards and stratigraphic nomendature.

Albuquerque, New Mexico

June 1983

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PRELIMINARY INVESTIGATION OF GROUND-WATER OCCURRENCES IN THE WELDON SPRINGS AREA, ST. CHARLES COUNTY, MISSOURI

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INTRODUCTION

Purpose and Scope of the Investigation

At the request of the Atomic Energy Commission the U.S. Geological Survey conducted an investigation during October 1951 of ground-water occurrences in the area of the Weldon Springs Ordnance Works, Weldon Springs, Missouri. During World War II TNT was manufactured on this reservation, which now contains the abandoned processing structures left idle since that time.

The purpose of this investigation was to determine the ground-water occurrences and subsurface conditions controlling its movement as a prerequisite to the location and design of special structures contemplated by the Atomic Energy Commission.

This report contains data gathered from observations of ground-water occurrence, geologic conditions affecting its movement and the structural soundness of the rocks.

Methods of Investigation

Early in October 1951, C. V. Theis, of the U.S. Geological Survey, in charge of ground-water investigations made for the Atomic Energy Commission, and the writer visited the area and set up a program of field investigation. Later in the same month the writer returned and spent about two weeks investigating the area. Reconnaissance of the entire reservation was first undertaken and this was followed by more intensive-field investigation of smaller areas of particular interest, especially in the southwestern part of the reservation.

Data were first gathered on the types of rock and soil and the characteristic features and water-bearing qualities of each. A very thorough search was then conducted for all visible springs, seeps, caves, and sinks, and for wells, within the area. A study of the map locations of these features indicated the areas where more detailed field investigation was necessary. The structural features of the rocks were carefully observed and recorded and all evidences of action by ground-water or possible passages or channels for ground-water to use were noted. The writer was especially on the lookout for any appearances of beds of shale, as indications of possible barriers to ground-water movement. Water level measurements were made in a number of wells readily available for that purpose. Core drilling operations of the U.S. Engineers in the area were visited, and the materials inspected.

Previous Reports

Detailed reports on the geology and water resources of this region have not been published. Unpublished special reports were available, such as that by Fishel and Williams[1/], of the U. S. Geological Survey, and one by Dames and Moore[2/], consulting engineers. The Missouri Geological Survey and Water Resources Division has geologic and ground-water data in its files, consisting of records of well borings, quarrying activities, and observations of its staff members. These data have not yet been assembled in the form of a published report of the area. Test borings within the reservation are now being made by the U.S. Engineers, St. Louis District. Reports of the Missouri Geological Survey and U. S. Geological Survey covering nearby areas contain general information on the geological aspects of the region.

1/Fishel, V. C., and Williams, C. C., The contamination of ground and surface waters by liquid wastes from the Weldon Springs Ordnance Works, Missouri: U.S. Geol. Survey, War File unpublished rept., Washington, D. C., January 1944.

2/Dames and Moore, Borings, Project A-12 Plant 21, Hidden Valley, prepared for California Research and Development Company, San Francisco, Calif., June 25, 1951.

Acknowledgments

Acknowledgment is due a number of persons and agencies who contributed information and services. The files of the Ordnance Works were made available through Mr. Wiley Goad, who also served as guide. The U.S. Engineers and staff at St. Louis, Missouri were consulted on test borings in the south-west part of the area. The Missouri Geological Survey and Water Resources Division at Rolla, represented by Mr. John Grohskopf, were most cooperative and helpful in interpreting the stratigraphy, certain well logs, and the water-bearing zones in the area. Father J. B. Macelwane and other members of the Geophysics staff of St. Louis University were consulted on earthquake liability. Wells in the area have been drilled by Putnam Brothers, and before them by their father, of Wentzville, Missouri. Records to confirm and supplement data on hand were made available and information on water-well drilling and water horizons was readily given.

THE AREA OF INVESTIGATION

Location

The Weldon Springs Ordnance Works is in St. Charles County, Missouri, about 30 miles west of St. Louis. The reservation lies north of the Missouri River and west of U.S. Route 61, where the Daniel Boone Bridge spans the Missouri River.

Relief

Much of the land is high above the Missouri River. Steep cliffs, almost 200 feet high, rise abruptly from the river and narrow, steep valleys extend back into the upland region toward a divide that is between one and one-half and two miles north of the river. Beyond this divide the relief is more gentle, or rolling.

Drainage

The drainage patterns of streams on opposite sides of this divide differ. On the south side of this divide the valleys are narrow and short and the slopes are steep. On the north side of the divide the valleys are much wider and develop longitudinally along more gradual slopes to the northeast. Drainage off the divide to the south goes into the Missouri River and that to the north and northeast enters the Mississippi River. The base flow or dry weather flow of these streams is maintained by springs and seeps from the ground water.

Climate

The climate of the State is subject to much variation. Records of the U.S. Weather Bureau used in this report are for the period 1888 to 1949, inclusive. The mean annual temperature is 55.2° F., the lowest recorded temperature in the State was -40° F. in 1905 and the highest 118°F. in 1936. The annual mean precipitation for the period of record is 40.43 inches, with the lowest recorded precipitation being 25.86 inches in 1901 and the highest 55.53 inches in 1928. However, there is much variation from average conditions in the monthly records of a number of years.

GEOLOGY

Areal Distribution of Rocks

The surface of the region is almost entirely covered by unconsolidated materials, consisting of river alluvium, glacial drift, and residuum from rock weathering. The bedrock that underlies the region at slight depth is limestone, chiefly of Mississippian geologic age. Locally, it intersects the surface where erosion, quarrying, or road construction has exposed it. Limestone of Ordovician geologic age appears in surface outcroppings along the southwest border of the reservation. The geologic column for the area is shown in Table 1, page 5. the chief characteristics of each rock group have been compiled from field observations and general descriptions contained in the literature, 3/,4/,5/,6/.

Alluvium

The beds of all the streams are occupied by alluvial deposits of Recent geologic age. These deposits are composed of variable amounts of silt, sand, and gravel, derived from the loose rock mantle overlying the more solid

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3/Fenneman, N.M., Geology and mineral resources of the St. Louis Quadrangle: U.S. Geol. Survey Bull. 438, 1911.

4/Krey, Frank, Structural reconnaissance of the Mississippi Valley area from Old Monroe, Missouri, to Nauvou, Illinois; Missouri Bureau of Geology and Mines, 2nd series, vol. 18, 1924.

5/Moore, R. C., Early Mississippian formations of Missouri: Missouri Bureau of Geology and Mines, 2nd series, vol. 21, 1928.

6/Gleason, C. D., Underground waters in St. Louis County and City of St. Louis, Missouri: Missouri Geol. Survey and Water Resources, reprinted from Appendix V. 58th Biennial Report, 1935.

Table 1.--Characteristics of bedrock formations encountered in walls in the Weldon Springs area

Geologic age		Formation	Characteristics
Recent and Pleistocene		Soil and glacial drift	
Mississippian	Osage Group	Keokuk	Limestone; medium to coarse, more or less crystalline; bluish, gray or buff in color; cherty; stylolites common; fossiliferous, less massive than Burlington.
		Burlington	Limestone, usually coarse grainod; light gray to almost white, yellowish buff or deep brown in color; chert in nodules and bands at varying intervals; parts of formation dolomitic; styolites common; contains large amounts of fossil remains, crinoidal.
		Fern Glen	Limestone; granular, light bluish gray or slightly greenish, reddish mottled green, limy shale and greenish shale partings between limestone beds; near top thin bands of chert are numerous, lower part non-cherty fossiliferous, scattered fine crinoidal fragments.
	Kinderhook Group	Chouteau	Limestone; compact to medium grained, massive; bluish or buff colored, silico-magnesium, argillaceous, and thin shale partings; contains small calcite geodes, fossiliferous.
		Hannibal	Sandy shale, bluish green and massive sandstone, fine grained, soft. Shale and sand cemented by lime carbonate, weathers to rounded surfaces, clastic.
		Sulphur Springs	Three members recognized. Upper sandstone, the Bushberg; celitic limestone member, the Glen Park; lower member a dark shale, sandy, sometimes absent.
Ordovician		Kimmswick	Limestone; crystalline, massive bedded; gray to white in color; small amount of chert; fossiliferous, contains fossil Receptaculitids.
		Decorah	Shaly limestone to dense gray limestone very thin bedded.
		Plattin	Limestone; dense to lithographic; gray to white in color, small amounts of chert; fossiliferous.
		Joachim	Limestones; dolomite and dolomitic limestone, gray to tan or buff; shale seams and thin sand, no chert.
		St. Peter	Sandstone; white, locally cross bedded.

bed-rock, and contain much chert and other hard fragments from the weathered bedrock along the valley slopes. Along the banks and flood plains of the two major rivers, and extending on up the valleys of the tributary streams to the level of backwater, relatively thick deposits of river silt are found overlying coarse river sands and gravels, the result of surface-water floods within recent time.

Glacial deposits

The soil mantle on the upland region is composed of unconsolidated sediments from less than one foot to more than fifty feet in thickness. Glacial drift occurs at the surface in many places within the Reservation but is not continuous over the entire upland area. It is characterized by silt, clay, and gravel poorly sorted and relatively thin. At several localities a fine-grained structureless soil that resembles loess, a windblown deposit, was found below the glacial drift.

Residuum

The most conspicuous material comprising the soil mantle is the zone of weathered limestone residuum which lies directly upon and grades into the limestone bedrock beneath. This residuum is very clayey, contains much chert, and in the lower part there are fragments of rock that have not yet been completely converted to the reddish residual soil.

Consolidated Rocks

Mississippian rocks

The consolidated rock or bedrock of the region is all of sedimentary origin. The Reservation is underlain by limestone of Mississippian geologic age. The topmost Mississippian rocks consist of a series of conformable limestones which include the Keokuk-Burlington and the Fern Glen formations of the Osage group. The Keokuk-Burlington limestones are from 150 to 200 feet thick and are exposed in the steep cliffs along the Missouri River. Most of the rock exposures at or near the surface on the Reservation belong to this group of rocks, and all wells north of the Mississippi-Missouri drainage divide encounter or pass through them first just below the over-burden. The Fern Glen, likewise a limestone, is encountered next below the Burlington and is 25 to 75 feet in thickness. Beneath the rocks belonging to the Osage group is an older group of Mississippian limestones, the Kinderhook group, which includes the Chouteau limestone, the Hannibal formation, and the Sulphur Springs formation. The Chouteau limestone crops out in the southwest part of the reservation. The rock underlying the area drilled by the U.S. Engineers is the Chouteau limestone. It is exposed along the sides of Hidden Valley and in the old abandoned quarries just west of

Hamburg in the vicinity of the railroad spur to the Ordnance Works. The Sulphur Springs formation is limited to a thin layer of sandstone and some soft shale. It was first reported in a well boring at Hamburg and has been found in deep wells drilled at scattered intervals within the reservation. The deeper test borings of the U.S. Engineers are reported to have encountered about five feet of the Sulphur Springs formation below the Chouteau limestone at elevation 480 feet. In Hidden Valley just above the level of the stream bed at several places a thin sandstone and soft shale are found at about elevation 520 feet that resemble the material penetrated by the U.S. Engineers to the east. At the base of the limestone exposed in the first road cut on Route D D. going north from Route 94 the same beds are found again at about elevation 580 feet.

An unconformity marks the contact between the Mississippian and Ordovician, as there are no Devonian and Silurian rocks present in this area.

Ordovician rocks

The Kimmswick limestone is the first rock of Ordovician geologic age that is prominent in the region and crops out in Callaway Creek valley to the west of the area of this investigation. However, it is reported in the boring at Hamburg just below the Sulphur Springs formation as occurring at 460 feet elevation, and in the report of Dames and Moore on Hidden Valley the bedrock encountered is referred to as the Kimmswick limestone. The Kimmswick is about 100 feet thick in the area, as indicated by well cuttings identified by the Missouri Geological Survey. Other Ordovician rocks not exposed at the surface but encountered in drilling are, in descending order: the Decorah shale, about 50 feet thick; the Plattin limestone, about 100 feet thick; the Joachim dolomite, also about 100 feet thick; and the St. Peter sandstone. Deeper wells of the area end in the St. Peter, the exact thickness of which is not known but believed to be about 130 feet or more.

Structural Conditions

Regional relationships

The stratified rocks of the region have been affected by the Ozark doming and are part of a monoclinal structure which dips northeast. The axis of the structure is northwest-southeast. There are slight differences between the angles of dip of various rock units. Gleason[7/] gives the average rate as 55 feet per mile on the top of the St. Peter sandstone. Fishel and Williams[8/] report a dip at the rate of 70 feet and 75 feet per mile on the base of the Fern Glen or top of the Chouteau, using different combinations of well logs. Krey[9/] in Plate 1 of his publication, using the base of the

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7/Gleason, Charles D., op. cit., p. 5.
8/Fishel, V. C., and Williams, C. C., op. cit., p. 2.
9/Krey, Frank, op. cit., p. 5.

Burlington as a datum, shows a general dip of about 30 feet to the mile. All these independent calculations agree that the direction of dip is northeasterly. A generalized map, Plate 2, has been prepared from Krey's Plate 1, which shows the regional structural conditions and the position of the Cap au Gres fault to the northeast of the reservation.

Rock features

Folds

Minor folds are found in the rocks exposed in the cliffs along the Missouri and Mississippi Rivers, and along the streams and in road cuts.

Faults

The rocks in the area of the reservation show no evidence of faulting or movement since the time their present dip was imparted to them.

Joints

All the rocks examined in outcroppings are jointed. The limestones of the Burlington-Keokuk, the Chouteau, and the Kimmswick formations all have two distinct sets of joints. One set of joints trends northeast with variations between N30°E and N72°E. The other set of joints trends northwest and varies between N30°W and N65°W.

Solution channels

In the bedded limestones that crop out in the area and in drill cores and well logs, shale partings and chert layers are found. Caves and good sized holes are found at different levels in the limestones. Many of these openings are partially filled with loose clay and chert, others are quite empty and dry, and when within the ground-water zone they are either quite moist or contain water. A few sink holes were seen in the upland area on the north side of the divide.

The joint systems criss-cross one another and intersect the bedding planes in the limestones, affording excellent communicating channels for downward-moving water.

HYDROLOGY

The Alluvium

The alluvium in the small streams or creeks of this area is not a source of large quantities or dependable yields of ground water. The sediments in these stream beds are of variable thicknesses, loosely bound and poorly sorted. However, where small lenses of sand and gravel do occur, limited quantities of water are obtained. Farms along the stream banks get some water from shallow wells into the alluvium. These wells are not very dependable, and where the stream is intermittent in character many wells are dry at times.

Along the Missouri River beneath the flood-plain silts and the bars in the stream channels water-bearing sands and gravels are found that yield large quantities of water, especially when the water-bearing zones are hydraulically connected with the river so as to permit infiltration. The present water supply at the Ordnance Works comes from coarse water-bearing sands and gravels beneath layers of river silt in the area where Femme Osage Creek empties onto the flood plain on the north bank of the Missouri River. In this well field there are eleven gravel-packed wells, 18 inches in diameter, all about 100 feet deep and each with about 40 feet of screen. The logs of these wells show silt to a depth of about 20 feet, followed by some 80 feet of sand and gravel. A thin lens of blue clay is found near the bottom about 80 feet from the surface and bedrock at about 100 feet.

Analysis of the data from the seven-day acceptance test of February 1942 of ten wells in this well field indicates that when they were all operating the system produced about 40 million gallons daily, with drawdowns ranging from 10 to 24 feet. Specific capacities of these wells ranged from 100 to 200 gallons per minute per foot of drawdown, and averaged about 150. An additional well was placed into operation in the system after this test; no test data were available on it. This well is of the same size, depth, and construction as the others. For purposes of total yield of the well field an average value of specific capacity was assigned to it. The yield from these eleven wells is estimated to be about 49 to 50 million gallons daily, or about 34,750 gallons per minute of continuous operation. Pumpage figures have not been seen; however, men present on the reservation who worked in the water plant when the Ordnance Works was in full operation claim that from 48 to 50 million gallons of water was used daily, and it was all pumped from the eleven wells in the present well field.

Glacial Deposits

Accumulations of glacial sands and gravels containing various amounts of clay occur scattered over tha land surface on the uplands. Locally where these deposits are water-bearing the water in them is above the main water table and is referred to as perched water. Water is discharged from these deposits normally in the form of slow seeps. These deposits are of little importance as ground-water sources within the area of the reservation.

The Residuum

On top of the rock there has been developed a reddish-brown residual soil. This residuum is relatively thick at the tops of the hills and becomes thinner on the slopes and in the valley bottoms. In the top part, this soil is almost all clay and is very heavy and dense. Rainfall penetrates it very slowly. After a day of rain it was observed to be moist to as much as four inches below the surface. The clayey upper portion of this overburden grades into a heterogeneous mixture of clay, chert, and rock fragments, and water in the lower portions of this overburden is gradually discharged as slow seeps. These seeps are common on the valley sides where the rock outcroppings are covered with the residuum. In the valley bottoms above the levels of the present stream beds, the residual soil is much thinner and closer to the rock, therefore contains more chert and other fragments. Moist zones were encountered in many of the test holes drilled by the U.S. Engineers along the lower side of the valley slope just above the bedrock and just before the water-bearing formation was penetrated. This residuum is not a ground-water source. However, it does permit some infiltration and downward movement of water into the rocks beneath it.

In Consolidated Rocks

Mississippian-Ordovician rocks

For all practical purposes, the consolidated rocks can be treated as a single hydrologic unit. This approach seems to be sound, in view of the fact that there is no evidence, either in the field or in the literature, that impervious shales occur between the limestone-members to act as barriers, and to prevent the movement of ground-water from one limestone to another. All rock wells drilled in this area, irrespective of depth, appear to have accordant water levels, and thereby to indicate a single water body.

Springs, sinks, and seeps are found in the Mississippian limestones on the sides and in the bottoms of the valleys to the south of the main divide. In Hidden Valley spring 10 (plate 3) flows from a cave in the limestone at an elevation of 589 feet and feeds a small tributary that enters Little Femme Osage at about elevation 530 feet. This spring contributes its flow to that of the main stream and then downstream about 1,000 feet from this point disappears into the rock in the bed of the stream at about elevation 520 feet, leaving a dry streambed downstream. Farther downstream, spring 4 (plate 3) is encountered at an elevation of 484 feet. It flows into a pool covered with watercress and disappears, probably into the rock beneath. About another 1,000 feet downstream, spring 2 (plate 3) comes from a large joint in the limestone at an elevation of 477 feet. This spring and numerous seepages feed the stream that joins Femme Osage Creek. Seeps are numerous beneath the overburden where the underlying rock is close to the surface. Discharge of water from the rocks and reentry back into the rocks at progressively lower levels in the valleys of this area accounts for their intermittent character. When the flow in the stream channel is continuous or perennial, the stream is fed by the main water table. The lower courses of these streams are perennial in character.

This downward movement of water through channels produced by the intersection of joints, along bedding planes, chert zones, and porous seams to the main water table within the limestones was found in the other valleys both to the east and most of Hidden Valley on the south side of the main divide.

The Kimmswick limestone of Ordovician geologic age appears to be the rock encountered in the bottom of Hidden Valley. This limestone is fed by ground water moving from the Chouteau and other Mississippian limestones above it. Water-bearing joints, fracture zones, and solution channels are encountered at considerable depths below the surface of the water table in wells drilled into the rock.

The yield of a rock well may fall off with the lowering of the water table and the well may even go dry as the water table falls in dry seasons.

The Water Table

Water-level observations

Measurements made by the writer of depth to water in available wells are recorded in Table 2, page 12. Comparisons can be made with observations made in these same wells by Fishel and Williams[10/] at the time of their investiagion in January 1944.

The water levels reported by Dames and Moore[11/], in borings made in Hidden Valley; those recorded by the U.S. Engineers in borings made in the valley to the east; the static water levels in the ten supply wells of the Ordnance Works' water supply; and additional data obtained from the driller's records of water levels in private wells at the time of drilling are all recorded in Table 2, page 12. The locations of all water-level observations are shown on Plate 3.

10/Fishel, V. C., and Williams, C. C., op. cit., p. 2.

11/ Dames and Moore, op. cit., p. 2.

Table 2.--Miscellaneous hydrologic data[a]

No.	Description	Owner[b]	Depth of well (feet)	Altitude of top of casing (feet)[c]	Altitude of water surface (feet)[c]	Date
77	well	Wm. Kaut	120			
78	boring 6	Dames and Moore[d]	49	518.6	499.6	May 16, 1951
79	do 10	do	42	521.4	501.9	May 17, 1951
80	do 11	do	53.5	504.1	495.6	May 17, 1951
81	do 12	do	40	512.5	500.7	May 18, 1951
82	do 13	do	64.5	517.9	498.1	May 16, 1951
83	do 14	do	14	588.2	579.0	May 25, 1951
84	do 15	do	45.5	555.7	530.7	May 25, 1951
85	well	Osage Femme Hunt Club	127	465	453	1923
86	Spring 13				520	
87	do 14				515	
88	do 15				525	
89	boring A-1	U.S. Engineers[e]	46.5	506.4	500.8	July 22, 1951
90	do A-4	do	15.4	518.1	512.9	July 31, 1951
91	do A-16	do	30.1	519.9	512.7	Aug. 16, 1951
92	do A-20	do	33.7	526.4	517.6	Aug. 28, 1951
93	do A-42	do		512.9	509.0	Nov. 5, 1951
94	well		440	600		
95	do 1	Ordnance Works[f]	105	461.8	439.6	Feb. 12, 1942
96	do 4	do	110	461.3	438.3	Feb. 12, 1942
97	do	P. H. Zeyen	170	670	610	1912
98	do	Pearl Cameron	194	670		
99	do			655		
100	do	Catholic Boy Scout Camp	112	480	450	

a/ Additional data to Table 1, given in report of Fishel and Williams.[14]

b/ All wells and springs are on U.S. Government property.

c/ Measured altitudes are in feet and tenths. All other altitudes are estimated.

d/ Selected borings from report of Dames and Moore.[15]

e/ From boring data by U.S. Engineers for Atomic Energy Commission, July - December 1951.

f/ Selected wells from well field of Weldon Springs Ordnance Works.

14/ Fishel, V. C., and Williams, C. C., op. cit., p. 2.

15/ Dames and Moore, op. cit., p. 2.

Slope

The slope of the water table on the north side of the main divide is shown on Plate 3. This slope is toward Dardonne Creek, the main stream that receives the drainage off the surface slopes on the north. The water table on the south side of the divide is not well defined because of the small number of observations and the close proximity of borings to one another in areas of limited extent and only slight topographic differences. However, the slope of the water table south of the divide is indicated using those scattered points of observations.

Configuration

The configuration of the main water table should roughly coincide with the topography of the land surface. Where the surface slopes are steep the gradient on the water table should increase and reasonable correspondence between the two should likewise follow where the land surface slopes are more gradual. This correspondence in configuration is found on the north side of the divide and is shown on Plate 3. The same relationship is believed to exist on the south slope but because of lack of sufficient data to definitely outline it in detail comparable with the variation in topography, it cannot be shown.

Chemical Quality of Water

The chemical quality of the ground water from the several sources described in this report is not known, because records of analysis that have been made of the well water in this area were not available at the time of this investigation. The ground water from shallow wells should not be as highly mineralized as that from the deeper rock wells. However, this depends upon the rock materials with which the water comes into contact and the amounts of various dissolved salts that are added to the water in its underground movement. The hardness of the water from the several ground-water sources which are chiefly in the limestones should vary only slightly.

OTHER PROBLEMS IN AREA INVESTIGATED

Earthquake Liability

In the upper Mississippi Valley around St. Louis, Missouri, earthquakes have been felt and recorded since settlement by white men. The earthquake of December 16, 1811 near New Madrid, Missouri, was one of the 20 great earthquakes of known history.

Data on the earthquakes of the St. Louis region have been compiled by N. H. Heck[12/] and R. R. Heinrich.[13/] [14/]

In Table 3, page 15, the earthquakes of the St. Louis region have been listed to give an idea of the number that have been recorded, their frequency and intensity. In every case the disturbance originated deep below the surface and the epicenter was outside the immediate area of Weldon Springs. However, it will be noted that some earthquake centers have been recorded quite nearby, yet very little effect has been noted. The exact cause of an earthquake is difficult to determine and most of the earthquakes around St. Louis occur in the valley of the Mississippi River.

Father Macelwane and Ross Heinrich, of the Geophysics Department, Institute of Technology, St. Louis University, have studied the earthquakes of the St. Louis area and feel that they are becoming less frequent and diminishing in intensity. This is just an observation and not a fact, according to Father Macelwane. Fault regions are usually suspected when earthquakes occur with any frequency in the same general locality. A number of prominent faults and fault zones have been located and mapped beneath the Mississippi Valley in the vicinity of St. Louis. The Cap au Gres fault shown on Plate 2 is a very old fault that extends from Missouri into Illinois just north of the confluence of the Illinois River and Mississippi River and about 20 miles to the north of the area of this report. Another fault zone is known to exist in the region south of St. Louis, called the St. Marys fault. Others that may be significant are the St. Genevieve and Cottage Grove fault zones of Illinois. There are a number of other smaller faults in the area between the Eastern Interior Basin and the Ozark uplift, the two regional tectonic elements associated with earthquakes in this area. According to R. R. Heinrich, a fault zone is suspected in the deeper basement rocks underneath St. Louis and St. Louis County just across the Missouri River south of the Weldon Springs area.

The earthquake of June 29, 1947 gave St. Louis quite a jolt, and was felt in St. Charles County. Also, if the two shocks recorded recently at Defiance, Missouri, on September 2, 1949 and April 27, 1951, were really earthquake shocks, it is quite possible that the suspected fault zone under the southern part of St. Louis and St. Louis County is an active one.

12/ Heck, N. H., Earthquake History of the United States, Part I - Continental United States and Alaska, U.S. Dept. of Commerce, Coast and Geodetic Survey, Serial No. 609, revised 1947 edition, 1947.

13/ Heinrich, R. R., Contributions to the Seismic History of Missouri, Bull. Seism. Soc. Amer., vol. 31, pp. 187-224, July 1941.

14/ Heinrich, R. R., the Mississippi Valley Earthquake of June 30, 1947, Bull. Seism. Soc. Amer., vol. 40, pp. 7-19, January 1950.

Table 3.--Record of earthquakes near St. Louis

Date	Location	Intensity	Remarks
Dec. 16, 1811	New Madrid, Mo.	10	Damage very small, due to lack of inhabitants.
Jan. 23, 1812	do	10	Chimneys thrown down in St. Louis
Feb. 7, 1812	do	10	
April 11, 1818			A smart shock felt at St. Louis and Kaskaskia, Ill.
Aug. 14, 1827	New Albany, Ind.		The last of a series of slight shocks felt in St. Louis
June 9, 1838	St. Louis, Mo.	6	Threw down chimneys and was quite noticeable in upper stories of buildings in St. Louis; reported as severe in St. Charles, Mo.
Jan. 4, 1843	Memphis, Tenn.	9	At St. Louis people manifested terror, one chimney fell.
Feb. 16, 1843	St. Louis, Mo.		Shock felt.
Oct. 8, 1857	Illinois, near St. Louis	7	Largest buildings rocked, windows rattled, houses with walls 10 inches thick were affected by horizontal movement in St. Louis.
Aug. 17, 1865	Southeastern Missouri	7	In St. Louis furniture rocked and there were cracking sounds in houses.
July 25, 1871			Tremor felt throughout St. Clair County, Ill.
Sept. 25, 1876	Evansville, Ind.	6-7	Felt in St. Louis.
Nov. 18, 1878	Southeast Missouri	7	Felt in St. Louis.
Sept. 27, 1882	Southern Illinois	5	Shock felt in St. Louis and St. Charles, Mo.
Oct. 15, 1882	do	5-6	Slight shock reported at St. Louis and St. Charles, Mo.
Jan. 11, 1883	Memphis, Tenn.	6-7	Strong shock at St. Louis.
Feb. 4, 1883	Indiana and Michigan	6	Felt at St. Louis.
Aug. 2, 1887	Cairo, Ill.	5	Felt distinctly in St. Louis
Oct. 21, 1895	Charleston, Mo.	8-9	Four acres sank and lake was formed; probably hardest shock since 1812 quakes. Felt over 1,000,000 square miles.
Jan. 24, 1902	Missouri	6-7	Two strong shocks felt particularly in westen St. Louis.
Feb. 8, 1903	Southern Illinois	7	Sharp at St. Louis, explosive sounds were heard.
Nov. 4, 1903	St. Louis	6-7	Preliminary shocks.
Aug. 21, 1905	Southeastern Missouri	6	Old roof collapsed at St. Louis.
Dec. 10, 1907			Distinct shock felt in downtown St. Louis.

Table 3.--Record of earthquakes near St. Louis (continued)

Date	Location	Intensity	Remarks
Aug. 16, 1909	Southwest Illinois		Shock strong at Waterloo, Ill.
Oct. 23, 1909	Southeast Missouri	5-6	Felt at St. Louis.
April 9, 1917	East Missouri	6	Painter thrown from ladder at Granite City, Ill. Windows broken and plaster cracked in St. Louis region; shock ½ to 1 minute.
Sept. 8, 1921			Two shocks at Waterloo, Ill.
Oct. 9, 1921			do
Jan. 26, 1925			Shock, accompanied by loud sounds felt at Waterloo, Ill.
July 13, 1925			Several shocks felt at Edwardsville, Ill.
Dec. 23, 1930			Earthquake with center near Fern Glen in St. Louis County.
Nov. 16, 1933			Earthquake in St. Louis County near Grover, Mo.
Nov. 23, 1939	Griggs, Ill.	5	Strong earthquakes with intensity short of damage at Griggs and Red Bud, Ill.
Nov. 23, 1940	Waterloo, Ill.	6	Felt in neighboring States
June 29, 1947	Close to confluence of Meremac River and Mississippi River	6	Felt in St. Louis with good jolt. Strong enough around St. Louis and south to crack plaster. Felt in St. Charles County.
Sept. 2, 1947	Defiance, Mo.		At Defiance, Mo. shock houses, rattled glass; recorded on St. Louis seismograph. Could have been blasting; both shocks at 11:30 a.m.
Apr. 27, 1951	Defiance, Mo.		do
Sept. 19, 1951	Alton, Ill.	2	Earthquake between Alton and Edwardsville in Illinois. Noticed in St. Charles County, no damage done. Just east of Cap au Gres fault.

Probable Distribution of any Effluent in the Missouri River

The problem of how and at what rate contaminated effluent would move from Femme Osage Creek out into the Missouri River and what the course and rate of advance would be in the current of this river could not be studied at this time. All available data will be gathered as soon as this report is completed and the investigation can be resumed.

Radiometric Analysis of Water Samples

The determination of the radioactive background of the natural waters of the area will require water samples from the ground-water sources and of the streams for radiometric analyses. Details of a sampling program cannot be completed until the several sources are made available for samples through rehabilitation of existing unused wells, and a study made of the flow characteristics of the Missouri River in the vicinity of Femme Osage Creek and downstream to or beyond the Daniel Boone Bridge. This phase of the investigation will follow as soon as arrangements have been completed for making such observations.

CONCLUSIONS

Rainfall on the surface of the area is the source of the water that ultimately finds its way to the water-bearing zones in the rocks; into the gravel bodies in the alluvium in the stream beds; the glacial sand and gravel deposits on the upland, and the cherty portions of the residuum very near to the bedrock. Thus water in getting to the main water table may travel a very circuitous route before it reaches the zone of saturation.

On the upland perched water that occurs in the alluvium of the stream-beds and the glacial deposits is discharged mainly through seeps to the rock beneath or into the streams. Springs issue from cherty beds and open joints or solution channels in the Mississippian limestones that crop out in the valleys that have been eroded by the streams moving down the dip to the northeast toward the Mississippi River.

Springs and seeps also discharge water along the valley sides at different levels in the valleys that drain the slopes to the Missouri River. It is in the lower portions of these valleys where the formations at the bottom of the Mississippian geologic column crop out and the Ordovician rocks lie close to the surface.

The main water table is located in these rocks on both sides of the divide and slopes toward the stream bottoms in these valleys. Ground water, therefore, moves toward the streams and down the valley bottoms in the direction of the surface drainage. Springs, seeps, and wells in the upper part of the water body may diminish or increase in yield as the water table fluctuates and may even go dry. Those wells within the zone of saturation will have continuous yields. There is a hydraulic connection between the Missouri River and the coarse sands and gravels beneath the river silt in the well field of the Ordnance Works that permits infiltration and sustained high yields at maximum pumping rates, with comparatively small drawdown in the wells.

All wells drilled into the rock formations intersect the water table and are supplied by systems of inter-connecting joints, crevices, and solution channels in the rocks.

RECOMMENDATIONS

There are places within the area of investigation where additional geologic and hydrologic data would be of considerable value to determinations of ground-water occurrences, position of the water table, and the direction of movement of ground water. This is particularly the case in the valley areas on the south slope of the divide where the data available for the writing of this report are limited to small areas and are often lacking in detail.

Test wells drilled to determine the formation characteristics and changes from the surface down to the bottom of the deepest water-bearing bed on the south side of the divide would be of great use in solving some geologic and hydrologic problems. The samples from test drilling should be carefully studied and correlated. All water-bearing zones should be noted and measurements made of water levels. This will clarify the relationship between the water levels in the deeper water-bearing zones with that of the main water table. Water samples should be taken of each occurrence for a mineralogic analysis. If possible, current meter and temperature tests should be made in each test well to determine amount of flow and direction. These wells could be used later for other tests connected with the problem of contamination and direction of movement of contamination, and could be used as outpost wells upon completion of all tests. The number and exact locations of the test wells can be determined later.

All unused rock wells in the area should be placed in good condition so that observations of the water table can be made over an area as wide as possible. These wells likewise can be used as outpost wells.

Analyses should be made of water samples from all used and unused rock wells in the area for background count. Depths should be determined for all rock wells, by sounding if necessary.

FURTHER NOTES ON PROBLEMS OF THE WELDON SPRINGS AREA, MISSOURI

By C. V. Theis

GROUND-WATER MOVEMENT

The water in the limestones of the area has, in general, three possible localities of disposal: (1) the small streams in the immediate neighborhood, such as Dardenne Creek; (2) the Mississippi River; and (3) the Missouri River.

The water-table map by Fishel and Williams reproduced herewith (plate 3) indicates definitely that north of the surface divide between the Mississippi and Missouri Rivers, lying about 1½ miles north of the Missouri, ground water moves to the northeast; that is, in general toward the Mississippi River and in the area of the old Ordnance Reservation down the dip of the strata. However, the water-table contours indicate a trough along Dardenne Creek and consequently a slope of the water table toward Dardenne Creek in the area north of the creek, as well as in the area south of it. Hence the ground-water drainage of the area of the Reservation north of the Mississippi-Missouri divide is indicated by the piezometric contours to be toward Dardenne Creek. It should be noted that in the area north of the creek the ground water is moving up or against the dip of the rocks.

Inasmuch as water levels in few wells north of Dardenne Creek have been measured, and hence control for the water-table contours north of the area is not good, it is advisable to consider the relation of the ground water in the Reservation to the Mississippi River. Sufficient water-level altitudes in wells are available south of Dardenne Creek to establish a water level in wells along the creek of about 480 feet above sea level. The nearest point of emergence of this water in the Mississippi River is north-northeast of Weldon Springs in a great southward bend of the Mississippi (compare plate 2). Here, the water level of the river is at 420 feet. Hence there is available a total loss in head of some 60 feet in a distance of about 9 miles from Dardenne Creek in the Reservation to the Mississippi River. The average hydraulic gradient would be about 7 feet to the mile, whereas the observed hydraulic gradient south of Dardenne Creek is from 30 to 50 feet per mile. To emerge into the Mississippi River the ground water would have to rise across the bedding of the rocks which are dipping in that direction. This presumably would oppose some additional resistance to emergences into the Mississippi, although, inasmuch as probably only limestones are involved, probably not a great deal. However, the evidence of the few wells on which observations are available north of Dardenne Creek, and the very limited head available north of Dardenne Creek, and the very limited head available to move the water over a considerable distance to the Mississippi, indicate that all--or nearly all--the ground water of the area of the Reservation north of the Mississippi-Missouri divide is discharged into Dardenne and perhaps into other local creeks.

Few data are available on the movement of water south of the divide. The presence of springs on the little streams tributary to the Missouri indicates ground-water drainage to the Missouri. The water levels in the test holes drilled in Hidden Valley and in those drilled by the Corps of Engineers may represent in part perched waters, and represent also water levels measured at different times; but, insofar as these data are representative of the water table, the water levels show a downward trend in the direction of the Missouri and therefore to the same extent indicate movement of the ground water to the Missouri.

Probably the most conclusive evidence that ground water south of the topographic divide is tributary to the Missouri River is found in the altitude of the water table near the divide. Inspection of Plate 3 shows that wells near the divide range in altitude from 583 to 622 feet, indicating that any ground water found south of the divide beneath land-surface altitudes of, say, 580 feet must be tributary to the Missouri.

It may therefore be definitely stated that any waste entering the ground on the Missouri side of the divide at altitudes less than 580 feet would return to the Missouri River, unless forced under pressure into deep aquifers in which case other problems would be encountered. If consideration were given to pumping waste over the divide and disposing of it underground, much of the waste so handled most probably would discharge into Dardenne Creek, although, if inserted at depths through a cased well, it might move slowly to the Mississippi River.

The movement of ground water through limestone is more difficult to predict in detail than movement through sands and gravels. Movement through limestone occurs through enlarged joint planes and through solution cavities. Because of preferential directions of development of these features, the movement of water may be at an acute angle to the piezometric or water-table contours. For engineering purposes it must be assumed, until detailed information is available, that any contaminant in the ground water would follow a streamline course and be undiluted, but would follow a course that might be at an angle to the slope of the water table or other piezometric surface.

THE PRESENT WELL FIELD

Several additional points may be of interest regarding the present well field. As indicated in the body of the report (p. 9) the wells were very productive and should yield a continuous supply of 40 or 50 million gallons a day.

If the wells are pumped at this rate recharge from the Missouri River will be induced. The water pumped will be freed of silt, and probably of bacteria, by its passage through the alluvium acting as a filter bed, but it will follow to some extent the changes in temperature and chemical character of the river water. The season and other changes in these characteristics in the well water will lag behind the changes in the river water, and will not be as large. The amount of lag and the range of fluctuations will vary among the different wells, depending upon their respective distances from the river. If temperature and chemical character of the water are important factors in industrial processes carried on in the area and the full capacity of the well field is not needed, probably it will be possible to work out a schedule of pumping of the individual wells to minimize fluctuations in temperature and chemical character. Planned pumping tests of the indivudual wells probably would indicate the general features of such a schedule.

Finally, it would be noted that the cone of depression formed by the wells will tend to extend inland from the wells, and that water originating in the river will move to some extent to the inland sides of the wells before entering them. The amount of such movement will depend on the area of alluvium extending inland from each individual well and to a considerable extent on the water carrying characteristics of the limestone forming the bluffs behind the well field. Hence there is a considerable probability that waste that might be discharged into Femme Osage Creek would infilter, in part, to the ground water and be carried to the well field. Further, there is a probability that wastes entering the ground at either of the present drilling sites would be drawn to the pump field. If more detailed consideration is given to this area it is probable that a fairly elaborate investigative program would be warranted. Such investigations would include test-pumping of the production wells to determine the hydraulic characteristics of the alluvium, and of deeper test drilling to determine the water-carrying characteristics of the limestone formations near the manufacturing sites.

EARTHQUAKE LIABILITY

The New Madrid earthquakes of 1811 and 1812 are considered among the earth's most severe earthquakes. One of the two next most severe earthquakes listed for the general area was centered at Memphis, occurred in 1843, and had an intensity of 9 on the Rossi-Forrell scale; the other occurred at Charleston, Missouri (near Cairo, Illinois in 1895), had an intensity of 8-9, and caused the sinking of 4 acres of ground. These localities are near the head of the Mississippi embayment, extending from the mouth of the Mississippi to about the mouth of the Ohio River, which has been the site of extensive loading and unloading by deposition and erosion in the most recent parts of geologic time. It may be suspected that these severe and numerous earthquakes are associated with the embayment, but such speculation is too uncertain to warrant minimizing the earthquake hazard farther north.

The list of earthquakes on pages 15-16 of the report includes shocks originating much closer to St. Louis. In particular, the occurrences at Defiance, Missouri, in the last few years, are only about 5 miles upstream from the Weldon Springs site. Even if these were only blasting shocks at the quarries in the neighborhood of Defiance, the shocks were recorded on the seismograph in St. Louis and need consideration in engineering construction in the close vicinity of their origin.

The nearest known fault to the Weldon Springs area is the Gap au Gres fault, about 20 miles north of the area shown on Plate 2. No movement on this fault has ever been reported, although the extremely feeble shock (intensity 2) at Alton, Illinois, on September 19, 1951, may have originated on an extension of this fault.

No faults are known within the Reservation.

It seems apparent that there is no reason to expect earthquake effects to be localized in the Weldon Springs area, but that the nearness of the Reservation to the centers of some of the most severe earthquakes on the North American Continent demands adequate design precautions against rather severe earthquake shocks for all critical structures. Buildings should be founded on definitely solid bedrock and definite precautions should be taken against the presence of solution cavities or other zones of weakness in the limestone beneath structures.

COURSE OF LOCAL DISCHARGE INTO MISSOURI RIVER

The farthest downstream gaging station maintained by the U. S Geological Survey on the Missouri River is at Herman, Missouri, some 50 miles upstream from Weldon Springs. Over a 20-year record at this station, extending from August 1928 to September 1948, the average discharge was 69,170 cubic feet per second, the maximum average daily discharge was 577,000 cubic feet per second (April 28, 1944), and the minimum was 4,200 cubic feet per second (June 10-12, 1940).__/ The minimum flow recorded is therefore some 50 times larger than the maximum production of the present well field--assumed at 50,000,000 gallons a day.

The inlets of one of the St. Louis city water supplies and of the St. Louis County water supply are on Howard Bend, some 11 and 11½ miles downstream, respectively, from the Weldon Springs site, and on the opposite, or south side of the river. The river is controlled by jetties extending from both banks of the river to channelize the low flow of the river. The jetties will promote turbulence and mixing of water in the river. The extent of mixing at all stages of the river or the minimum mixing to be expected on the opposite side of the river at a distance of 11 miles forms a difficult problem. Further work will be done on this problem and the results given in a supplemental report.

__/Paulsen, C. G., Surface-water supply of the United States, Pt. 6, The Missouri Basin, 1948; U.S. Geol. Survey Water-Supply Paper 1116.

BACKGROUND RADIOACTIVITY

The sampling of waters from the Weldon Springs area has not been completed. Results of such testing will also be given in a supplemental report.

It is of interest to note that of samples of 33 large municipal water supplies tested for radium content, the radioactivity of the St. Louis water supply and of that of Omaha, Nebraska (also on the Missouri River) were exceptionally high. The radium content of the St. Louis water supply is given as 10.4×10^{-16} gms. radium per cc before treatment, and 0.13×10^{-16} after treatment; that of Omaha as 16.3×10^{-16} before treatment, and 0.66×10^{-16} after treatment. The highest tested elsewhere--at Wichita, Kansas (on the Arkansas River) was 2.42×10^{-16} and 0.66×10^{-16} before and after treatment, respectively. __/

RECOMMENDATIONS FOR FURTHER WORK

The body of the report presents recommendations for work to develop the geologic and hydrologic background of the area. These notes will call attention to probable problems in operation of the area and work necessary to elucidate some of the background.

If large quantities of ground-water are to be used for industrial purposes and if variations in temperature and chemical quality will be of importance, extensive and carefully controlled pumping tests of the supply wells should be made in order to determine the hydraulic characteristics of the aquifer. Temperatures and variations in chemical quality of the pumped water during the pumping should be determined. An extensive program of sampling of the Missouri River water, which will be tributary to the well field, to determine variations in chemical quality, should be undertaken. Such a program would provide an outline for operation of the wells, to minimize fluctuations in chemical and temperature characteristics of the water used in operation of the plant, and would provide basic data which will be needed in case the well field is extended at a later date. It would also indicate what hazard there may be of contamination of the water supply by wastes discharged at certain points.

In case discharge of waste into the ground north of the topographic divide is contemplated, or if for any other reason the details of ground-water movement in that area are needed, an extensive program of rehabilitation of existing wells, and probably of drilling additional wells at critical points, will be needed. Controlled test pumping of properly constructed wells would indicate some important features of ground-water circulation in the area. Probably for public-relation purposes, if for no

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Hursh, J. B., and Gates, A., Radium analyses of municipal water supplies, University of Rochester, Atomic Energy Project, Quarterly Technical Report July 1 September 30, 1951; UR-189.

more definite reason, the features of ground-water movement in the area north of the topographic divide should be worked out, in view of the possible settling of airborne radioactive materials upon the ground.

In view of the possibility of earthquake shocks, it would seem of importance to test the foundation rock of the construction area for the presence of possible large cavities or weak zones in the underlying limestones by deeper drilling, supplemented by seismic geophysical exploration. Such wells would also help in determining the underground drainage characteristics of the area.

Finally, a geological map, on a fairly large scale, of the area that will be involved in future operations will be almost necessary, to indicate local character of the surficial materials and local dips, fracture zones, and other structural features of the underlying limestones in order to intelligently choose burial grounds and other operational sites for the projected plant.

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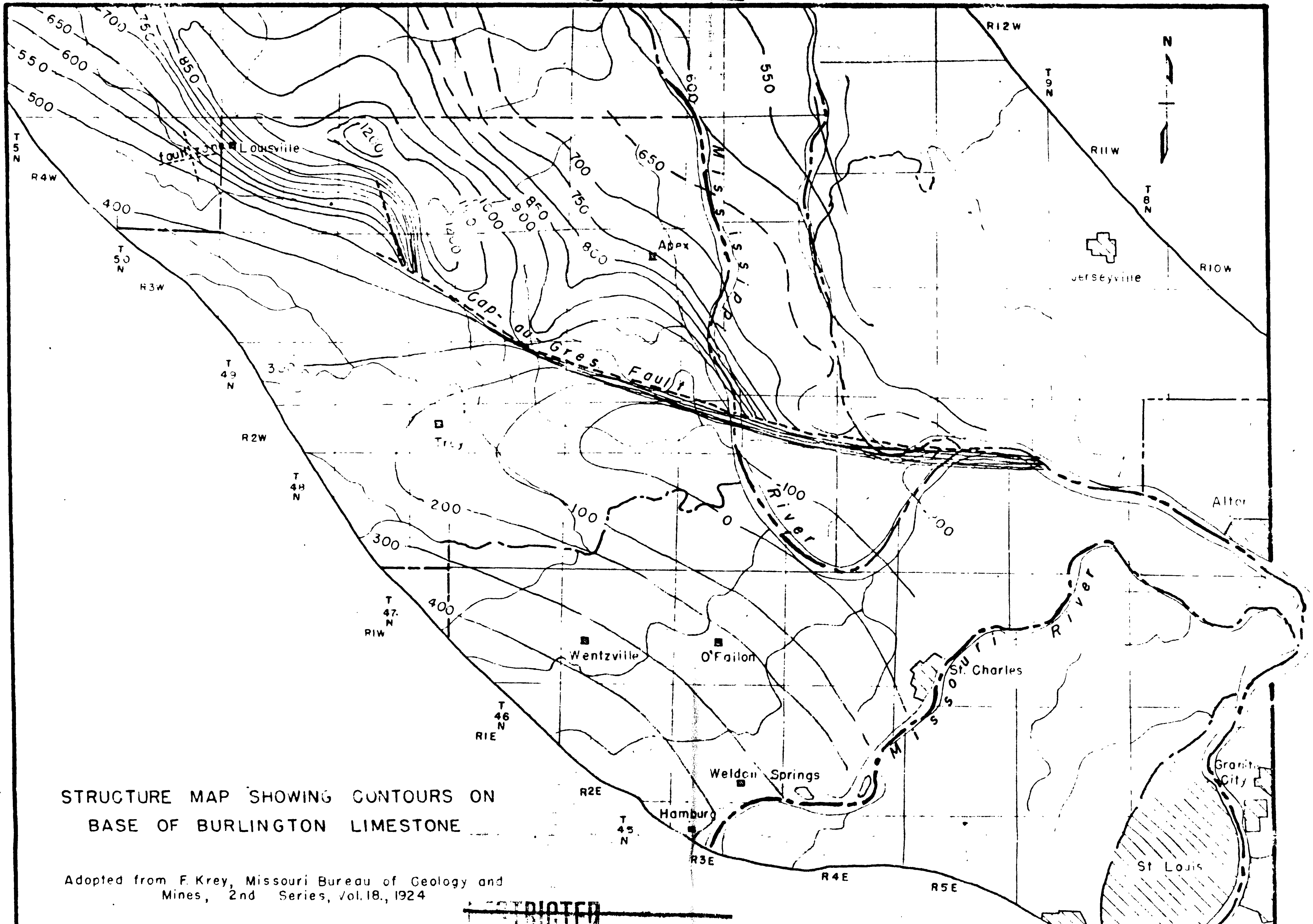
PLATE 2



STRUCTURE MAP SHOWING CONTOURS ON BASE OF BURLINGTON LIMESTONE

Adopted from F. Krey, Missouri Bureau of Geology and Mines, 2nd Series, Vol. 18., 1924

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