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A STUDY OF THE PIEZOMETRIC SURFACE
OF THE GRAND FALLS FORMATION
IN THE DUEWEK - ORONOGO MINING BELT
EAST OF JOPLIN, MISSOURI

BY

RENNY ROGER NICHOLS

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A
THESIS

submitted to the faculty of the
UNIVERSITY OF MISSOURI AT ROLLA
in partial fulfilment of the work required for the
Degree of
MASTER OF SCIENCE, GEOLOGY MAJOR

Rolla, Missouri

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ABSTRACT

The Joplin area of Missouri, which includes the Duermweg-Cronogo belt, was a famous zinc and lead mining district. Many mines were abandoned after World War I and filled with water. These provide a large potential supply of ground water. Expansion of industries and population in the area since World War II has caused a demand for water. In 1964, the Ground Water Branch, Water Resources Division, of the United States Geological Survey began a project to study the surface and ground water resources of the area. As part of his work on this project, the author measured the piezometric level of the water in the area's principal aquifer, the Mississippian Grand Falls Formation.

Piezometric levels were measured in mine shafts and wells. Additional information was obtained through interviews with drillers and well owners, and by studying records of well logs. A map of the Grand Falls piezometric surface, drawn by interpolating between points of known piezometric elevation, revealed troughs, highs, lows, and locally steep gradients. A structure contour map of the surface of the Grand Falls Formation by Smith and Siebenthal (1906) showed similar structural features in the same areas. The association of these features led to the hypothesis that geologic structure of the Grand Falls Formation affects the permeability of this formation and the configuration of the aquifer's piezometric surface.

The piezometric contour map indicates that the Grand Falls aquifer is only partially confined, and that it discharges mine water to Center Creek. Quantitative estimate of permeability could not be made from the data available. Concentrations of abandoned mines,
and an area of heavy pumping, affect the piezometric surface. Changes of the surface in the near future are expected to be small.
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ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to Mr. E. J. Harvey of the United States Geological Survey, Water Resources Division, Ground Water Branch, who first suggested this project. Dr. James C. Maxwell of the University of Missouri at Rolla was faculty advisor for this thesis, and I wish to thank him for his instruction, advice, and constructive criticism during this study. My thanks also go to Mr. Gerald L. Feder, Geologist, United States Geological Survey, with whom I worked in the Joplin area.

This investigation was partially financed through employment with the United States Geological Survey, Water Resources Division, Ground Water Branch, and by financial assistance from my mother, Mrs. J. R. Nichols.
CHAPTER I. INTRODUCTION

Statement of the Problem

The Duemweg - Oronogo area was famous as a zinc and lead mining region from about 1880 to 1918. During this time, extensive underground mine workings were opened, especially in the Duemweg - Oronogo mining belt. In the years following World War I, both population and zinc mining decreased rapidly. Many of the mines were abandoned. As they were abandoned, they filled with water. In the remaining active mines, bulwarks were erected to prevent flooding from the abandoned mines. After World War II, the remaining underground mines were closed and allowed to flood.

An increase in the manufacturing and chemical industries in the area since World War II has caused a sharp increase in the demand for water. Because of this, an evaluation of the water supply contained in the abandoned mines is needed for future development of this area. From interviews with mine owners and operators it was determined that most of the water in mines came from a single geologic unit, the Grand Falls Formation. Water from this formation rises above the level of the forma-
tion indicating that the Grand Falls aquifer is confined. An essential step in evaluating the supply of water in a confined aquifer is to determine the piezometric (pressure) surface of the water in the aquifer. This thesis is primarily a description of the determination and interpretation of the piezometric surface of the Grand Falls aquifer.
Mine Water

A large volume of water is apparently in storage in the mines in the Duenweg - Oronogo mining belt. An indication of the quantity of water involved is the pumping capacity of 53,000 gpm (118 cfs.) needed to dewater the mines during World War II (Harvey, 1964). Water obtained from these mines is of fair quality. Known contamination ranges from 300 to 1200 parts per million total dissolved solids (U.S.G.S. Specific Conductance Measurements, 1964). Although the quality of the mine water is too poor for municipal and domestic use, it is used by some industries after treatment.

Surface Water

There are two major streams which drain the Duenweg - Oronogo mining belt. Center Creek, which flows westward through the northern quarter of this area, is the main waterway. The mining belt is bounded on the southwest by Turkey Creek. The physiographic late maturity of these two streams is responsible for the extensive dendritic drainage pattern in the area. These streams both carry large quantities of industrial and municipal waste. Center Creek has a high concentration of dissolved minerals, at least part of which may come from mine water discharge.

Ground Water

There are three principal ground water aquifers in the Joplin area: the Grand Falls Formation, the Swan Creek Sandstone, and the Roubidoux Sandstone (see Figure 2 and Plates III & IV). The water which is used by the Joplin-Webb City municipal complex comes from
from aquifers deeper than the Grand Falls Formation, primarily the Roubidoux Sandstone. An industrial complex southeast of Prosperity, Missouri, obtains its water supply from mine shafts which penetrate the Grand Falls Formation. Most of the water in the mine shafts comes from the Grand Falls aquifer, with some water being supplied by direct rainfall into the mine shafts. In a 1964 United States Geological Survey report, it was assumed that ground water flowed through the mining belt from south to north and discharged into Center Creek.

Ground water supplies in the Joplin vicinity are obtained from wells 80 to 1300 feet in depth. The water is generally of good quality except where it is contaminated by mixture with mine water or by pollution from surface waters. Many deep wells were drilled for concentrating mills during the time when zinc mining flourished in the area, but most of these wells were plugged. However, the ones which were not located, or were inadequately plugged, are a continuing source of contamination for the aquifers beneath the Grand Falls Formation, primarily the Roubidoux Sandstone and the Swan Creek Sandstone.

Some of the towns shown on the location map (Figure 1), e.g., Duenweg, Carterville, Oronogo, Joplin, and Webb City, have deep wells which range from 800 - 1300 feet in depth. Water lines from these wells supply the immediate vicinity with water.

Scope of the Research

In the United States Geological Survey proposal (Harvey, 1964), entitled, "Water Resources of the Joplin area, Missouri," it was proposed that information concerning inflow of water to the area;
pumpage, movement of ground water; water in storage; transmission characteristics of the rocks; sampling of mine water, water wells, lakes, and streams, be gathered and assimilated. The Duemweg-Cronogo mining belt was chosen in which to map the piezometric surface of the Grand Falls aquifer as part of this United States Geological Survey project. The thesis investigation includes the piezometric surface map, stratigraphic cross sections, mine water hydrographs, and a structure contour map of the area. Flow directions, gradients, and piezometric features are discussed.
LOCATION MAP of the
DUENWEG—ORONO GO MINING BELT
EAST of JOPLIN, MISSOURI

FIGURE 1
CHAPTER II. LOCATION AND GEOLOGY OF THE
DUENWEG - ORONOGO MINING BELT

The Duenweg - Oronogo mining belt is in the Joplin area of Jasper County, Missouri. The area is approximately 45 square miles in extent, centered around 37° 8' North latitude and 94° 26' West longitude. The Joplin area lies on the more plateau-like, less dissected part of the western flank of the Ozark uplift.

Description of the Area

The topography of the Duenweg - Oronogo mining belt is essentially flat except for the area south and east of Webb City where hills rise twenty to thirty feet above the general ground level. The natural flatness of the whole area has been altered by many chat piles and mine dumps from five to fifty feet in height and up to several city blocks in areal extent.

The main highway in this area is U. S. Highway 66-71 which traverses the area from the west to the northeast. An extensive network of paved and unpaved roads follow section lines in the area.

Eighty to ninety percent of the land in this area is presently in farms. The main crops grown are corn, wheat, soy beans, and oats.

The average spring precipitation is 13 to 14 inches; the average summer precipitation is 12 to 13 inches; the average autumn precipitation is 11 to 12 inches; and the average winter precipitation is 5 to 6 inches. The average annual precipitation for this area is 43 inches. During the summer of 1964, the precipitation was 20 inches.
Figure 2 (a). View of a sixty-foot chat pile just north of Duenweg, Missouri. More chat piles not quite as high can be seen near the right edge of the picture. The picture was taken from the top of a thirty-foot mine dump.

Figure 2 (b). Rugged countryside characteristic of the Duenweg-Oronogo mining belt. Fifteen to twenty-five foot high mine dumps and chat piles can be seen in the background. This photograph was taken about 1\(\frac{1}{2}\) miles northwest of Duenweg, Missouri.
Figure 3. View of Oronogo Circle looking west from the eastern edge. The diameter of the Circle is about 300 yards; the pit, filled with water, is approximately 300 feet deep.
The average daily temperature for this area in January is 35 degrees Farenheit, and in July the average daily temperature is 78 degrees Farenheit.

**Geology of the Area**

The main geologic unit with which this thesis is concerned is the Grand Falls Formation, Mississippian in age. Its position in the stratigraphic column of southwest Missouri may be seen in Figure 4. The Grand Falls Formation is described in the *Stratigraphic Succession in Missouri* (Spräng, 1961) as follows:

"The Grand Falls formation is present only in southwestern Missouri and in adjacent parts of Arkansas, Oklahoma, and Kansas. It consists of finely crystalline, gray limestone and abundant amounts of chert. The chert is nodular and massively bedded and varies in color from white to gray to brown. Some of the chert which is brecciated and has a gnarly structure is widespread but does not appear to be confined to any particular stratigraphic horizon. Much of the chert when weathered breaks into sharp slivers. In this form the chert is commonly referred to as "butcher knife flint". In well cuttings, the chert has a smooth texture and is either tan or cream colored or mottled tan and cream.

The formation is 24 to 40 feet thick in its type area in western Jasper and Newton Counties where exposures are numerous. It is reported to be as much as 100 feet thick in other parts of the Tri-State district. The formation pinches out north of Springfield and thickens to 120 feet along the southern border of Missouri.

Discussion of the Grand Falls is complicated by the fact that there is no definite agreement that the cherty limestone succession beneath the Burlington limestone in the eastern part of southwestern Missouri is the same unit as that type section in Newton County where the Burlington limestone is absent. Some geologists
Mississippian System; Kinderhookian, Osagean, Meramecian, and Chesterian Series, and unassigned Devonian-Mississippian formations in southwestern Missouri.

Figure 4.

Source: Stratigraphic Succession in Missouri, Spreng, 1961.
regard the entire cherty limestone succession that lies between the Pierson and the Burlington in the eastern part of the area as the Reeds Spring formation, and some regard the lower part as the Reeds Spring. Those who believe that the entire succession is Reeds Spring interpret the Grand Falls as being a lateral facies of the Reeds Spring that is restricted to the Joplin area. Those that regard the unit as being composed of both formations usually designate it as Reeds Spring-Grand Falls..."

The Joplin area is located on the western flank of the Ozark uplift. Dip of the strata in the Duenweg - Oronogo mining belt is to the northwest. As can be seen on Plate II, the surface of the Grand Falls Formation has up to 80 feet of structural relief due to the configuration of the structural trends.
CHAPTER III. PREVIOUS STUDIES

There have been many papers written about the Joplin mining district, but these have been primarily concerned with the problems of the lead and zinc ores. Johnson’s Guidebook to the Geology in the Vicinity of Joplin, Missouri, (1963), gives clear, concise information concerning the geology of the area. Smith and Siebenthal (1907) describe in some detail the physiography, geology and metalliferous ores of the Tri-State Area. Their folio also includes geologic maps, topographic maps, and a structure contour map of the Joplin area.

In a later publication, Siebenthal (1915) advances the theory that the occurrence of lead and zinc deposits in the Joplin area were caused by a circulation system which flows horizontally from the Ozark Dome, in the St. Francois Mountain Area in the east, to the Joplin area and points west in Oklahoma and Kansas, and vertically upward, in southwest Missouri. Siebenthal bases his theory on these premises: that the Paleozoic sedimentary rocks on the western flank of the Ozark dome act as one homogeneous aquifer; that the Precambrian basement complex and the overlying Pennsylvanian shale act as aquicludes; that the source area for ground water in this aquifer is the St. Francois Mountains; that the ground water travels from the St. Francois Mountains to the Joplin area, a distance of about 250 miles; that under Joplin the ground water circulates upward beneath the overlying Pennsylvanian Shale; and that the minerals in solution are deposited in the fractured Mississippian limestones and dolomites. The criticism of this theory is that it is an oversimplification to
consider the Paleozoic sedimentary rocks in this area as a homogeneously permeable aquifer because relatively impermeable shales are included in the stratigraphic section in this area.

A publication by Robertson et al. (1963) contains a map of ground water areas, a map of ground water quality of deep aquifers, and a water well yield map for the entire state of Missouri. In this publication, Knight states that the aquifers in the Joplin area are comprised of sandstones, dolomites, and limestones and that the yields from these aquifers are unpredictable. Also available in this same publication is a compilation of data on public water plants of the state which includes well records for the Joplin area.

Recently, a geologic map of the Joplin area has been prepared by Mr. E. J. Harvey, District Geologists of the United States Geological Survey, Water Resources Division, Ground Water Branch, but has not yet been published.

Several measurements of specific conductance of mine and surface water in the Duenweg - Oronogo area were made by the United States Geological Survey during the summer of 1964. Results of these measurements are in the United States Geological Survey's Open File.
CHAPTER IV. PROCEDURES IN THE STUDY

In determining the piezometric surface in the Duxweg - Oronogo mining belt, as many water wells and mine shafts as possible were examined and located within and on the outskirts of the mining belt.

Selection of Measuring Points

The water wells were selected on the basis of several criteria. They had to be cased deeply enough so as not to be influenced by surface water such as the "dug wells" in the area, but they could not be so deep as to penetrate the Swan Creek Sandstone or the Roubidoux Sandstone because each of these deeper aquifers has its own piezometric surface. Another requirement which these wells had to meet was that it must be possible to measure their water levels. As most of the water wells in this vicinity had various types of pressure systems, and thus pump seals, it proved difficult to locate measurable observation wells in a predetermined pattern. Many exploration holes were drilled in this area in order to locate lead and zinc deposits, but these holes were plugged as part of a Works Progress Administration project during the 1930's.

Methods of Measurements

The water levels in both the mine shafts and water wells were measured in the same manner. A weighted steel tape was used with blue chalk applied to its surface so that as the tape was lowered into the water it would be easier to read the water mark on the tape. The weight at the end of the tape, which was usually a large lead sinker,
had to be replaced on occasion with a smaller weight in order to get it through small apertures in pump seals.

Many of the mine shafts in the area were badly caved and presented obstacles in trying to get close enough to their edges to lower the chalked steel tape to the water. On the mine shafts which were measured, a spot was painted on the edge of the shaft collar to mark the measuring point for future reference. An additional complication which arose in designating and referring to the mine shafts was that the names of the mines were not the same on different maps used to locate them.

**Other Sources of Ground Water Information**

In addition to measuring the water levels in the mine shafts, some water samples were taken by means of a tube type sampler. Water level recorders (Stevens Water Level Recorder Type A35) were installed over five mine shafts in the mining belt (Figure 5). These devices continuously record the water level fluctuations caused by rainfall, drought, earthquakes, and pumping in the area. The mine shafts over which water level recorders were installed are indicated on Plate I by a circle around the mine shaft symbols. The five shafts equipped with recorders are the Rhea, the Mont B, the McGregor, the Florine, and the Nowata.

Information was obtained from interviews with residents in the area as to what the water level had been in years past, what the water level was recently, and also any information as to excessive pumping in the area. This information from the residents was used to supplement the author's field observations.
Figure 5. This is one of the five Stephens Type A35 water level recorders installed on mine shafts in the area. The thin red object to the left of the wheel is a six-inch pencil. The planks at the base of the recorder cover the opening of the seven-foot square shaft. This recorder is operating on the McGregor mine shaft which is about one mile southeast of Webb City.
To safeguard against incorrect results, the information received from the residents was carefully checked against personal field observations. For instance, if a resident stated a certain water level figure, all available information in the immediate vicinity, such as other stated water levels and measured water levels, was used to determine if the information given was accurate. Some of the resident's water level information came from having their pumps "pulled" and examined in the past. If this took place within three to four months prior to the study, the data was adjusted with the help of the mine hydrographs and then used. These interview results are noted in Appendix A.

After the water level information was compiled, a piezometric map was drawn of this area by connecting the points of known water level with contour lines. The contour interval used was ten feet. The elevations of the mine shafts and water wells were taken from the United States Geological Survey topographic maps of the area (Webb City (1963) and Joplin East (1963) quadrangles). The elevations of the Nowata, Florine and McGregor mine shafts were determined by spirit levelling.

While the data to make a piezometric contour map was being gathered, geological information also was being gathered about the main aquifer in the area, the Grand Falls Formation. This aquifer is intersected by the mine shafts, or at least supplies ground water to the shafts. The Grand Falls Formation is a relatively permeable, extremely cherty limestone with a sequence of less permeable limestone aquicludes above and below it. Because the aquicludes are not highly
impermeable, the Grand Falls Formation is what is known as a "leaky" aquifer. That is, the water is not strictly confined to the aquifer and may, at places, rise above the aquifer. This phenomena is believed to be caused by extensive fracture systems in the limestones. Geologic information was gained from studying approximately 100 well logs on file at the Missouri Geological Survey located in Rolla, Missouri, and from talking to the local residents and water well drillers in the Joplin area. This information was used to draw the correlations of well logs of the area which are included as Plates III and IV.
CHAPTER V. DESCRIPTION OF THE PIEZOMETRIC SURFACE

The map of the piezometric surface of the Grand Falls Formation was drawn to indicate the height to which water from this aquifer will rise in this area, and to indicate directions of piezometric gradients. As can be seen from the map (Plate I), the major directions of gradient are from the west central portion of the area, outward, toward the north and east in a somewhat radial pattern.

Hydrographs

The hydrographs of the water level recorders on the five mine shafts in the area, Figures 6 - 10, show the following relationships. The rise of the water levels in these mine shafts closely approximate each other. However, the rate of recession of the water levels in the five shafts varied greatly. The water level of the Rhea mine shaft receded at the rate of two feet per 26 days. The water level of the Mont B mine shaft receded at the rate of two feet per 16 days. The water level of the McGregor mine shaft receded at the rate of two feet per 14 days. The water level of the Florine mine shaft receded very irregularly, but the rate of lowering was approximately two feet per 22 days. The water level of the Nowata mine shaft was also somewhat irregular, but receded at the rate of approximately two feet per 33 days. The difference in the rates of rise and fall of the water levels of the five mine shafts is probably caused by a variety of factors.

The mine shafts in this area have been subject to caving in the past. Trash has also been dumped into these mine shafts, and this
Figure 6. Hydrograph for RHEA SHAFT - Maximum Level of Day (1964)
Figure 7. Hydrograph for MONT B SHAFT - Maximum Level of Day (1964)
Figure 8. Hydrograph for McGREGOR SHAFT - Maximum Level of Day (1964)
Figure 9. Hydrograph for FLORINE SHAFT - Maximum Level of Day (1964)
Figure 10. Hydrograph for NOWATA SHAFT - Maximum Level of Day (1964)
Figure 11. Precipitation - 1964
practice still continues. The exact volumes of the shafts and their drifts (lateral mine openings) are unknown. The only factor which is known accurately is the water level of these five mine shafts. The caved material which has sloughed off of the walls of the shaft, the trash which has been dumped in, and the location of the drifts, are all hidden from view by the water in these mine shafts. The water levels stand above this material. The cross-sectional areas of the mine shafts are approximately the same from the water levels to the ground surface. At the time of precipitation, the water which raises the water level in the shafts is presumed to be direct surface seepage into the shaft which is a much more direct form of recharge than is percolation of precipitation down through the limestone to the ground water level. Therefore, the rate of rise in water levels of the five mine shafts would be approximately the same, as precipitation would cause similar rates of rise to take place when the receiving areas for the precipitation are similar. The recession of water from these mine shafts depends on the ability of the mine shafts' underground environment to disperse this new supply of water into regular avenues of flow. This ability of the shaft depends on the depth of the main shaft, the drifts, and the volume of water (storage space) which they can hold. Other factors affecting the recession of water in mine shafts are permeability (which undoubtedly varies) of the rocks in the area, permeability barriers erected during mining periods, such as bulwarks to keep out water when the shafts approached the Grand Falls Formation, and the amount of percolation, if any, down to the aquifers below the Grand Falls Formation.
Areas of the Piezometric Surface

The following description of the configuration of the piezometric contours of the piezometric surface of the Grand Falls Formation has been sectionalized into parts corresponding to areas located on the map.

Part A -- Center Creek Area

This area is adjacent to Center Creek and encompasses its flood plain. In the interpretation of piezometric elevation illustrated in Plate I, it is assumed that ground water in the Grand Falls aquifer is hydraulically connected with Center Creek. In this interpretation or hypothesis, topographic elevations on Center Creek are used in determining the location of piezometric contours. An alternate hypothesis is illustrated in Figure 12. In the alternate hypothesis the location of piezometric contours is interpolated from elevations of water levels in wells only. Figure 12 shows that in the alternate interpretation, the 880 and 890 foot contours are shifted south of Center Creek, which would imply that the Creek might supply water to the aquifer.

Part B -- Trough Northwest of Carterville

The configuration of the 910, 920, and 930 foot piezometric contour lines in sections 8 and 17 of T 28 N, R 32 W, suggest a very shallow north-northwest trending trough.

Because flow directions is perpendicular to piezometric contour lines, there must be some convergence of flow toward the trough. This may be the path taken by most of the water from the extensive mine
FIGURE 12
ALTERNATE HYPOTHESIS FOR CENTER CREEK AREA
RENNY R. NICHOLS

CONTOUR INTERVAL 10 FEET, SEE PLATE I FOR LEGEND
SCALE 1:24000
workings in sections 3 and 17 of T 28 N, R 32 W, as it flows northward and discharges into Center Creek, the primary stream valley in this area.

There is a tributary to Center Creek which flows along the axis of this piezometric trough (See Figure 13). The elevation of this tributary at the south edge of section 3 is 929 feet. Leakage from the Grand Falls aquifer to this tributary possibly controls the elevation of the piezometric surface at the head of the shallow piezometric trough. Although the tributary stream was mapped by the U.S.G.S. as having perennial flow, the stream bed was dry in the summer of 1964. Pumping from the Halbert domestic well (labelled H on Plate I) in the south half of section 5 of T 28 N, R 32 W, has caused a slight cone of depression in the piezometric surface.

Smith and Siebenthal's structure contour map of the surface of the Grand Falls Formation (1906) shows up two structural features in this area. A NE-SW elongated structural basin formed by the surface of the Grand Falls Formation is found in section 17, T 28 N, R 32 W. The western edge of this structural low becomes a trough or a plunging syncline as it extends northward into sections 8 and 5 of T 28 N, R 32 W. This structural trough, or low, is bounded on both the west and east by structural highs.

Part C -- Southwest of Carterville

A recharge area is suggested by the apparent piezometric "bench" or relatively high and level piezometric surface, in the western portion of this area (sections 19, 30, of T 28 N, R 32 W). According to Siebenthal's structure contour map of the surface of the Grand Falls
Formation (Plate II), a structural dome, or high, occurs here, also. A piezometric high, higher than the piezometric bench described above, was found to occur in sections 31 and 32, T 28 N, R 32 W.

As field data to control piezometric contour lines is at a minimum in this area, it is impossible to tell if these two piezometric highs are connected or whether there is a piezometric low separating them. On Siebenthal's structure contour map of the Grand Falls Formation there is a structural high in sections 31 and 32 of T 28 N, R 32 W, and another in sections 19 and 30 of T 28 N, R 32 W, with a structural low separating them. This indicates an association between the piezometric surface and the underlying structural trends of the surface of the Grand Falls Formation. The piezometric highs in this recharge area will be maintained if no change in permeability or recharge occurs.

In the remaining sections of this area (sections 20, 21, 22, 27, 28, and 20 of T 28 N, R 32 W), the water is seen to follow a pattern of eastward radial flow. These central sections of this area have been extensively mined and an intricate network of underground tunnels and drifts are undoubtedly traversed by flowing water. Because the distance between the piezometric contours locally increases, a less steep gradient is indicated, showing that permeability boundaries are apparently at a minimum in this area. Pumping is known to have occurred in the George H shaft in section 28, but this pumping has been of an intermittent nature and shows up only on the hourly hydrographs of the Florine and McGregor water level recorders.
Part D -- Southern Quarter

By far, the steepest gradients shown on the map of the piezometric surface are in this area. There is a curvature, or a nosing configuration, of the piezometric contour lines indicating a piezometric high in sections 31 and 32 of T 28 N, R 32 W. There is an apparent association of this high with the underlying structure, as the northeast quarter of a crescent-shaped dome is shown in this area on the structure contour map of the surface of the Grand Falls Formation (Plate II).

Immediately east of this piezometric high, a nearly parallel group of east-west trending piezometric contour lines occurs in sections 32 and 33 of T 28 N, R 32 W. The steep gradient shown by these piezometric contour lines indicates a permeability barrier in this area. The structural feature underlying this parallel group of piezometric contour lines is a structural low in the east one-half of section 32 and the west one-half of section 33 of T 28 N, R 32 W.

There is an abrupt change in direction of the piezometric contour lines from almost east-west to northwest-southeast in sections 3 and 4 of T 27 N, R 32 W. This change is apparently associated with a N-S elongate dome shown in sections 33 and 34 of T 28 N, R 32 W, and sections 3 and 4 of T 27 N, R 32 W, on Plate II.

Part E -- Southeast of Prosperity

The piezometric contour lines in sections 26, 27, 34, and 35 of T 28 N, R 32 W, and sections 2 and 3 of T 27 N, R 32 W, form an arcuate pattern which may be a part of a circle, but with only the northwest part of the circle shown. The center of this presumed circle would be
about two and one-half miles southeast of Prosperity. The piezometric
gradient is southeastward toward this center.

There is an individual complex located at the common corner of
sections 35 and 36 of T 28 N, R 32 W, and sections 1 and 2 of T 27 N,
R 32 W. The industries in this complex have been pumping water from
the mine shafts in sections 34 and 35 of T 28 N, R 32 W, and sections
2 and 3 of T 27 N, R 32 W. Mine shafts from which this industrial
complex pumps water are not accessible for measurement.

The structure of the Grand Falls Formation underlying this south-
eastern area dips northwest which is opposite to the southeasterly slope
of the piezometric surface. The only known factor which may control
this southeasterly slope is the large volume of water pumped in this
area.

Through interviews with the residents in this area, it was
established that water levels had dropped noticeably in this vicinity
since the initiation of this pumping of mine water for industrial use.
This was corroborated by information that within the last two years,
many residents in the area have had to deepen their wells to obtain
an ample supply of water. A drought condition which existed in the
Joplin area for two years prior to the summer of 1964 also may have
affected the local drop in water levels.
CHAPTER VI. ANALYSIS AND CONCLUSIONS

The Grand Falls piezometric surface in the Duenweg - Oronogo mining belt is irregular. Many factors, known and unknown, play a part in determining this surface. Some established controlling factors are: the variabilities of permeability and porosity; pumping in any particular vicinity in the area, or outside it; storage capacities of the mine shafts and their drifts; the extend of structural deformation such as faulting, folding and fracturing and its controlling effect upon the secondary permeability of the Grand Falls aquifer and the formations overlying it. The effect of these factors is considered in the following analysis.

Flow to Center Creek

Ground water flow in the vicinity of Center Creek can be analyzed from a comparison of the piezometric map (Plate I) and the map of an alternate hypothesis (Figure 12). Because lines of flow are perpendicular to piezometric contour lines (Todd, 1961, p. 66), it can be seen that according to the interpretation shown in Plate I, Center Creek is an effluent stream. According to this interpretation, ground water supplies the creek with a quantity of water. The water enters the flood plain and is discharged into Center Creek. Wide spacing of piezometric contours indicates higher permeability. There is little mining along the flood plain and thus there is less chance of bulwarks having been erected to cause permeability barriers. With sustained flow of ground water to or from the creek the channels of flow of the
ground water may have been enlarged, allowing easier passage of water.

An alternate interpretation of the field data is shown by the piezometric contours of Figure 12. With this configuration of the piezometric contours, Center Creek would supply surface water to the ground water as shown in sections 4, 5, 8, and 9 of T 23 N, R 32 W. Measurements (U.S.G.S., 1964) have shown that mine and well water in the area has a higher specific conductance than the water in Center Creek. The mine water is a principal source of ground water in the Grand Falls aquifer. If this ground water entered Center Creek, it would raise the specific conductance of the Creek water. The specific conductance of Center Creek has been measured northeast of Carterville and just west of Cronojo Circle, and has been found to increase over this reach of the Creek. Therefore it is concluded that Center Creek is an effluent stream and the Grand Falls aquifer does discharge to Center Creek. Thus the hypothesis, illustrated in Figure 12, that Center Creek discharges to the aquifer, is rejected. The hypothesis illustrated in Plate I is believed to be correct.

Flow through Overlying Strata

The Grand Falls Formation is believed to be a semi-confined or "leaky" aquifer. It was found through interviews with water well drillers and the local inhabitants of the Joplin area that most drilled water wells are "dry holes" until they go through the Burlington-Keokuk Formation and intersect the Grand Falls Formation, locally called "sheet ground" or "blue flint", at which point water flows into the hole and rises to the piezometric level of the Grand Falls Forma-
tion. However, some wells are drilled which obtain an ample supply of water before reaching the Grand Falls Formation and so are completed somewhere within the Burlington-Keokuk Formation. The water level in these Burlington-Keokuk wells corresponds to the piezometric surface of the Grand Falls Formation, as can be seen in the Blair well (Burlington-Keokuk) adjacent to the Roy well (Grand Falls) (see Appendix A for locations). From this information it is assumed that water from the Grand Falls aquifer is supplying Burlington-Keokuk wells. For this to occur, water must "leak" upward from the Grand Falls Formation into the Burlington-Keokuk Formation. Also, water may "leak" laterally from Grand Falls wells into the adjacent territory where Burlington-Keokuk wells are drilled.

The Grand Falls Formation lies approximately 120 feet below Center Creek according to Plate II. If Center Creek is an effluent stream, it must intersect the "water table" of the Grand Falls Formation in order to secure water from it. The elevation of Center Creek seems to control the elevation of the piezometric surface of the Grand Falls Formation. It then follows that there must be a hydraulic connection and upward seepage from the Grand Falls aquifer to the vicinity of Center Creek. This penetration upward is very likely due to a system of interconnecting fissures and cracks developed in the Grand Falls Formation and the overlying Burlington-Keokuk Formation. These fissures and cracks may have been caused by mining procedures and blasting as well as the original forces causing the structural trends now seen in this area.
**Permeability**

Assigning a permeability figure to the formations of this area seems unrealistic in view of the variety of factors which affect it. The most important of these factors are: the extent of the mine openings in this area, none of whose volumes are accurately known; the bulwarks erected during the mining of this area, and their locations and present condition; and finally the avenues of flow the water takes in limestone rocks whether through fissures and cracks in the formations, or between the grains making up the limestones. The stratigraphic cross-sections of this area (Plate III and IV) show thickening and thinning of the Grand Falls Formation which may or may not cause a change in the permeability of the Grand Falls aquifer in this area.

**Structural Control of the Piesometric Surface**

The present configuration of the contour lines of the piezometric surface of the Grand Falls aquifer is seen to be associated with the underlying structural trends of the surface of the Grand Falls Formation as mapped by Smith and Siebenthal (1906). This association was described in parts B, C, and D of Chapter V of this thesis. Plate II shows that the Grand Falls surface has undergone some structural deformation in the form of anticlines, synclines, basins, domes, and faults. Because accurate information is lacking with regard to the thickness of the Grand Falls Formation, any conclusions drawn about the tectonic activity which it has undergone would be questionable. However, structural deformation of this surface has some implications regarding fracturing. If a surface, or sheet, is bent, the convex side is subjected to tension, but the concave side is subjected
to compression and there is presumed to be an intermediate surface
of no strain. If the sheet is ductile, plastic deformation will
occur with the convex portion of the sheet thinning and the concave
portion of the sheet thickening. If, however, the sheet is brittle
(as in the case of limestone with shallow overburden), it would
yield by rupture. Tension fractures or small gravity faults would be
formed on the convex side; small reverse faults might be formed on the
concave side. Under certain conditions, the concave side of the sheet
might be crumpled (Billings, 1954, p. 89). If the fracturing which
takes place is aligned in one direction, the permeability will be
greatest parallel to these fractures, and least perpendicular to
them. However, if many sets of fractures are produced, the resultant
permeability would be intermediate in magnitude.

In the Duenweg - Cronogo mining belt the topography is essentially
flat and does not correspond to the underlying structural trends of the
Grand Falls Formation. Therefore, with a greater overburden over the
structural lows, the reverse faulting or crumpling which may have taken
place will be more “healed” or more tightly closed than the tensional
fractures of the structural highs which have less overburden. There-
fore the permeability of fractures over structural highs would be
expected to be greater than that over structural lows.

From the above discussion it can be seen that high permeability
and possibly, piezometric troughs would be expected to be associated
with structural highs. In Part B of Chapter V it was pointed out
that the piezometric trough in sections 8 and 17 of T 28 N, R 32 W,
was associated with a structural trough. This association may be only
a coincidence. The shallow piezometric trough with its more widespread contour lines indicates a path of slightly higher permeability, while the structural trough theoretically implies a path of lower permeability. Being a concave portion of the structural surface, it could be expected to have undergone compression and thus less fracturing. Mine shafts in sections 8 and 17 of T 28 N, R 32 W, act as piezometers. If collar elevations of the mine shafts occur below the normal piezometric surface of this area, the mine shafts would discharge water onto the land surface and thereby limit the height to which the piezometric surface can rise. Interconnection between the mine openings is the presumed reason for this trough.

In Part C of Chapter V, the hypothetical recharge area shown by the piezometric contours is seen to be in direct association with structural highs in that area. Presumably these structural highs in the surface of the Grand Falls Formation have undergone tensional fracturing, thus causing a higher degree of permeability. The wider spacing of the piezometric contours in this area indicates a higher permeability. Structural control of the piezometric surface of the Grand Falls Formation is believed to occur here.

In Part D of Chapter V, the configuration of the piezometric contours is shown to be in association with two structural highs and a low between them. The piezometric contours in the north one-half of sections 31 and 32 of T 28 N, R 32 W, are directly underlain by the north one-half of a crescent-shaped structural high. This structural feature being on the convex side of the surface of the Grand Falls Formation has presumably been subjected to tensional fracturing. Because the shape of this structural feature is
irregular, the fracture patterns developed here are very likely to be oriented in many directions. This perhaps accounts for the intermediate spacing of piezometric contour lines in this vicinity.

There is seen to be a close spacing of east-west piezometric contour lines across sections 32 and 33 of T 28 N, R 32 W. Their steep gradient indicates the presence of a permeability barrier. There is known to be extensive mine workings throughout section 30 of T 28 N, R 32 W. Because of this, there is a very good possibility that an underground bulwark was erected in this area during mining times to prevent water from flooding the mine workings.

A structural low of 80 feet relief immediately underlies the configuration of the piezometric contours in sections 32 and 33 of T 28 N, R 32 W. The low permeability expected in this concave portion of the surface of the Grand Falls Formation may in part cause the steep piezometric gradient in this area.

There is a fault which runs east-west through the southern portion of sections 3, 4, and 5 of T 27 N, R 32 W. Piezometric contours overlying this fault are sparse, due to lack of control points. However, there does seem to be an increase in permeability associated with this fault as shown by the wider spacing of the piezometric contour lines in sections 3 and 4 of T 27 N, R 32 W.

The sudden change in direction and the wider spacing of the piezometric contours in sections 33 and 34 of T 28 N, R 32 W, and sections 3 and 4 of T 27 N, R 32 W, is seen to overlie a north-south elongate structural high in this same area. This high has presumably been subject to tensional fracturing. The shape of this feature makes
it hard to judge in which direction the fracturing has occurred. In any case, the permeability presumably would increase in this structural high and this increase is apparently reflected on the piezometric contour map of the Grand Falls Formation by the wider spacing of the contours in this area, particularly section 3 of T 27 N, R 32 W.

The piezometric contours described in Part E of Chapter V are seen to be widely spaced, suggesting moderately high permeability. The direction of flow is southeast in this area. The underlying structural trend of the surface of the Grand Falls Formation is a broad, slightly nosing structural trough which perhaps would have been fractured slightly, if at all. The dip of the structure is opposite to the slope of the piezometric surface in this case. This would indicate that structural control of the piezometric surface in this area is not effective. However, there is known to be substantial pumping in this area. Interview information concerning this area indicates that without this pumping, the water levels in the water wells would stand well above their present level. With the higher (normal) water levels, the piezometric surface would probably slope northward. The structure of the underlying Grand Falls Formation would then be reflected in the piezometric surface of the Grand Falls Formation under "normal" conditions.

From the foregoing analysis of the configuration of the piezometric contours of the Grand Falls Formation, it is the author's contention that the faulting and structural deformation in this area control to some extent the permeability of the Grand Falls Formation. Because permeability is a dominant factor in shaping
piesometric contour lines, it follows that there should be a direct relation between the structural trends of the surface of the Grand Falls Formation and the piesometric surface of the Grand Falls aquifer.

**Fluctuation of Piesometric Surface**

Over a period of time, the contour lines of the piesometric surface of the Grand Falls Formation will shift location because of rise or fall of water levels in the area, but general configuration will remain the same. This fluctuation of water level could be caused by many factors, two of which are precipitation and pumping. Present piesometric trends should exist in the future if there are no local or extreme changes in existing conditions.

**Summary of Conclusions:**

1. Center Creek is thought to be an effluent stream.
2. The Grand Falls Formation is thought to be a semi-confined or "leaky" aquifer.
3. It would be unrealistic to assign permeability figures to the strata discussed in this thesis.
4. Structural control of the piesometric surface of the Grand Falls aquifer is believed to exist.
5. No extreme changes of the piesometric configuration (Plate I) are anticipated.
BIBLIOGRAPHY


VITA

The author was born November 3, 1941, in Longview, Texas, the son of Mr. and Mrs. J. R. Nichols. In 1942 he moved with his parents to Kansas City where he received his primary education. He received his secondary education at Northeast High School in Kansas City, Missouri. After graduation from high school, he attended the Junior College of Kansas City, Missouri, for two years. He then attended the University of Missouri at Kansas City for two years, and successfully completed the requirements for the Bachelor of Science degree in Geology at that University in June, 1963.

In September, 1963, he was accepted into Graduate School at the University of Missouri at Rolla, formerly the Missouri School of Mines and Metallurgy, to work toward the Master of Science degree in Geology. In September, 1963, he was awarded a V. H. McNutt Fellowship which he held until January, 1964, at which time he was offered and accepted a Graduate Assistantship in the Department of Geological Engineering and Geology at the University of Missouri at Rolla. Successful completion of the Master of Science degree in Geology is expected in February, 1965.
## APPENDIX A

### MINE SHAFT AND WATER WELL DATA

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>NAME</th>
<th>DESIGNATION</th>
<th>ELEVATION OF TOP OF WELL OR MINE SHAFT</th>
<th>DEPTH TO WATER LEVEL</th>
<th>ELEVATION OF WATER ABOVE SEA LEVEL</th>
<th>DATE OF MEASUREMENT</th>
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<td>R</td>
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<tr>
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<td>46.8</td>
<td>903</td>
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<td>House burned down and left water well which is not in use now. T.D. = 170'. Within 1' of 9/8/64's water level according to Rhea's hydrograph.</td>
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<td>8/28/64</td>
<td></td>
<td>Water level higher by 1', according to Nowata's hydrograph on 9/8/64. T.D. = 84'.</td>
</tr>
</tbody>
</table>
## APPENDIX A

### MINE SHAFT AND WATER WELL DATA

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>NAME</th>
<th>WELL OR MINE SHAFT</th>
<th>DESIGNATION</th>
<th>ELEVATION</th>
<th>DEPTH</th>
<th>ELEVATION</th>
<th>DATE OF MEASUREMENT</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>Spicer</td>
<td>Water Well</td>
<td>970</td>
<td>90.1</td>
<td>880</td>
<td>9/ 3/64</td>
<td></td>
<td>Within 1' of 9/ 8/64's water level according to Rhea's hydrograph. T.D. = 206'.</td>
</tr>
<tr>
<td>H</td>
<td>Halbert</td>
<td>Water Well</td>
<td>940</td>
<td>60.6</td>
<td>879</td>
<td>9/ 3/64</td>
<td></td>
<td>Within 1' of 9/ 8/64's water level according to Rhea's hydrograph. T.D. = 105'.</td>
</tr>
<tr>
<td>OV</td>
<td>Overfelt</td>
<td>Water Well</td>
<td>950</td>
<td><strong>58.0</strong></td>
<td>895</td>
<td>5/15/64</td>
<td></td>
<td>Water level higher by 3' according to Rhea's hydrograph on 9/ 8/64. T.D. = 221'.</td>
</tr>
<tr>
<td>S</td>
<td>Sheckles</td>
<td>Water Well</td>
<td>1010</td>
<td>69.7</td>
<td>940</td>
<td>9/ 9/64</td>
<td></td>
<td>Within 1' of 9/ 8/64's water level according to McGregor's hydrograph. T.D. = 96'.</td>
</tr>
<tr>
<td>X</td>
<td>Dry</td>
<td>Water Well</td>
<td>1070</td>
<td><strong>155.0</strong></td>
<td>918</td>
<td>8/19/64</td>
<td></td>
<td>Water level higher by 3' according to Novata's hydrograph on 9/ 8/64. T.D. = 160'.</td>
</tr>
</tbody>
</table>
### APPENDIX A

**MINE SHAFT AND WATER WELL DATA**

<table>
<thead>
<tr>
<th>SYMBOL OF PLATE I WELL OR MINE SHAFT</th>
<th>NAME</th>
<th>DESIGNATION</th>
<th>ELEVATION OF TOP OF WELL OR MINE SHAFT</th>
<th>DEPTH TO WATER MANAGEMENT LEVEL</th>
<th>ELEVATION OF WATER ABOVE SEAM</th>
<th>DATE OF MEASUREMENT</th>
<th>REMARKS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Dickson</td>
<td>Water Well</td>
<td>1060</td>
<td><strong>130.0</strong></td>
<td>926</td>
<td>9/19/64</td>
<td>T.D. = 163'.</td>
</tr>
<tr>
<td>BU</td>
<td>Buck</td>
<td>Water Well</td>
<td>980</td>
<td><strong>54.0</strong></td>
<td>927</td>
<td>8/1/64</td>
<td>Within 1' of 9/8/64's water level according to McGregor's hydrograph. T.D. = 305'. Pump pulled on 8/1/64.</td>
</tr>
<tr>
<td>A</td>
<td>Athey</td>
<td>Water Well</td>
<td>970</td>
<td><strong>65.0</strong></td>
<td>908</td>
<td>4/25/64</td>
<td>Water level higher by 3' according to Rhea's hydrograph on 9/8/64. T.D. = 190'.</td>
</tr>
<tr>
<td>CL</td>
<td>Clark</td>
<td>Water Well</td>
<td>1000</td>
<td>54.5</td>
<td>943</td>
<td>9/19/64</td>
<td>Water level lower by 2' according to Rhea's hydrograph on 9/8/64. Not in use as water well now. T.D. = 207'.</td>
</tr>
<tr>
<td>B</td>
<td>Brooks</td>
<td>Water Well</td>
<td>1080</td>
<td><strong>105.0</strong></td>
<td>973</td>
<td>6/20/64</td>
<td>Water level lower by 2' according to McGregor's hydrograph on 9/8/64. T.D. = 285'.</td>
</tr>
</tbody>
</table>
## APPENDIX A

### MINE SHAFT AND WATER WELL DATA

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>NAME</th>
<th>DESIGNATION</th>
<th>ELEVATION</th>
<th>DEPTH</th>
<th>ELEVATION ABOVE SEA LEVEL</th>
<th>DATE OF MEASUREMENT</th>
<th>REMARKS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>Weems</td>
<td>Water Well</td>
<td>1060</td>
<td>42.3</td>
<td>1018</td>
<td>9/19/64</td>
<td>Within 1' of 9/ 8/64's water level according to Novata's hydrograph. T.D. = 236'.</td>
</tr>
<tr>
<td>PS</td>
<td>Perseverence</td>
<td>Water Well</td>
<td>1030</td>
<td>90.6</td>
<td>940</td>
<td>9/19/64</td>
<td>Within 1' of 9/ 8/64's water level according to Rhea's hydrograph. T.D. = 104'.</td>
</tr>
<tr>
<td>WL</td>
<td>Wilson near Oronogo</td>
<td>Water Well</td>
<td>960</td>
<td>75.9</td>
<td>886</td>
<td>10/3/64</td>
<td>Water level higher by 2' according to Rhea's hydrograph on 9/ 8/64. T.D. = 270'.</td>
</tr>
<tr>
<td>SH</td>
<td>Shepherd N. of Lakeside</td>
<td>Water Well</td>
<td>925</td>
<td>30.0</td>
<td>897</td>
<td>10/3/64</td>
<td>Water level higher by 2' according to Rhea's hydrograph on 9/ 8/64. T.D. = 100'.</td>
</tr>
</tbody>
</table>
APPENDIX A

MINE SHAFT AND WATER WELL DATA

<table>
<thead>
<tr>
<th>SYMBOL OF PLATE I</th>
<th>NAME OF WELL OR MINE SHAFT</th>
<th>DESIGNATION</th>
<th>ELEVATION</th>
<th>DEPTH</th>
<th>ELEVATION OF WATER LEVEL</th>
<th>DATE OF MEASUREMENT</th>
<th>REMARKS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>No One</td>
<td>Water Well 1040</td>
<td>63.1</td>
<td>977</td>
<td></td>
<td>10/3/64</td>
<td>Within 1' of 9/8/64's water level according to Novata's hydrograph. T.D. = 253'.</td>
</tr>
<tr>
<td>HD</td>
<td>Head</td>
<td>Water Well 1045</td>
<td>**18.0</td>
<td>1027</td>
<td></td>
<td>10/3/64</td>
<td>Within 1' of 9/8/64's water level according to Novata's hydrograph. T.D. = 163'.</td>
</tr>
</tbody>
</table>

* Elevation determined by spirit levelling.

**Reported.
### APPENDIX B

**WELL LOG DATA FROM FILES OF THE MISSOURI GEOLOGICAL SURVEY**

<table>
<thead>
<tr>
<th>MAP NUMBER</th>
<th>LOCATION</th>
<th>ELEV. OF TOP OF WELL (FEET)</th>
<th>OWNER</th>
<th>DRILLER</th>
<th>DATE DRILLED</th>
<th>STATIC WATER LEVEL (FEET)</th>
<th>TOTAL DEPTH (FEET)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>*1908</td>
<td>890</td>
<td>Webb City - Carterville</td>
<td>L. Crossman</td>
<td>4/11</td>
<td>100</td>
<td>1305</td>
</tr>
<tr>
<td>2</td>
<td>2035</td>
<td>984</td>
<td>Media Mine</td>
<td>J. Grace</td>
<td>12/36</td>
<td>-</td>
<td>1715</td>
</tr>
<tr>
<td>3</td>
<td>*1834</td>
<td>1000</td>
<td>Webb City Smelter</td>
<td>J. Holmgren</td>
<td>1/14</td>
<td>126</td>
<td>945</td>
</tr>
<tr>
<td>4</td>
<td>*1910</td>
<td>960</td>
<td>Interurban Ice Co.</td>
<td>L. Crossman</td>
<td>10/07</td>
<td>228</td>
<td>931</td>
</tr>
<tr>
<td>5</td>
<td>8400</td>
<td>946</td>
<td>Brown &amp; Root Co.</td>
<td>T. Donahue</td>
<td>10/43</td>
<td>-</td>
<td>287</td>
</tr>
<tr>
<td>6</td>
<td>*195</td>
<td>1010</td>
<td>Missouri Zinc Field's Co.</td>
<td>L. Crossman</td>
<td>11/02</td>
<td>100</td>
<td>854</td>
</tr>
<tr>
<td>7</td>
<td>*1829</td>
<td>1032</td>
<td>M &amp; S Mine</td>
<td>H. Ballard</td>
<td>10/07</td>
<td>112</td>
<td>1008</td>
</tr>
<tr>
<td>8</td>
<td>2047</td>
<td>1090</td>
<td>Gotham Mine</td>
<td>E. Joseph</td>
<td>8/16</td>
<td>228</td>
<td>978</td>
</tr>
<tr>
<td>9</td>
<td>*1950</td>
<td>1071</td>
<td>Coahuilla Mine</td>
<td>R. Blosser</td>
<td>106</td>
<td>188</td>
<td>973</td>
</tr>
</tbody>
</table>
# APPENDIX B

## WELL LOG DATA FROM FILES OF THE MISSOURI GEOLOGICAL SURVEY

<table>
<thead>
<tr>
<th>MAP (PLATE I)</th>
<th>NO.</th>
<th>LOCATION</th>
<th>ELEV.</th>
<th>OWNER</th>
<th>DRILLER</th>
<th>DATE DRILLED</th>
<th>STATIC WATER LEVEL (FEET)</th>
<th>TOTAL DEPTH (FEET)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER SURVEY</td>
<td>GEOL.</td>
<td>(T 28 N, R 32 W)</td>
<td>OF TOP OF WELL (FEET)</td>
<td>OWNER</td>
<td>DRILLER</td>
<td>DATE DRILLED</td>
<td>STATIC WATER LEVEL (FEET)</td>
<td>TOTAL DEPTH (FEET)</td>
</tr>
<tr>
<td>FILE NO.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2018</td>
<td>SW/NE Sec. 34</td>
<td>1046</td>
<td>Porto Rico Mine</td>
<td>E. Knox</td>
<td>2/16</td>
<td>170</td>
<td>944</td>
</tr>
<tr>
<td>11</td>
<td>1947</td>
<td>NW/NE Sec. 19</td>
<td>1030</td>
<td>Webb City - Carterville Water Co.</td>
<td>L. Crossman</td>
<td>8/46</td>
<td>255</td>
<td>1015</td>
</tr>
<tr>
<td>12</td>
<td>1948</td>
<td>NW/NW Sec. 17</td>
<td>990</td>
<td>Ball &amp; Gunning</td>
<td>R. Crossman</td>
<td>-</td>
<td>-</td>
<td>860</td>
</tr>
<tr>
<td>13</td>
<td>9257</td>
<td>NE/SW Sec. 3</td>
<td>915</td>
<td>G. Dixon</td>
<td>C. Whitehead</td>
<td>8/46</td>
<td>-</td>
<td>195</td>
</tr>
<tr>
<td>14</td>
<td>7772</td>
<td>SE/SW Sec. 1</td>
<td>993</td>
<td>J. Wimer</td>
<td>L. Meares</td>
<td>5/12</td>
<td>50</td>
<td>217</td>
</tr>
</tbody>
</table>

* Driller's Log, Unrevised by Missouri Geological Survey.
STRUCTURE CONTOUR MAP
OF
TOP OF GRAND FALLS FORMATION
RENNY NICHOLS
JANUARY 1965
CONTOUR INTERVAL 10 FEET
SCALE 1:24,000
AFTER SMITH AND SIEBENTHAL (1906)
PLATE III
CORRELATION OF WELL LOGS (A–B)

ELEVATION IN FEET

1100
1000
900
800
700
600
500
400
300
200
100
0
-100
-200

MISSESPPN
ORDOVICIAN

(1) (2) (3) (4) (5) (6) (7) (8) (9) (10)

(A) (B)

PIEZOMETRIC PROFILE

FOR LEGEND: SEE PLATE III
HORIZONTAL SCALE 1"=2000'
VERTICAL SCALE 1"=100'
VERTICAL EXAGGERATION 20

RENNY NICHOLS
JANUARY 1965
PLATE IV
CORRELATION OF WELL LOGS (C-D)

LEGEND

CORRELATION
SUGGESTED CORRELATION
FORMATION
WARS W
Short Creek Dolomite Member
BURLINGTON KEOKUK
GRAND FALLS
REED SPRING
FERN GLEN
NORTHVIEW

CORRELATION
SUGGESTED CORRELATION
FORMATION

SYMBOLS

NOTES
1) THE THICKENING OF THE ROUBIDOUX FORMATION MAY BE INCORRECT BECAUSE
THICKNESSES AS REPORTED IN DRILLERS' LOGS WERE USED.
2) NAMES GIVEN TO UNITS ARE THOSE USED ON THE MISSOURI GEOLOGICAL
SURVEY WELL LOGS.
3) A-E, C-D, INDICATE LOCATION OF DIAGRAMS ON PLATE I. COLLAR ELEVATIONS
SHOWN AT TOPS OF LOGS.

HORIZONTAL SCALE 1"=2000'
VERTICAL SCALE 1"=100'
VERTICAL EXAGGERATION 20

RENNY NICHOLS
JANUARY 1965