Arkansas Water
Resources Center

LANDSAT LINEAR TREND ANALYSIS
A TOOL FOR GRONDWATER EXPLORATION
IN NORTHERN ARKANSAS

By

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ABSTRACT

Intelligent development of groundwater resources is a process that requires a thorough understanding of the availability and movement of groundwater. In northern Arkansas knowledge of the deep aquifers is fairly limited, perhaps because economic factors and uncertain yields have discouraged exploitation. The development of these deeper aquifers to their fullest potential as reliable water sources depends on the delineation of high yield areas, a process that may be facilitated by linear trend analysis as outlined in this study.

Satellite and photolineament maps of the 13 counties were prepared by use of LANDSAT images and Agricultural Stabilization and Conservation Service photo indexes. The lineaments and fracture traces on aerial photographs and LANDSAT images are natural linear features such as aligned stream segments, soil tonal and vegetal alignments, and topographic sags. These features are the surface manifestation of subsurface fracture zones of undermined origin, which are areas where increased solutioning of carbonate rocks has taken place.

The results of statistical testing of well yields in the study area show that the fracture trace-lineament method of well location can result in improved well yields. The fact that higher yields are obtained from wells on lineaments shows that these linear features are indeed surface manifestations of increased solutioning in the subsurface. These zones of fracture, enlarged by groundwater circulation, are capable of transmitting a greater volume of water at a faster rate than rocks between lineaments. Wells tapping these zones consequently show higher yields than those drilled randomly.

In northern Arkansas where shallow groundwater supplies soon may not meet the demands of a growing population, linear trends interpreted from LANDSAT can be useful in the search for more reliable groundwater sources. Their use will help the development of the deep aquifers of the area as reliable sources for domestic, municipal and industrial water supplies.

TABLE OF CONTENTS

INTRODUCTION 1
    Purpose and Objectives 2
    Locations 4
REGIONAL STRATIGRAPHY 9
    Precambrian Rocks 9
    Paleozoic Rocks 9
        Cambrian System 9
            Lamotte Formation 9
            Bonneterre Formation 9
            Potosi-Eminence Formations 10
        Ordovician System 10
            Gasconade Formation 10
            Roubidoux Formation 11
            Jefferson City Dolomite 11
            Cotter Formation 12
            Powell Formation 12
            Smithville Formation 12
            Black Rock Formation 12
            Everton Formation 13
            St. Peter Sandstone 13
            Post-St. Peter Strata of Ordovician Age . . 13
        Silurian System 14
        Devonian System 14
            Chattanooga Shale 14

Mississippian System 14
    St. Joe Formation 14
    Boone Formation 15
    Moorefield Shale 15
    Batesville Formation 15
    Fayetteville Formation 16
    Pitkin Formation 16
Pennsylvanian System 17
    Hale Formation 17
    Bloyd Formation 18
    Atoka Formation 18
GENERALIZED REGIONAL STRUCTURE 19
PREVIOUS INVESTIGATIONS AND BACKGROUND 22
Method of this Investigation 26
    Sources of Data 42
HYDROGEOLOGY 43
Groundwater in Northern Arkansas 43
Hydrogeology of the Deeper Aquifers 44
    Potosi and Eminence Dolomites 44
    Gasconade Formation and Gunter Sandstone Member 45
    Roubidoux Formation 46
    Jefferson City and Cotter Dolomites 46
Well Hydraulics 46
Well Yields and Lineaments 46
Results of Similar Studies Elsewhere 55

WATER QUALITY 59
  Introduction 59
    Total Hardness 60
    Total Dissolved Solids 61
    Calcium and Magnesium 61
    Sulfate 62
    Chloride 62
    Nitrate 63
    Iron 63
    Sodium and Potassium 63
  Water Quality and Lineaments 64
SUMMARY AND CONCLUSIONS 69
RECOMMENDATIONS 71
Appendix A 81
Appendix B 86
Appendix C 90
Appendix D 95
Appendix E 106

LIST OF FIGURES

1. Location of the study area.................... 5
2. Physiography of the southern United States..... 6
3. Arkansas physiographic regions. 7
4. Generalized regional statigraphy of northern Arkansas.................................. 8
5. Section A-A' from Figure 6 showing a north-south profile of the Precambrian surface.......20
6. Map showing location of profile A-A' in Figure 5...................................21
7. Relationship between fractures and solution cavities in a carbonate rock...................25
8. Lineament map of Baxter County......... 29
9. Lineament map of Benton County.................30
10. Lineament map of Boone County.. 31
11. Lineament map of Carroll County...............32
12. Lineament map of Fulton County....... 33
13. Lineament map of Izard County.................34
14. Lineament map of Madison County...............35
15. Lineament map of Marion County................36
16. Lineament map of Newton County..... 37
17. Lineament map of Searcy County................38
18. Lineament map of Sharp County.................39
19. Lineament map of Stone County 40
20. Lineament map of Washington County............41
21. Graphical representation of the concept of transmissivity.......................... 50

Plot of a pump test made in Well No. 19N 16W 32 ada at Summit, Arkansas................52

23. Two examples of four-celled contingency tables for the Fisher Exact Probability test on well yields............................53

24. LANDSAT image of the western Ozarks under snow cover....................................84

LIST OF TABLES

1. Yield, specific capacity and coefficient of transmissibility for 13 wells in the study area.................................... 52

2. Results of the Fisher Exact Probability test for well yields.......................... 56

3. Probabilities obtained from the Fisher Exact Probability test for water quality data................................. 65

INTRODUCTION

The need for a reliable source of water in northern Arkansas has been intensified in recent years by rapid growth in population. In some areas surface supply has been adequate to keep up with demand. Other areas, particularly those farther from the large lakes near the Missouri border, are not well supplied with surface water. Consequently, interest is shifting toward the development of groundwater resources. In past years the yields obtained from shallow aquifers have been sufficient to support the largely agricultural economy of the region. Two factors recently have combined to make these shallow aquifers undesirable sources of supply; inadequacy of yield for an economy that is changing in emphasis, and the carbonate lithology of the aquifers which makes them very susceptible to contamination. In more densely populated areas shallow groundwater already has shown signs of severe degradation.

New sources for municipal and industrial supply definitely are needed in northern Arkansas. For this reason, previously undeveloped deeper aquifers have become more attractive in spite of the greater cost of drilling to them. In the Ozarks of Arkansas four carbonate and sandstone units have potential as aquifers: the Potosi and Eminence dolomites, the Gunter Sandstone Member of the Gasconade Formation, and the Roubidoux Formation.

Being predominantly carbonate rocks, these aquifers show highest yields where secondary porosity has developed. Therefore, yields are haphazard and often disappointing when the cost of drilling is considered. LANDSAT imagery, in conjunction with photo index sheets, was used in this study to determine whether remote sensing can help to locate areas of increased porosity and permeability. Lineaments may represent zones of fractures and jointing where development of secondary porosity has been concentrated. If wells close to satellite lineaments can be shown to have significantly higher yields, analysis of such trends may prove to be a valuable exploration technique that can cut costs and uncertainty in well drilling.

Purpose and Objectives

The purpose of this study was to determine the value of interpretative data from LANDSAT imagery and photo index sheets in defining areas of high water well yields in northern Arkansas. Originally, the objectives of the study were to 1) prepare a potential water well yield map of northern Arkansas, based on satellite imagery and well yield data; (2 determine the effect of lineament orientation on groundwater movement in deep aquifers; and (3) determine whether wells on or near lineaments show any significant difference in water quality and if lineaments provide a route for the entry of contaminants into deep aquifers

After the study was begun it became evident that the objectives initially outlined were unrealistic in terms of the data available. The number of wells that reach the deeper aquifers is not large, and the paucity of adequate data points is intensified by the gross inaccuracy of well records. Many records submitted to the Arkansas Committee on Water Well Construction have inadequate data for accurate well location, poor or no estimates of yield, and sketchy lithologic logs; in short, a large proportion of the records are of no value to a study of this nature. Data for water quality are equally sparse. Records for 36 municipal wells in the study area were obtained from the Arkansas State Health Department and the U.S. Geological Survey in Little Rock. Additional historical data were solicited from more than 30 small cities and water districts; four responded. The U.S. Army Corps of Engineers was helpful in providing the available current water quality data for their wells, but does not retain historical data. Available water level data were not sufficient to draw a piezometric surface map of the area that would improve upon those drawn by Melton 1976 or Lamonds (1972). Without this map, an accurate determination of the direction of water movement cannot be made, nor can the role of lineaments in water movement be analyzed

With the available data it was impossible to achieve the original objectives of this study. What eventually evolved as the final product was (1 the preparation of photo and satellite lineament maps for the 13 counties of the study area, (2) a comparison of yields from deep wells on and off these lineaments, and (3) a comparison of water quality in deep wells on and off lineaments.

Location

The two northernmost tiers of Arkansas counties (Fig. extending eastward from the Oklahoma state line to the fall line of the Mississippi embayment, were selected for study because information on groundwater resources is needed in this area. The counties included are Benton, Washington, Carroll, Madison, Boone, Newton, Marion, Searcy, Baxter, Stone, Fulton, Izard and Sharp. This area comprises a large part of the Ozark Plateaus province of the Interior Highlands of the United States (Fig. 2), which consists of a series of fairly low plateaus developed astride a broad upwarp known as the Ozark Dome. In Arkansas the Ozark Plateaus province is subdivided into three sections: the Boston Mountains, the Springfield Plateau, and the Salem Plateau(Fig. 3). The boston Mountains constitute the sountern one-third of the study area. These erosional remnants of an ancient plateau surface are flat-topped ridges capped by Pennsylvanian sandstone. The northern boundary of the Boston Mountains is the Boston Mountain escarpment, which separates this province from the Springfield Plateau.

Parts of all the counties in the study area are on the Springfield Plateau, with the exception of Fulton, Izard and Sharp Counties. The Springfield Plateau is characterized by broad outcrops of Mississippian limestones. It is bounded on the north by the Eureka Spring escarpment

The Salem Plateau is north of the Springfield Plateau, is characterized by limestones and dolomites of Cambrian and Ordovician age.

Figure 1. Location of the study area.

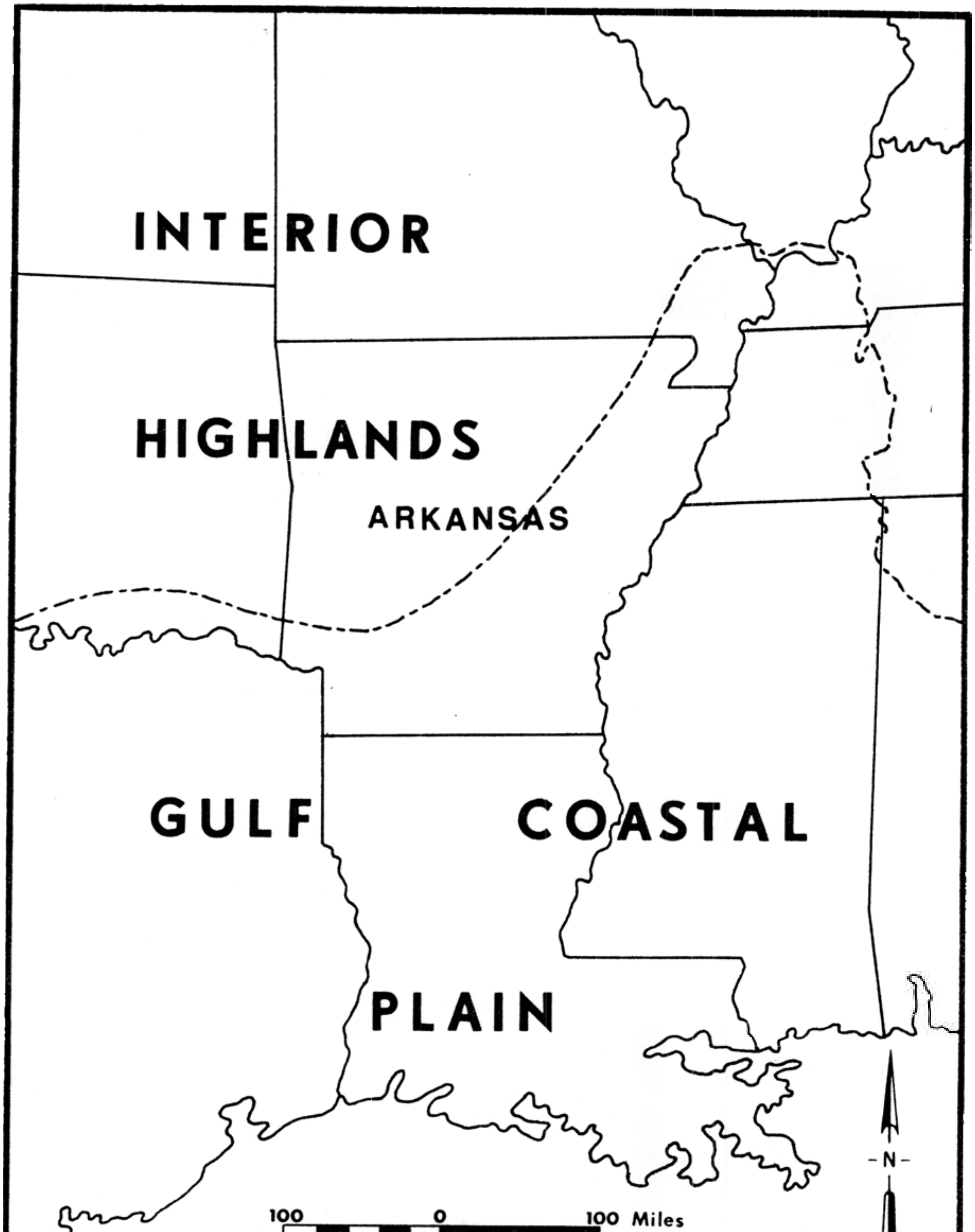
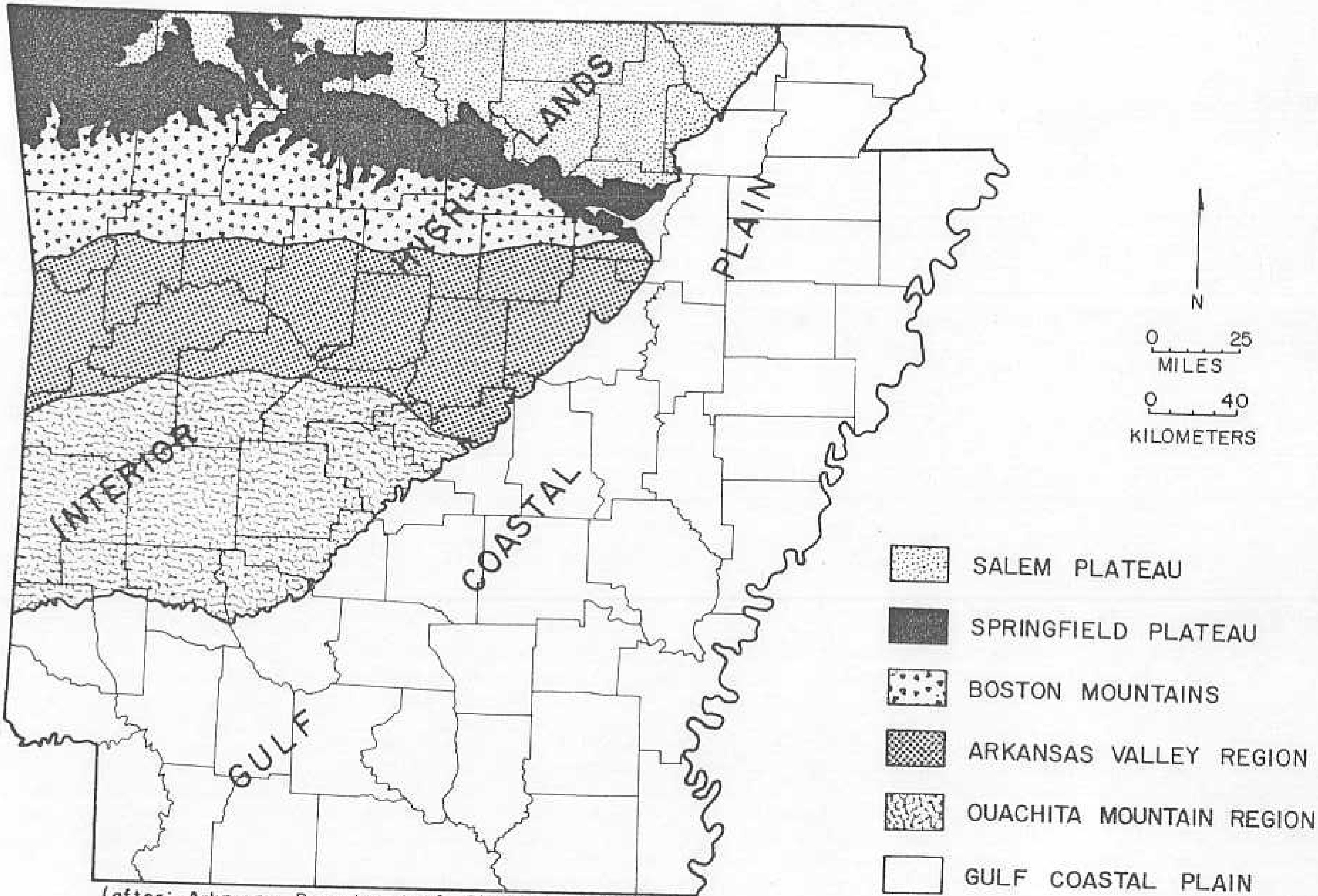


Figure 2. PHYSIOGRAPHY OF THE SOUTHERN UNITED STATES (after Croneis, 1930)



(after: Arkansas Department of Planning, 1973).

Figure 3. Arkansas physiographic regions

SYSTEM	SERIES	FORMATION	MEMBER
PENNSYLVANIAN		ATOKA	
	MORROWAN	BLOYD	
		HALE	PRAIRIE GROVE CANE HILL
MISSISSIPPIAN	CHESTERIAN	PITKIN	
		FAYETTEVILLE	
		BATESVILLE	HINDSVILLE
	MERA-MECIAN	MOOREFIELD	
	OSAGEAN	BOONE	
		ST. JOE	
		CHATTANOOGA	SYLAMORE
DEVON-IAN			
SILUR-IAN		LAFFERTY ST. CLAIR BRASSFIELD	
ORDOVICIAN		CASON FERNVALE KIMMSWICK PLATTIN JOACHIM	
		ST. PETER	
		EVERTON	
		BLACK ROCK SMITHVILLE	
		POWELL	
		COTTER	
		JEFFERSON CITY	
		ROUBIDOUX	
		GASCONADE	GUNTER
CAMBRIAN		POTOSI-EMINENCE	
		BONNETERRE	
		LAMOTTE	
PRECAMBRIAN BASEMENT ROCKS			

Figure 4. Generalized regional stratigraphy of northern Arkansas.

REGIONAL STRATIGRAPHY

PreCambrian Rocks

The Ozark Plateaus province in northern Arkansas is underlain by a PreCambrian basement of igneous rocks which appear to be granitic in the few wells that reach their depth (Caplan, 1960). The surface of this basement is irregular, probably because of Early Cambrian exposure and erosion.

Paleozoic Rocks

Systems of the Paleozoic Era represented by strata in northern Arkansas are mainly the Cambrian, Ordovician, Mississippian, and Pennsylvanian. During these times conditions in the area were stable; shallow seas covered the area and gentle downwarping permitted the accumulation of moderate amounts of sediment. Occasional uplifts generated disconformities at some horizons.

Cambrian System

Lamotte Formation. The Lamotte Formation, loosely cemented white quartzose sandstone, is the basal Cambrian unit in Arkansas. Scattered dolomite patches are present in this Late Cambrian unit which, in the few wells that reach it, ranges from 30 to 60 feet in thickness (Caplan, 1960)

Bonneterre Formation. The contact between the Bonneterre and Lamotte Formations may be locally conformable or disconformable. The Bonneterre is light-gray crystalline dolomite that contains glauconite and pyrite. Where present in Arkansas, it is about 70 feet thick (Caplan, 1960)

Potosi-Eminence Formations. Because of their lithologic similarity, the Potosi and Eminence Formations are undifferentiated in northern Arkansas. They are composed of light colored crystalline dolomite with white or gray chert. Scattered sandy lenses are present in the Eminence, but are not abundant enough to distinguish it from the Potosi. The combined thickness of the two formations ranges from 300 to 385 feet (Caplan, 1960).

Ordovician System

Gasconade Formation. Unconformably overlying the Eminence is the basal unit of the Ordovician System, the Gunter Sandstone Member of the Gasconade Formation. The Gunter ranges from loosely cemented white to gray sandstone, present in a narrow belt extending through the central part of the study area, to light gray sandy dolomite east and west of this belt. Because the Gunter was deposited on an irregular erosional surface, its thickness ranges from 30-40 to 120 feet (Melton, 1976)

The Gunter Sandstone Member is conformably overlain by 350 to 600 feet of the Gasconade Formation, a light-colored, crystalline, vuggy dolomite. The lower part of this dolomite sucession contains a large amount of chert which decreases upward. In places this chert, which may be blue, cream, or gray, contains oolites. Local inclusions of sand grains and dolomite rhombs have been reported (Snyder, 1976).

Roubidoux Formation. The Roubidoux Formation unconformably overlies the Gasconade, and is composed chiefly of dolomite, sandstone, and chert in northern Arkansas. The dolomite, which predominates in the Roubidoux, is light to medium gray and sandy. Caplan 1960) reports that thin shale units have been found within the dolomite

Sandstone in the Roubidoux is loosely cemented, light gray to white, and fine to medium grained. Quartz sand content is greatest in the eastern part of the study area, where it composes as much as 48 percent of the total section

The chert of the Roubidoux is dense and ranges in color from white to dark gray and black. It is commonly sandy or oolitic; oolitic chert is often considered diagnostic of the Roubidoux (Eddie Adcock, water well driller, personal communication, 1976).

Thickness of the Roubidoux ranges from 180 to 265 feet in northern Arkansas. Like the Gasconade, the Roubidoux thickens southeastward (Snyder, 1976

Jefferson City Dolomite. The Jefferson City Dolomite, which conformably overlies the Roubidoux Formation, is the oldest unit that crops out in northern Arkansas. Exposed in Fulton, Marion, and Sharp Counties, it is composed of light to medium-gray crystalline dolomite with some sand and chert Ooliths are common within the formation. The Jefferson City ranges in thickness from 100 to 500 feet in the study area (Caplan, 1960).

Cotter Formation. The Cotter Formation can be distinguished from the Jefferson City, which it conformably overlies, by a thin basal bed of sandstone or sandy dolomite. This unit is not laterally continuous and consequently the two formations commonly are undifferentiated. Outcrops of the Cotter are present in all but four counties in the southwest part of the study area. The average thickness is about 200 feet, but as much as 500 feet has been reported (Caplan, 1960).

Powell Formation. The Powell Formation has been reported to overlie the Cotter both conformably and disconformably at different localities. It is described by Caplan (1960) as light-gray crystalline shaly dolomite, with scattered layers of shaly dolomite, green pyritic shale, and dark oolitic chert The Powell crops out extensively in Benton, Carroll, Boone, Marion, Newton, Fulton, Izard, and Sharp Counties and ranges in thickness from 150 to 200 feet (Croneis, 1930).

Smithville Formation. The Smithville Formation, which crops out in Sharp County, is gray, finely granular dolomitic limestone with sandstone and lead-zinc minerals in places. Its contact with the Powell is believed to be conformable, but the relationship is not well understood in Arkansas. The thickness ranges up to 150 feet (Caplan, 1960)

Black Rock Formation. In its limited area in northeastern Arkansas, the Black Rock Formation uncomformably overlies the Smithville and is similar lithologically. Thickness of the Black Rock ranges from 55 to 200 feet in surface exposures Caplan, 1960).

Everton Formation. The Everton Formation unconformably overlies either the Black Rock Formation where present or other rocks of the Canadian Series. It consists of sandy dolomite and friable to well-cemented sandstone containing frosted quartz grains. Changes in rock type and facies are common in the study area, to the extent that Caplan (1957) believes the Black Rock and Smithville Formations are facies of the Everton

St. Peter Sandstone. The contact between the St. Peter Sandstone and the Everton Formation is disconformable, at places very irregular where the St. Peter has infilled solution cavities in the Everton (Croneis, 1930) Lithologically the St. Peter is very similar to the Everton, and the two units can be difficult to differentiate in well cuttings (Caplan, 1957). The St. Peter ranges in thickness from a few inches to 175 feet, thickening southeastward

Post-St. Peter Strata of Ordovician Age

Newton County eastward to the fall line of the Mississippian embayment, five units of middle and late Ordovician age crop out discontinuously: the Joachim Dolomite, Plattin Limestone, Kimmswick Limestone, Fernvale Limestone, and the Cason Shale. Each is distinct lithologically and separated by unconformities from overlying and underlying strata. Where the lowermost unit, the Joachim, overlies the St. Peter, the contact is conformable; however, the Joachim is locally absent. Combined thickness of these units ranges from a bevelled edge to more than 500 feet, increasing on the south and east (Frezon and Glick, 1959).

Silurian System

Rocks of Silurian age crop out in basically the same pattern as the post-St. Peter strata. The gray, crystalline limestone is divided into the Brassfield, St. Clair, and Lafferty Formations. Outcrops of the Brassfield are limited to Searcy County; the St. Clair and Lafferty are present from Newton County eastward. Maximum thickness of all three formations is about 250 feet, decreasing notably on the north and east (Frezon and Glick, 1959).

Devonian System

Chattanooga Shale. Unconformably overlying rocks of Ordovician age, the Chattanooga Shale is chiefly black carbonaceous fissle shale. A thin sandstone member, termed the Sylamore Sandstone, is present locally at the base of the unit. Limited to that part of the study area west of Harrison, the Chattanooga is markedly jointed, and ranges in thickness from a few inches to 85 feet (Croneis, 1930).

Mississippian System

St. Joe Formation. The St. Joe Formation recently has been elevated to formational status in Arkansas by MacFarland (1975 and Shanks (1976) In the western part of the study area, the St. Joe is subdivided into three members: the basal fine-grained crystalline limestone of the Compton Member, the

Northview Member consisting of either calcareous shale or interbedded shale and limestone, and the finely crystalline limestone of the Pierson Member. Combined thickness of these three members ranges from 35 to 60 feet. East of Carroll County, the Northview Member pinches out; the Compton and Pierson Members become lithologically indistinguishable Shanks, 1976 and consequently are undifferentiated. North and east of Marion County, the St. Joe and younger rocks are removed by erosion.

Boone Formation. The Boone Formation, which conformably overlies the St. Joe Formation, is one of the most extensively exposed units in the western part of the study area. Much of the Boone is composed of gray fossiliferous limestone interbedded with abundant blue to gray chert. Near the top of the formation the limestone is lighter colored, massive, oolitic. Total thickness ranges from 300 feet near the Oklahoma border to 400 feet near Ponca in Newton County (Croneis, 1930).

Moorefield Shale. Disconformably overlying the Boone Formation is the Moorefield Shale which crops out in Searcy and Stone Counties. This unit is composed of dark gray limy shale and a thin basal bed of fossiliferous limestone. In its westernmost outcrop the Moorefield is about two feet thick, but thickens on the south and east to an average of about 75 feet Croneis, 1930

Batesville Formation. The Batesville Formation conformably overlies the Moorefield Formation where present and disconformably may be conformable on the south (Croneis, 1930). Erosion completely removed the Pitkin in many places prior to Pennsylvanian deposition.

The Pitkin Formation consists of massive, dense blue-gray limestone that is commonly sandy. Fossil remains of the bryozoan *Archimedes* are common enough to be diagnostic of this unit. On the north the Pitkin is truncated by a pre-Pennsylvanian erosion surface. The maximum thickness of the Pitkin, about 100 feet, was measured in an area south of Bellefonte (Croneis, 1930).

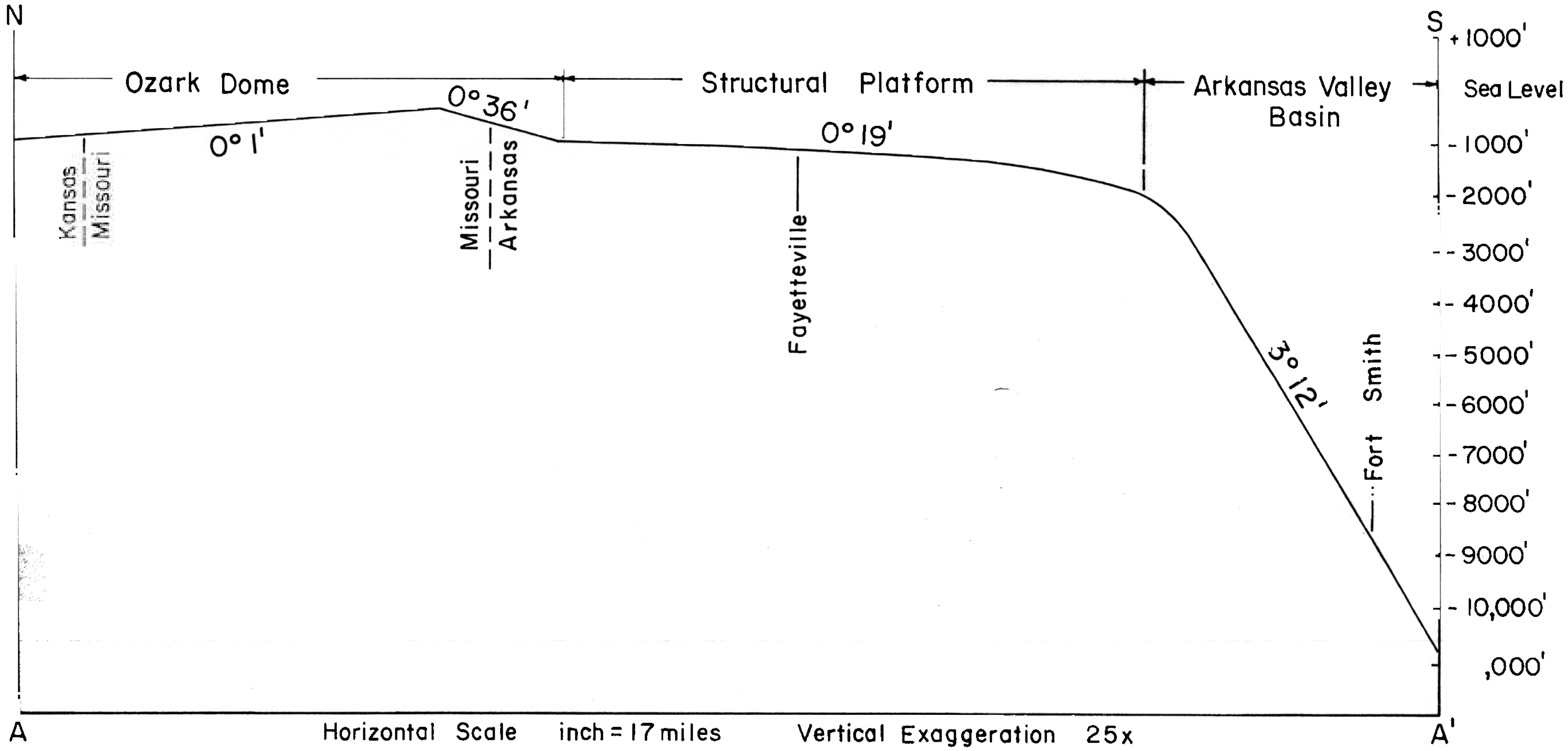
Pennsylvanian System

Hale Formation. The Hale Formation unconformably overlies the Pitkin or, where that unit is absent, the Fayetteville. In its type area in Washington County, the Hale is divided into the Cane Hill and Prairie Grove Members. The Cane Hill Member is composed of varied percentages of fine-grained sandstone and silty black shale. Both Croneis (1930) and Frezon and Glick (1959) noted a local basal conglomerate containing well-rounded limestone pebbles, evidently of Pitkin origin, cemented in a ferruginous matrix. The Cane Hill ranges in thickness from a thin edge to more than 700 feet and thins locally in Washington and Newton Counties.

The Prairie Grove Member, a more persistent unit, unconformably overlies the Cane Hill or Mississippian rocks where this unit is absent (Frezon and Glick, 1959). In Washington, Madison, and western Newton Counties, the Prairie Grove consists of very sandy oolitic limestone that grades eastward into calcareous fine- to medium-grained sandstone. Thicken- increases eastward in a trend that parallels that of the sand content; in the western part of the study area the Prairie Grove is 70 feet thick, and increases to 300 feet on east (Frezon and Glick, 1959).

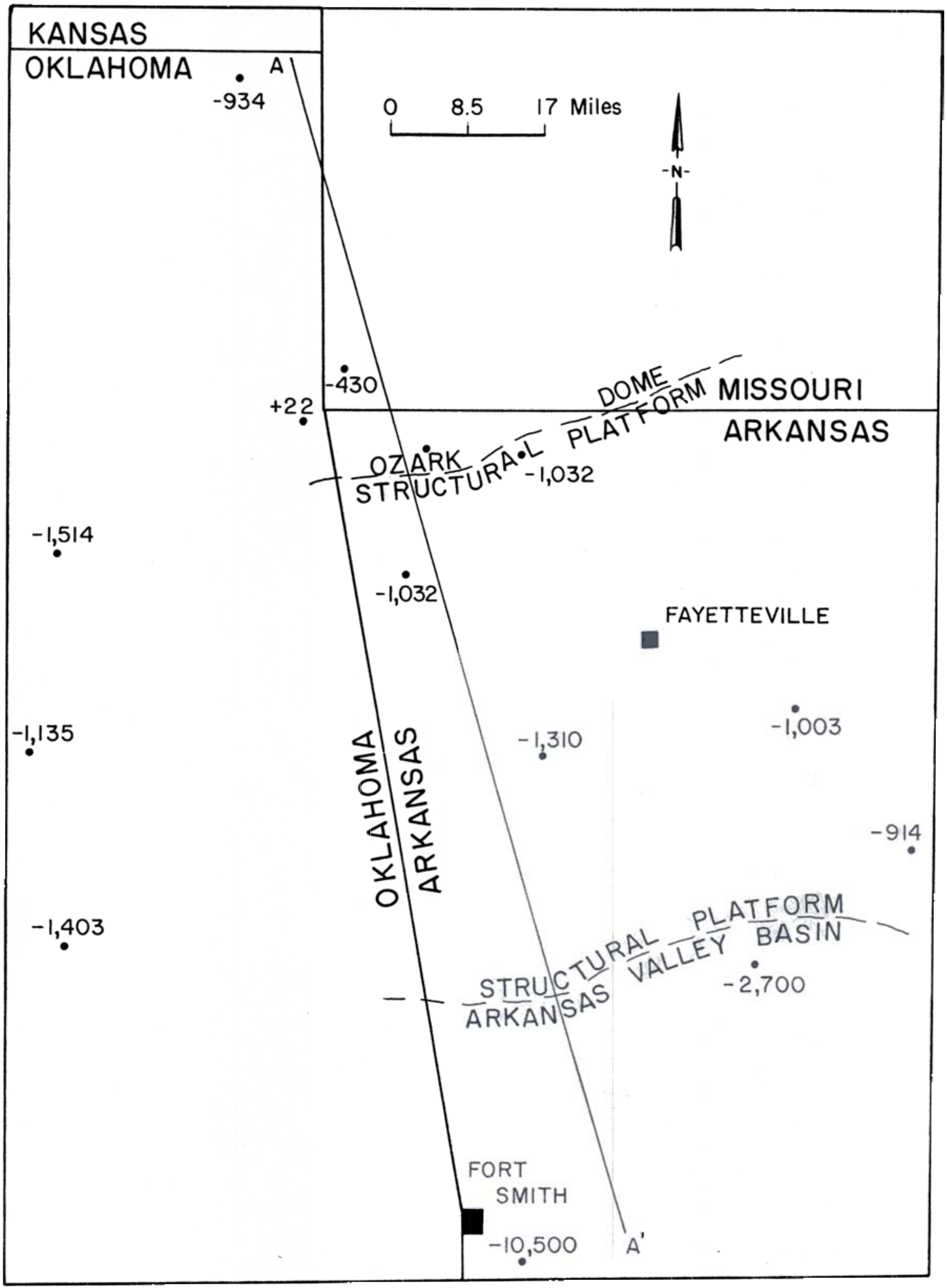
Bloyd Formation. The Bloyd Formation conformably over- the Prairie Grove, and in the Washington County type area is a series of shale units, two sandy limestone units, some limy sandstone, and a thin seam of coal. On the east the limestone units are replaced as the facies changes to gray, fine-grained limy sandstone and black micaceous shale The boundary between the Bloyd and the overlying Atoka is conformable. From a thin edge in the northern part of the study area, the Bloyd increases to a thickness of 650 feet in Cleburne County, south of the study area Frezon and Glick, 1959

Atoka Formation. The outcrop of the Atoka Formation the greatest areal extent of any Paleozoic rock in Arkansas. Capping the Boston Mountains, it is presently at the top of high ridges on the north and extends southward through the Arkansas Valley to the Ouachitas. It consists of alternate beds of medium-grained sandstone and black carbonaceous shale. The sandstone beds range in thickness from 1 to 125 feet; thin beds are commonly ripple-marked, and thicker beds may show cross-bedding. Some patches of calcareous cement are present. The maximum thickness of the Atoka is more than



(after Mapes, 1968)

Figure 5. Section AA' from Figure 6 showing a north - south profile of the Precambrian surface.



(After Mapes, 1968)

Figure 6. Map showing location of profile A-A' in Figure 5. Numbers beside points show elevation of Precambrian surface with respect to sea level.

on the southeast side. The other set of faults trends east and west along the southern margin of the platform; these are believed to be related to growth faulting under increased sediment loads in the Arkoma Basin

PREVIOUS INVESTIGATIONS AND BACKGROUND

Fracture analysis long has been recognized as a tool in understanding the structural and stratigraphic characteristics of an area (Blanchet, 1957). With the development of remote sensing techniques, fracture analysis has been used in exploration for petroleum, minerals, and, as in this study, groundwater.

The origin of the stresses that produce fractures is not clear. Wilson (1948) related them to structural activity in orogenic belts, whereas Mollard (1957) and Blanchet (1957) believed that they are linked to flexing caused by earth tides. Lattman (1958) developed the terminology that prevails today; his "lineament" is a natural linear feature longer than one mile, and his "fracture trace" is a linear feature shorter than one mile. The terms used in this study conform to Lattman's usage

Lattman and Parizek (1964) studied the relationship between fracture traces mapped from aerial photographs and water well yields. Specific capacity was determined in 11 wells drilled in dolomite and sandy dolomite in the Nittany Valley of Pennsylvania. Wells between fracture traces showed significantly lower yields than those on or near one or two fracture traces. In addition, the authors found the weathered mantle underlying fracture traces to be considerably thicker than that between traces. These observations led them to conclude that fractures in carbonate rocks aid in the development of horizontal and vertical permeability by facilitating deep solutioning and weathering.

Sonderegger (1970) did a similar study in Alabama, using black and white, color and color infrared photographs to map lineaments. Sixteen wells were then drilled to test yield relationships. Wells on lineaments taken from color and color infrared photographs yielded an average of 100 gpm, whereas wells on lineaments from black and white photographs yielded an average of 150 gpm. Wells between lineaments averaged 23 gpm. Sonderegger concluded that the fracture trace-lineament method of well-site selection is more effective than random location when high-yield wells are desired

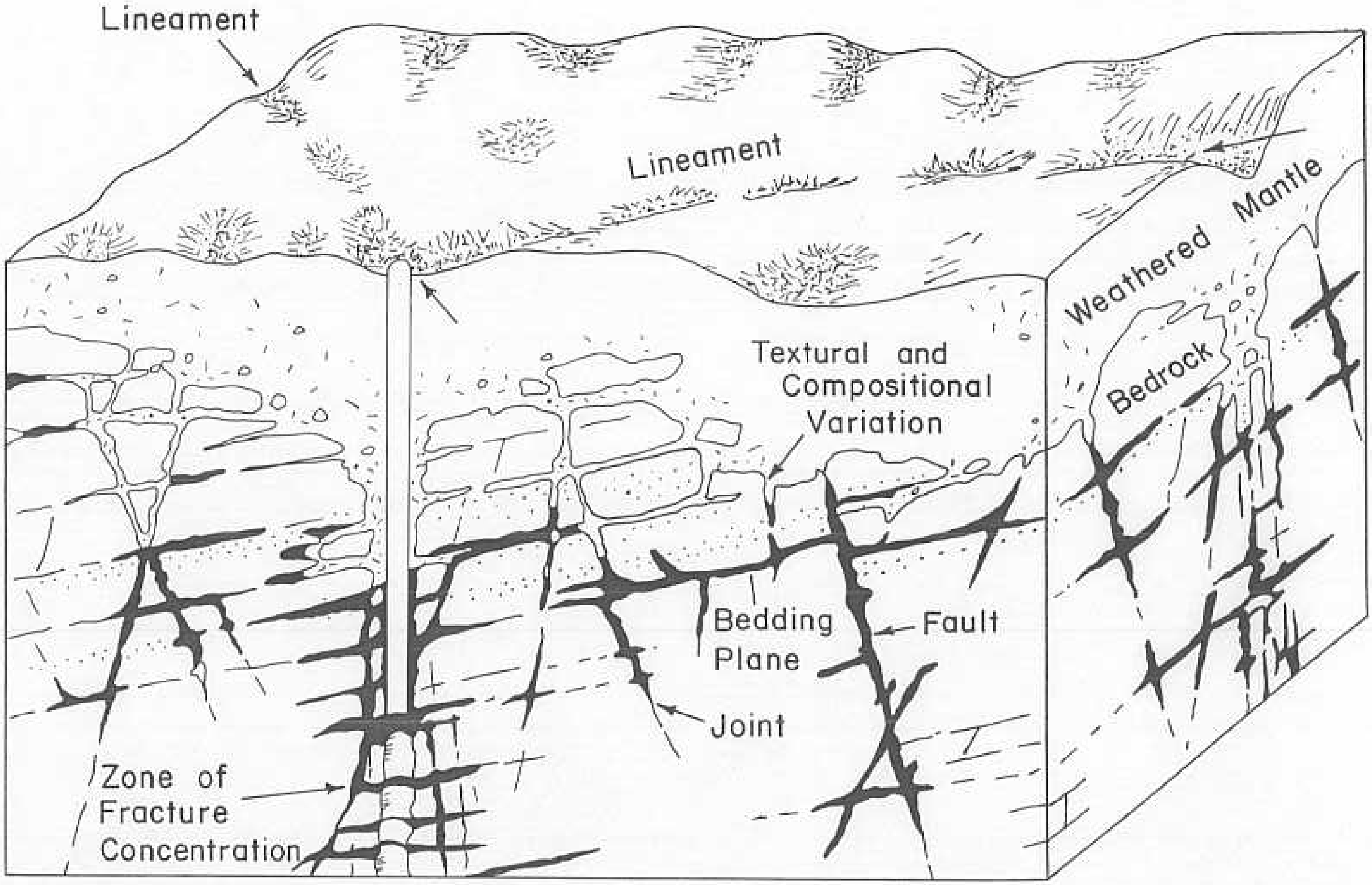
Parizek 1976), continuing his work in the Nittany Valley, considered the relationship between well yield and fracture trace location in light of other factors influencing yield. These factors included such well parameters as well depth and diameter, casing depth, and method of drilling and development, and such geologic parameters as depth to water, rock type, dip, topographic setting, and structure. In spite of the yield variations produced by these factors, he found that placing wells near intersections of fracture traces or lineaments favors increased well yields.

Moore (1976) mapped lineaments from SKYLAB photographs of an area in central Tennessee, and used data from both new test wells and previously drilled wells to determine the hydrologic significance of these lineaments. Wells on SKYLAB lineaments were found to yield an average of six times more water than randomly located wells.

The development of the fracture trace method of wellsite location was the first step in alleviating the uncertainty involved in well drilling in carbonate terranes. In areas such as northern Arkansas, where adjacent wells may show opposite extremes in yield, the fracture trace-lineament method of well location is a means of pinpointing areas where secondary porosity is present.

Secondary porosity is significant in carbonate terranes because primary porosity often is eliminated during the process of lithification. For example, the original pore spaces between sand grains in the Roubidoux Formation have been filled by the deposition of dolomite. What would otherwise be a permeable medium has been made impermeable, at least until secondary pore spaces are developed.

In carbonate aquifers, secondary porosity develops when parts of the rock are dissolved by groundwater circulation. This water is made slightly acidic by the addition of dilute carbonic acid, formed when carbon dioxide dissolves in water. Any space large enough to provide permeability, such as a joint, fracture, or bedding plane, is a potential site for enlargement by dissolution. Consequently the patterns in which secondary porosity develops are commonly not so random as they might first appear; rather they closely follow joint and fracture patterns (Figure 7).



(After Lattman and Parizek 1964)

Figure 7. Relationship between fractures and solution activity in a carbonate rock

The key to drilling higher-yielding wells in the Ozarks, then, is the interception of one of these zones of secondary porosity. Lattman and Parizek found that their chances were improved by the use of aerial photographs, because fracture traces on the photographs are related to fracture porosity development in the subsurface. Similar studies have been done for areas in northwestern Arkansas by Hanson (1973) Coughlin (1975), both of whom concluded that wells near fracture traces were more productive than those between fracture traces. Coughlin, however, found that fracture traces provide an entry for contaminants into groundwater, particularly in areas where soil filtration capabilities are poor

Method of This Investigation

Lamonds (1972) made a generalized study of water resources in the Ozark Plateaus province of Arkansas which was concerned primarily with shallow sources of groundwater. Yields reported were on the order of 10 to 50 gpm, sufficient for the agricultural uses that predominate in the area. Recent population increases in the northern part of the state, however have increased demand so that these yields soon may not be adequate to supply the area. Melton (1976 investigated the hydrogeologic properties of two deep-seated aquifers; the Roubidoux Formation and the Gunter Member of the Gasconade Formation, in southern Missouri and northern Arkansas. He found that yields from the Roubidoux range from 4 to 600 and average 50 to 60 gpm, whereas Gunter yields range from

4 to 732 gpm and average 170 gpm. Though these figures do represent an improvement over yields obtained from shallower aquifers, they are not uniform throughout the formations. This fact, combined with the high cost of drilling deeply enough to reach them, has limited their development. Their utility as a reliable water source will be better realized if consistently higher yields can be obtained. One of the objectives of this investigation is to determine whether the fracture trace-lineament method of well location can be as successful in northern Arkansas as it has been elsewhere.

size of the study area dictated that the scale of the final lineament map be reduced somewhat in reproduction; for this reason it was decided to plot only those lineaments longer than one mile. Inclusion of the numerous fracture traces that are present would degrade the clarity of the reduced maps. In addition, mapping short lineaments from straight stream segments could lead to confusion and error if used in the search for groundwater. Because of the rugged topography of parts of the study area, straightness of shorter stream segments may be due not to fracture control but to the force of gravity inducing streamflow to travel straight downhill

According to Lattman 1958), a lineament is a natural linear feature more than one mile long. Manifested in such forms as topographic sags, aligned segments in water-courses, vegetation alignments, and linear soil tonal anomalies, these features are most easily seen from the synoptic view afforded by remote sensing techniques. In addition to studying the image from directly above, as one would read a book, viewing it obliquely or from a distance of a few feet may aid in the recognition of lineaments. LANDSAT images, because they are taken from a spaceborne platform orbiting at an altitude of 565 miles, provide clear definition of long regional lineaments which because of sheer size may not be visible on larger scale images. Both LANDSAT images and aerial photographs of the study areas were studied by Lattman's technique. The LANDSAT lineaments, shown as dashed lines in Figures 8 through were obtained from two winter scenes in Bands 5 and 6 These lineaments were mapped on acetate overlays and transferred to 1:125,000 scale county highway maps by means of a Bausch and Lomb Transfer Scope model ZT-4. This instrument enables its user to view two images simultaneously, in this case a LANDSAT image and a county highway map, and facilitates the transfer of information from the image to the map. The transfer involved a considerable change of scale, because LANDSAT images in the 7.3" format have a scale of 1:1,000,000. Enlarging the image to eight times its normal size blurred the drainage features used to align the image and the map, also increased the width of the lines drawn on the acetate to mark the lineaments on the LANDSAT image. Consequently transferral of the LANDSAT lineaments was not exact and introduced a margin of location error of about one quarter mile.

Additional lineaments were obtained from ASCS photo index sheets of each of the 13 counties. The Zoom Transfer Scope could not be used to transfer these photo-lineaments because the photomosaics were larger than the maps, therefore

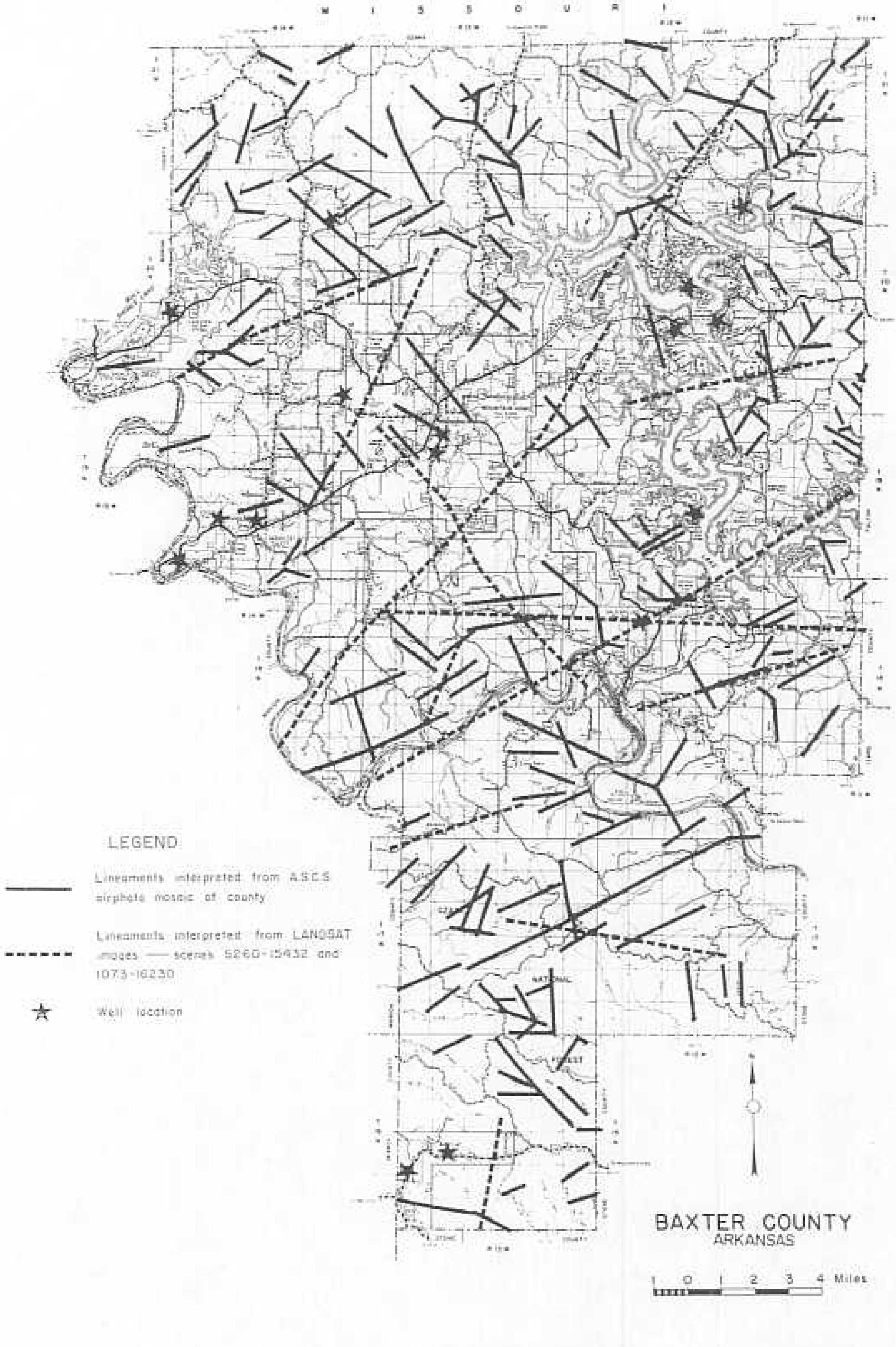


Figure 8. Lineament map of Baxter County.

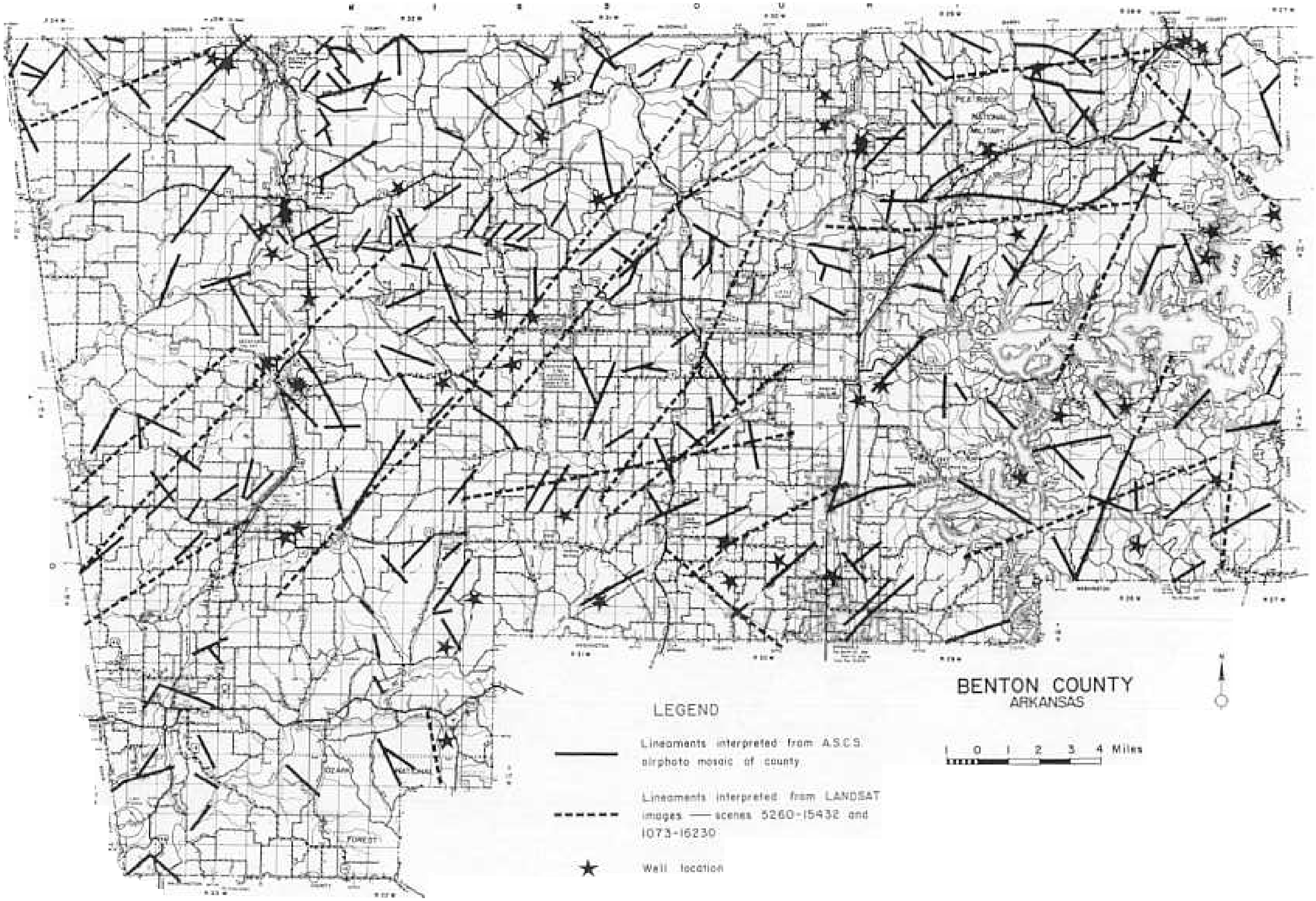


Figure 9. Lineament map of Benton County.

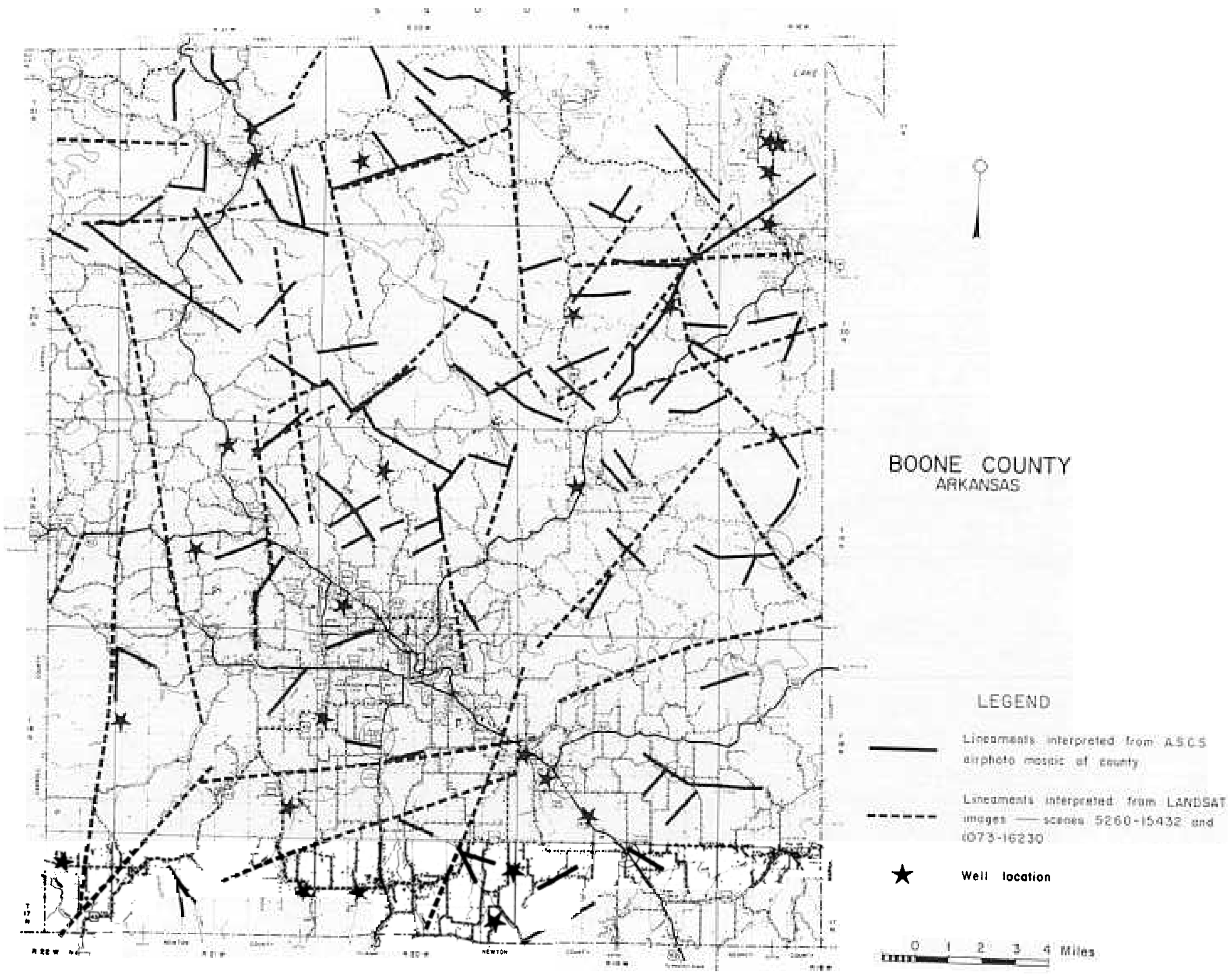


Figure 10. Lineament map of Boone County.

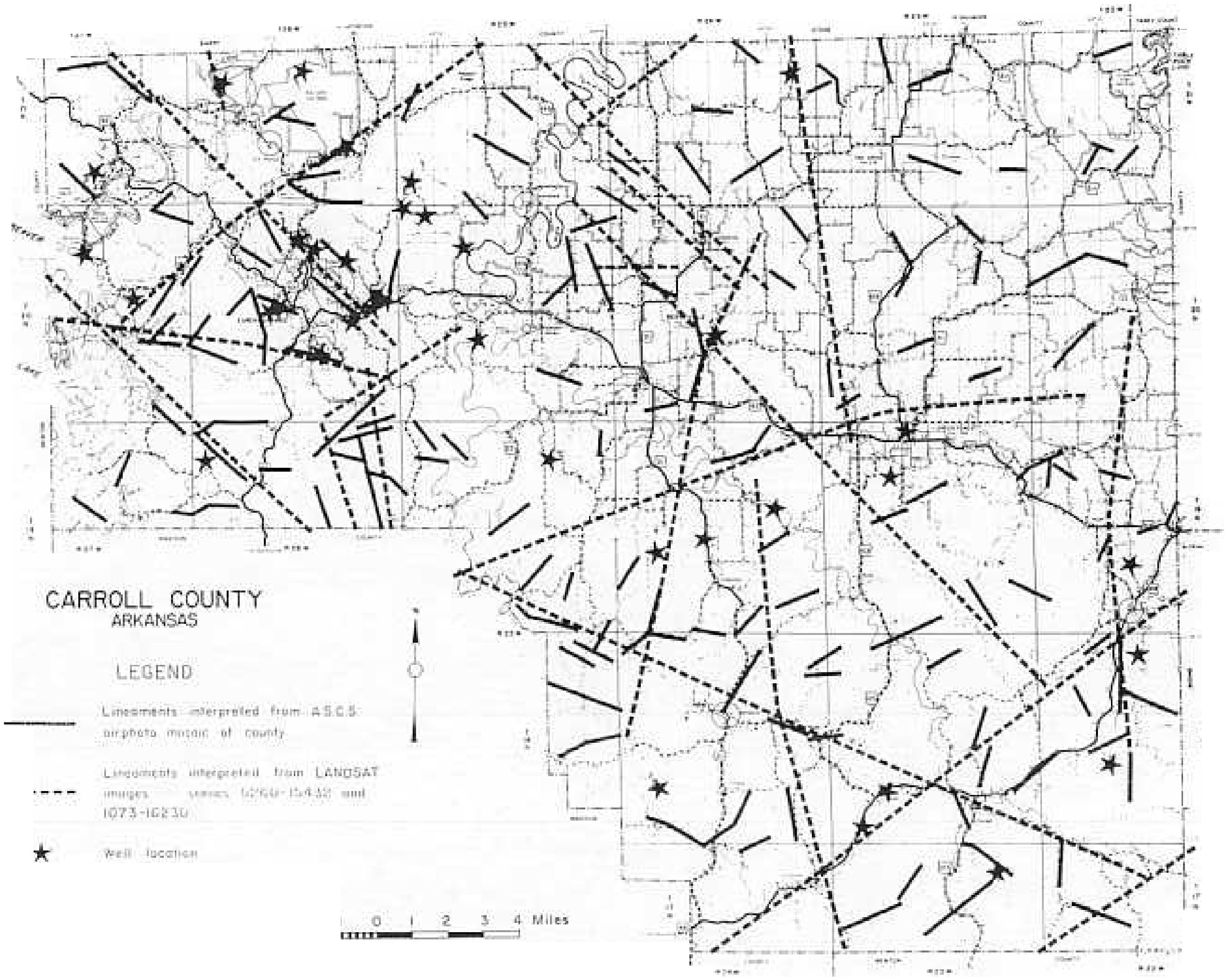


Figure 11. Lineament map of Carroll County.

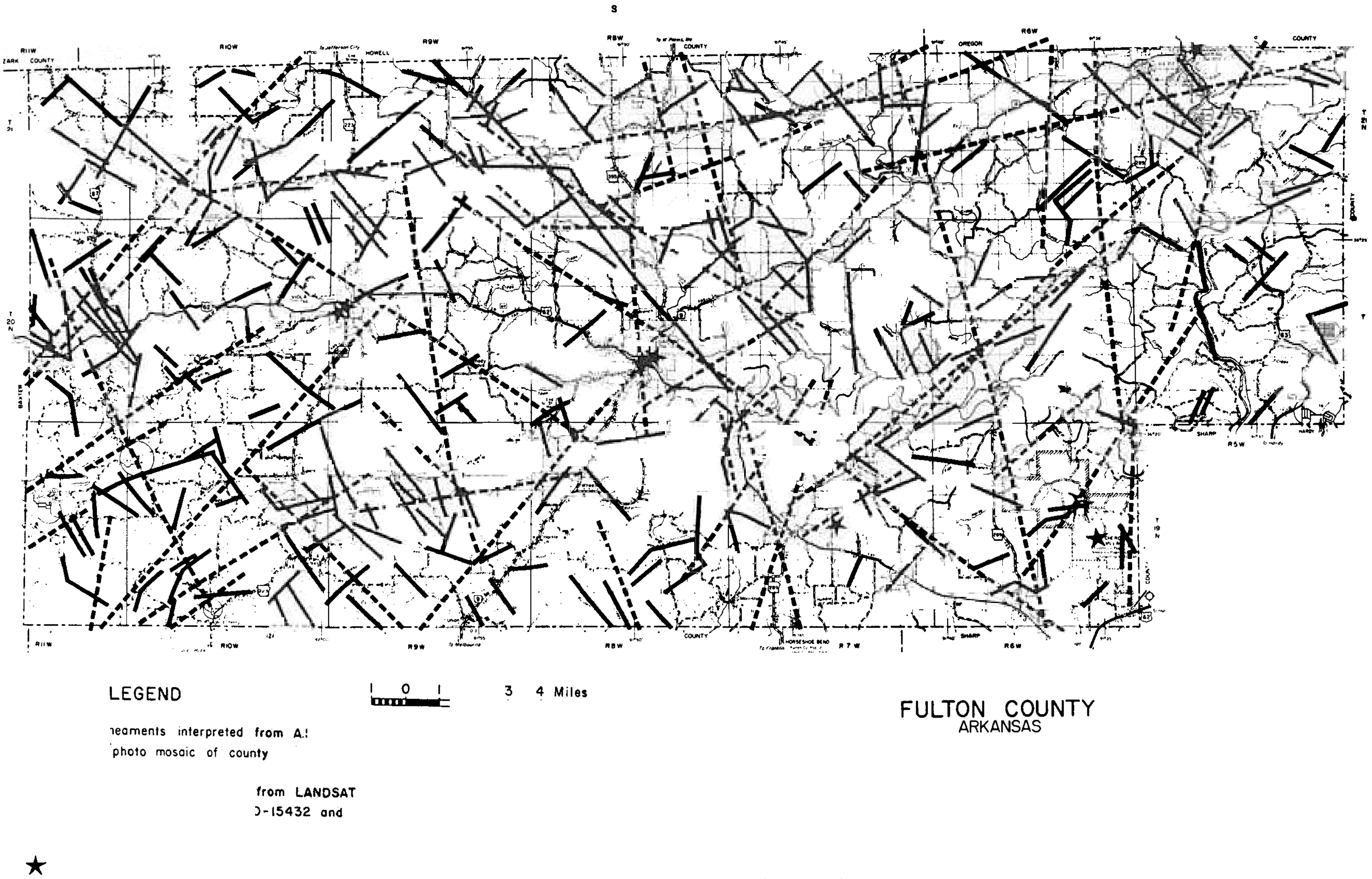


Figure 12 Lineament map of Fulton County

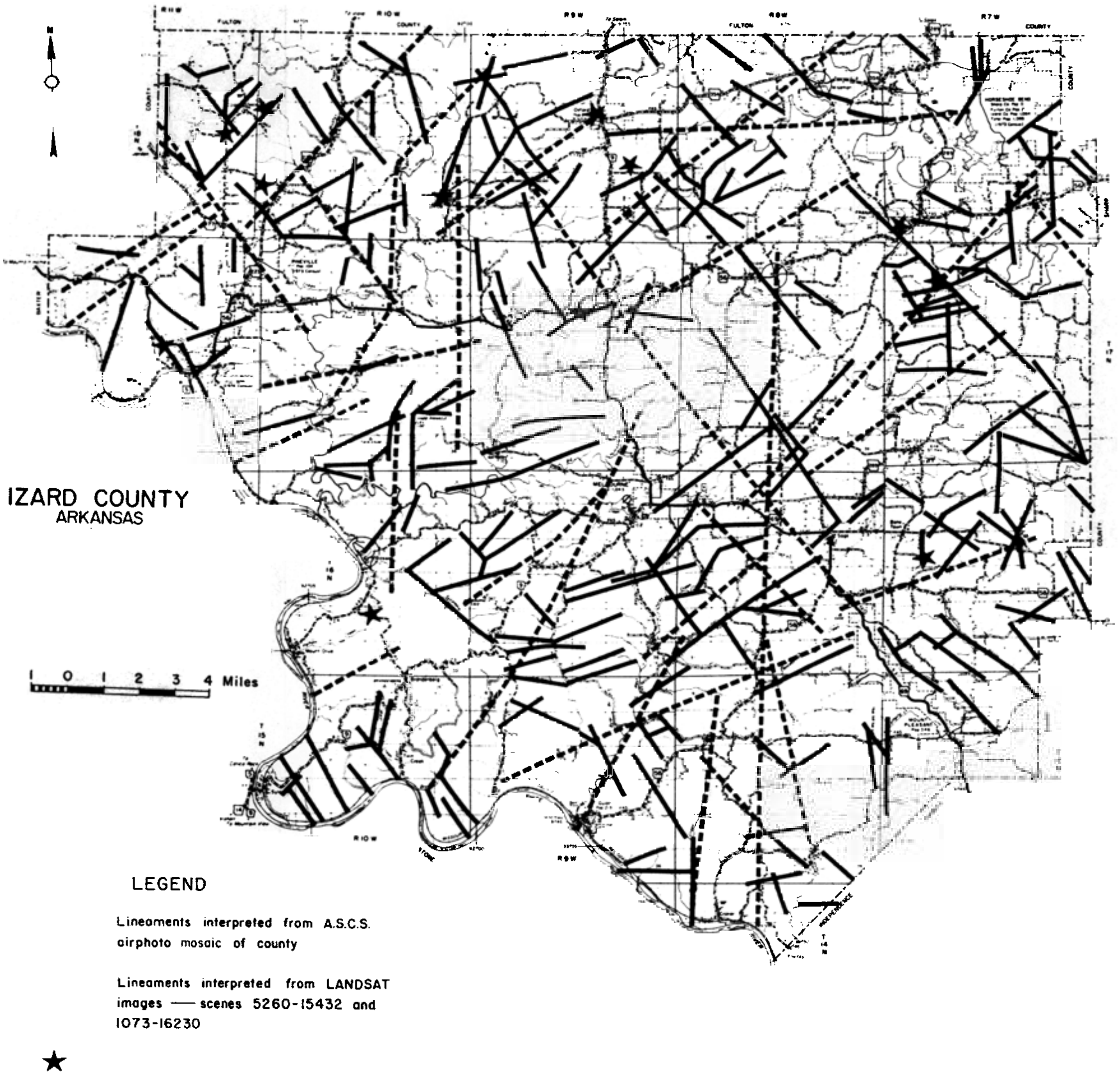


Figure 13. Lineament map of Izard County

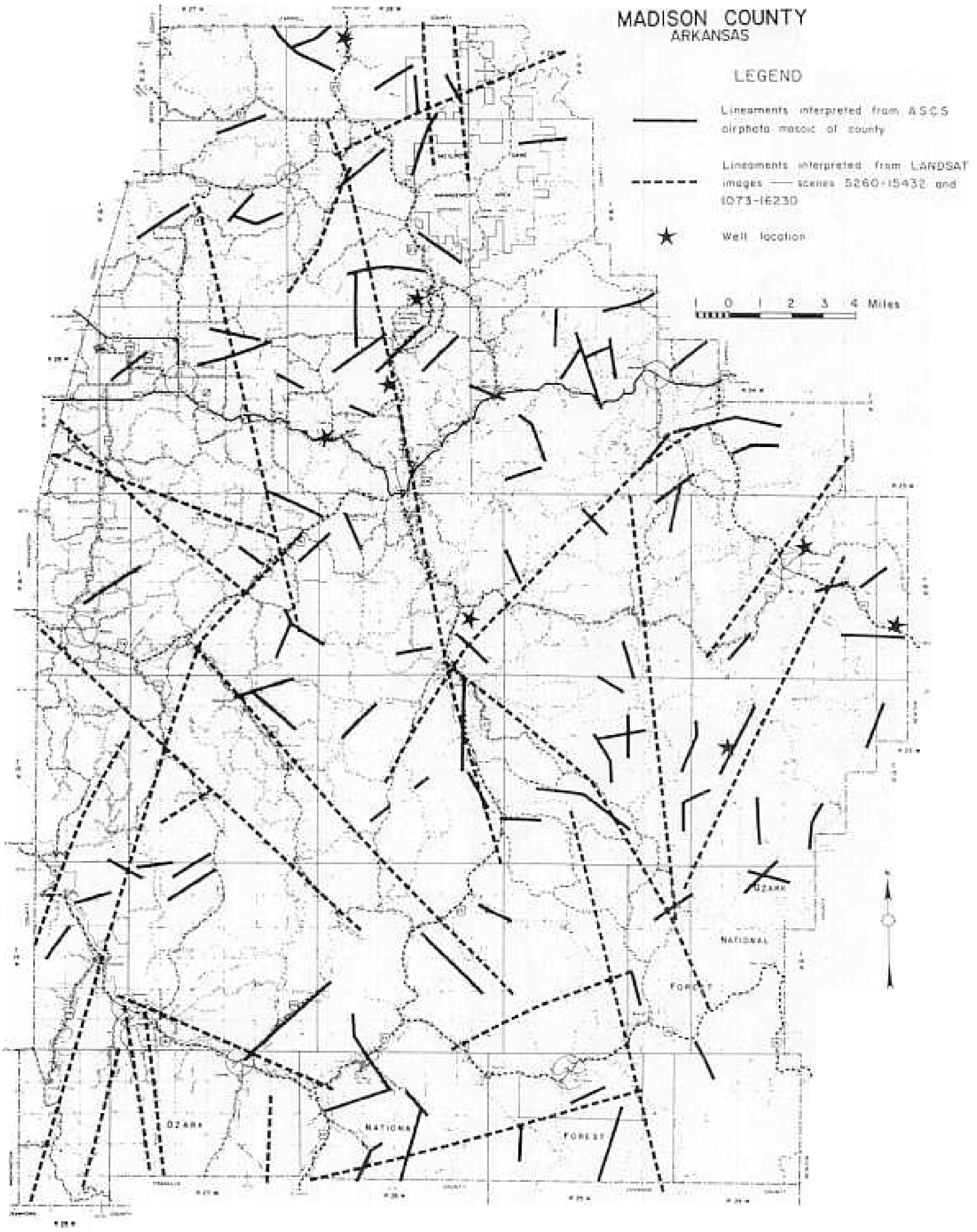


Figure 14. Lineament map of Madison County

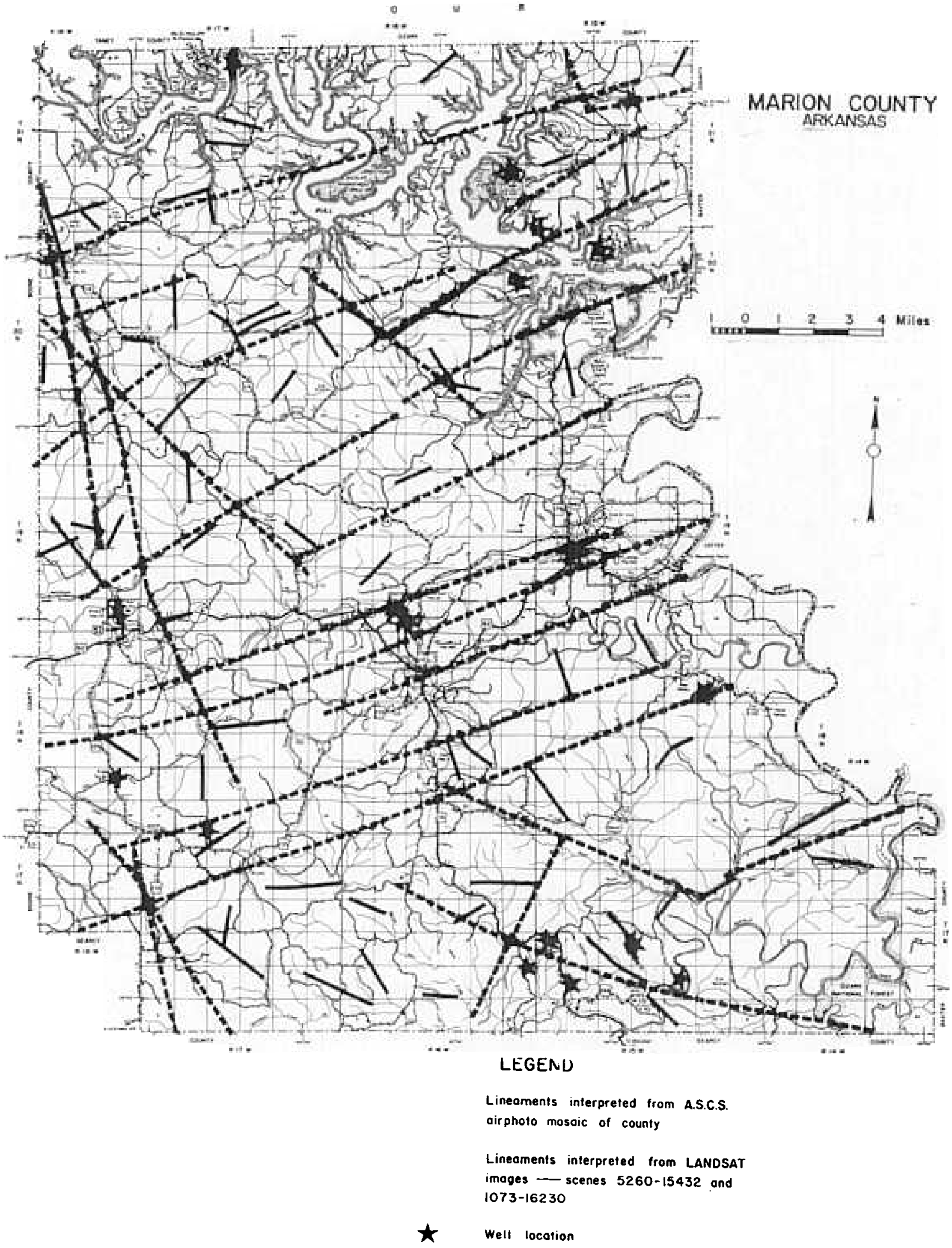


Figure 15. Lineament map of Marion County.

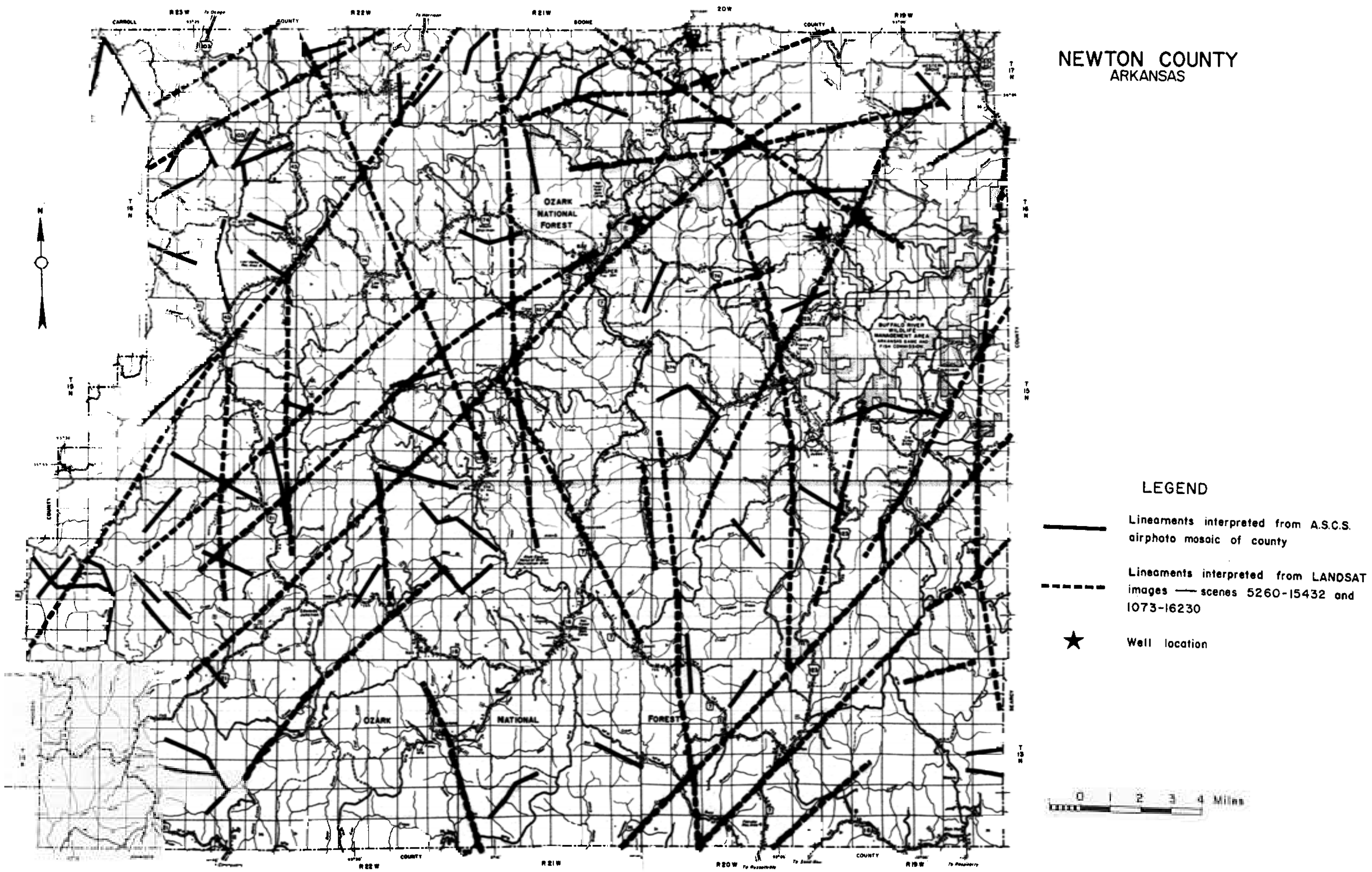


Figure 16. Lineament map of Newton County.

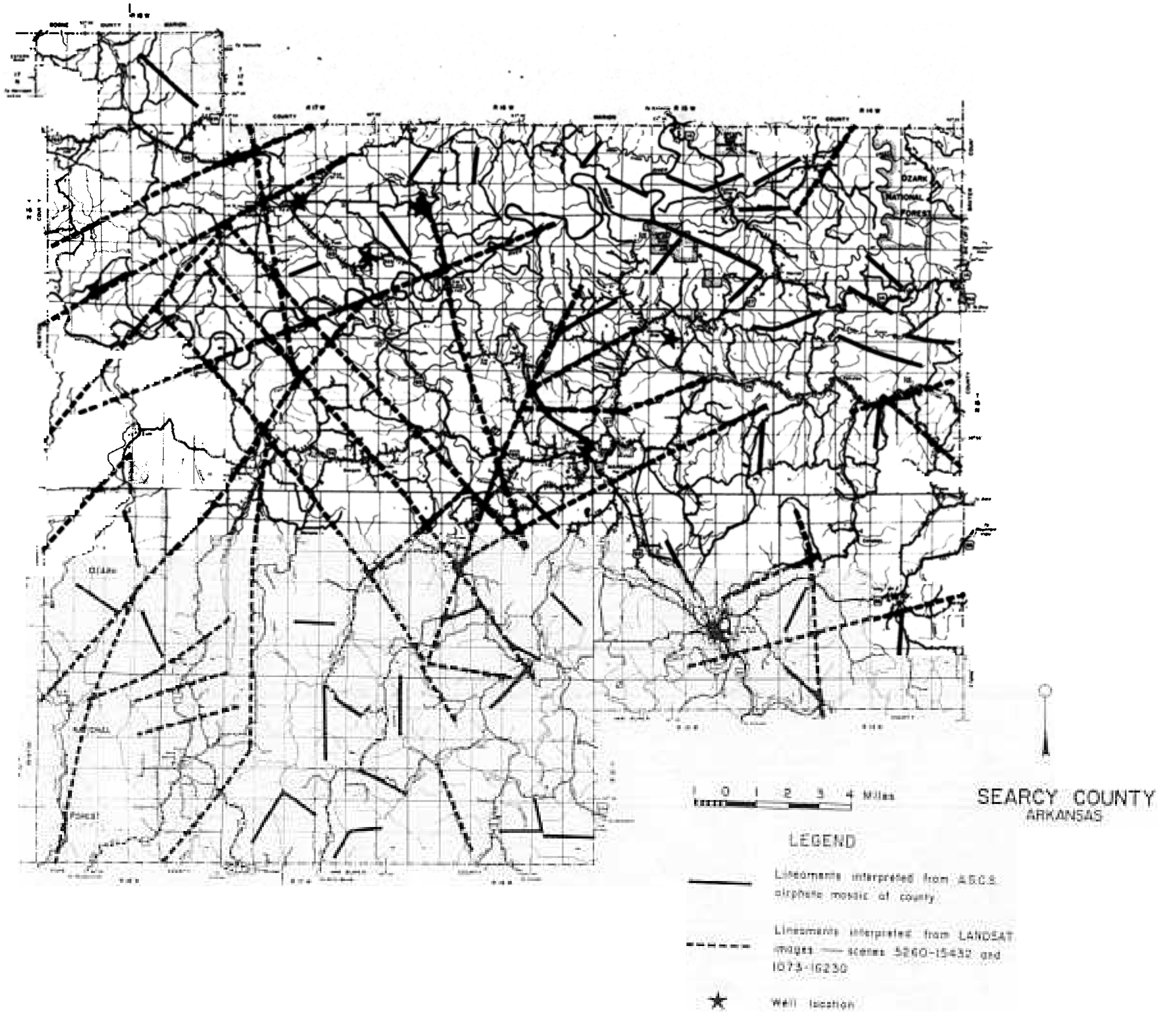


Figure 17. Lineament map of Searcy County.

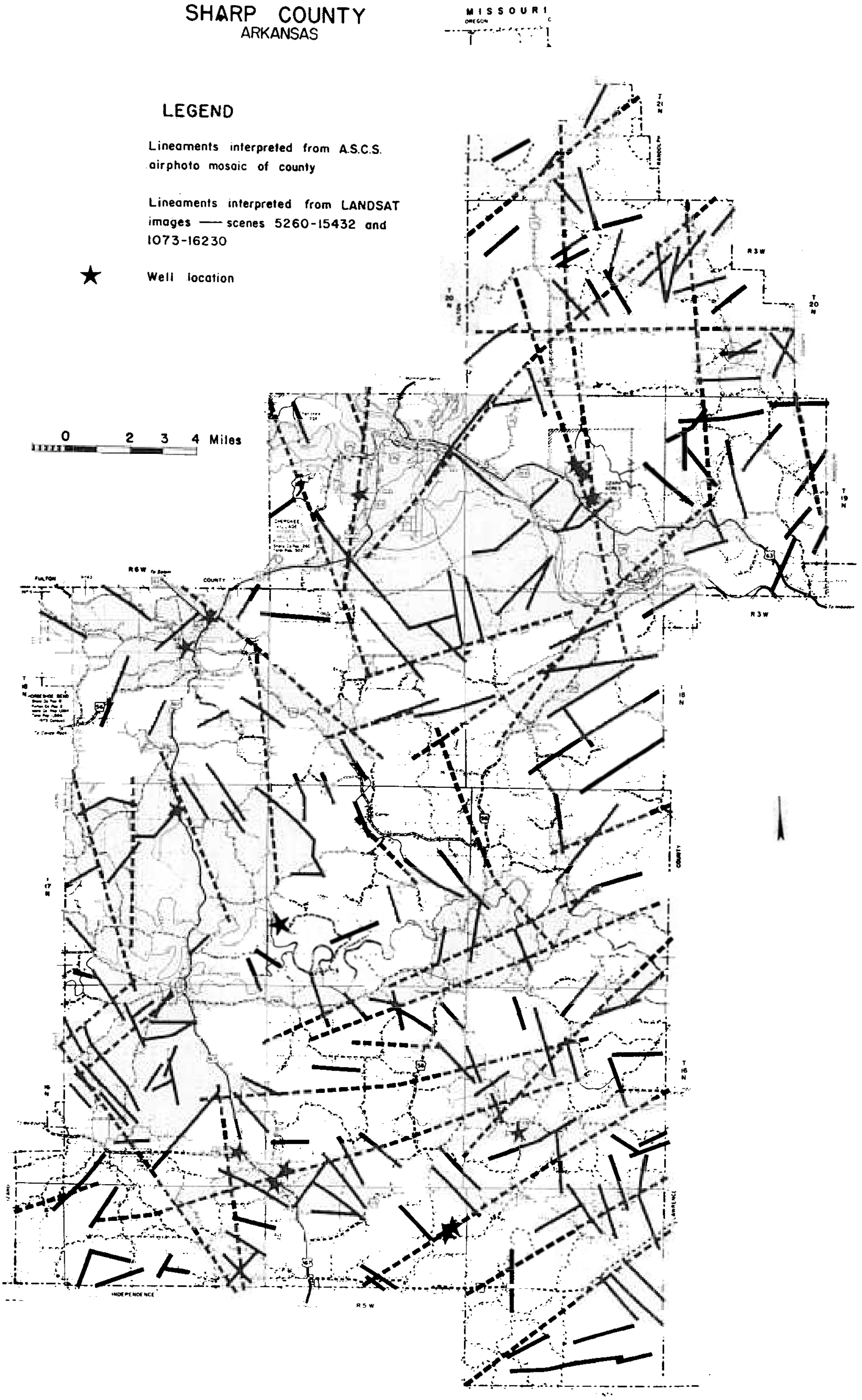


Figure 18. Lineament map of Sharp County.

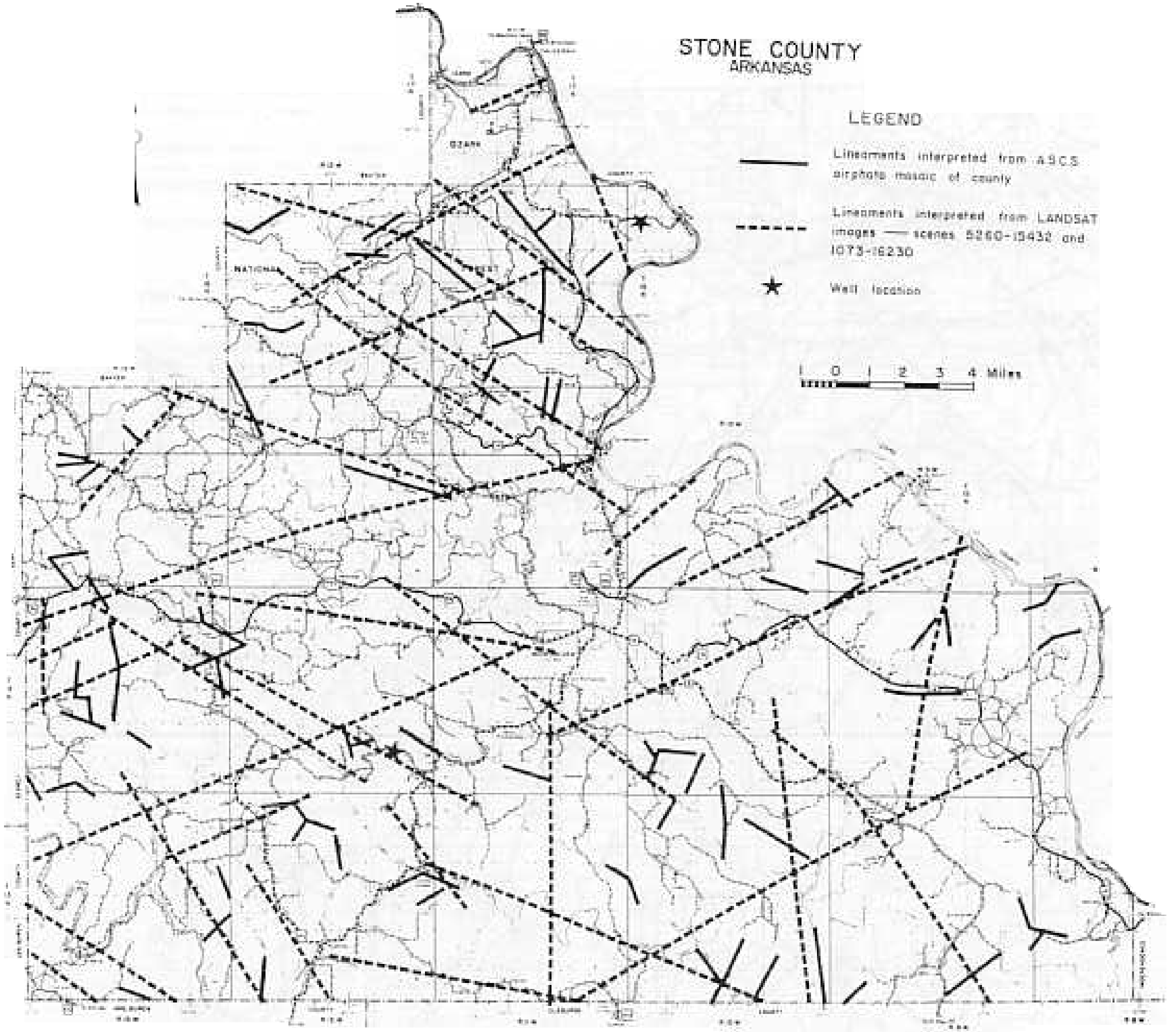


Figure 19. Lineament map of Stone County.

they were added to the county highway maps without its aid The transfer of these lineaments (shown as solid black lines in Figures 8 through 20) was more precise than the transfer of LANDSAT lineaments, because cultural features on the photographs could be correlated easily with corresponding map features.

Sources of Data

Well data were collected from the Arkansas State Geolog- Commission, the Arkansas Committee on Water Well Construction, the U.S. Geological Survey and local engineering firms. The well data submitted to the Committee on Water Construction by drillers are extremely varied in quality For example, the location cited in a particular well record may be as precise as the quarter-quarter-quarter section or as general as "stop at Roberson Gro. and ask how to get to Doyle Davenport's father's place". Records of a total of 130 wells had to be discarded because their locations could be determined from the driller's descriptions. Reported well yields are equally unreliable, because they are normally not supported by pump tests and are merely the driller's best guesses, which more often than not are extremely conservative.

The size of the study area prohibited the sampling of wells; historical water quality had to suffice for this study. Data were collected from the Arkansas Department of Public Health and the U.S. Geological Survey. These data, together with the yield data, were classified and tabulated according to the position of the well in relation to lineaments (Figs. 8 through 20).

Whether or not a well is on a lineament can be a subjective decision, because the actual width of the lineament often cannot be determined without field work. Consequently wells that are within a certain distance of a lineament are considered to be on that lineament. Parizek 1976) considered any wells within 1 km of a lineament to be on-lineament wells. Such a figure reflects the increase in secondary porosity near a lineament due to solutioning along bedding planes joints, and more soluble beds on either side of the lineament. Moore (1976) assigned a width of 500 meters to the lineaments he detected on SKYLAB photographs, which have better resolution than LANDSAT images. In the present study a distance of 0.5 mile was used; this figure takes into account the scale of the images used, and the margin of error introduced in lineament transferral, as well as the actual lineament width.

HYDROGEOLOGY

Groundwater in Northern Arkansas

The areas of groundwater availability in northern Arkansas can be divided into three units closely related to the physiographic divisions of the region. Water in the Salem Plateau province is derived from rocks of Cambrian and Ordovician age; because these aquifers crop out or are near the surface in this area, deep wells are not common. In the Springfield

Plateau and Boston Mountains provinces, groundwater can be drawn from near-surface Mississippian and Pennsylvanian rocks whose yields are low but sufficient for rural and domestic needs. Water in these aquifers usually enters a well under water table conditions; that is, it will not rise above the water table level in the well bore. In contrast, artesian conditions characterize the deeper aquifers exploited on the Springfield and Salem Plateaus and in the Boston Mountains. Water in all three provinces from aquifers of Cambrian and Ordovician age generally will rise to within a few hundred feet of the surface.

The presence of groundwater in shallow aquifers of the study area has been well documented viz. Coughlin, 1975; Hanson, 1973; Hunt, 1974 Deeper aquifers may furnish sufficient yields to supply industrial and municipal as well as domestic uses, and were chosen for concentration in this study because of their high-yield potential.

Hydrogeology of the Deeper Aquifers

Potosi and Eminence Dolomites. The deepest aquifers penetrated in the study area are the Potosi and Eminence dolomites of Cambrian age. These light-gray crystalline dolomite units are riddled with interconnected vugs which allow water to pass readily. Thus, the Potosi-Eminence aquifer is capable of excellent yields. A well drilled near Eureka Springs in Carroll County (well number 20N26W23aca, in Figure 11 penetrates nearly 300 feet of the Potosi-Eminence and produces gpm.

Although the Potosi-Eminence shows great promise as a high-yielding aquifer, little is known about it. The three wells in the study area which penetrate and produce from it in Benton and Carroll Counties (Figs. 9 and 11). In the Benton County well the elevation of the top of the Potosi-Eminence is 230 feet above sea level, whereas in the Carroll County well it is 85 and 110 feet below sea level. To reach horizon these wells penetrated to depths ranging from 1420 to 1630 feet, which are not unusual for the area. However, many wells which penetrate the Roubidoux and Gunter Formations have sufficient yields from these units and drilling ceases before the Potosi-Eminence is reached. In areas where overlying aquifers are insufficient, drilling through the Gunter to the Potosi-Eminence may prove to be an excellent alternative.

Gasconade Formation and Gunter Sandstone Member. The basal sandstone of the Gasconade Formation, known as the Gunter Sandstone, is one of the principal deep aquifers of the region. In the central part of the study area, this unit consists of a clean, mature sandstone; east and west the Gunter becomes progressively more dolomitic. Water from this unit is generally hard to very hard and is of the calcium-magnesium bicarbonate type (Lamonds, 1972) In the study area, yields range from 50 to more than 500 gpm and average about 250 gpm.

Water availability from the overlying dolomite of the Gasconade Formation is not understood in northern Arkansas.

Studies of wells in the Gasconade in Missouri indicate two zones: an upper, relatively impermeable zone, and a lower zone yielding sufficient supply for domestic use (Melton, 1976).

Roubidoux Formation. The Roubidoux Formation, also of Ordovician age, is often the target of drillers seeking reliable deep aquifers. This sandy, cherty dolomite yields water of the calcium-magnesium type that is hard to very hard (Lamonds, 1972). Yields in this study range from 30 to 600 gpm and average about 200 gpm.

Jefferson City and Cotter Dolomites. Because of their lithologic similarity, these two units are frequently undifferentiated in the subsurface. These sandy, cherty dolomites yield hard to very hard water of the calcium-magnesium bicarbonate type. Yields in the study area range from 4 to 100 gpm and average about 40 gpm

Well Hydraulics

The formulas and tests involved in the study of well hydraulics aid in the understanding of how a particular aquifer behaves under different conditions. In essence, hydraulics is a study of how much water is present in an aquifer and how readily the water will pass into a well. The index of productivity used for most of the wells in this study is the yield; although the amount of yield is determined by many factors besides available water (Parizek, 1976).

Reliability of the yield figure can be a function of well construction, well location, and aquifer characteristics.

A more accurate measure of the productivity of a well is its specific capacity, C, which is the yield of a well divided by its drawdown. Specific capacity is measured by means of pumping tests, during which a well is pumped for a period of several hours while the amount of water level drop, or drawdown is measured periodically. Though drillers make pumping tests primarily to determine the safe level to set a submersible pump, information gained from them is also useful in determining properties of the aquifer(s) involved

One property that can be derived from a pumping test is the transmissivity of the aquifer, or its coefficient of transmissibility. It is a measure of the rate at which water travels through a strip of the aquifer one foot wide and extending through the saturated thickness of the aquifer (Fig. 21) under a unit hydraulic gradient (Johnson Division UOP, 1975). Transmissivity, or T, can be determined by plotting drawdown against the log of time on semi-log paper. From this plot, T can be determined using the formula

$$T = \frac{264Q}{\Delta s}$$

where Q is the pumping rate, in gallons per minute and Δs is the change in drawdown in feet between two values of time on the log scale whose ratio is ten. The value of T is only an estimate of the true value, because the use of the equation involves certain assumptions which may not hold true in the aquifer being tested (Johnson Division, UOP, 1975

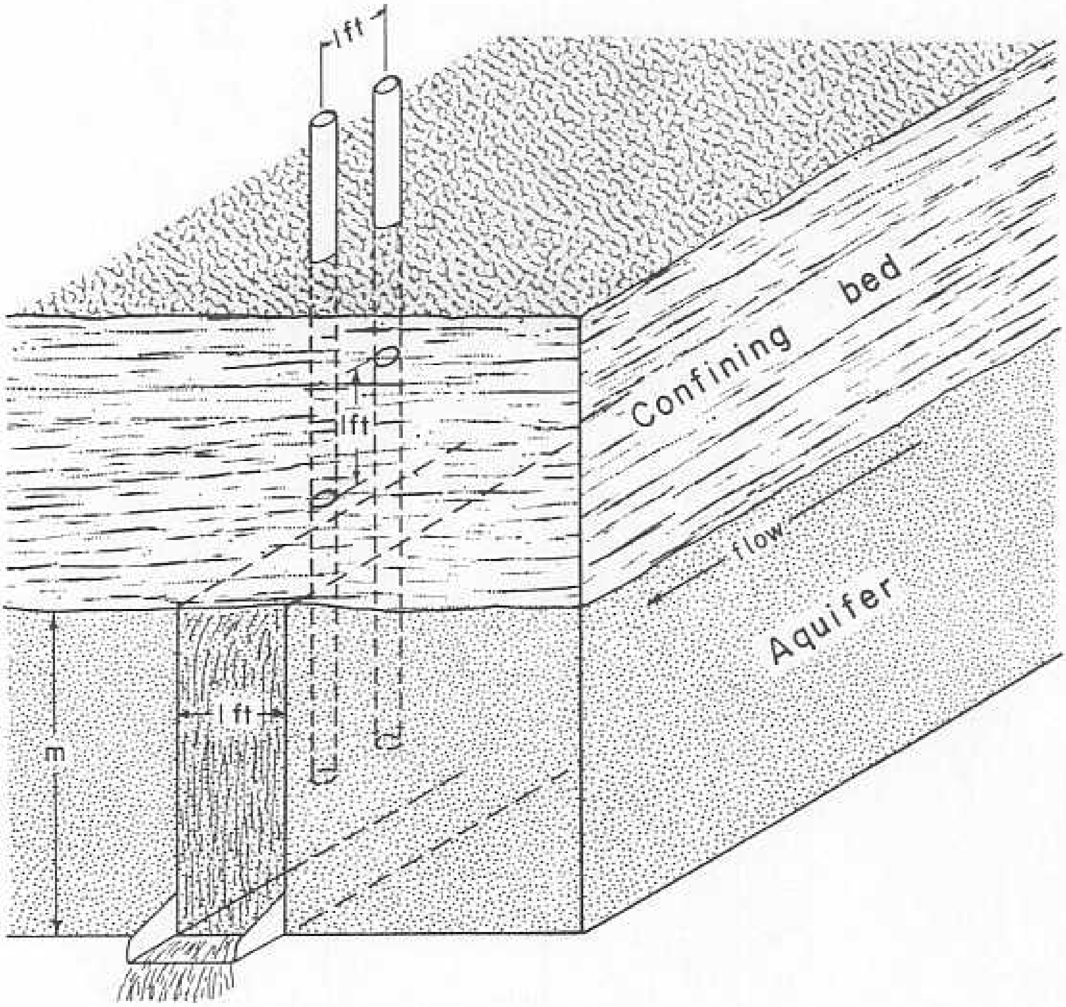


Figure 21. Graphical representation of the concept of transmissivity, or the rate at which water will travel through the saturated thickness (m) of the aquifer (from Johnson, UOP, 1975).

As an example of how T is calculated, information from a pump test of Well Number 19N16W32ada at Summit is plotted in Figure 22. Here the pumping rate is 85 gpm and Δs is 66 feet between 20 and 200 minutes of pumping:

$$T = \frac{(264)\ (85)}{66}$$

$$= 340 \text{ gpd/ft.}$$

Drillers are required by Section 10.3 of the Arkansas Water Well Construction Code (Appendix B) to test each new well for yield and drawdown. However, there is no provision in the code specifying how to conduct or record this test. In consequence, valid pump tests of domestic wells are rarely made and when made are rarely recorded.

The 13 pump tests available for this study were made in wells drilled for municipalities. These wells commonly are drilled under the direction of a civil engineer, who uses knowledge of hydraulics to ensure that the well will meet the greater demands of a town or water district. Because pump testing helps to determine the maximum yield that can be drawn from a well without lowering its water level, it is often done in new municipal wells drilled under the supervision of a civil engineer. The data used in this study were obtained from Melton (1976) and the engineering firms of John Mahaffey and McGoodwin, Williams and Yates, both in Fayetteville.

The pump test data were used to determine whether specific capacity and transmissivity values differ in wells on and off lineaments. Values obtained for pumping rate (Q),

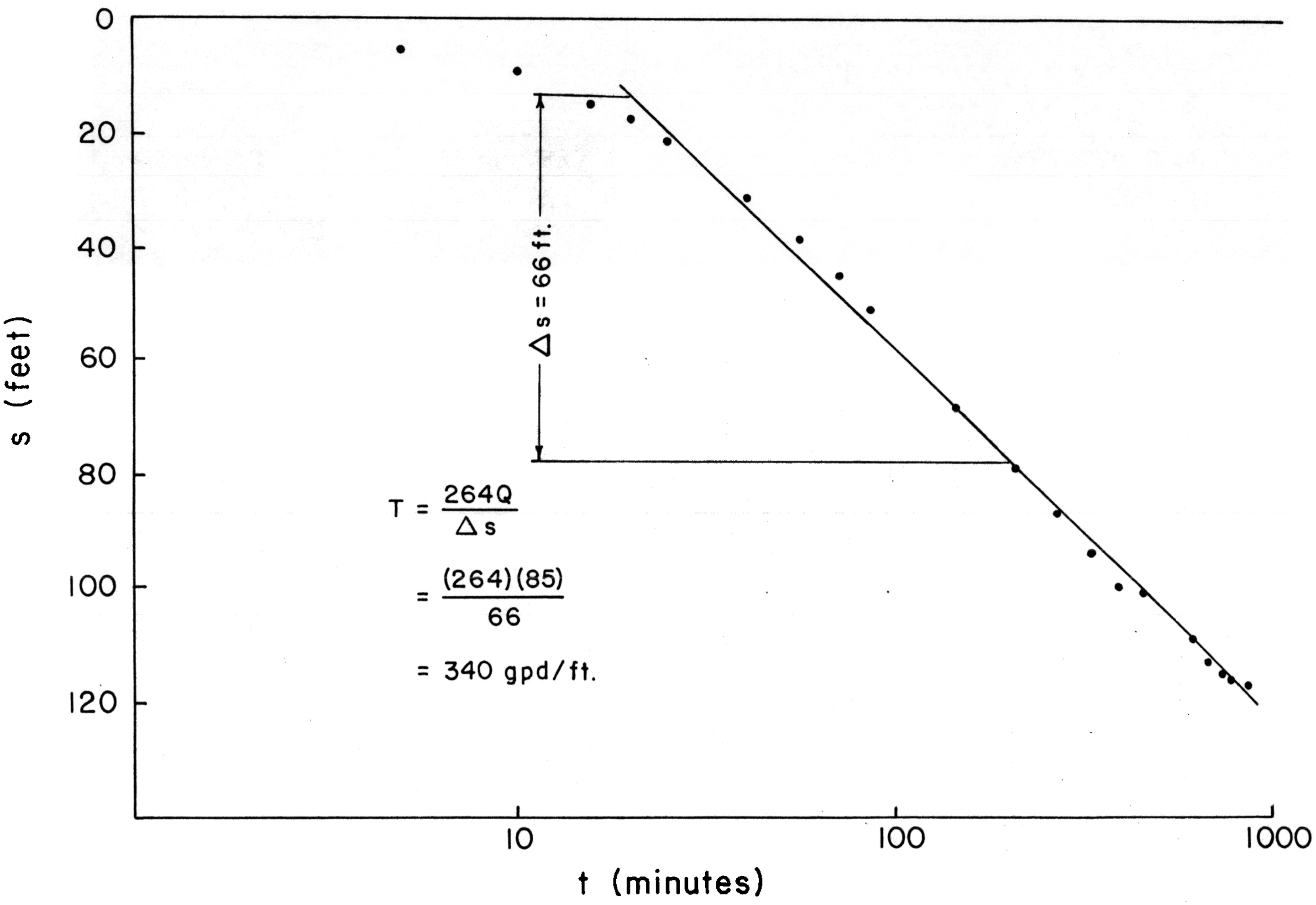


Figure 22. Plot of a pump test made in Well Number 19N 16W 32 ada at Summit, Arkansas.

transmissivities can be seen for wells on lineaments; however, the data are too sparse to constitute conclusive evidence of a relationship. It should be noted that these values commonly represent the contribution of more than one aquifer; for example, a well completed in the Gunter Member of the Gasconade Formation draws water from that unit as well as from the overlying strata. Thus it is impossible to assign specific values of T or C to individual aquifers, although figures may give a rough estimate of how the units differ in these properties

Well Yields and Lineaments

For most of wells in the study area no pump test data available. Consequently, comparisons of productivity of on-lineament and off-lineament wells had to be made on basis of yield alone. Unfortunately, this figure is influenced by many factors other than available water. Had drawdown figures been available, specific capacity would have been used, but yields were the only data given on most well records. These yield figures were analyzed statistically to determine whether a correlation could be found between high yields and well location.

The statistical test used in this investigation was the Fisher Exact Probability test (Siegel, 1956). The populations of two random samples are divided into two classes which are mutually exclusive by construction of a four-celled contingency table such as the one in Figure 23. Four tests were performed for this study: (1 wells described by drillers

Table 1. Yield, specific capacity, and coefficient of transmissibility for 13 wells in the study area.

Aquifer Well Number	Q (gpm)	C (gpm/ft)	T (gpd/ft)	Location
Roubidoux				
15N 21W 13 c	63	0.5	385	On-lineament
19N 14W 28 dba	500	2.72	5245	Off-lineament
20N 16W 12 ba	61	1.0	2000	Off-lineament
21N 21W 27 aad	52	1.04	685	Off-lineament
21N 26W 17 bcc	600	8.82	6100	On-lineament
21N 26W 26 ada	502	5.9	6300	On-lineament
Gunter				
17N 20W 21 bca	300	0.85	1100	On-lineament
18N 19W 33 bbb	200	1.27	1550	Off-lineament
19N 14W 29 dbc	300	1.56	1200	Off-lineament
19N 16W 32 ada	82	0.3	340	On-lineament
20N 26W 16 cd	250	1.31	1450	Off-lineament
21N 26W 26 ada	502	5.9	9500	On-lineament
Potosi-Eminence				
20N 26W 23 aca	250	8.62	12,000	On-lineament

Driller - Reported Wells

	Yield	
	<10 gpm	≥10 gpm
Wells off lineaments	A 34	B 25
Wells on photo-lineaments	C 7	D 8

U.S.G.S. - Reported Wells

	Yield	
	<150 gpm	≥150 gpm
Wells off ineaments	A 11	B 10
Wells on satellite lineaments	C 27	D 22

Figure 23 Two examples of four=celled contingency tables used for the Fisher Exact Probability test on well yields.

on photolineaments versus those between lineaments; (2) wells described by drillers on satellite lineaments versus those between lineaments; 3) wells described by the U.S. Geological Survey on photolineaments versus those between lineaments; and (4) USGS - described wells on satellite lineaments versus those between lineaments. A distinction between driller- and U.S. Geological Survey-described wells was made because yields reported on driller's logs are usually an order of magnitude lower than those reported by the USGS. This difference is a reflection not of the skill of the drillers involved in finding water but rather of the care and accuracy with which yields are reported. The yields cited on USGS-described wells are obtained from accurate pump tests, while those on driller reports appear to be rough estimates made simply to fill in the blank on the report form.

The numbers obtained from the contingency table are substituted into the Fisher Exact Probability formula (Siegel, 1956):

$$P = \frac{(A+B)!\ (C+D)!\ (A+C)!\ (B+D)!}{N!A!B!C!D!}$$

where A, B, C, and D are the number of wells in each respective cell, and N is the sum total of all wells used in that test

The results of the Fisher test are shown in Table 2. In all cases except one, alpha probability is well under the 0.05 maximum chosen to indicate statistical significance. Thus in these instances there is a definite relationship between lineaments and high well yields.

The one instance in which the alpha probability exceeds the 0.05 limit is the test on driller-reported wells on photolineaments. In all three tests on driller-reported wells the alpha probability level is considerably higher than it is for USGS-reported wells. These observations may reflect the inaccuracy with which both yield and location often are reported on drillers' logs. The possibility of geologic factors causing this lack of correlation is excluded by the fact that USGS-reported wells on photolineaments show a positive correlation. Presumably those lineaments which are intersected by driller-reported wells are of the same nature and origin as those intersected by USGS-reported wells. Therefore, the difference between them must be related to the manner in which drillers' well reports are written. Inaccuracy in well location is such a common feature of these reports that the Arkansas Geological Commission allows a margin of error of plus or minus one mile in working with these records (Hanson, 1973).

Results of Similar Studies Elsewhere

With one exception, the Fisher Exact Probability test shows that fracture traces and lineaments are surface manifestations of increased secondary porosity, and as such are a means by which higher yields can be obtained in wells in northern Arkansas. These positive results are substantiated by workers elsewhere. Two lineaments of major proportions were mapped in Alabama by Drahovzal et al. (1973), who found that they had a marked influence on movement and distribution

Table 2. Results of Fisher Exact Probability test for well yields.

Comparison	Number of Wells in Each Cell A	 B	 C	 D	Alpha Probability P
Driller-Reported Wells					
Wells between Lineaments vs. Wells on Photolineaments	34	25	7	8	0.17
Wells between Lineaments vs. Wells on Satellite Lineaments	34	25	7	22	0.006
Wells between Lineaments vs. Wells on Either Type Lineament	34	25	17	30	0.011
U.S. Geological Survey-Reported Wells					
Wells between Lineaments vs. Wells on Photolineaments	27	22	5	6	0.004
Wells between Lineaments vs. Wells on Satellite Lineaments	27	22	11	10	0.002
Wells between Lineaments vs. Wells on Either Type Lineament	27	22	16	16	0.0003

of groundwater in the area. Wells and springs in areas of lineament concentration showed consistently higher yields, and streams in nearby drainage basins showed abrupt increases in flow after crossing a lineament. Gravity surveys across one lineament showed a sharp negative anomaly, which led the authors to conclude that the lineaments may be related to offsets in the basement complex. In a later paper, Drahovzal (1974) theorized that these lineaments are a landward extension of the Bahama fracture zone and as such are related to major crustal stresses

Studies in the Pampa of Argentina (Kruck and Kantor 1975 show that LANDSAT lineaments commonly serve as guides to good water in this area where near-surface water is brackish. Runoff from the uplands surrounding elongate, flat-bottomed depressions bajos collects and infiltrates the subsurface. Small lenses of fresh water are localized by these bajos, which have no surface drainage. The fresh water source thus created is sufficient for the rural need of the region. LANDSAT, with its synoptic view of the area, aids in identification and mapping of these features, which appear as sharply defined dark strips on the images.

Tomes (1975) found that lineaments and fracture traces in the Bighorn Mountain region of Wyoming are expressions of structures which affect the movement and availability of groundwater in the area. Sinks, springs, and cave systems are localized along lineaments in the Bighorn Dolomite. Dye traces indicate that at least parts of these underground systems are involved in recharge to the aquifer as well as temporary underground transmission of surface waters (Tomes, 1975).

Moore 1976) tested the hydrogeologic significance of lineaments taken from SKYLAB images of central Tennessee By comparing yields in both new test wells and in previously drilled wells, he found that wells on SKYLAB lineaments show an average yield about six times higher than that of wells located randomly

The studies cited and the present study, have shown that lineaments and fracture traces are useful tools in the search for groundwater. However, in some instances these tools have not been effective. Meisler (1963), for example, studied the relationship between well productivity and fracture traces in the Lebanon Valley of Pennsylvania, which is underlain chiefly by limestone. Using specific capacity instead of yield, he found no significant increase in productivity in wells located on fracture traces. Ogden (1976), working in an area in West Virginia lithologically similar to the Lebanon Valley, used statistics to compare well yields on and off lineaments. His results show that well yields were not significantly improved by location near lineaments

Thus in two studies, one supported by statistical analysis, the lineament-fracture trace method of well location was unsuccessful. Why the method has failed in some limestone terranes and succeeded elsewhere is not well understood, and is a subject that warrants additional study.

WATER QUALITY

Introduction

The geochemical character of water from a well is determined largely by the type of rock from which the water is drawn. Thus water from limestone can be expected to contain a predominance of calcium and bicarbonate ions, whereas water from shale contains a higher percentage of other dissolved constituents such as sodium, chloride, and sulfate ions. In general water from the wells in the study area is of the calcium-magnesium bicarbonate type, which reflects its residence time in dolomite. Determination of water quality in individual aquifers, however, is not possible once a well has been completed. Because casing depth usually does not exceed the limit set by state laws, water entering a well from a particular level is mixed with water coming in above and below it. Samples taken at the surface therefore may represent a mixture of several different sources of water to the well

The relationship of groundwater quality to lineament location has not been studied extensively. Coughlin (1975) noted that wells and springs along fracture traces in the Boone Formation in Washington County show lower concentrations of dissolved solids than those between fracture traces. He attributed this difference to higher flow rates, which allow less opportunity for dissolution of solids from the surrounding rock. He also noted that wells on fracture traces show evidence of bacteriological contamination originating at the surface. Because the wells used in this study tap confined aquifers and are deeper than those used by Coughlin (1975) it is not likely that surface contamination affects the quality of water from them. However, a comparison of water quality in on-lineament and off-lineament wells is of value to this study because it may elucidate the effect of lineaments on water quality.

Water quality data from 36 wells in the area were obtained from the Arkansas State Department of Health and the U.S. Geological Survey. These were tabulated according to the position of the well in relation to lineaments. Values for total hardness, and dissolved solids, as well as calcium, magnesium, sulfate, chloride, nitrate, iron, sodium, and potassium ion concentrations were tested by the Fisher Exact Probability test (Siegel, 1956) for significant correlation between water quality and location.

Total Hardness. The concept of total hardness is difficult both to define and to understand. In general, hardness is understood as a property that greatly affects the behavior of soap in water. Observations of encrusting scale formed by soap and water led to the development of a procedure titrating hardness with a standard soap solution (Hem, 1972). Today the most widely accepted definition of hardness is in terms of two constituents which are most often responsible for its effects; calcium and magnesium. Hardness usually is computed by multiplying the sum of milliequivalents per liter of calcium and magnesium by 50, and is reported as mg/l $CaCO_3$ (Hen, 1972)

Hardness by nature is an inexact term, but has been quantified somewhat in the classification devised by Durfor and Becker (1964), as follows

Hardness Range (mg/l $CaCO_3$)	Description
0 - 60	Soft
61 - 120	Moderately hard
121 - 180	Hard
Higher than 180	Very hard

Although the U.S. Public Health Service has set no standards for hardness, levels greater than 100 mg/l are considered troublesome for domestic use. Hardness values for wells in the study area range from 80 to 300 mg/l $CaCO_3$, and reflect the dominantly dolomitic lithology of deep aquifers in the area.

Total Dissolved Solids. The dissolved solids content of a water sample is a good general indicator of its overall quality and is a useful parameter in comparing samples. Two methods are used in its determination: (1 evaporating an aliquot of the sample and weighing the residue, and (2) summing the concentrations of all ions tested. Dissolved solids values for wells in the study area range from 160 to more than 500 mg/l, and average 260 mg/l. The USPHS recommends that total dissolved solids not exceed 500 mg/l.

Calcium and Magnesium. Calcium is the dominant cation in most natural fresh water because of its common presence in all rock types. In limestone and dolomite, calcium is most commonly in the form of calcite $CaCO_3$) and dolomite ($CaMg(CO_3)_2$). In the study area dolomite prevails in the subsurface; consequently the magnesium ion is also important in local water samples. Concentrations of Ca^{+2} in well samples from the study area range from 14 to 85 mg/l, and average about 45 mg/l. Concentrations of Mg^{+2} range from 2 to 82 mg/l and average about 25 mg/l.

Sulfate. Sources of the sulfate anion, SO_4 , are metallic sulfide minerals in igneous and sedimentary rocks. Pyrite, commonly found in sedimentary rocks deposited under reducing conditions (such as shale), can be seen as the chief source of sulfate to wells in the study area. Both the Chattanooga Shale and the Fayetteville Formation contain considerable pyrite Croneis, 1930), which when oxidized may contribute sulfate to well waters. Values for sulfate concentrations in the study area range from 0 to 60 mg/l and average about 15 mg/l, well below the USPHS limit of 250 mg/l

Chloride. Chloride is rare in all rock types, with the exception of chloride included as connate brines and/or evaporates in sediments. Melton (1976) reported that in the study area chloride concentrations appear to increase with the regional gradient. From an average of 17 mg/l in Benton County, chloride concentrations increase to 2000-3000 mg/l in two deep gas wells south of the study area. Melton's observation cannot be substantiated for the entire study area because few analyses are available for wells in the southern half. The USPHS limit for this anion is 250 mg/l; greater concentrations may cause an unpleasant taste in the water

Nitrate. Nitrate (NO_3^-) concentrations can be attributed to the small contribution of bacteria living in soil and water, and to the potentially large contribution of fertilizers and the decomposition of human and animal waste. Excessive concentrations have been linked to the incidence of infant methemoglobinemia; consequently, Public Health officials have set a limit of 45 mg/l in drinking water. Chloride is also an important anion in raw sewage, and may actually persist longer than nitrate in natural water systems (George and Hastings, 1951). In the study area, chloride concentrations range from 0 to 42 mg/l, and average about 6.6 mg/l. Nitrate concentrations range from 0 to 3.6 mg/l and average 0.29 mg/l

Iron. Sources of iron in sedimentary rocks include pyrite (FeS_2) and hematite (Fe_2O_3). Iron is an abundant element, which even if present in low concentrations may make water unacceptable for certain uses. Consequently analyses for iron commonly are made in the evaluation of the overall utility of a potential supply. Concentrations of iron in study area wells range from less than 0.05 to 2.25 mg/l, and average about 0.16 mg/l. Quantities greater than the USPHS limit of 0.3 mg/l may cause staining of fixtures and an unpleasant taste in the water.

Sodium and Potassium. Sodium and potassium are of fairly equal distribution in igneous and sedimentary rocks. However sodium is more easily removed from minerals and remains in solution readily, whereas potassium, when liberated from a mineral, usually becomes part of a solid weathering product Consequently sodium concentrations can be expected to be much higher in natural waters than potassium concentrations. This is true in the study area, where sodium values range from 1 to 93 mg/l and average 14 mg/l, and potassium values range from 1 to 7.5 mg/l and average 2.8 mg/l. The USPHS limit for sodium in drinking water is 500 mg/l; higher concentrations may cause a bitter or salty taste.

Water Quality and Lineaments

The water quality data used in this study are tabulated in Appendix E. These data were classified according to the position of the well in relation to lineaments and were tested statistically by the Fisher Exact Probability test. Results of the Fisher test are shown in Table 3. Alpha probabilities for chloride, hardness, and dissolved solids are below the 0.05 maximum chosen to indicate a significant relationship, and the P value for combined calcium and magnesium is just above it. Within the area tested, therefore, wells on lineaments show significantly higher values for chloride, hardness, and dissolved solids and a strong probability of higher calcium and magnesium concentrations than wells off lineaments.

The increases in hardness and dissolved solids were unexpected in light of previous work; in fact, the results obtained in this study for dissolved solids content are directly opposite those obtained by Coughlin (1975 in his

Table 3. Probabilities obtained from the Fisher Exact Probability test for water quality data.

Test	Number of Wells in Each Cell A	B	C	D	Alpha Probability
Total Hardness	14	8	4	9	0.05
Total Dissolved Solids	14	8	3	10	0.02
pH	12	10	8	6	0.2
$Ca^{+2} + Mg^{+2}$	14	8	5	9	0.07
Fe^{+2}	8	12	7	6	0.2
Na^{+}	7	8	5	3	0.2
K^{+}	3	2	4	3	0.4
Cl^{-}	11	7	4	7	0.00001
SO_4^{-}	10	8	5	6	0.2
NO_3^{-}	10	11	5	6	0.28

study of the Boone Formation in northern Washington County.

wells used in Coughlin's study are shallower than those used here, and penetrate rock units which are unconfined. Discharge areas are close to recharge area, therefore groundwater moves rapidly through these aquifers, particularly where solution cavities are present. Under such rapid transport, it is to be expected that water within shallower aquifers will have little opportunity to dissolve ions from the rock.

With the exception of the Jefferson City and Cotter dolomites, which crop out in that part of the study area on Salem Plateau, the deep aquifers considered in this study do not crop out in Arkansas. Therefore over a very broad area, there is little opportunity for natural discharge from these aquifers. Water movement appears to be generally downdip, to the south and southwest, but is not facilitated by large amounts of discharge at any point; thus the hydraulic gradient is probably no steeper than the very gentle dip ($<1^{\circ}$ of the rocks themselves. Consequently water movement is expected to be very slow, even within the solution-widened fractures manifested by fracture traces and lineaments. These passages provide water to wells because they act as areas for storage as well as transport

The rapid movement of water responsible for Coughlin's lower values on lineaments is absent here; in consequence, time may not be a limitation on the amount of dissolution can occur within a fracture in a deep aquifer. The removal of this limitation may help to explain why the results of this study contradict what is generally considered to be the expected pattern.

Because the length of residence time within the rocks is not expected to differ for water in wells on and off lineaments, another variable must be acting to create the higher values for hardness, calcium and magnesium, and total dissolved solids in on-lineament wells. Perhaps this variable is the degree of fracturing in the rock. Rocks in fractures are often broken or crushed, and thus expose a greater amount of surface area to circulating groundwater than unbroken rock. On this larger surface area more dissolution occurs than would take place on the surface of unbroken rock. That a greater amount of dissolution is taking place in these fracture zones is demonstrated by the high concentrations of Ca^{+2} and Mg^{+2} in on-lineament wells. An increase in these ions will cause a similar increase in hardness and total dissolved solids. Additional study of whether increased dissolution is facilitated by increased surface area in fracture zones, as described here, would contribute to the understanding of how lineaments affect groundwater quality.

Two mechanisms are suggested to explain the higher concentrations of chloride in on-lineament wells. The first is coincidence; the highest on-lineament chloride content is in wells in the southern tier of counties in the study area. These wells may reflect the pattern observed by Melton (1976) of a southward increase in chloride content. Most of the wells in the southern half for which water quality data are available are on lineaments, and these wells in turn show some of the highest chloride values. Unfortunately no water quality data for wells off lineaments are available for Madison, Newton, Searcy and Stone Counties; such data would allow a more meaningful comparison to be made, and perhaps a relationship could be established for the southward increase in chloride content.

The second mechanism for chloride enrichment might involve vertical leakage from overlying shale units. These units are known to contain water which is more highly mineralized than waters from other rock types (Coughlin, 1975). Because of the low permeability of shale units, their waters do not mix with water from adjacent units until they are penetrated by an uncased well. Similar penetration by a fracture may provide a mixing zone in which mineral-rich waters from shale affect the composition of waters from above and below. If this were the case, enrichment of many anions and cations, such as Na^+, K^+, Fe^{+2}, and SO_4^-, might be observed; however, chloride is the only ion to show statistically higher concentrations in on-lineament wells.

Detailed study of the role of lineaments in groundwater quality was hampered by the small number of data points. This comparison of water quality in wells on and off lineaments is of limited value, because the number of data from either type well was imbalanced in most of the counties in the study area. For Example, all the wells in Benton County for which water quality data were available are off-lineament wells, whereas all the data for Izard and Marion Counties are from on-lineament wells. Field testing of wells was not possible in this study because of the large size of the study area and time limitations. However, for future studies of water quality in the deep aquifers in northern Arkansas, extensive field work will be necessary to obtain a sufficient coverage of data. Without such data coverage, a meaningful study of lineaments and groundwater quality will be very difficult.

SUMMARY AND CONCLUSIONS

Intelligent development of groundwater resources is a process that requires a thorough understanding of the availability and movement of groundwater. In northern Arkansas knowledge of the deep aquifers is fairly limited, perhaps because economic factors and uncertain yields have discouraged exploitation. The development of these deeper aquifers to their fullest potential as reliable water sources depends on the delineation of high yield areas, a process that may be facilitated by linear trend analysis as outlined in this study.

Fulfillment of the specific objectives of this study was accomplished, although not to the degree initially anticipated. The consideration of how groundwater moves and is recharged, as well as some aspects of water quality, was an original objective of this investigation that could not be fulfilled because of lack of accurate data. Other objectives were met in the following manner

1) Satellite and photolineament maps of the 13 counties were prepared, by use of LANDSAT images and Agricultural

Stabilization and Conservation Service photo indexes. Lineaments were drawn on acetate overlays and transferred to county highway maps.

The Lineaments and fracture traces on aerial photographs and LANDSAT images are natural linear features such as aligned stream segments, soil tonal and vegetal alignments, and topographic sags. These features are the surface manifestation of subsurface fracture zones of undetermined origin, which are areas where increased solutioning of carbonate rocks has taken place.

2) A comparison of yields in wells on and off lineaments was made by statistical analysis. In all statistical tests except one, wells on lineaments showed significantly higher yields than did those between lineaments. The one test in which the relationship did not hold was on wells reported by drillers on photolineaments. The lack of correlation for yield and location of these wells was ascribed to inaccuracy of locations and yield figures on the drillers' reports

The fact that higher yields are obtained from wells on lineaments shows that these linear features are indeed surface manifestations of increased solutioning in the subsurface. These zones of fracture, enlarged by groundwater circulation, are capable of transmitting a greater volume of water at a faster rate than rocks between lineaments. Wells tapping these zones consequently show higher yields than those drilled randomly

3) Water quality data for 36 wells on and off lineaments were compared statistically. Higher concentrations of

chloride, total hardness, and total dissolved solids were indicated by the test, which also indicated a strong probability of higher combined calcium and magnesium concentrations in on-lineament wells. All other ions tested did not show significant increases in wells on lineaments.

Although water in wells both on and off lineaments is hard to very hard, its general quality is good. Those constituents which show greater concentrations in on-lineament wells still do not exceed limits set by the U.S. Public Health Service. However, chloride concentrations may increase downdip; data were not sufficient to establish a regional trend of chloride concentration that corresponds to the regional gradient

RECOMMENDATIONS

The results of statistical testing of well yields in the study area show that the fracture trace-lineament method of well location can result in improved well yields. In northern Arkansas where shallow groundwater supplies soon may not meet the demands of a growing population, linear trends interpreted from LANDSAT can be useful in the search for more reliable groundwater sources. Their use will help the development of the deep aquifers of the area as reliable sources for domestic, municipal and industrial water supplies.

More detailed analysis of the relationship between lineaments and groundwater was prevented by the inconsistency of data available for the area. Future studies of the hydrogeology of the deep aquifers will be impaired by the lack of data, unless data standards are improved. Recommendations for improving data gathering standards include the following.

1) Water well drillers must be encouraged to improve the data content of their well construction reports. Section 12c of Arkansas Act 641 terms a violation any failure to turn in a "Report of Water Well Construction" to the Arkansas Committee on Water Well Construction within 30 days after completion of a well. In many cases drillers fulfill this requirement in such a cursory manner that the data they submit are useless (see Appendix C)

The parts of the well reports most used in this study were the well yield and location, and these parts showed the greatest tendence towards inaccuracy. Drillers are required by Section 10 of the Arkansas Water Well Construction Code to test each well for yield and drawdown. However, there is no space on the construction report form in which to report drawdown, and the yield figures quoted by most drillers are so uniformly low that they seem to be placed there to fill in the blank without attracting attention. It is questionable whether pump tests are carried out correctly if at all in most wells.

The Committee on Water Well Construction is empowered by Act 641 to license all water well drillers in the State of Arkansas, to renew the licenses yearly, and to revoke licenses when Act 641 has been violated. Before licensing, each prospective driller must pass an examination made up by the Committee qualifying him for a certification of registration. Thus it is within the capability of the Committee to insure that each new water well driller in Arkansas is familiar with the Federal Land Office system of location by township, range, section, and quarter-quarter-quarter section, and is cognizant of the proper methods of making a pump test

Because most water well drillers in Arkansas already have been licensed, the Committee has not been able to demand more accurate reporting of well locations and yields. In Appendix C is a copy of a well construction report with several x's. The spaces marked were originally left blank by the driller, and were later filled in by request of the Committee. Unfortunately these marks are common in Committee files. Where the location blanks are filled in they are commonly inaccurate; the State Geological commission allows a margin of error of one mile in using information from these reports (Hanson, 1973).

To increase the utility of well construction reports in Arkansas, some means must be found to alleviate the inaccuracy that characterizes them. P. D. Huff, head of the Committee, has suggested that each driller be provided with maps on which he might mark the location of a new well. In this way a map with the precise location of the well would be submitted with the construction report, and the inaccurate verbal location could be eliminated. This method would be somewhat expensive because of the added cost of maps, and it would not alleviate the problem of inaccurate yield reporting.

The Committee on Water Well Construction is empowered by Section 11a of Act 641 to adopt or amend the rules and regulations governing licensing of water well drillers. Therefore it is in the Committee's power to require that all drillers familiarize themselves with location and pump test methods. A simple way to do this would be to require driller's attendance at a seminar on the township and range system of well location, methods of making a pump test and other problems in data collection. Understanding of the topics discussed could then be tested by examination before licenses are renewed

2) The program of monitoring water levels in northern Arkansas wells is limited in scope and utility. Water levels are measured by the USGS once a year in November or December The understanding of groundwater movement and recharge would be greatly improved by the installation of continuous recording devices in several wells on and off lineaments in the study area. Information from these wells, with precipitation data, would aid immeasurably in the study of the role of lineaments in groundwater recharge.

Additional recommendations to help the development of the deep aquifers as water sources include the following.

3) A more detailed study of lineaments and groundwater quality may be helpful in outlining recharge zones and groundwater movement. The study must generate more accurate, consistent, and plentiful data than are now available to obtain the thorough data coverage that is needed

4 In areas of known recharge, locations characterized by fracture traces and lineaments should be avoided as potential sites for the location of sanitary landfills, sewage treatment plants, and possible sources of contaminants.

Detailed hydrogeologic studies are necessary to define the areas of recharge and precise movement of groundwater. The aquifers of northern Arkansas are a valuable resource that should not be degraded by careless placement of such facilities.

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Appendix A

The LANDSAT Program

LANDSAT satellites, formerly known as ERTS (Earth Resources Technology Satellite), have been part of a successful NASA experiment to demonstrate the value of viewing the earth from space. LANDSAT I, launched in July 1972, and LANDSAT II, launched in January 1975, have provided images that have proved valuable in all types of resource evaluation and planning.

Each 2000 lb., 10 ft. long spacecraft travels in a sun-synchronous polar orbit at an altitude of 565 miles. Fourteen orbits are made in each 24 hour period, resulting in complete global coverage by each satellite every 18 days.

The LANDSAT satellites carry four subsystems: the return beam vidicon (RBV), the data collection system (DCS), the wideband video type recorder (WBVTR), and the multispectral scanner (MSS). Imagery from the MSS system was used in this project for the detection of major lineaments

The MSS continually scans the Earth with an oscillating mirror which moves back and forth approximately 13 times a second. This scanner is sensitive to Earth-reflected solar energy, which it detects in four spectral bands. Band 4 (Bands 1, 2, and 3 are on the RBV) is sensitive to 0.5 - 0.6 μm wavelengths (green light), Band 5 records radiation in 0.6 - 0.7 μm wavelengths (red), Band 6 records 0.7 - 0.8 μm wavelengths red and infrared), and Band 7 records 0.8 - 1.1 μm wavelengths (infrared) Detected energy is recorded electronically as a scan line, essentially an instantaneous view of a strip.260' wide along the path of the satellite. Later, on the ground at NASA's Goddard Space Flight Center the electronic signals are converted to imagery. Each LANDSAT scene produced at Goddard covers an area 185 by 185 km (100 by 100 nautical miles) in each of the four spectral bands.

The utility of imagery in each band depends on its intended use and the season in which it was taken. In general, winter imagery in Band 5 is considered most useful for geologic studies because it provides maximum topographic definition with minimum attenuation by vegetation.

The study area of this project, an area of about 7500 square miles, was large enough to require two LANDSAT scenes for study. Both of these scenes were winter images; Band 5 was used for the western half (Figure 24), and Band 6 was used in the eastern half.

LANDSAT imagery has proved valuable in applications ranging from water resources monitoring to range management. Additional information about the satellites and their imagery can be obtained from the Eros Data Center in Sioux Falls, South Dakota 57198

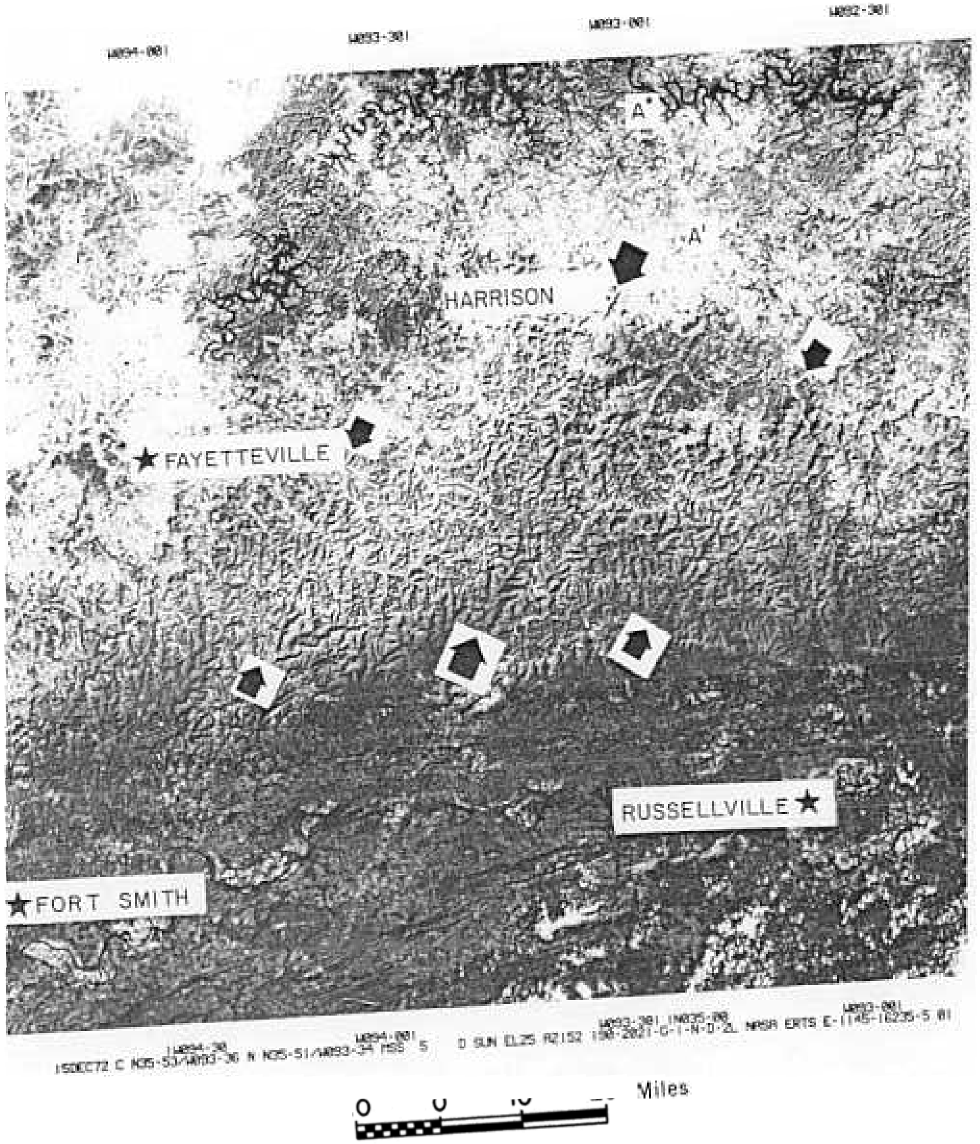
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Figure 24. LANDSAT image of the western Ozarks under a light snow cover. Arrows indicate lineaments. Line A-A' is a lineament for which well control is available; Well Number 21N 20W 13 is located at the dot near A.

Appendix B

Portions of the Arkansas Water Well Construction Code Rules and Regulations

Section 4 - Design Factors

The design of each well shall include consideration of the following:

4.1 NATURAL PROTECTION. Location of the well shall include utilization of every natural protection available to promote sanitary conditions.

4.2 UNDESIRABLE GEOLOGICAL FORMATIONS. The exclusion of water bearing formations which are or may become contaminated or formations which have undesirable characteristics.

4.3 DURABILITY. The use of construction methods and materials which will result in a durable well producing safe water, without excessive sediment and sand, or harmful bacteria.

Section 5 - Location

5.1 GENERAL. In establishing the location of a well the constructor shall give consideration to sources of contamination which exist on or adjacent to the premises where the well is to be located. As far as possible, the well shall be located on ground which is higher than sources of contamination and shall have ready access for repairs, maintenance, and inspection.

5.2 RELATION TO SOURCES OF CONTAMINATION. Determination of minimum lateral distances to locate a well from potential sources of contamination involves evaluation of the character and location of the sources of contamination, types of geologic formations present, depth to the aquifer, effect on groundwater movement by well pumping and possibilities of flooding of the site by surface waters. Based on practice and experience, accepted minimum lateral distances for some common sources of pollution with respect to a well have been established. The lack of specific distance for other possible sources of contamination such as streams, refuse disposal sites, excavations, waste treatment facilities, buried oil and gasoline storage tanks, improperly constructed wells and cisterns, etc., does not minimize their potential hazards. These must be evaluated in each particular situation and a distance arrived at based on the pertinent facts. The following minimum lateral distances shall apply for the common sources of contamination listed:

SOURCE OF CONTAMINATION	MINIMUM LATERAL DISTANCES FOR CLAY AND LOAM SOILS
Cess pools	100 feet
Leaching pit	100 feet
Pit privy	100 feet
Subsurface Seepage Tile	100 feet
Manure Piles	100 feet
Septic Tank	100 feet
Sewers	50 feet.

When the upper formations are more pervious, the lateral distances shall be increased (i.e., double the distance highly pervious gravel formations).

5.3 FLOOD WATER. Locations subject to flooding should be avoided. If no reasonable alternate site exists, wells may be constructed in flood zones provided special protective construction is included.

Section 10 - Finishing and Testing

10.1 UPPER TERMINAL. The casing, well curb or riser pipe shall be terminated at a height above ground surface less than eight inches above ground surface or 24 inches above maximum high water level where flooding occurs.

10.2 DISINFECTION. If the constructor of the well is also responsible for preparing the well for the pump installations and making the pump installations, disinfection may be postponed until his work is completed. In the event the constructor does not have this responsibility, it is required before capping the well an appropriate amount of chlorine solution be introduced into the well.

10.3 YIELD. Each well shall be tested for yield and drawdown by pump, bailer, or air.

Appendix C

Typed Replicas of Well Construction Reports
Submitted to the Committee on Water Well Construction

NEW WELL ☒ REPLACEMENT WELL ☐

STATE OF ARKANSAS

Report of Water Well Construction

County in which well is located: Benton

(Please print or type)

OWNER OF WELL

WELL CONTRACTOR

CONTRACTOR LICENSE NO.

NAME OF DRILLER

DRILLER REGISTRATION NO.

DATE WELL WAS COMPLETED MO. DAY YR.

Well is near Hy Way 12 road, approximately 14 miles N NE E [✓ SE] S SW W NW of Rogers (TOWN, ETC.)

xSectionx 19, Townshipx 19N, Rangex 28W.

Directions for reaching well:
x(use permanent landmarks) x 1 mile west of Hyvilla

1. Total Depth of Well 527 ft.
2. Water Producing Formation: From 515 ft. To 518 ft.
3. Method of Construction: Rotary X Cable R.C. Driven Jetted Bored
4. Water Level Below Land Surface ft.
5. Gallons per Hour 300 Gallons per Minute 5
6. Well disinfected with
7. Cased to 40 ft. with 6¼ Diameter 13 lb. Casing
8. Cemented from 2 Sacks ft. to ft.
9. Casing Perforated from ft. to ft.
10. Well Backfilled with: from ft. to ft. (SAND, CLAY, CEMENT, MUD)
11. Gravel Pack from ft. to ft.
12. Screen Diameter: inches from ft. to ft.
13. Type Screen Fittings Slot Size
14. Use of Well: X DOMESTIC IRRIGATION MUNICIPAL OTHER

Description and Color of Formation: (Sand, Shale, Sandstone, etc.)	Depths in Feet From	To
0-B	0	37
Lime	37	170
B Shale	170	218
W Sand	218	270
Lime	270	515
Sand	515	518
Lime	518	527

Remarks:

This well is guaranteed against defective material or workmanship for a period of

Signed:

Date: MONTH DAY YEAR

Mail to: Committee on Water Well Construction — 3815 W. Roosevelt Road — Little Rock, Arkansas 72204

FORM NO. WD-1

COMMITTEE COPY

NEW WELL ☒ REPLACEMENT WELL ☐

STATE OF ARKANSAS
Report of Water Well Construction

County in which well is located: Marion

(Please print or type)

OWNER OF WELL
WELL CONTRACTOR
CONTRACTOR LICENSE NO.
NAME OF DRILLER
DRILLER REGISTRATION NO.
DATE WELL WAS COMPLETED MO. DAY YR.

Well is near 14 road, approximately 14 miles N NE E SE [✓ S] SW W NW of Yellville (TOWN, ETC.)
Section 36, Township 17, Range 16.
Directions for reaching well: (use permanent landmarks) Stop at Roberson Gro., ask how to get to Doyle Davenpor fathers place

1. Total Depth of Well 1000
2. Water Producing Formation: From 160 ft. To ft.
3. Method of Construction:
Rotary X Cable R.C. Driven Jetted Bored
4. Water Level Below Land Surface 150 ft.
5. Gallons per Hour Gallons per Minute 1½
6. Well disinfected with purex
7. Cased to 80 ft. with 6" Diameter Steel Casing
8. Cemented from 70 ft. to 80 ft.
9. Casing Perforated from ft. to ft.
10. Well Backfilled with: from ft. to ft.
(SAND, CLAY, CEMENT, MUD)
11. Gravel Pack from ft. to ft.
12. Screen Diameter: inches from ft. to ft.
13. Type Screen Fittings Slot Size
14. Use of Well: X IRRIGATION MUNICIPAL OTHER

Description and Color of Formation: (Sand, Shale, Sandstone, etc.)	Depths in Feet From	To
clay	0	65
Red marble	65	300
Sandstone	300	1000

Remarks:

This well is guaranteed against defective material or workmanship for a period of

Signed:

Date: MONTH DAY YEAR

Mail to: Committee on Water Well Construction — 3815 W. Roosevelt Road — Little Rock, Arkansas 72204

FORM NO. WD-1

NEW WELL ☒ REPLACEMENT WELL ☐

STATE OF ARKANSAS
Report of Water Well Construction

County in which well is located: Carroll

(Please print or type)

OWNER OF WELL
WELL CONTRACTOR
CONTRACTOR LICENSE NO.
NAME OF DRILLER
DRILLER REGISTRATION NO.
DATE WELL WAS COMPLETED ______ MO. ______ DAY ______ YR.

Well is near 62 road, approximately 1½ miles N NE E SE S SW [✓ W] NW of Busch, Arkansas (TOWN, ETC.)

Section 13, Township 21N, Range 27W.

Directions for reaching well: (use permanent landmarks) Across road on top of hill in front of Hunts Log Cabin

1. Total Depth of Well 720 ft.
2. Water Producing Formation: From 650 ft. To 655 ft.
3. Method of Construction:
Rotary ______ Cable X R.C. ______ Driven ______ Jetted ______ Bored ______
4. Water Level Below Land Surface 570 ft.
5. Gallons per Hour 180 Gallons per Minute 3
6. Well disinfected with Sodium Hypochlorite
7. Cased to 11½ ft. with 6¼ Diameter Steel Casing
8. Cemented from Ground Surf ft. to 11½ ft.
9. Casing Perforated from ______ ft. to ______ ft.
10. Well Backfilled with: ______ from ______ ft. to ______ ft. (SAND, CLAY, CEMENT, MUD)
11. Gravel Pack from ______ ft. to ______ ft.
12. Screen Diameter: ______ inches from ______ ft. to ______ ft.
13. Type Screen ______ Fittings ______ Slot Size ______
14. Use of Well: X ______ IRRIGATION ______ MUNICIPAL ______ OTHER

Description and Color of Formation: (Sand, Shale, Sandstone, etc.)	Depths in Feet From	To
Clay	1	3
Gray Lime	3	110
Gray Flint	110	130
Blue Flint	130	245
Gray Lime	245	260
Red Lime	260	270
Gray Lime	270	280
Shale	280	295
Gray Lime	295	505
Gray Lime and Flint	505	520
Gray Lime	520	565
[redacted] Gray Lime and Flint	565	720

This well is guaranteed against defective material or workmanship for a period of ______

Signed: ______

Date: ______ MONTH ______ DAY ______ YEAR

Mail to: Committee on Water Well Construction — 3815 W. Roosevelt Road — Little Rock, Arkansas 72204

FORM NO. WD-1

NEW WELL ☐ REPLACEMENT WELL ☐

STATE OF ARKANSAS
Report of Water Well Construction

County in which well is located: Marion

(Please print or type)

OWNER OF WELL
WELL CONTRACTOR
CONTRACTOR LICENSE NO.
NAME OF DRILLER
DRILLER REGISTRATION NO.
DATE WELL WAS COMPLETED MO. DAY YR.

Well is near Welcome Ridge Road road, approximately 20 miles N [✓ NE] E SE S SW W NW of Yellville (TOWN, ETC.)
Section 13, Township 20, Range 17.
Directions for reaching well: (use permanent landmarks) Welcome Ridge Road to Fay Zigler house then ask him how to get there he sold the land

1. Total Depth of Well 525
2. Water Producing Formation: From 510 ft. To 525 ft.
3. Method of Construction:
Rotary X Cable R.C. Driven Jetted Bored
4. Water Level Below Land Surface 200 ft.
5. Gallons per Hour Gallons per Minute 4
6. Well disinfected with Purex
7. Cased to 21 ft. with 6¼ Diameter Steel Casing
8. Cemented from 10 ft. to 21 ft.
9. Casing Perforated from ft. to ft.
10. Well Backfilled with: from ft. to ft.
(SAND, CLAY, CEMENT, MUD)
11. Gravel Pack from ft. to ft.
12. Screen Diameter: inches from ft. to ft.
13. Type Screen Fittings Slot Size
14. Use of Well: X IRRIGATION MUNICIPAL OTHER

Description and Color of Formation: (Sand, Shale, Sandstone, etc.)	Depths in Feet From	To
Dirt	0	5
Limestone	5	525

Remarks:

This well is guaranteed against defective material or workmanship for a period of

Signed:

Date: MONTH DAY YEAR

Mail to: Committee on Water Well Construction — 3815 W. Roosevelt Road — Little Rock, Arkansas 72204

FORM NO. WD-1

COMMITTEE COPY

Appendix D

Wells Used in This Study

Key

*denotes a well for which water quality data was available.

σ means this record was obtained from the U.S. Geological Survey, Division of Water Resources, in Little Rock.

δ means this is a driller's well construction report obtained from the Committee on Water Well Construction or the Arkansas Geological Commission, also in Little Rock.

County Well Number	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
Baxter							
16N 13W 20 cad	620	6	1,200		200		δ
16N 13W 30 bac*	2698	54	1,305	Rbdx.	656		σ
18N 12W 09 bdd	835	170	725		132	Satellite	σ
19N 12W 27 aba	652	150	645		78		σ
19N 13W 16 bab	1540	275	775	Gunter	179	Photo	σ
19N 13W 16 bbb	1505	185	740		167		σ
19N 14W 01 cbd	505	6	780		205		δ
19N 14W 28 dba*	1503	500	690	Gunter	219		σ
19N 14W 29 dbc*	1625	250	720	Gunter	180		σ
20N 12W 01 cca	606	110	705	Rbdx.	137		δ σ
20N 12W 26 dbb	510	100	605	Rbdx.	70		δ σ
20N 12W 27 dbd	550	100	665	Rbdx.	120		δ σ
20N 14W 29 dbc	650	7	775		300	Photo	δ
Benton							
18N 28W 10	518	10					δ
18N 30W 05	545	10				Satellite	δ
18N 30W 10 bdd	1425	15		Rbdx.			σ
18N 30W 17	619	4		Cotter			δ

County Well Number Benton	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
18N 31W 15	578	20				Photo	δ
18N 32W 13 cda	1414	100	1,240	Boone&Rbdx.	226		δ
19N 28W 16 aad	520	20					δ
19N 28W 18	700	4			200		δ
19N 28W 25	585	10					δ
19N 29W 07 dab	1659	275	1,220	Rdx.&Gunter	142	Photo	σ
19N 31W 07 bda	540	5	1,340		325		δ
19N 32W 11 cda*	1723	300	1,235		380		σ
19N 33W 11 bab	1700	500	1,200	Gunter	235	Satellite	σ
20N 27W 08 dca	1875	20	1,295	Gunter	240	Satellite	δ σ
20N 27W 20	600	15					δ
20N 28W 03 adc	600	3	1,540		475	Satellite	σ
20N 28W 24 acc*	1150	300	1,380	Gunter	354		σ
20N 29W 13 bca*	1968	230	1,430	Potosi-Emin.	131		σ
20N 31W 10	525	15				Satellite	δ
20N 31W 31	1050	100					δ
20N 31W 32	665	4				Satellite	δ
20N 33W 11 ddd*	1600	190	1,199	Gunter	170		σ
20N 33W 14 aaa	1603	125	1,275	Gunter	170		σ
20N 33W 14 dbc*	1610	360	1,275	Gunter	231		σ
20N 33W 23 dbc	1133	8	1.165	Rbdx.	292		σ
20N 33W 36	1112	20	1,200		400		δ

County Well Number	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
Benton							
21N 28W 13 bdb	700	10	1,600		540		δ
21N 28W 14 abc	1255	40			565	Satellite	δ
21N 29W 24 aab	523	19	1,462	Boone	344	Satellite	σ
21N 29W 31 cbc	1274	50	1,300	Rbdx.	185		σ
21N 29W 35 ddb*	1769	185	1,406	Gunter	296		σ
21N 30W 30	504	23	1,300		100		δ
21N 31W 20	1115	50	1,242	Rbdx.	220		σ
21N 31W 32 dba	905	20	1,280		80	Photo	δ
21N 33W 21 daa	800	100	955	Rbdx.	21	Satellite	σ
21N 33W 22	900	30	900	Rbdx.		Photo	σ
Boone							
17N 20W 01 ddb	545	20	1,300	Jeff. City	80		δ
17N 20W 08 cca	700	2	1,340		210		δ
17N 20W 13 bdc	560	5	1,380		330		δ
17N 21W 12 dba	700	2			435		δ
17N 22W 02 dbc	942	2	2,180		558		σ
18N 19W 19 bcd*	1649	96	1,150	Rdx.&Gunter	141		σ
18N 19W 19 ddd*	2000	88	1,050	Rbdx.	124		σ
18N 19W 33 bbb*	2055	267	1,300	Gunter	332		σ
18N 20W 18 bca	600	12	1,450		380		δ
18N 21W 36 bbb	519	3					δ

County Well Number	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
Boone							
19N 19W 08 acd*	1725	150	1,285	Rbdx.	355		σ
19N 20W 09 bbc	507	15					δ
19N 21W 03 cab	539	60					δ
19N 21W 21 cba	520	65					δ
20N 19W 14 abc	2205	100	760	Jeff. City		Photo	σ
20N 19W 17	519	20				Satellite	δ
21N 18W 20 cba	760	140		Rbdx.			σ
21N 18W 20 caa*	602	60	830	Rbdx.			σ
21N 18W 29 bdc*	703	650	750	Rbdx.	88		σ
21N 20W 13	350	200			Flows	Sat.&Photo	δ
21N 21W 27 aad*	1315	52	1,527	Rbdx.	450		σ
Carroll							
17N 23W 02 dcb	630	8				Photo	δ
18N 22W 04 dbd	600	3		Everton			δ
18N 22W 20 dad	701	3					δ
18N 23W 29 acc	670	15					δ
18N 23W 31 add	507	12				Photo	δ
18N 24W 29 bbd	895	3					δ
19N 22W 28 abb	575	3	1,420		320		δ
19N 23W 04 bad	1587	60	1,350	Rbdx.	187		σ

County Well Number	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
Carroll							
19N 23W 08 daa	2300	200	1,325	Gunter	277		σ
19N 24W 14 acc	537	8					δ
19N 24W 20 cca	701	15		Cotter		Photo	δ
19N 24W 21	640	30					δ
19N 25W 11 bb	944	10	1,662		554		δ σ
19N 26W 07 bac	507	45				Sat. & Photo	δ
20N 24W 22 cbc	1008	35				Satellite	δ
20N 25W 06 aac	619	10		Cotter			δ
20N 25W 08 aab	804	40					δ
20N 25W 21	557	20					δ
20N 26W 03 cdc	517	15				Satellite	δ
20N 26W 10 aac	804	300				Photo	δ
20N 26W 11 acc	516	15				Satellite	δ
20N 26W 13 bdc	1029	50	1,525	Rbdx.	373	Photo	δ
20N 26W 13 cad	926	75	1,525	Rbdx.	382		δ σ
20N 26W 13 dad	660	6		Cotter			δ
20N 26W 16 cd	1418	250	1,250	Potosi-Emin.	259		σ
20N 26W 16 dcd	1332	500	1,250	Gunter	179	Photo	σ
20N 26W 23 aca	1713	250	1,334		305	Sat. & Photo	δ
20N 26W 27 aad	1385	450		Gunt. & P-E		Sat. & Photo	σ
20N 26W 34 cad	557	8					δ

County Well Number	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
Carroll							
20N 27W 10 bcc	870	55	1,172	Rbdx.	80		σ
20N 27W 14	537	30				Satellite	δ
21N 24W 13 bdb	864	100				Satellite	δ
21N 25W 31 aac	701	4		Cotter			δ
21N 26W 15 baa*	1122	500	1,102	Rbdx.	133		σ
21N 26W 17 bcc*	1058	600	1,010	Rbdx.	100	Satellite	σ
21N 26W 26 ada	1880	502	1,520		520	Sat.&Photo	σ
21N 27W 34 baa	901	60	1,300	Rbdx.	313		σ
Fulton							
19N 06W 23 ada	1630		682	Gunter	210		σ
19N 07W 16 ccc	580	15	760		60	Satellite	δ
20N 08W 27 abd*	1282		660			Satellite	σ
20N 09W 18 cad*	1250	140	880	Rbdx.	126		σ
Izard							
16N 07W 17 cac	585	3	680		50	Photo	δ
16N 10W 27 bbd	540	1					δ
17N 07W 05 dca	605	1				Photo	δ
17N 09W 10 bcc	597	20				Photo	δ
17N 11W 15 bcc	590	20	540		150	Photo	δ

County Well Number	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
Izard							
18N 07W 31 cdd*	1300	70		Rbdx.		Photo	σ
18N 09W 14 aca*	600	86	820	Cotter	101	Satellite	σ
18N 09W 23 acd	700	4					δ
18N 10W 18 bbd	500	1				Photo	δ
18N 10W 25 cdb	616	3	600		103	Photo	δ
18N 10W 30 bcd	520	7	780		75		δ
18N 11W 13 ccc	500	2				Photo	δ
Madison							
15N 24W 17 bbd	680	15				Photo	δ
16N 23W 30 ada	989	3					δ
16N 26W 26 aad	778	100					δ
17N 26W 15 bdc	1120	100	1,400	Rbdx.	194	Satellite	σ
17N 26W 29 bac	1525	17	1,440	Jeff. City	350		σ
18N 26W 35 cac	1970	219	1,558	Rdx. & Gunter	265		δ σ
19N 26W 20 ada	600	5			440		δ
Marion							
17N 15W 19 bad	856	2	1,220		260		δ
17N 15W 22 bcb	794	2			500	Photo	δ
17N 15W 26 bdd	755	2					δ

County Well Number	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
Marion							
17N 16W 24 dcd	560	2					δ
18N 15W 12 cbd	950	15	780		300	Satellite	δ
18N 17W 33 ccc	835	4	1,160		300	Satellite	δ
18N 18W 25 bdb	525	30	1,040		225		δ
19N 15W 20 dbb*	900	80	630	Rbdx.	87	Satellite	σ
19N 16W 32 ada	1520	61	950	Gunter	472	Satellite	σ
19N 16W 33 ccb	753	60	840	Rbdx.	328		σ
19N 18W 36 bdc	1392	236	760	Rbdx.	35		σ
20N 16W 12 ba	1080	350	775	Rbdx.	130		σ
21N 15W 06 abc	506	100	725	Rbdx.	37		σ
21N 15W 26 bbb	556	15	1,100		390	Satellite	δ
21N 17W 22 aab	525	100	755		70	Satellite	σ
Newton							
15N 21W 13 c	3134	63		Rbdx.			σ
16N 20W 24 ddb	550		1,240		240		δ
17N 20W 21 bca*	2576	300	1,344	Gunter	355	Satellite	σ
17N 20W 27 bdd	625	2	1,420		410	Satellite	δ

County Well Number	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
Searcy							
14N 15W 26 dbc*	1210	30	978		240	Satellite	σ
15N 15W 04 dcd	500	1	1.160		200		δ
15N 16W 25 dca	2415	55	1,045	Rbdx.	206	Satellite	σ
15N 18W 04 aa	575	30	860		210		δ
16N 16W 18 cca	580	40			200	Satellite	δ
16N 17W 07 bab	580				300	Satellite	σ
16N 17W 16 dbb	545	2	800	Jeff. City	50		δ
16N 17W 26 acc	581	50	760		250	Satellite	δ
16N 18W 32 dba	865	15	860		400	Satellite	δ
Sharp							
15N 05W 12 bdd	550	13	440		93	Satellite	δ
16N 04W 29 aca	700	5	450		60		δ
16N 05W 31 cdc	900	7	600		79	Satellite	δ
16N 05W 31 acc	600	3	600		111	Satellite	δ
16N 25W ccd	525	20				Satellite	δ
17N 05W 30 bab	525	12					δ
17N 06W 03 cca	536	5	770		90	Satellite	δ
18N 06W 02 ccc	1250	600	600	Rbdx.	23	Satellite	σ
18N 06W 10 dcc*	1525	180	555	Gunter	128		σ

County Well Number	Depth (Ft.)	Yield (Gpm)	Elevation	Aquifer	Static Water Level	Lineament	Source
Sharp							
19N 04W 15 baa	611	280	590	Rbdx.		Satellite	σ
19N 04W 22 aaa*	940	155	473	Rbdx.	66	Satellite	σ
19N 05W 21 aab	1555	280	750	Gunter	210	Satellite	σ
Stone							
14N 12W 26 dac	500	1	1,480		250	Satellite	δ
16N 10W 07 bab	771	30	580		50		δ
Washington							
13N 33W 10 dcd	516	2					δ
15N 31W 17 bbb	2104	55	1,140	Gunter	128	Satellite	σ
15N 31W 30 cab	2485		1,175	Gunter	27	Satellite	σ
16N 31W 30 aaa*	1500	60		Rbdx.	656		σ
16N 32W 07 abd*	1815	26	1,135	Gunter	101	Photo	σ
16N 33W 03 cdd	672	15	1,160		300		δ
17N 29W 09 abd*	2071	400	1,481	Gunter	414	Satellite	σ
17N 31W 01 acd	1416	60	1,300	Rbdx.	255	Satellite	σ
18N 29W 31 dbd	852	6	1,360	Cotter	36		σ

Appendix E

Water Quality Data Used in This Study

All parameters, other than pH, in mg/l

*denotes wells on lineaments

County Well Number	Depth	Date	pH	Total Solids	Total Alk.	Total Hardness	Ca^{2+}	Mg^{2+}	Fe^{2+}	Mn^{2+}		SO_4^{2-}	F^-	NO_3^-	Na^+	K^+	Ni^{2+}	Zn^{2+}
Baxter																		
16N 13W 30 bac	2598	8-72	7.7	304	270	180	40.0	19.5	0.05	<0.005	4.5	52.0	1.2	<0.2	38		0.014	0.053
*18N 12W 09 bdd	835	6-75	8.4	280	220	200	42.8	22.6	<0.05	<0.01	7.0	16.0	<0.2	0.18				
19N 14W 28 dba	1503	4-73	7.35	298	287	294	56.0	37.4	<0.05	<0.0005	5.0	9.0	<0.2	0.12	2.0		<0.005	0.27
19N 14W 29 dbc	1625	1-73	7.5	260	253	260	50.4	32.6	0.36	<0.003	2.8	14.0	<0.2	<0.02	1.0		<0.001	0.02
Benton																		
19N 32W 11 cda	1723	?	8.0	161		143	26.8	18.4	0.08	0.02				0.2	2.7			
19N 33W 13	1430	10-72	7.8	115		118	24.4	13.85	<0.05	<0.05	2.5	11.0	0.17	<0.02	5.8		<0.002	<0.02
20N 28W 24 acc	1150	2-76	8.4	202	160	194	43.4	20.8	<0.05	<0.01	17.0	13.0	0.22	0.25	4.2			
20N 29W 13 bca	1968	8-74	8.5	254		84	20.4	8.0	0.05	0.01				24.0	30.0			
20N 33W 11 ddd	1600	6-71	7.7	174	125	104	23.2	11.2	0.0	0.0	16.0	13.5	1.0	0.25	29.0	2.5		
20N 33W 14 dbc	1133	7-64	7.6	137		100	22.4	10.7		0.0	4.0	11.0	1.2	0.3	13.0	2.4	2.0	0.0
21N 29W 35 ddb	1769	6-72	8.0	198	171	160	44.0	11.0	0.02		5.8	11.0	0.2					
Boone																		
18N 19W 19 bcd	1649	9-74	8.09	186	170	168	35.8	19.0	<0.05	<0.01	9.4	18.0	0.4	<0.01		2.4	<0.01	<0.1
18N 19W 19 ddd	2000	8-69	7.6	246		256	54.8	29.0	0.15	0.0			0.0	0.1	2.0			
18N 19W 33 bbb	2055	6-74	7.7	216	173	192	41.0	21.7	<0.05	0.01	1.3	20.0	<0.2	<0.01				
19N 19W 08 acd	1725	9-71	7.7	129	159	159	40.0	2.0	0.08	0.05	2.0	12.5	0.0	0.15				
21N 18W 20 cba	602	1-70	7.8	270	244	280	58.0	32.8	T	0.0	0.5	14.0	0.0	1.15	1.5			
21N 18W 29 bdc	703	9-72	7.3	333	245	260	50.4	82.6	0.4	0.05	0.0	11.3	0.2	0.02				
21N 21W 27 aad	1315	2-75	8.1	346	191	213	45.0	24.5	0.07	<0.01	2.0	4.0	0.25	0.08				
Carroll																		
21N 26W 15 baa	1122	1-72	7.7	253			50.4	28.7	0.05	<0.002	1.5	22.0	0.04	0.02	1.8			
*21N 26W 17 bcc	600	1-72	7.7	277			58.1	36.2	<0.05	0.013	1.5	22.0	0.05	<0.02	1.4			
*21N 26W 26 ada	502	3-73	7.6	200			38.4	28.7	0.32	0.013	1.5	8.0	<0.2	<0.02				

County Well Number	Depth	Date	pH	Total Solids	Total Alk.	Total Hardness	Ca^{2+}	Mg^{2+}	Fe^{2+}	Mn^{2+}	Cl^-	SO_4^{2-}	F^-	NO_3^-	Na^+	K^+	Ni^{2+}	Zn^{2+}
Fulton																		
*20N 08W 27 aab	1280	8-64	7.5	256	244	250	46.8	32.3	0.0	0.0	0.0	3.0	0.0	0.25	1.0	1.2		
		4-75	7.7	244	258	288	52.0	29.0	0.01		2.5	3.6	0.2	0.13	1.9	1.2		
20N 09W 18 cad	1250	5-70	7.8	238	232	246	47.6	30.9	0.1	0.0	2.0	0.0	0.0	0.1				
Izard																		
*18N 07W 31 ddd	1300	8-70	7.9	314	270	322	61.2	41.1	T	0.0	5.5	11.2	0.1	0.1	4.0	1.2		
*18N 09W 15 aca	600	8-64	7.5	262		127	42.0	29.0	0.2	0.0	5.0	3.0	0.0					
Marion																		
*19N 15W 20 dbb	900	9-74	7.8	287	283	288	58.0	34.8	<0.05	<0.01	6.9	18.0	0.2	0.24		2.0	<0.01	0.1
*19N 16W 32 ada	1520	9-72	7.8	261		270	57.2	30.9	0.05	0.05			0.1	0.1	1.5			
Newton																		
*17N 20W 21 bca	2576	10-74	7.5	261	241	227	53.3	22.7	<0.05	0.02	12.1	17.0	0.85	0.18		7.5	<0.01	<0.1
Searcy																		
*14N 15W 26 dbc	1210	9-75	7.9	359	220	278	86.8	14.8	2.25	0.04	10.3	60.0	0.45	0.12				
Sharp																		
▪ 15N 06W 10 dcc	1525	9-64	7.4	300	279	304	59.2	37.9	0.2	0.0	3.0	16.0	0.0	3.6	3.5	1.8		
*19N 04W 22 aaa	940	2-69	7.5	326	322	320	71.6	34.5	0.0	0.0	0.5	6.0	0.1	0.1	1.0			
Washington																		
16N 31W 30 aaa	1500	3-73	7.6	535		72	14.8	8.5	0.35	0.01			2.3	0.5	37.0			
*16N 32W 09 abd	1815	4-68	7.6	381		118	32.8	8.5	0.2				0.9	0.8	93.0	3.5		
*17N 29W 09 abd	2271	8-74	8.5	254	188	58	20.4	8.0	0.05	0.005	42.0	17.0	1.55		24.0	4.2		