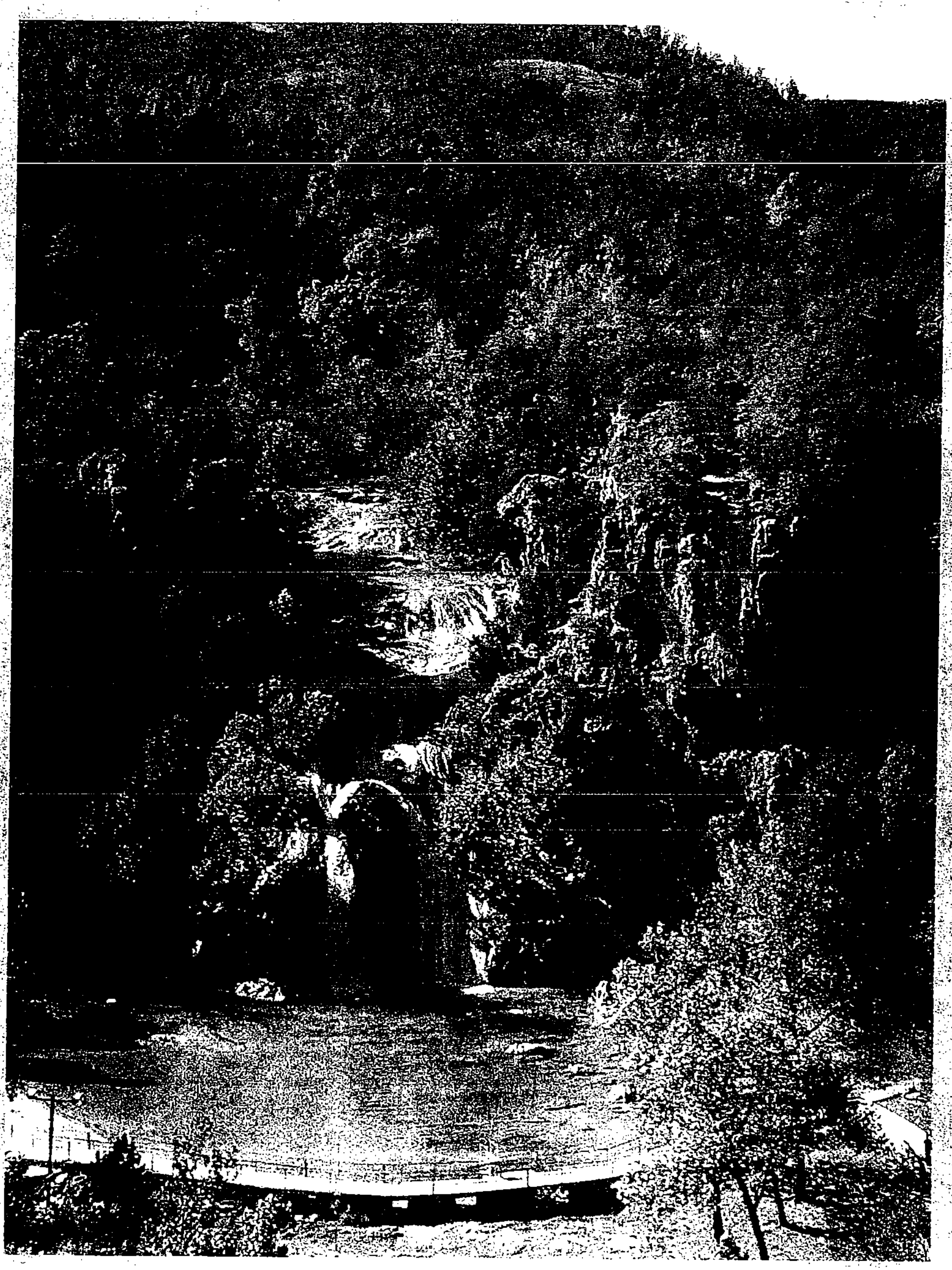
OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 4-2006

Hydrogeology and Water Management of the Arbuckle-Simpson Aquifer, South-Central Oklahoma

Geological Society of America
2006 South-Central Section Meeting



Field Trip March 4, 2006
Noel Osborn, Scott Christenson, Todd Halihan

Hydrogeology and Water Management of the Arbuckle-Simpson Aquifer, South-Central Oklahoma

South-Central Section, Geological Society of America
Saturday, March 4, 2006

Field-Trip Leaders: Noel Osborn[1], Scott Christenson[2], Todd Halihan[3]

The Arbuckle-Simpson aquifer, which underlies more than 500 square miles in south central Oklahoma, is the source of several springs and streams, including those in the Chickasaw National Recreation Area and Blue River, Pennington Creek, and Honey Creek. The field trip will examine the geologic histories of the Arbuckle and Hunton anticlines, and how the different structural and geologic frameworks can affect aquifer characteristics and groundwater flow. A multidisciplinary team of researchers from various agencies and universities will discuss techniques they are employing to understand the highly fractured carbonate aquifer and associated springs and streams.

Time	Stop	Description	Topics
8:30-9:30		Drive from Norman to Arbuckle Mountains	
9:30-10:30	1	Scenic overlook on southbound I-35, Turner Falls overlook on US-77	Geologic setting
10:30-11:30	2	Turner Falls Park	Stream gage, travertine deposits, Arbuckle outcrops
11:30-12:00		Drive to Sulphur	
12:00-12:30	3	Vendome Well	Artesian wells, geochemistry/age dating
12:30-2:00		Lunch at Travertine Nature Center, CNRA	Chickasaw National Recreation Area
2:00-2:30		Drive to Mesonet station	
2:30-3:00	4	Fittstown Mesonet weather station	Mesonet station, water budget, monitoring efforts
3:00-3:30		Drive to Spears Ranch	
3:30-4:30	5	Spears test hole site	Well drilling, fracture characterization, geophysical techniques, Blue River
4:30-6:30		Drive back to Norman, with stop at I-35 rest stop	

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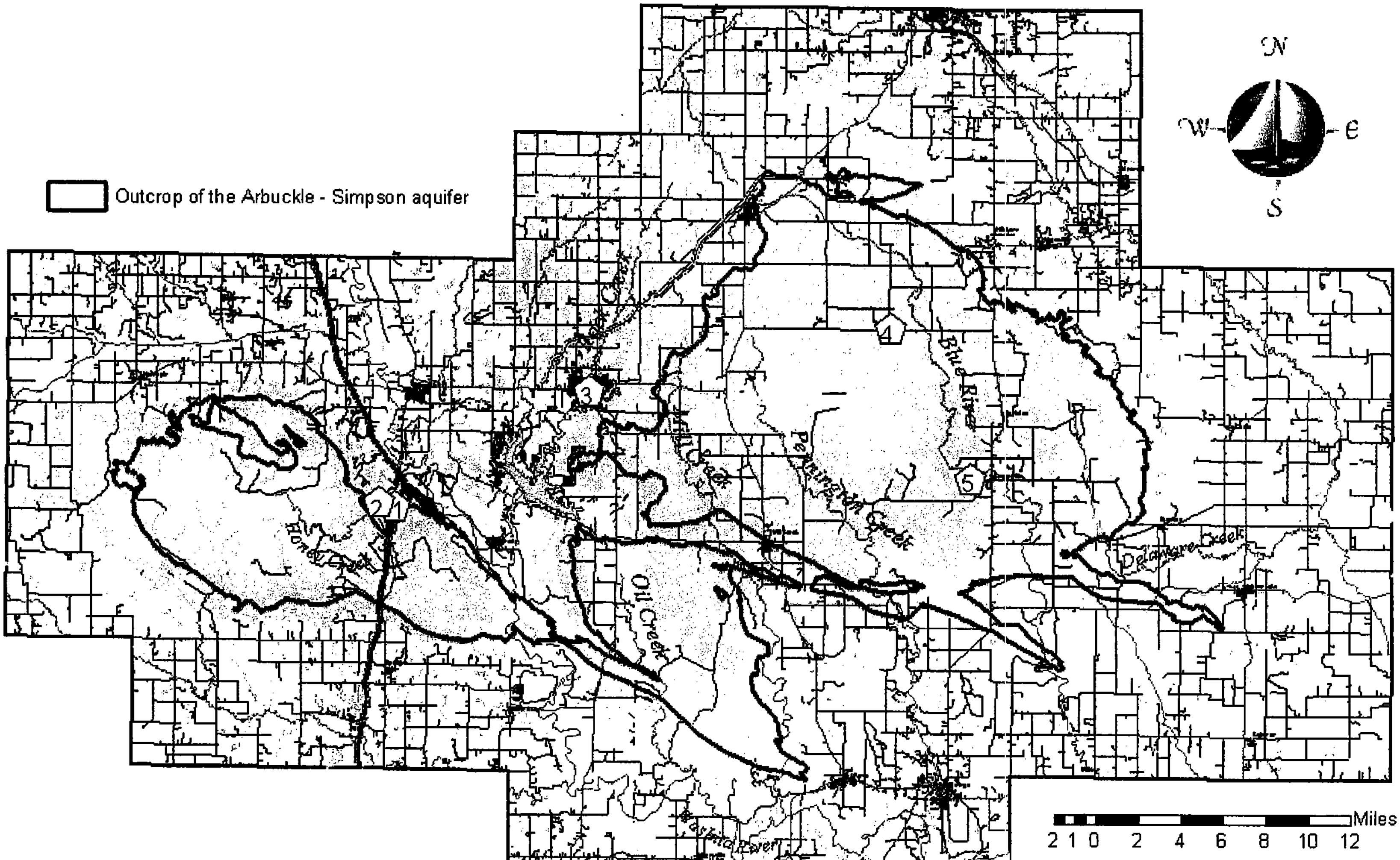
[1] Oklahoma Water Resources Board
[2] U.S. Geological Survey
[3] Oklahoma State University

Stratigraphic Column

System	**Geologic Unit**	
SILURIAN	Hunton Group	
ORDOVICIAN	Sylvan Shale	
	Viola Group	
	Simpson Group	Bromide Fm.
		Tulip Creek
		McLish Fm
		Oil Creek Fm.
		Joins Fm
	Arbuckle Group	West Spring Creek
		Kindblade Fm.
		Cool Creek Fm.
		McKenzie Hill
		Butterly Dolomite
CAMBRIAN		Signal Mountain
		Royer Dolomite
		Fort Sill Limestone
	Timbered Hills Group	Honey Creek Limestone
		Reagan Sandstone
	Colbert Rhyolite	
PRE-CAMBRIAN	Granite and Gneiss	



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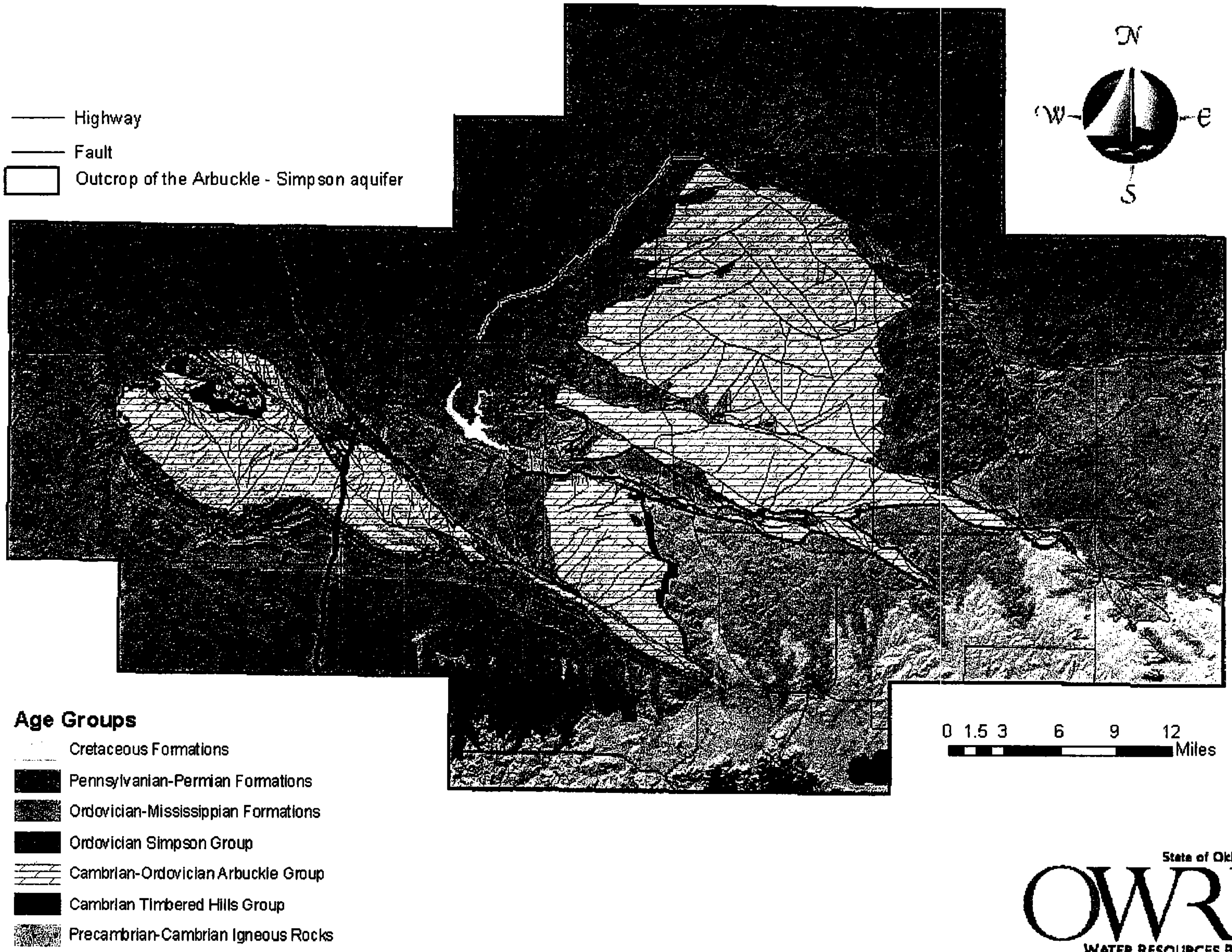
Stops for the Hydrogeology and Water Management of the Arbuckle-Simpson Aquifer GSA Field Trip, March 4, 2006.



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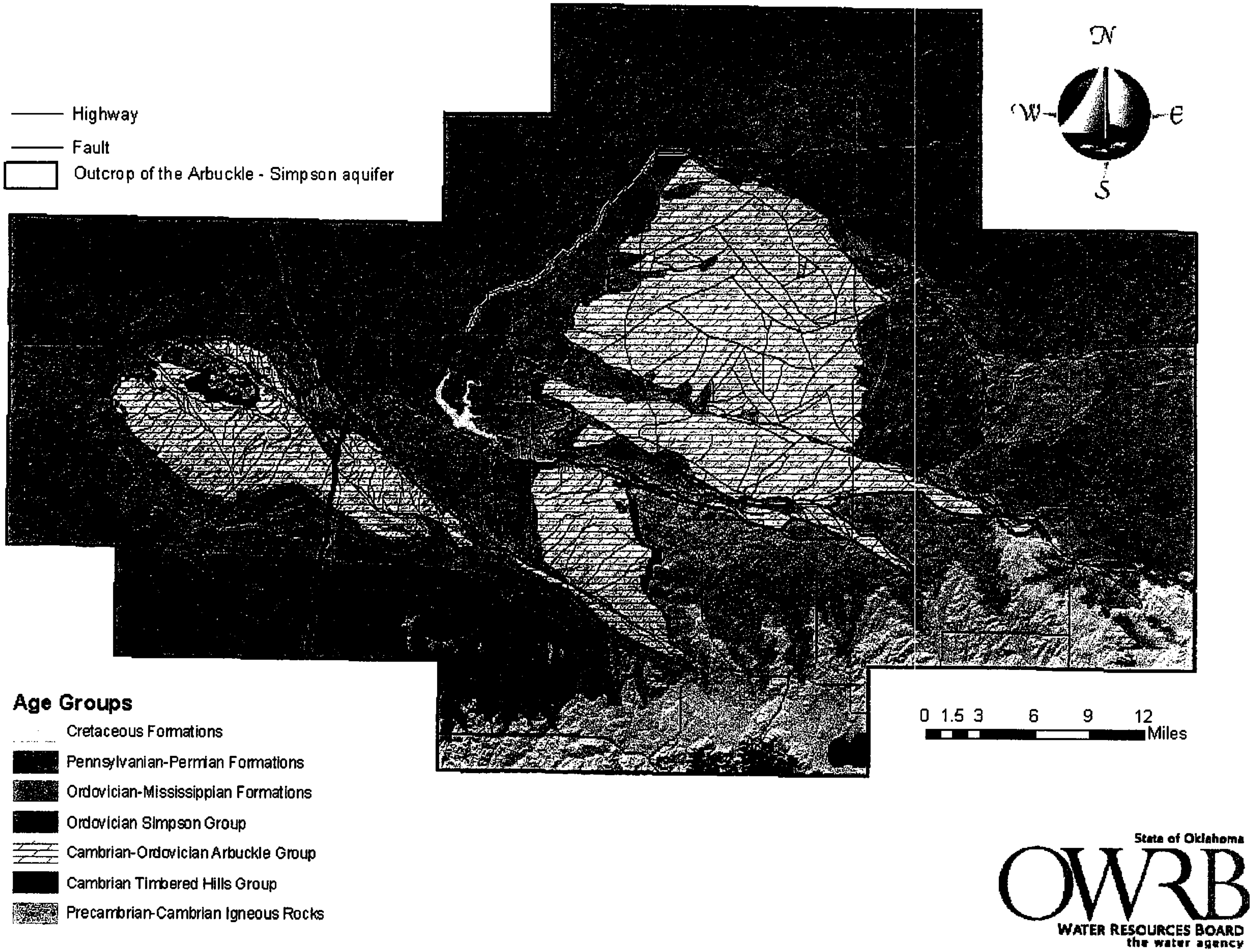
Map showing generalized surficial geology of the Arbuckle-Simpson Hydrology Study area.

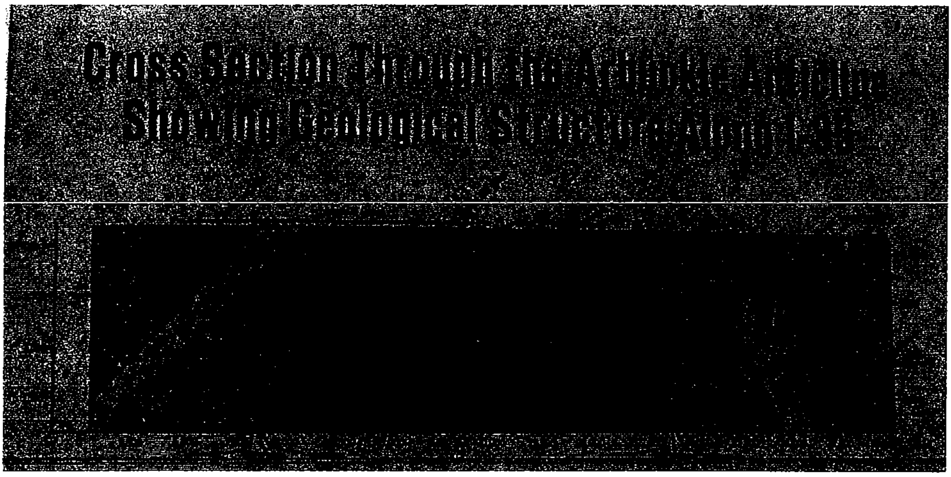


Map showing generalized surficial geology of the Arbuckle-Simpson Hydrology Study area.

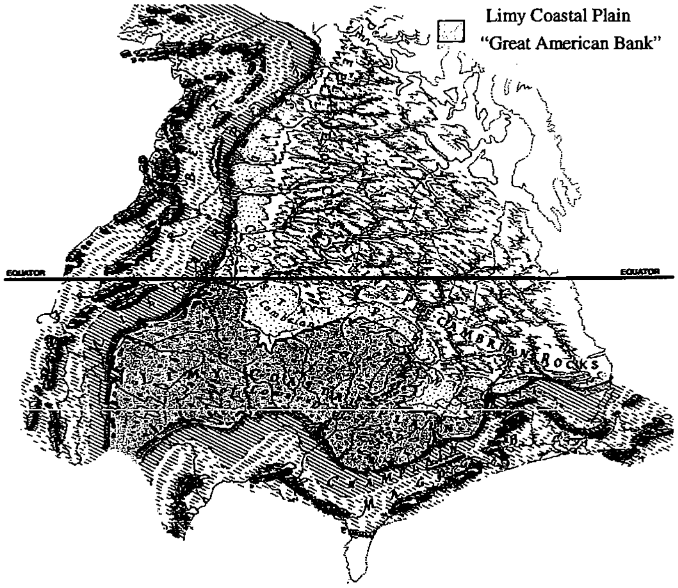
Stop 1

Scenic Overlook on I-35

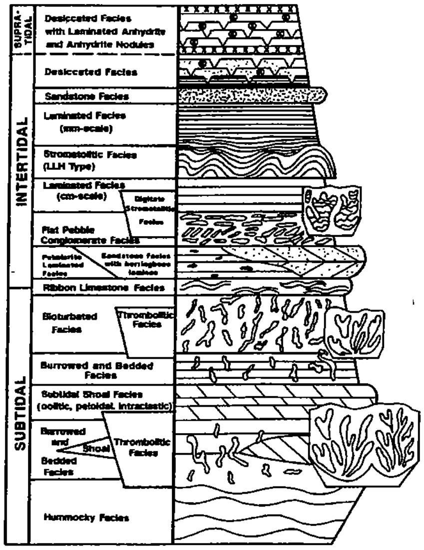
Noel Osborn



Geology students in camp near White Mound, 1909.
(From Gould, 1959, "Covered Wagon Geologist")



Paleogeography of early Middle Ordovician (from Wilson and others, 1991).



Typical shallowing upward sequence of the Arbuckle Group (from Wilson and others, 1991).

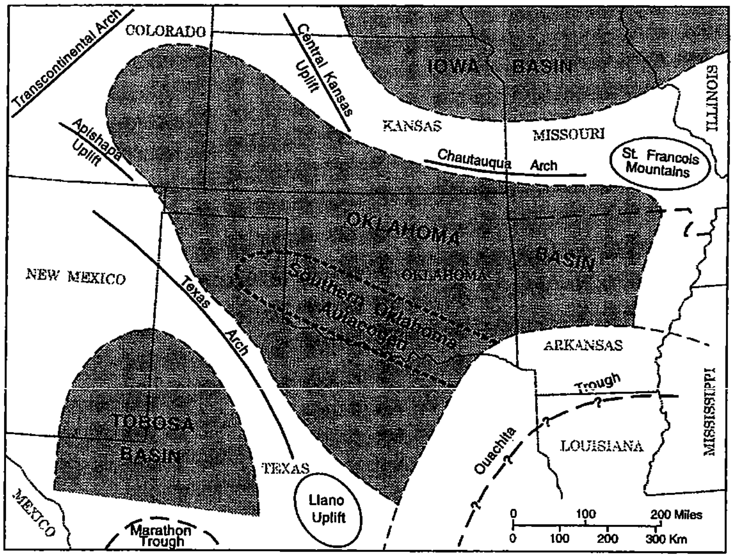
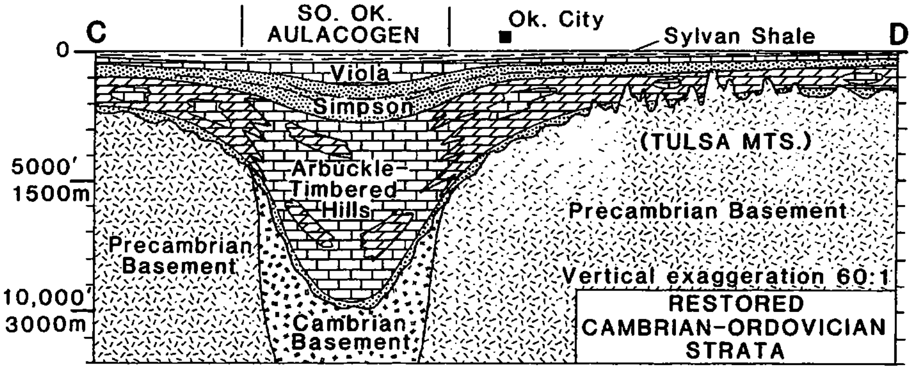
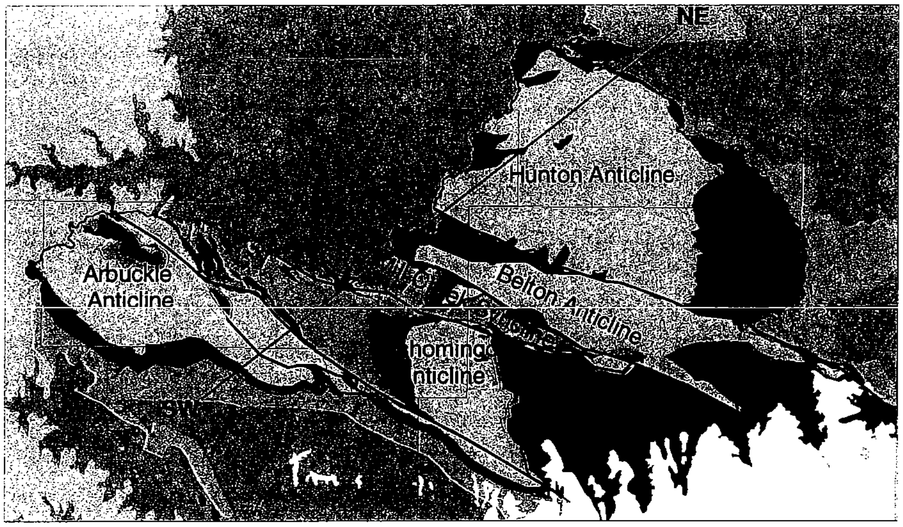


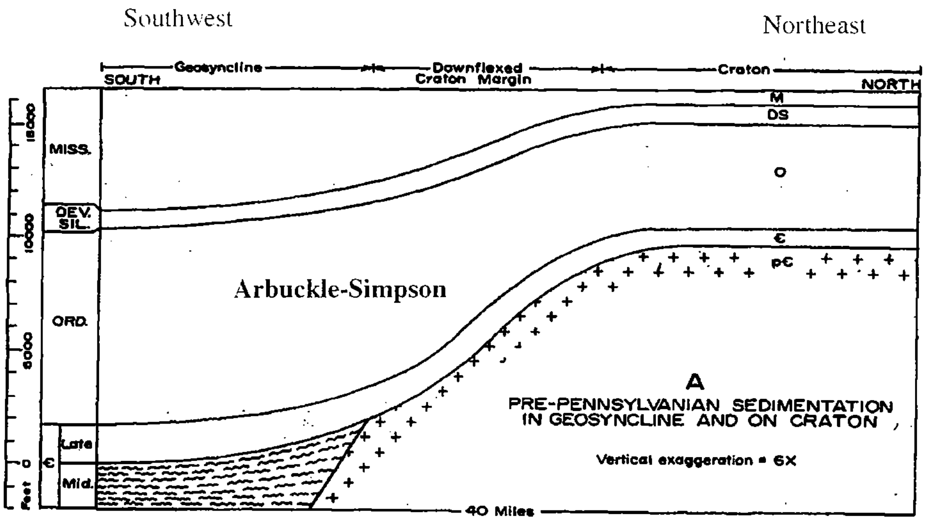
Figure 2. Map of southwestern United States showing outline of Oklahoma basin and other major features that existed in early and middle Paleozoic time (from Johnson and others, 1988).



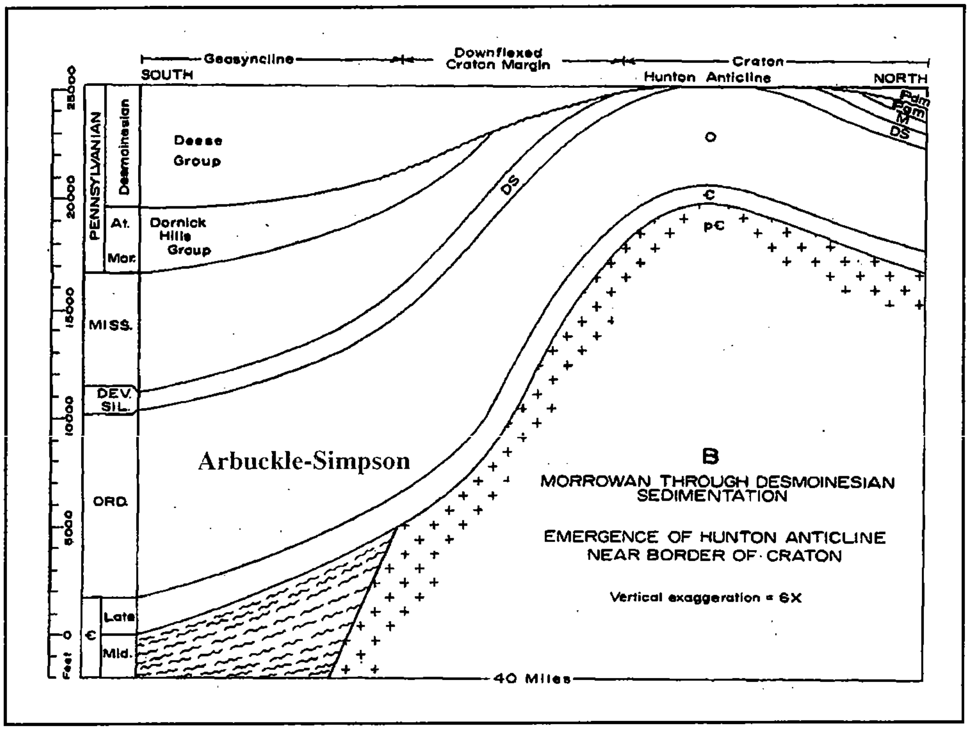
Schematic cross section showing restored thickness of strata in Oklahoma at the end of Ordovician time, after deposition of the Sylvan Shale (from Johnson and Cardott, 1992).

Major Structural Features





Major elements in depositional and structural evolution of Arbuckle Mountains (from Ham, 1973).


Geosyncline
Downflexed Craton Margin
Craton
SOUTH
Hunton Anticline
NORTH
Feet
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PENNSYLVANIAN
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€
Late
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Deese Group
Dornick Hills Group
DS
O
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pC
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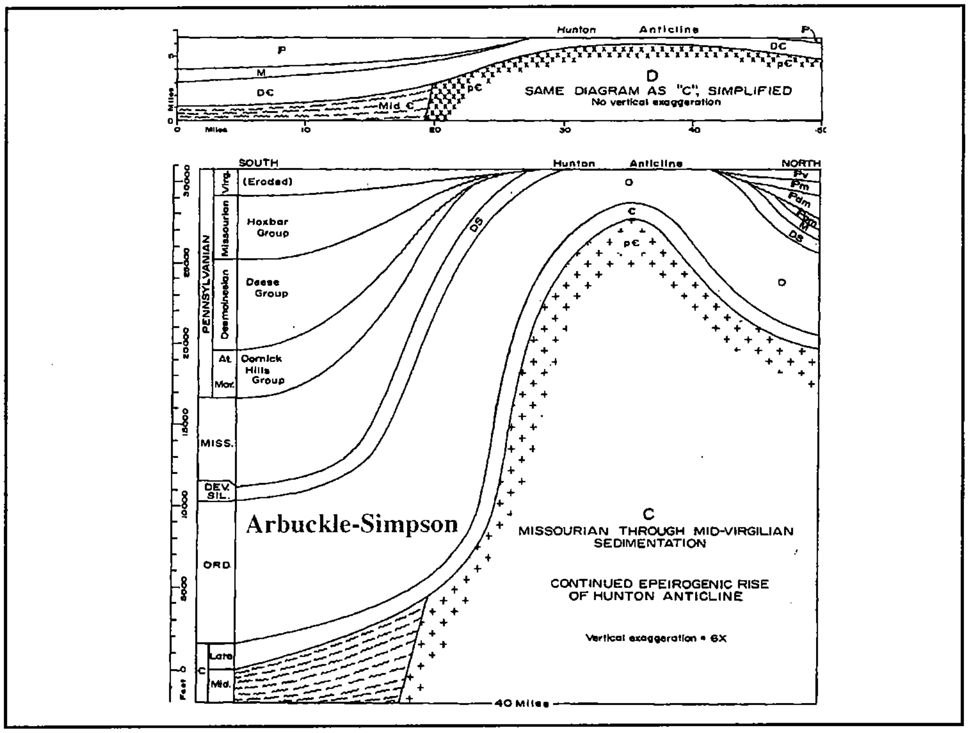
M
DS
Arbuckle-Simpson
40 Miles
B
MORROWAN THROUGH DESMOINESIAN SEDIMENTATION
EMERGENCE OF HUNTON ANTICLINE NEAR BORDER OF CRATON
Vertical exaggeration = 6X


Hunton Anticline
P
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D
SAME DIAGRAM AS "C", SIMPLIFIED
No vertical exaggeration
Miles
0
10
20
30
40
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SOUTH
Hunton Anticline
NORTH
Feet
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5000
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PENNSYLVANIAN
Virg.
Missourian
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(Eroded)
Hoxbar Group
Deese Group
Dornick Hills Group
MISS.
DEV. SIL.
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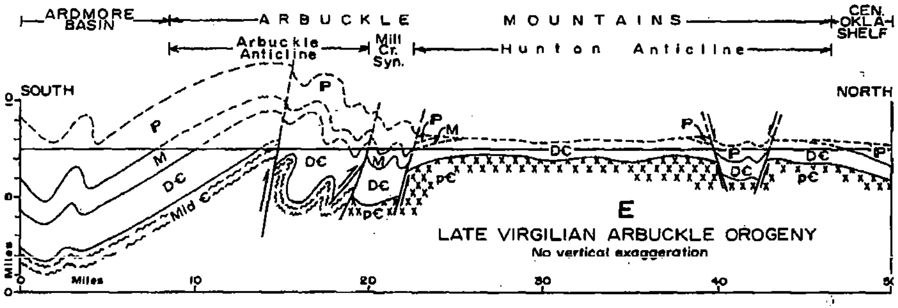
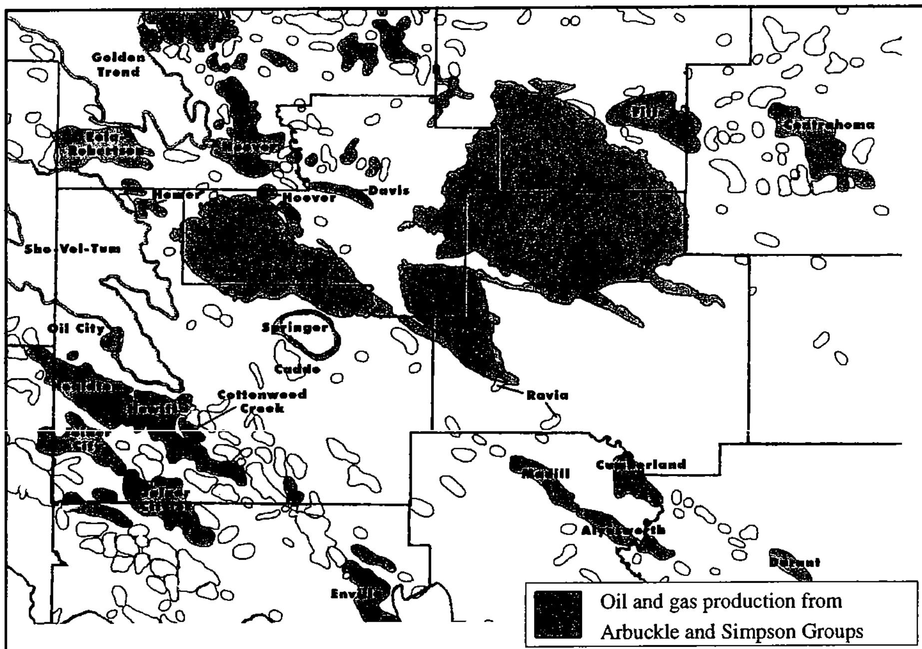
C
pC
Pv
Pm
Pdm
Pgm
M
DS
Arbuckle-Simpson
40 Miles
C
MISSOURIAN THROUGH MID-VIRGILIAN SEDIMENTATION
CONTINUED EPEIROGENIC RISE OF HUNTON ANTICLINE
Vertical exaggeration = 6X

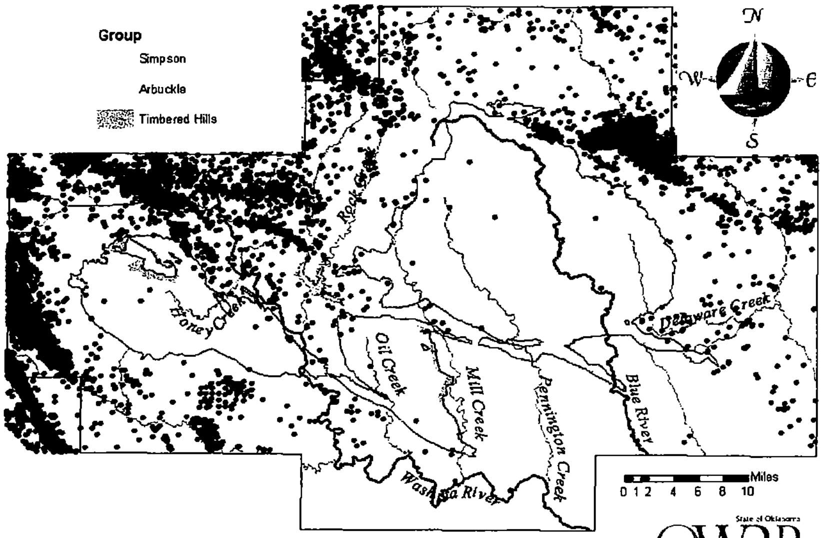


LATE VIRGILIAN ARBUCKLE OROGENY
No vertical exaggeration

Arbuckle Anticline	Hunton Anticline
• 9,000 ft sequence	• 4,000 ft sequence
• buried under 20,000 ft of younger rocks	• exposed
• limestone	• dolomite
• intensely faulted and folded	• faulted
• rugged topography “Arbuckle Hills”	• gently rolling plains “Arbuckle Plains”



(Modified from Boyd, 2002, Oklahoma Oil and Gas Fields: OGS Map GM-36.)



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Oil and gas wells (NRIS Data from Oil-Law Records)

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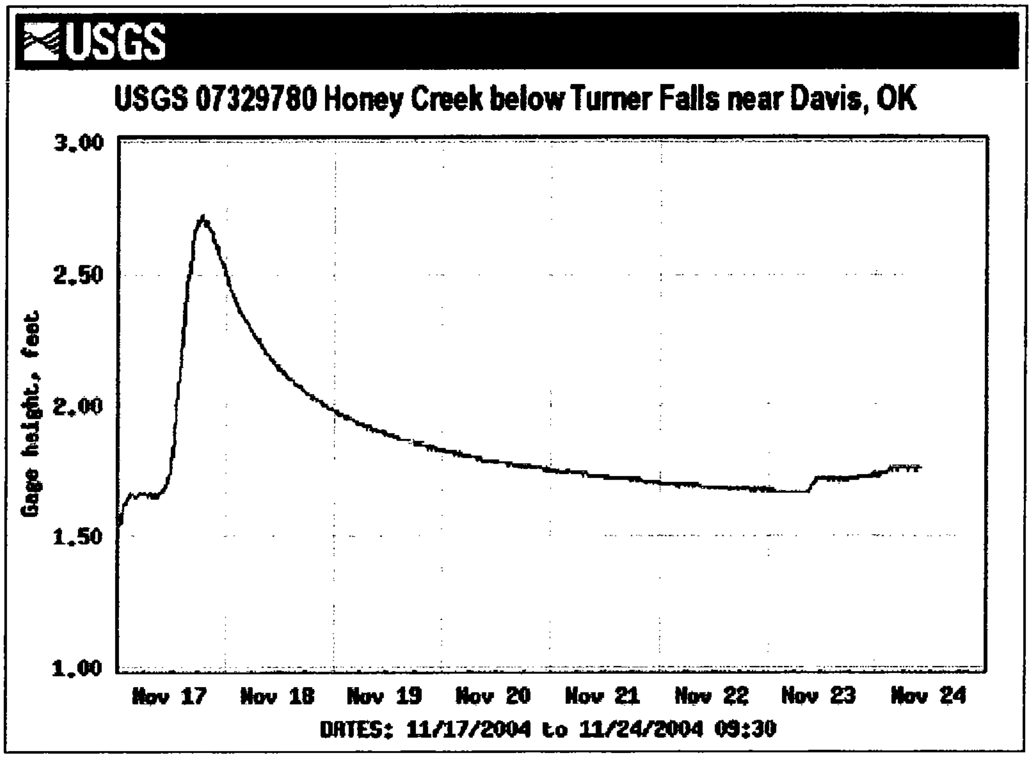
Stop 2
Turner Falls Park

Honey Creek Gage

As part of the Arbuckle-Simpson Hydrology Study, a USGS stream gage was installed on Honey Creek in October 2004. Long-term maintenance of the gage may be turned over to the City of Davis, which owns Turner Falls State Park, after the study is complete. Data from the gage can be used to monitor local flooding potential.



Real-time data relayed by satellite is used to plot gage height at Honey Creek, which has a contributing drainage area of 16.4 square miles. The term "gage height" refers to the height of the water surface above the gage datum (zero point). Graphs and other data from the Honey Creek site, as well as other stream and groundwater stations throughout Oklahoma, are available online at http://waterdata.usgs.gov/ok/nwis.

Turner Falls

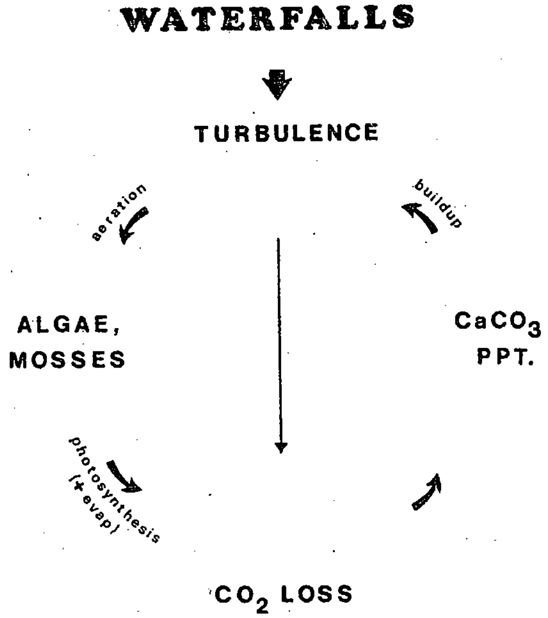
Springs originating in the Arbuckle Mountains are the source of Honey Creek, which ends as a seventy-seven foot waterfall, known as Turner Falls. The falls are named after Mazeppa Turner, who is credited with their discovery in the late 1800s. Operated by the City of Davis, Turner Falls Park is the oldest park in Oklahoma.

Turner Falls is geologically interesting because the tumbling waters of Honey Creek have deposited a thick layer of travertine. As a result, the waterfall scarp has advanced downstream, rather than receding upstream like most waterfalls. The creek itself provided the materials to construct the precipice over which it falls (Ham, 1973).

The primary source of water to Honey Creek is from three large springs. The headwater spring is Bitter Enders, which emerges from an underground cave. Downstream from the springs, travertine precipitation occurs at discrete intervals, forming small cascades or dams. These small accumulations of travertine eventually give way to major travertine waterfall deposits, the largest of which is Turner Falls (Utech, 1998).

Travertine has been defined as "a form of 'freshwater' carbonate deposited by inorganic and organic processes from spring waters" (Chafetz and Folk, 1984). *Tufa* is a more ancient term for travertine. Tufa refers to a cellular variety of calcite deposited around nuclei of algae, mosses, leaves, twigs, and other plant structures (Emig, 1917).

The spring water is saturated with $CaCO_3$ and supersaturated in carbon dioxide (CO_2) with respect to the overlying atmosphere. As water discharges from springs, CO_2 is released and $CaCO_3$ is precipitated on the streambed materials.



Love (1985) attributes turbulence as the primary factor in the precipitation of travertine at the falls. The turbulence at the falls aerates the water, which provides a favorable environment for growth of algae and mosses. The spongy mosses and algae provide absorbent, porous substrates for travertine to accrue. CO_2 is lost from the water by photosynthesis, evaporation, and turbulence, resulting in the precipitation of travertine. This precipitation builds up waterfalls, resulting in greater turbulence, thereby continuing the entire cycle.

The rate of travertine precipitation is affected by a number of factors, including temperature, nature of the substrate, and degree of turbulence (Love, 1985). Precipitation of travertine is higher during the summer months due to increased temperatures and/or photosynthesis (Utech, 1988). The average summer precipitation rate for the travertine at waterfalls is 2 mm/month (Love, 1985).

The travertine precipitates in response to both inorganic and organic processes. Inorganic deposits mainly consist of spelean deposits, which include stalactites, flowstone, cave popcorn, and cave pearls. These deposits are precipitated in cavernous areas within the travertine. Organic-rich deposits include algally-laminated crusts, "mossy" deposits, and algally-coated grains. Algally-laminated crusts consist of alternating layers of sparry *Phormidium* "bushes" and micrite-bearing *Schizothrix* filaments (Love, 1985).

The first person to study the travertine deposits at Turner Falls was Emig in 1917. Emig recognized that the Turner Falls travertine is a complex deposit that records climatic fluctuations. Five distinct stages can be recognized in the evolution of the deposit.

The following summary is from Donovan and Ragland, 1991:

1) Initial dissection of the area by vigorous streams with steep gradients. During this phase the Honey Creek valley was first excavated. The long profile of the creek was irregular, reflecting the lithological contrasts, faults, and variations in dip found in the bedrock.
2) Subsequently, the climate became warmer and drier, calcite saturation increased, and as a result, a major accumulation of travertine took place. This initial travertine deposit grew downstream until the creek tumbled over a travertine cliff ~100 ft (~30 m) high and 300 ft (~90 m) wide. The base of this deposit has a complicated unconformable relationship with the underlying McKenzie Hill Formation. The unconformity is marked by a discontinuous pebble conglomerate containing clasts of Colbert Rhyolite, Arbuckle Group carbonates, and reworked travertine. The overlying travertine is a complex of banded travertine and moss tufa. Examples of thick travertine tubes, deposited around now-vanished tree logs, are common. The dominant fabric, which emphasizes the downstream progradation of the deposit, is formed by beds of petrified moss that dip downstream at angles of up to 85 degrees. These beds, which vary in thickness from 1 to 4 in. (2-10 cm), can persist for as much as 33 ft (~10m). Within each bed the individual moss-plant casts are horizontal.
3) Subsequently, speleothems developed within the older travertine during a semi-arid stage, when the flow of Honey Creek was diminished and probably intermittent. For example, flowstone and crude stalactites have precipitated on the walls of cavities, and some cave popcorn is present near the base of the deposit.
4) Eventually, the climate became wetter and cooler, carbonate precipitation ceased, and Honey Creek eroded its own deposit, eventually cutting a few feet into the underlying bedrock and forming the steep-sided gorge above the modern waterfall.
5) Finally, the climate became warmer and drier, and Honey Creek re-established its constructive mode. The modern travertine-tufa screen at the falls is the result.

Travertine deposits occur in many other spring-fed streams from the Arbuckle-Simpson aquifer. These include Price Falls at Falls Creek, Travertine Creek in the Chickasaw National Recreation Area, Blue River, Pennington Creek, and Delaware Creek.

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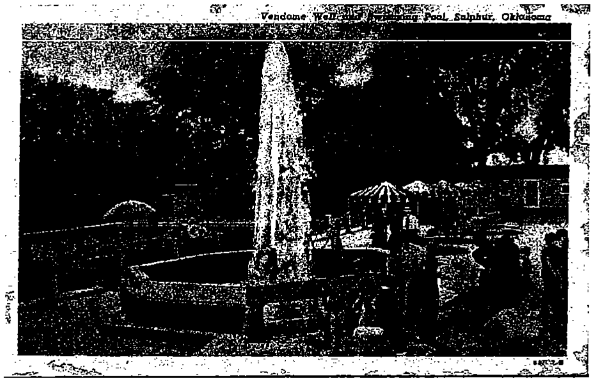
Stop 3
Vendome Well

Vendome Well, located near downtown Sulphur, Oklahoma, is one of the most significant landmarks of the Chickasaw National Recreation Area. The National Park Service acquired the well from a private owner in the 1970s. Vendome well was originally drilled in 1922 to a depth of 365 feet and flowed approximately 2,500 gallons per minute (gpm). The mineralized groundwater that discharges from Vendome Well not only contributes to the "sulphurous" smell and taste, but made Sulphur a very popular destination for travelers during the first half of the twentieth century.



The mineral water emanating from Vendome Well once flowed into a heated medicinal pool (no longer present) where many soaked in hopes of curing a variety of ailments and disease. The upwelling groundwater also plunged into a public swimming pool, which was eventually closed in 1975. During the height of its popularity, Vendome Well and other mineralized flowing wells and springs drew 13 trains of visitors daily to this once thriving prairie oasis and highly acclaimed resort community.

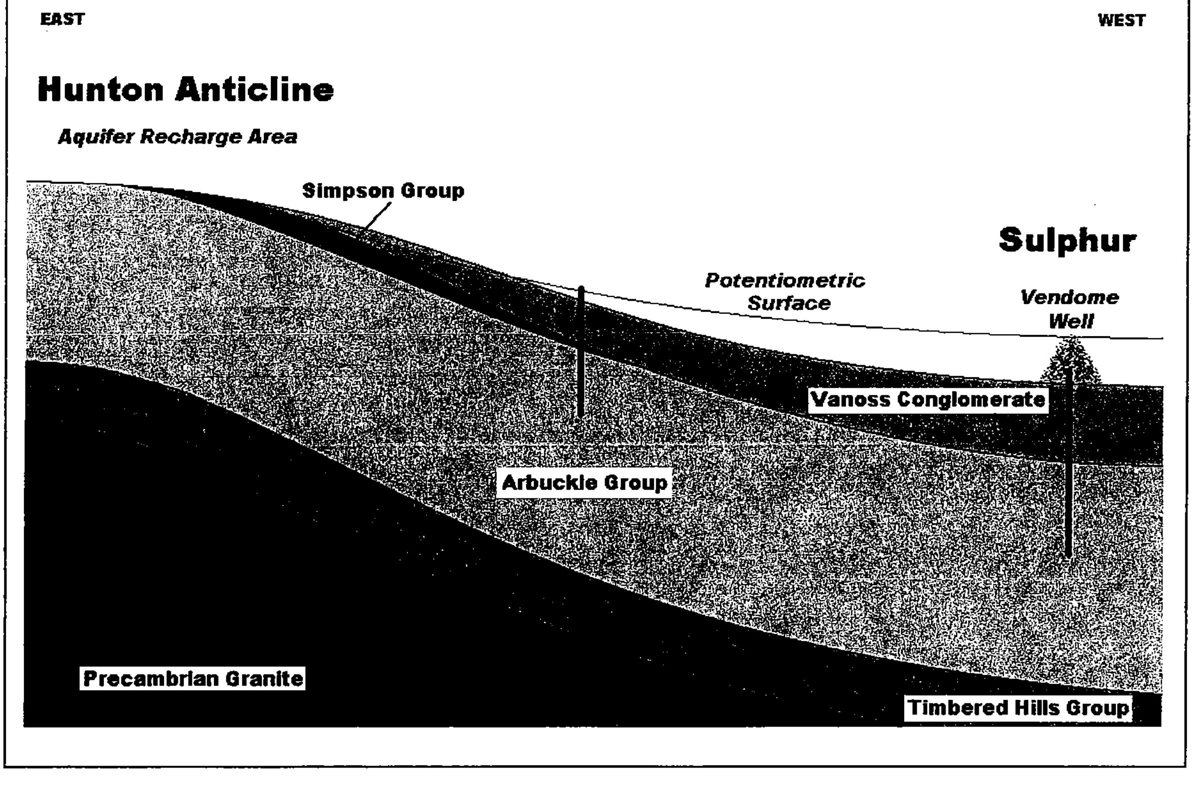
The water you see spouting from Vendome today does not emanate from the original well. In 1998, the new well was drilled 35 feet west of the old site to an initial depth of 400 feet (surpassing the 365 foot depth of the original well). Park officials decided to drill this new well after the fountain height declined to just a few feet (reduced to an average flow of 620 gpm and minimal flow of only 359 gpm in the summer of 1986). It was believed that the extremely corroded state of the old well casing was a contributing factor to the diminished flow. Officials hoped that a new well and casing would revitalize Vendome to its nostalgic form.

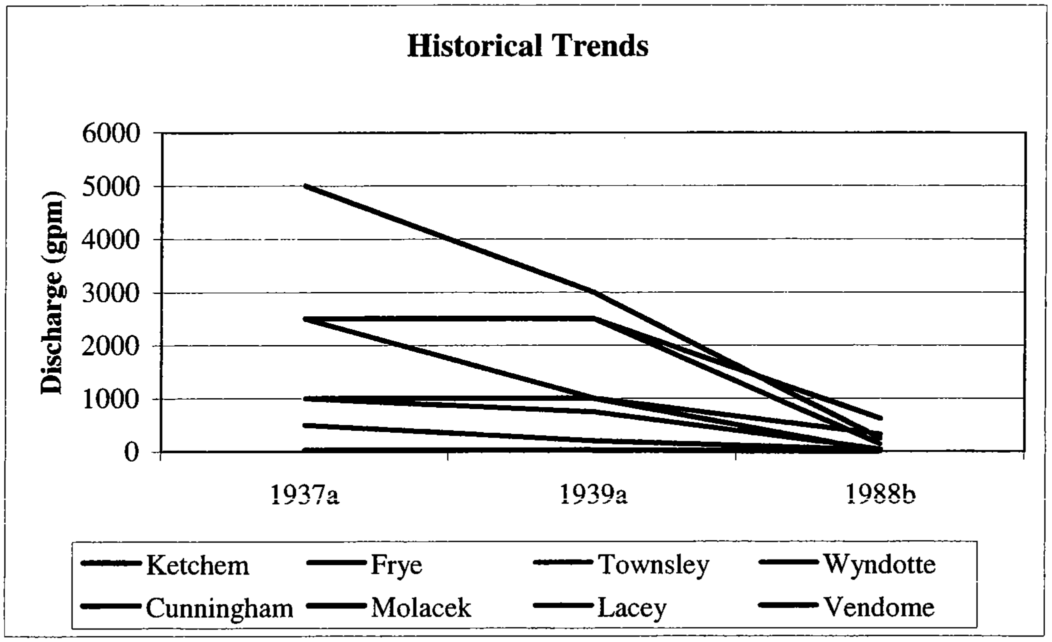
Unfortunately, the new well only yielded 60 gpm, implying that the deterioration of the old casing was not the only factor contributing to the reduction of artesian flow.

Therefore, park officials elected to drill deeper in an attempt to increase groundwater production from additional portions of the aquifer below, which eventually resulted in a sustained flow of 900 gpm after drilling 775 feet. Today, the vertical spout of Vendome Well rarely exceeds 7-8 feet in total height, flowing approximately 500 gpm.

What is an Artesian Well?

An artesian well is one that has been drilled into a pressurized aquifer, such as the Arbuckle-Simpson aquifer, where the underground pressure is great enough for the water to rise inside the well and, in some cases, discharge to the surface without the aid of a pump (referred to as a *flowing artesian well*). The amount of water that flows from artesian wells is a direct function of pressure within the aquifer. The pressure, also called the hydraulic head, is created as groundwater is compressed under the weight of overlying rock and newly infiltrating waters. In the case that groundwater is forced beneath an impermeable, confining rock layer, such as the Vanoss Conglomerate, a well drilled in a topographic low (having a potentiometric surface that is higher than ground level) will likely yield artesian flow.





USGS attributes the declines of Vendome and other artesian wells in the area "to a gradual reduction in the hydraulic head of the Arbuckle-Simpson aquifer resulting from the many years of continued uncontrolled discharge from flowing wells in the study area" Hanson and Cates, 1994.

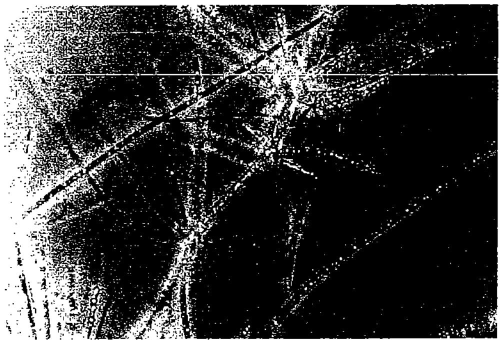
Charles Gould was especially concerned by the potential impact of flowing artesian wells on the spring flow in the Park. In 1939, he wrote that it was only a question of time until the water in the Sulphur artesian basin would begin to fail from the unrestricted waste of water from the artesian wells. On two different occasions, he prepared and introduced into the State Legislature bills to regulate the flow of water in artesian wells throughout the State. Both bills died in committee (Gould and Schoff, 1939).

Gould identified about 41 flowing wells in the 1930s, which he estimated were flowing about 30,352,000 gpd, (34,000 acre-ft/yr). That amount has declined. In 2005, OWRB staff identified 14 flowing wells in the Sulphur area, flowing an estimated 2,400 acre-ft/yr. Groundwater withdrawals from the entire aquifer average about 5,000 acre-ft/yr. In 2004, reported withdrawals for permits located within 5 miles of the Park totaled 1,959 acre-ft/yr. The flow from Vendome Well alone accounts for about 55% of what is normally used by the City of Sulphur each day.

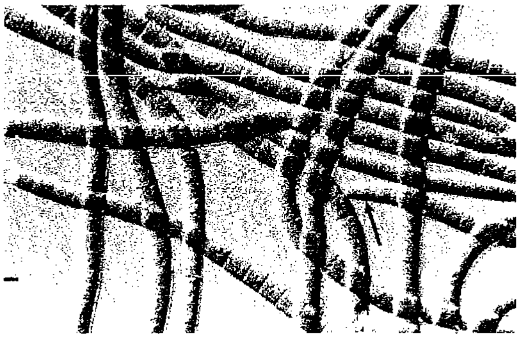
What is that smell??? What are those white things???

That rotten egg smell is sulfide—and there is a lot of it. This is a form of sulfur, which as we know, is abundant in the town of Sulphur. Sulfur in the water provides a thriving community of sulfate munching bacteria. Those are the white things growing everywhere. The bacteria produce sulfide, causing the distinct odor.

These organisms are named, ***Thiothrix.*** Thio (*sulphur)*- thrix (hair-like). Under a microscope, they are long white strands of sulfide storing bacteria. These bacteria are accompanied by a photosynthesizer, ***O. terebriformis***, which are also known to respire sulfide and form algal mats.



Thiothrix



O. terebriformis

References

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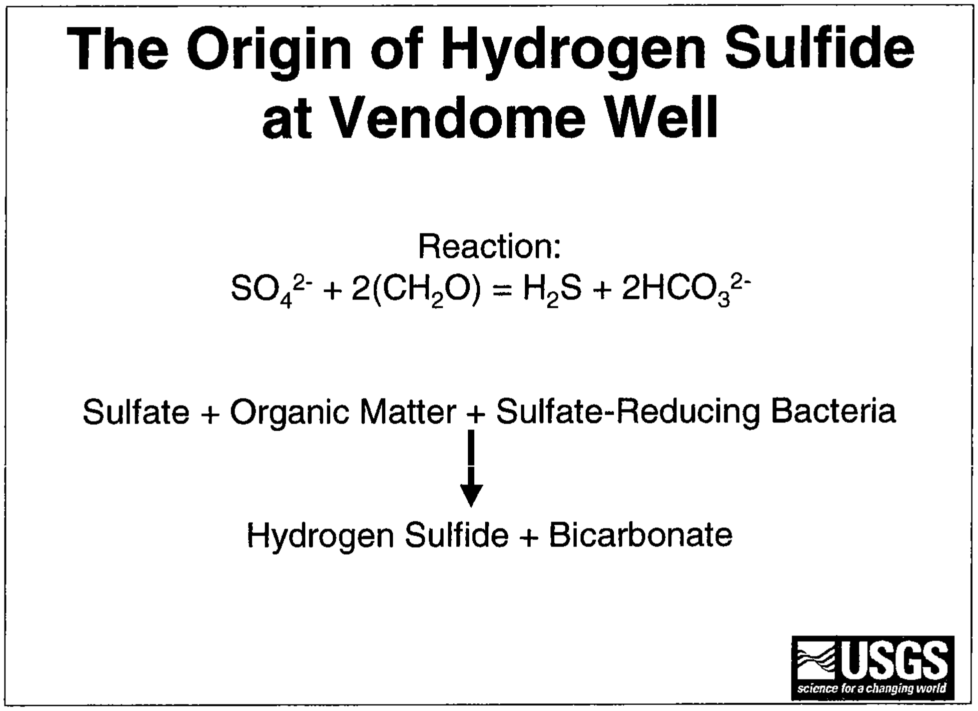


The Origin of Hydrogen Sulfide at Vendome Well

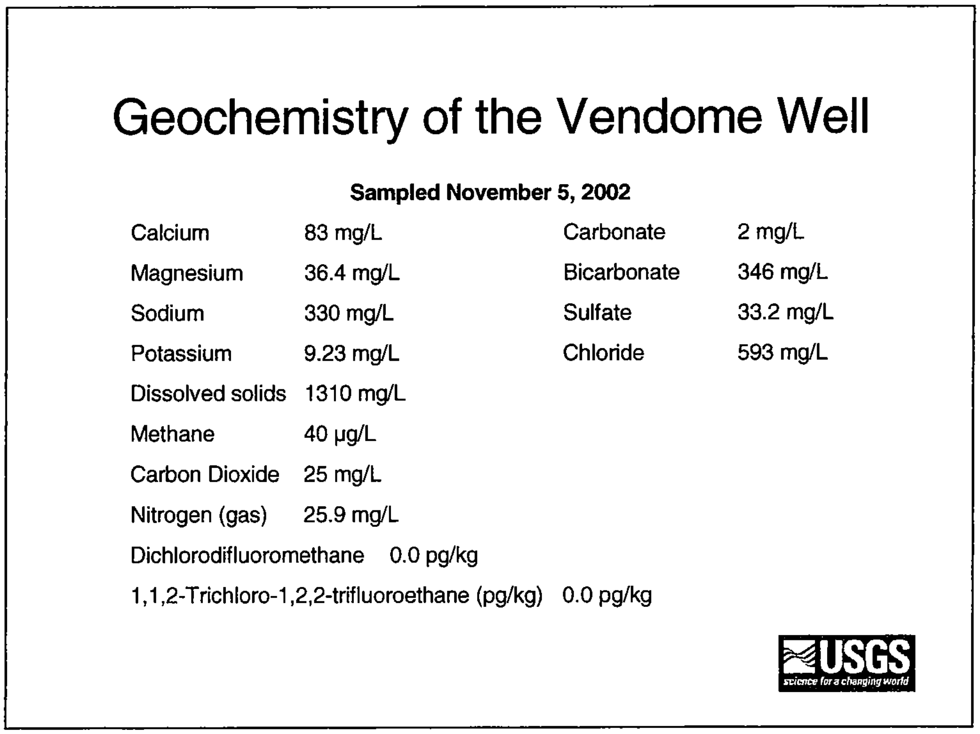
Reaction:

$SO_4^{2-} + 2(CH_2O) = H_2S + 2HCO_3^{2-}$

Sulfate + Organic Matter + Sulfate-Reducing Bacteria

↓

Hydrogen Sulfide + Bicarbonate



Geochemistry of the Vendome Well

Sampled November 5, 2002

Calcium	83 mg/L	Carbonate	2 mg/L
Magnesium	36.4 mg/L	Bicarbonate	346 mg/L
Sodium	330 mg/L	Sulfate	33.2 mg/L
Potassium	9.23 mg/L	Chloride	593 mg/L
Dissolved solids	1310 mg/L		
Methane	40 µg/L		
Carbon Dioxide	25 mg/L		
Nitrogen (gas)	25.9 mg/L		
Dichlorodifluoromethane	0.0 pg/kg		
1,1,2-Trichloro-1,2,2-trifluoroethane (pg/kg)	0.0 pg/kg		

A Brief Overview of the Geochemistry of the Arbuckle-Simpson Aquifer

By Scott Christenson

Introduction

The Arbuckle-Simpson aquifer outcrops in south-central Oklahoma over an area of about 500 square miles. The aquifer consists of limestone, dolomite, sandstone, and shale of the Arbuckle and Simpson Groups of Late Cambrian to Middle Ordovician age. The aquifer is underlain by Cambrian and Precambrian rhyolite and granite basement rocks. The underlying Timbered Hills Group, which ranges in thickness from 0 to about 700 feet, consists of the Honey Creek Limestone and Reagan Sandstone and probably is part of the same ground-water flow system. The basement rocks are found at the land surface in portions of the study area and as deep as about 8,000 feet in the few wells that penetrate the outcrop of the aquifer (Campbell and Weber, in preparation).

The Arbuckle-Simpson aquifer is highly folded, faulted, and fractured. The rocks were subjected to intensive folding and faulting associated with major uplift of the area during early to late Pennsylvanian time. Small karst features can be seen over much of the outcrop area of the aquifer, but air-filled caves are found in only a few locations.

The Arbuckle-Simpson aquifer study area commonly is divided into three sub-areas, the Hunton, Tishomingo, and Arbuckle Anticlines (fig. 1). These sub-areas are based loosely on geologic and topographic similarities, and the terms are not based strictly on structural geology. The geologic units tend to be thinner within the Hunton Anticline and thicken to the southwest in the Tishomingo and Arbuckle Anticlines. Structural deformation also increases to the southwest, with rocks more flat lying in the Hunton Anticline (dips less than 20 degrees) but increasing to the southwest with vertical and overturned beds to be found within the Arbuckle Anticline.

Hydrology

The primary source of water in the aquifer is diffuse recharge from precipitation, estimated to be about 4.7 inches per year (Fairchild and others, 1990) in the Hunton Anticline. Ground-water flow in the Hunton Anticline generally is to the southeast and ground water discharges to streams and springs, with the largest discharges near the down-gradient portion of the aquifer. Available potentiometric data in the Arbuckle and Tishomingo Anticlines show generally radial flow patterns (Fairchild and others, 1990). As in the Hunton Anticline, ground water in the Arbuckle and Tishomingo Anticlines discharges to streams and springs. The maximum depth of fresh ground water within the outcrop area is not known, but a small number of wells exceed 1,000 feet in depth and did not encounter saline water. A recently drilled test hole produced fresh water from a depth of 1,820 feet.

The freshwater zone of the aquifer generally coincides with the outcrop area of the aquifer, although a few small confined zones are located in some areas at the edge of the aquifer. The best known confined zone is located near the town of Sulphur and the Travertine District of the Chickasaw National Recreation Area. Ground water flows west from the Hunton Anticline and becomes confined beneath Pennsylvanian-age cemented conglomerates.

Ground water discharges to springs, Travertine and Rock Creeks, and wells, some of which are artesian. Another confined zone occurs on the eastern part of the Hunton Anticline, as indicated by a small number of artesian wells where low-permeability geologic units within the Simpson Group appear to act as confining layers.

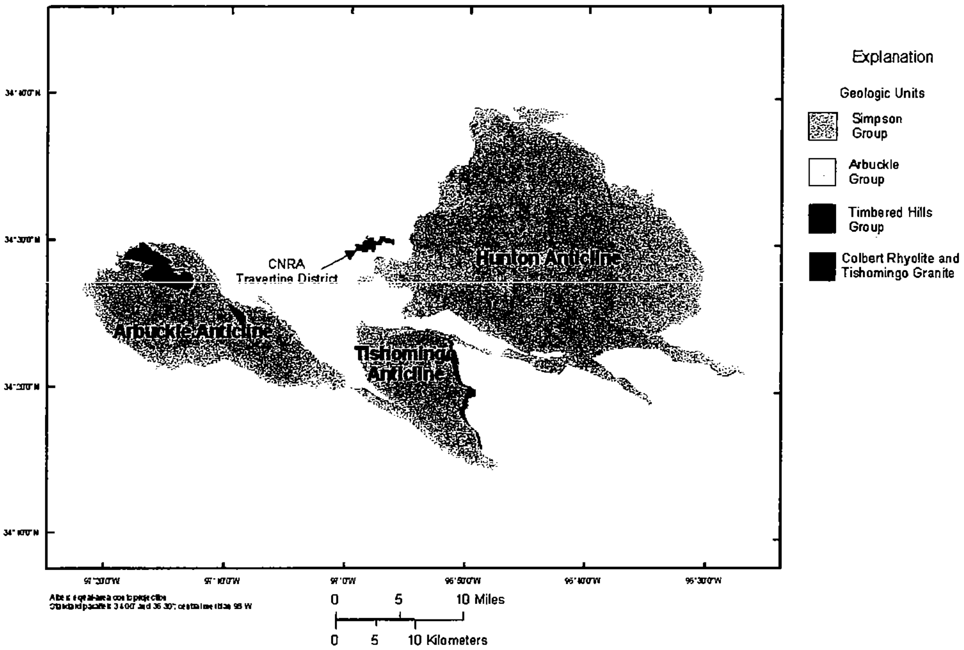


Figure 1. -- Subdivisions of the Arbuckle-Simspon aquifer.

Geochemical Reconnaissance

Ground- and spring-water samples were collected by the U.S. Geological Survey from 24 wells and 5 springs during 2004 as a geochemical reconnaissance for the current investigation of the Arbuckle-Simpson aquifer. The wells and springs included in the reconnaissance were selected in order to obtain broad coverage of the study area, including all three sub-areas. Shallow wells were selected (less than 500 feet deep) because most deep wells in this aquifer are completed with long open intervals and produce water from many zones. The suite of constituents for most samples included major cations and anions, trace metals, nutrients, bacteria, oxygen and hydrogen isotopes, carbon-14, noble gases, and tritium.

The geochemical reconnaissance showed that the quality of ground-water in the Arbuckle-Simpson aquifer is generally good, with most samples suitable for domestic and municipal uses. Two samples had nitrate concentrations that exceeded the U.S. Environmental Protection Agency's 10 mg/L Maximum Contaminant Level (MCL)(U.S. Environmental Protection Agency, 2002). No other MCLs were exceeded.

Water quality was very consistent in water samples from wells and springs in the outcrop areas. For all water samples, dissolved solids concentrations ranged from 222 to 1,250 milligrams per liter (mg/L) with a median concentration of 351 mg/L (table 1).

However, for samples from the outcrop area, the inter-quartile range (50 percent of the data centered on the median) of dissolved solids was 332 to 384 mg/L. Most water-quality constituents listed in table 1 have small inter-quartile ranges, indicating relatively uniform water quality.

Water type

Most of the water samples from wells and springs producing water from the outcrop area were of a calcium bicarbonate or calcium magnesium bicarbonate water type. Figure 2 shows Stiff diagrams, which graphically represent the dominant major cations and anions dissolved in the water. On figure 2, the Stiff diagram is positioned above the well or spring (shown as a black dot) from which the water sample was collected. Wells or springs such as the Line Camp well produce water in which calcium is the dominant cation (the middle left axis of the Stiff diagram) and bicarbonate (the middle right axis of the Stiff diagram) is the dominant anion. Stiff diagrams of water samples from wells and springs producing water from the Arbuckle Anticline show a distinct diamond shape characteristic of calcium bicarbonate waters. Stiff diagrams of water samples from wells and springs producing water from the Hunton Anticline have a slightly different shape in which the lower left axis, representing magnesium, is longer (see for example the Stiff diagram for Antelope Spring). Water from the Hunton Anticline tends to have higher magnesium concentration than water from the Arbuckle Anticline, which is consistent with the geology. The Arbuckle Anticline tends to have more limestone, which consists mostly of calcium carbonate, and the Hunton Anticline tends to have more dolomite, a form of carbonate rocks similar to limestone but with a substantial amount of magnesium.

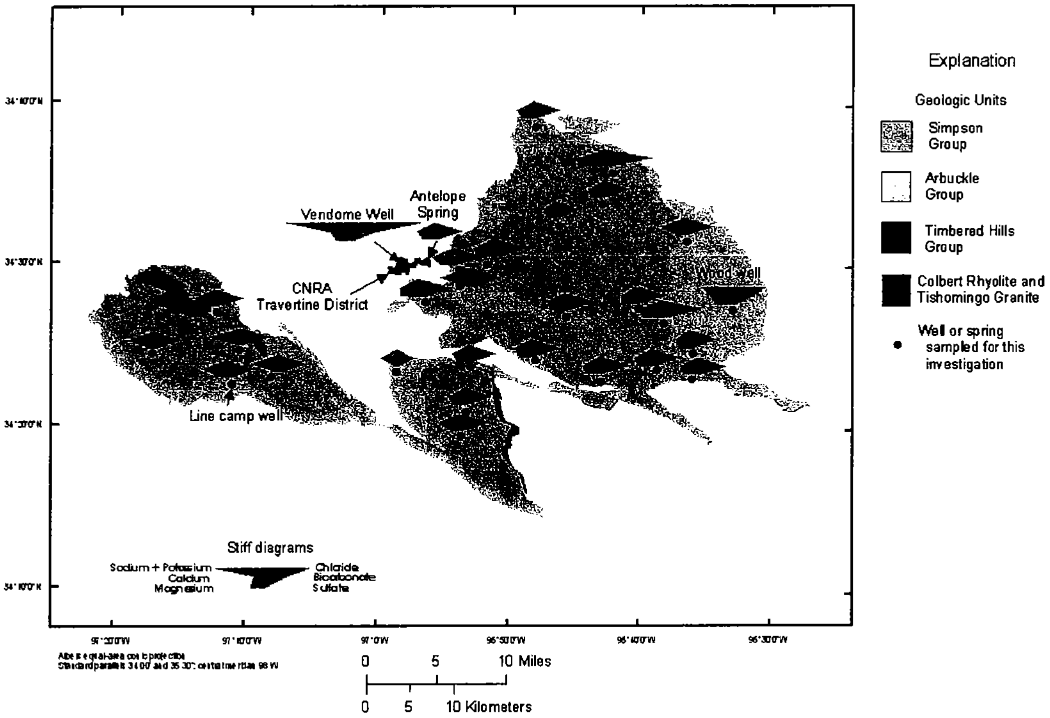


Figure 2. -- Stiff diagrams of the major ion chemistry of the Arbuckle-Simpson aquifer

Age-dating tracers

Chemicals and isotopes that are dissolved in ground water can be used to determine the apparent age of ground water. The apparent age of ground water is considered to be the amount of time determined from an age-dating tracer that has elapsed since the water was last in contact with the atmosphere. These chemicals and isotopes are referred to as "age-dating tracers." Several different age-dating tracers were used for the geochemical reconnaissance, helium-3/tritium and carbon-14.

Tritium is a short-lived radioactive isotope of hydrogen with a half-life of 12.32 years. Tritium forms naturally as cosmic radiation interacts with the upper atmosphere, and all precipitation that falls to Earth has small amounts of tritium. During the 1950s and early 1960s, global atmospheric testing of nuclear weapons raised the atmospheric concentrations of tritium hundreds of times above the normal background concentration. After the early 1960s, when the Nuclear Test Ban Treaty was signed and atmospheric testing of nuclear weapons ceased, tritium concentrations in the atmosphere have decreased and are approaching natural levels. By measuring both the helium-3 and tritium content from a ground-water sample, an apparent age can be determined because the rate that tritium decays to helium-3 is known (Lucas and Unterwager, 2000).

Carbon-14 is the radioactive isotope of carbon with a half-life of 5,730 years. Carbon-14 is widely used and is well-known to the public as a tool for dating archeological sites, but carbon-14 also can be used to date ground water. Like tritium, carbon-14 is produced in the upper atmosphere and thus occurs naturally. Atmospheric carbon-14 concentrations were elevated by as much as 50 percent by the testing of nuclear weapons after 1954 (Coplen, 1993).

Figure 3 shows the results of the age-dating tracer samples for the Arbuckle-Simpson geochemical reconnaissance. Most water samples were considered to be modern water. The fact that most water in the aquifer is modern indicates the water is circulating relatively rapidly though the aquifer, in less than about 60 years. Modern ground water generally is more susceptible to contamination than old ground water because of the many man-made contaminants introduced to the environment during the 20th century.

Ground water at the edge of the Arbuckle-Simpson aquifer

Two samples were dissimilar to samples from wells and springs producing water from the outcrop area, the Vendome and Wood artesian wells (fig. 2). The Vendome well is 775 feet deep and completed in the Arbuckle Group west of the Hunton Anticline in the town of Sulphur. The Wood artesian well, on the eastern Hunton Anticline, was logged in 1978 as 950 feet deep but it is not known if it is completed in the Arbuckle or Simpson Groups. These two wells produced the highest dissolved solids concentrations of the wells sampled for this study. Both wells produce water with sodium and chloride as the dominant cation and anion (fig. 2), and the waters from both wells have a distinct hydrogen sulfide odor. Carbon-14 samples from these wells show the waters to be quite old. The uncorrected carbon-14 concentration from the Vendome well water sample indicated an age of about 17,000 years, and water samples from the Wood well indicated an uncorrected carbon-14 age of over 30,000 years. Noble gas analysis of the water samples from these wells indicate a recharge temperature of about 8 degrees (Vendome) and 9 degrees (Wood) Celsius, which is consistent with cooler temperatures from the Pleistocene Epoch during which the water from these wells probably entered the aquifer. Both the Vendome and Wood wells are considered to be producing water from the edge of the freshwater flow system in the Arbuckle-Simpson aquifer. Connate saline brine surrounds the freshwater portion of the aquifer and the Vendome and Wood wells probably represent a mixture of freshwater and brine at the edge of the freshwater flow system in the aquifer.

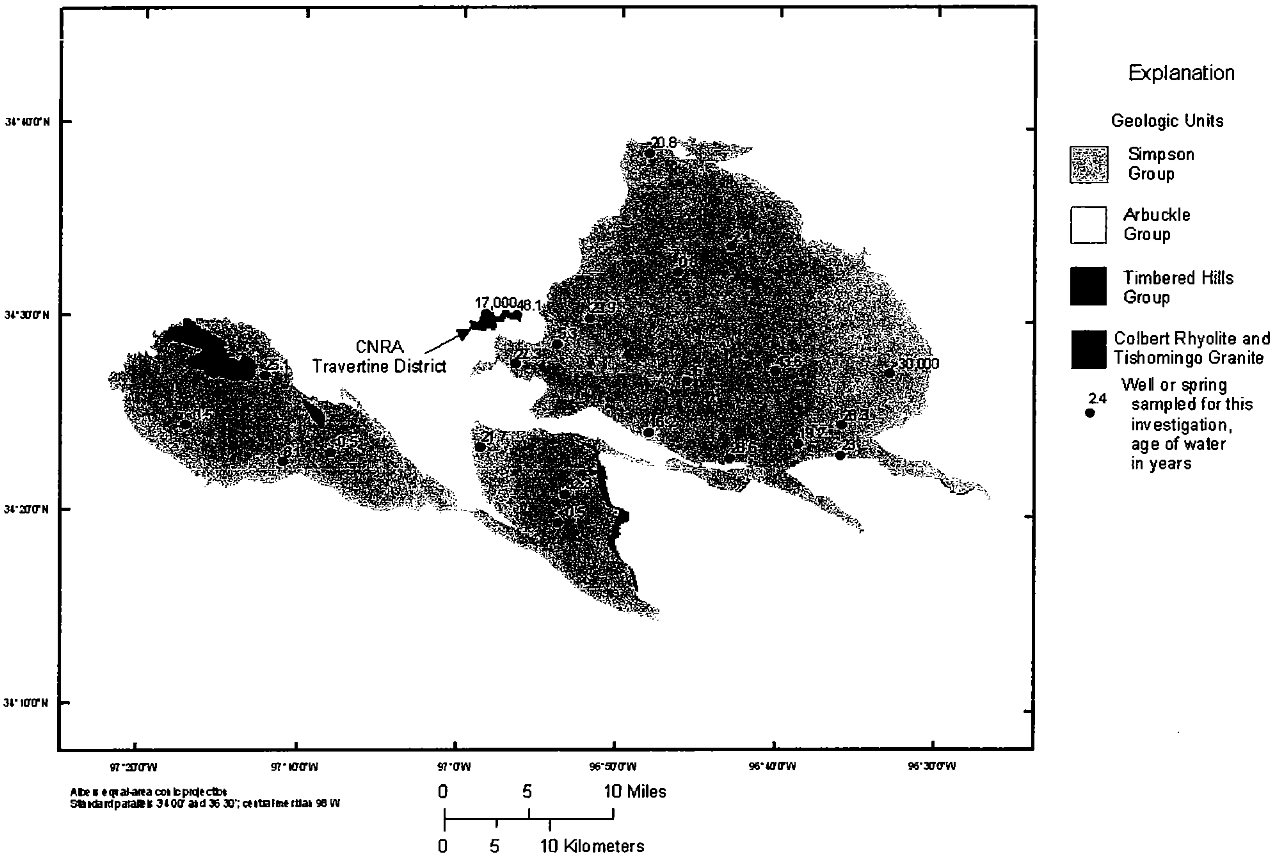


Figure 3. -- Age of water samples from wells and springs.

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Table 2. Chemical analyses of water samples from the Wood and Vendome wells

STATION NUMBER ------ 342722096325501
STATION NAME -------- 01S-07E-23 BCC 1 Wood well
DATE OF COLLECTION -- 10-21-2004 1000

Concentration	Constituent
18.4	Temperature, water, degrees Celsius
1350	Specific conductance, water, unfiltered, microsiemens per centimeter at 25 degrees C
1.6	Dissolved oxygen, water, unfiltered, milligrams per liter
7.2	pH, water, unfiltered, field, standard units
.0	Carbonate, water, filtered, incremental titration, field, milligrams per liter
314	Bicarbonate, water, filtered, incremental titration, field, milligrams per liter
.30	Ammonia, water, filtered, milligrams per liter as nitrogen
< .008	Nitrite, water, filtered, milligrams per liter as nitrogen
< .06	Nitrite plus nitrate, water, filtered, milligrams per liter as nitrogen
< .02	Orthophosphate, water, filtered, milligrams per liter as phosphorus
84.8	Calcium, water, filtered, milligrams per liter
38.7	Magnesium, water, filtered, milligrams per liter
141	Sodium, water, filtered, milligrams per liter
9.52	Potassium, water, filtered, milligrams per liter
279	Chloride, water, filtered, milligrams per liter
39.9	Sulfate, water, filtered, milligrams per liter
.7	Fluoride, water, filtered, milligrams per liter
12.4	Silica, water, filtered, milligrams per liter
.2	Arsenic, water, filtered, micrograms per liter
79	Barium, water, filtered, micrograms per liter
< .06	Beryllium, water, filtered, micrograms per liter
321	Boron, water, filtered, micrograms per liter
< .04	Cadmium, water, filtered, micrograms per liter
< .8	Chromium, water, filtered, micrograms per liter
.270	Cobalt, water, filtered, micrograms per liter
.7	Copper, water, filtered, micrograms per liter
18	Iron, water, filtered, micrograms per liter
< .08	Lead, water, filtered, micrograms per liter
.9	Manganese, water, filtered, micrograms per liter
< .04	Thallium, water, filtered, micrograms per liter
< .4	Molybdenum, water, filtered, micrograms per liter
1.22	Nickel, water, filtered, micrograms per liter
--	Silver, water, filtered, micrograms per liter
2480	Strontium, water, filtered, micrograms per liter
< .3	Vanadium, water, filtered, micrograms per liter
E .5	Zinc, water, filtered, micrograms per liter
< .20	Antimony, water, filtered, micrograms per liter
< 2	Aluminum, water, filtered, micrograms per liter
37.9	Lithium, water, filtered, micrograms per liter
1.1	Selenium, water, filtered, micrograms per liter
< .04	Uranium (natural), water, filtered, micrograms per liter
258	Alkalinity, water, filtered, incremental titration, field, milligrams per liter
.670	Carbon-14, water, filtered, percent modern
768	Residue on evaporation, dried at 180 degrees Celsius, water, filtered, milligram
.034	Iodide, water, filtered, milligrams per liter
.96	Bromide, water, filtered, milligrams per liter
-8.44	Carbon-13/Carbon-12 ratio, water, unfiltered, per mil
-31.60	Deuterium/Protium ratio, water, unfiltered, per mil
-5.57	Oxygen-18/Oxygen-16 ratio, water, unfiltered, per mil
239	Acid neutralizing capacity, water, unfiltered, fixed endpoint (pH 4.5) titration

Table 2. Chemical analyses of water samples from the Wood and Vendome wells—Continued.

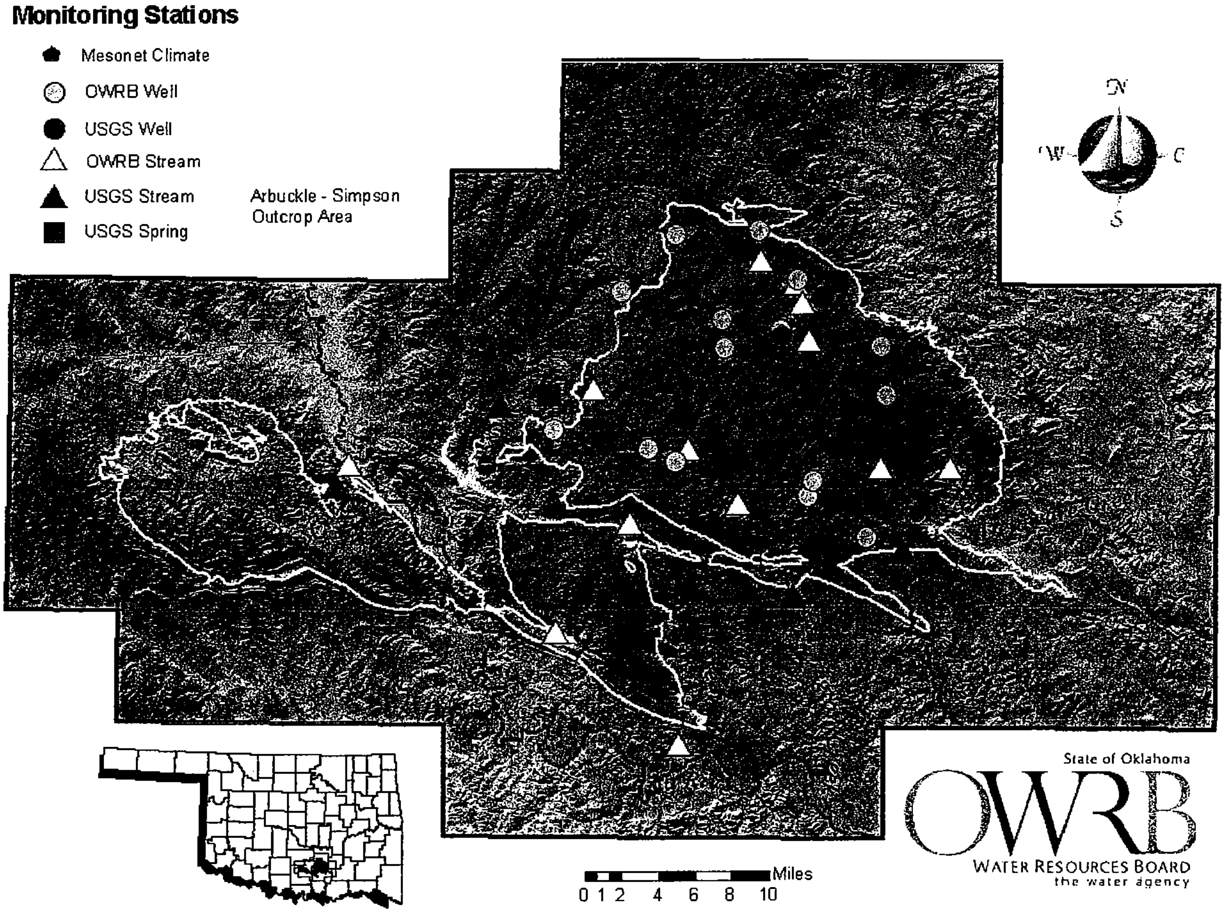
STATION NUMBER ------ 343020096582301
STATION NAME -------- 01S-03E-03 ABA 1 Vendome Well
DATE OF COLLECTION -- 10-20-2004 1000

Concentration	Constituent
19.6	Temperature, water, degrees Celsius
80020	Agency analyzing sample, code
2100	Specific conductance, water, unfiltered, microsiemens per centimeter at 25 degrees C
.1	Dissolved oxygen, water, unfiltered, milligrams per liter
7.1	pH, water, unfiltered, field, standard units
.0	Carbonate, water, filtered, incremental titration, field, milligrams per liter
339	Bicarbonate, water, filtered, incremental titration, field, milligrams per liter
.43	Ammonia, water, filtered, milligrams per liter as nitrogen
< .008	Nitrite, water, filtered, milligrams per liter as nitrogen
< .06	Nitrite plus nitrate, water, filtered, milligrams per liter as nitrogen
< .02	Orthophosphate, water, filtered, milligrams per liter as phosphorus
86.6	Calcium, water, filtered, milligrams per liter
37.4	Magnesium, water, filtered, milligrams per liter
316	Sodium, water, filtered, milligrams per liter
9.60	Potassium, water, filtered, milligrams per liter
558	Chloride, water, filtered, milligrams per liter
35.1	Sulfate, water, filtered, milligrams per liter
.7	Fluoride, water, filtered, milligrams per liter
13.0	Silica, water, filtered, milligrams per liter
.5	Arsenic, water, filtered, micrograms per liter
202	Barium, water, filtered, micrograms per liter
< .06	Beryllium, water, filtered, micrograms per liter
496	Boron, water, filtered, micrograms per liter
< .04	Cadmium, water, filtered, micrograms per liter
< .8	Chromium, water, filtered, micrograms per liter
.310	Cobalt, water, filtered, micrograms per liter
1.2	Copper, water, filtered, micrograms per liter
< 18	Iron, water, filtered, micrograms per liter
< .08	Lead, water, filtered, micrograms per liter
2.2	Manganese, water, filtered, micrograms per liter
< .04	Thallium, water, filtered, micrograms per liter
< .4	Molybdenum, water, filtered, micrograms per liter
1.57	Nickel, water, filtered, micrograms per liter
< .2	Silver, water, filtered, micrograms per liter
6860	Strontium, water, filtered, micrograms per liter
< .1	Vanadium, water, filtered, micrograms per liter
.6	Zinc, water, filtered, micrograms per liter
< .20	Antimony, water, filtered, micrograms per liter
M	Aluminum, water, filtered, micrograms per liter
66.2	Lithium, water, filtered, micrograms per liter
2.5	Selenium, water, filtered, micrograms per liter
< .04	Uranium (natural), water, filtered, micrograms per liter
278	Alkalinity, water, filtered, incremental titration, field, milligrams per liter
11.97	Carbon-14, water, filtered, percent modern
1250	Residue on evaporation, dried at 180 degrees Celsius, water, filtered, milligram
.062	Iodide, water, filtered, milligrams per liter
2.08	Bromide, water, filtered, milligrams per liter
-8.21	Carbon-13/Carbon-12 ratio, water, unfiltered, per mil
-31.20	Deuterium/Protium ratio, water, unfiltered, per mil
-5.40	Oxygen-18/Oxygen-16 ratio, water, unfiltered, per mil
263	Acid neutralizing capacity, water, unfiltered, fixed endpoint (pH 4.5) titration

Stop 4
Fittstown Mesonet Weather Station

Monitoring

Monitoring of groundwater, surface water, and climate is critical for model calibration and for water planning and management. Currently, the Arbuckle-Simpson Hydrology Study monitoring network consists of 3 USGS stream gages, 12 OWRB periodic stream stations, 1 OWRB continuous stream station, 15 OWRB wells for monitoring water levels, and 1 Mesonet weather station.



Monitoring stations for the Arbuckle-Simpson Hydrology Study, March 2006.

Fittstown Mesonet Station

The Oklahoma Mesonet was designed and implemented by scientists at the University of Oklahoma and Oklahoma State University. The Oklahoma Climatological Survey (OCS) has operated and maintained the Mesonet since 1994. Funding for the core operations of the Mesonet is provided by the Oklahoma State Regents for Higher Education. Currently, more than 20 variables are measured every five minutes and are transmitted through the Oklahoma

Law Enforcement Telecommunications System. Data are sent to the Mesonet Operations Center at OCS in Norman, Oklahoma, where they undergo rigorous quality assurance before release to customers. The Oklahoma Mesonet is considered the premier regional network of meteorological stations in the nation, perhaps the world. Mesonet customers include state agencies, K-12 schools, public safety agencies, growers, ranchers, electric utility cooperatives, the media, and private citizens.

OCS commissioned the Fittstown Mesonet station on May 12, 2005. The station measures precipitation, temperature, barometric pressure, relative humidity, wind speed and direction, solar radiation, soil temperature, and soil moisture. Data are transmitted to a central facility every 5 minutes and can be viewed on the Internet (www.mesonet.org). These data provide researchers with information essential to understanding the aquifer and how it responds to variations in precipitation and other factors.

The Fittstown Mesonet site was selected because the location is on top of the Arbuckle-Simpson aquifer and in the watershed of the Blue River. The location satisfies OCS Mesonet siting requirements related to accessibility, geography, and vegetation. In addition, the area contains few obstructions and the site maintains consistency with spatial distribution of other Mesonet stations.

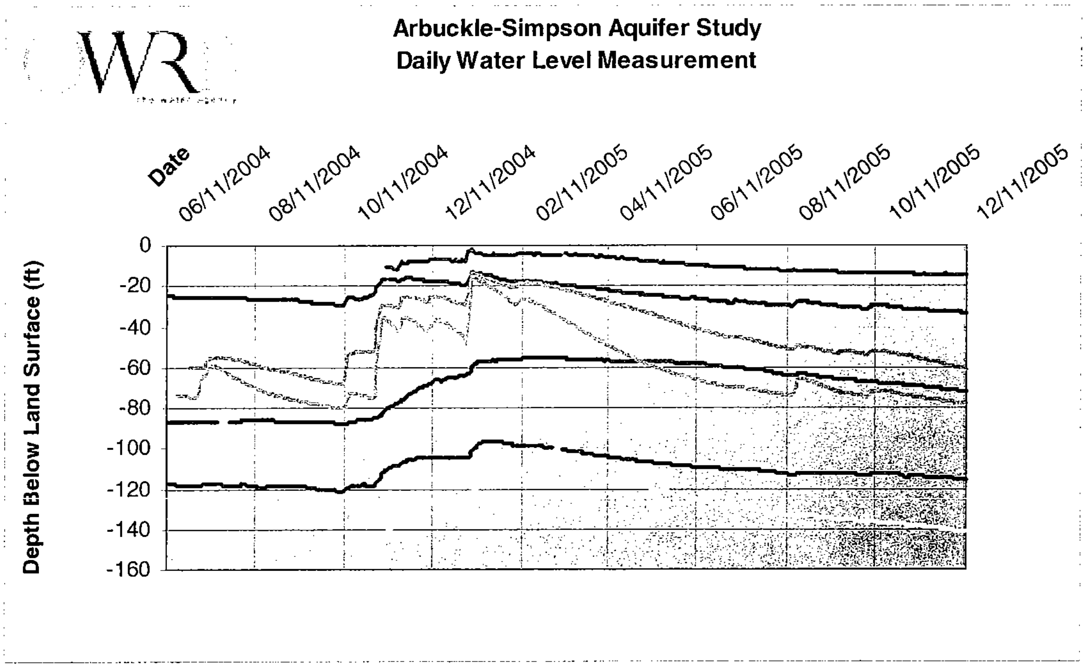
A 255-ft observation well was drilled at the station in October 2005. The well encountered only small amounts of water. Static water level is about 105 ft below land surface. A pressure transducer and data logger will record continuous water level measurements. Real-time daily water level measurements and hydrographs will be available on the Mesonet website, along with the other climatological data.

The Fittstown station has already made the news and broken records in 2005. The station recorded the record low of 8° for December 8 in Pontotoc County. The previous record for that date was 9° in Ada, in 1927. A wind speed of 66 mph, one of the highest wind speeds in the state, was recorded on November 27. The highest temperature recorded at the station was 97° on various days in June, July, and August. The lowest was 2° on December 9. August had the highest rainfall of 7.15 inches, and November the lowest of 0.11 inches. The greatest rainfall in 24 hours was 3.80 inches on September 15.

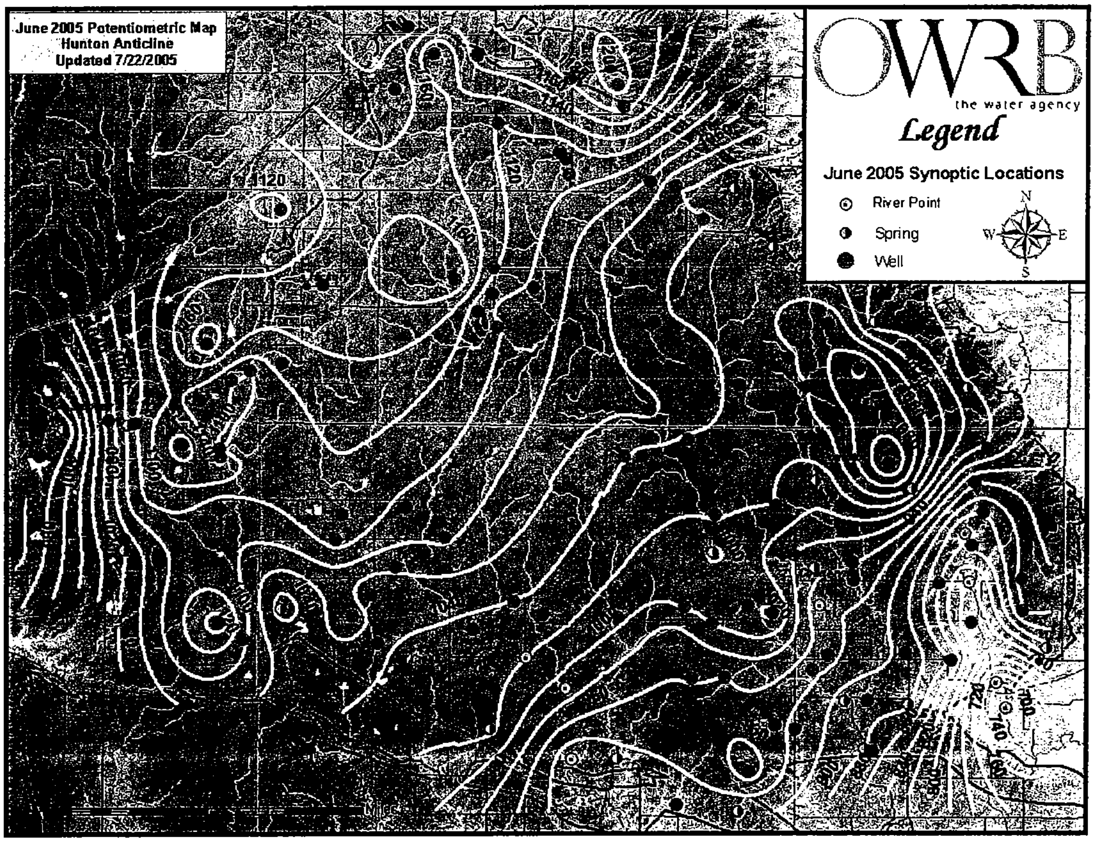
Groundwater

Continuous water-level measurements provide information on how the aquifer responds over time to various stresses, such as precipitation and pumping. Currently, OWRB is maintaining In-Situ units in 15 wells. In addition to the OWRB data loggers, USGS maintains the Fittstown groundwater-observation well, for which real-time data are available on the USGS web site.

Synoptic water-level measurements provide a "snapshot" of the water table for a specific time. OWRB is conducting quarterly synoptic water-level measurements using a network of about 100 wells in the Hunton Anticline region. Data from these measurement events are used to construct potentiometric maps of the aquifer.

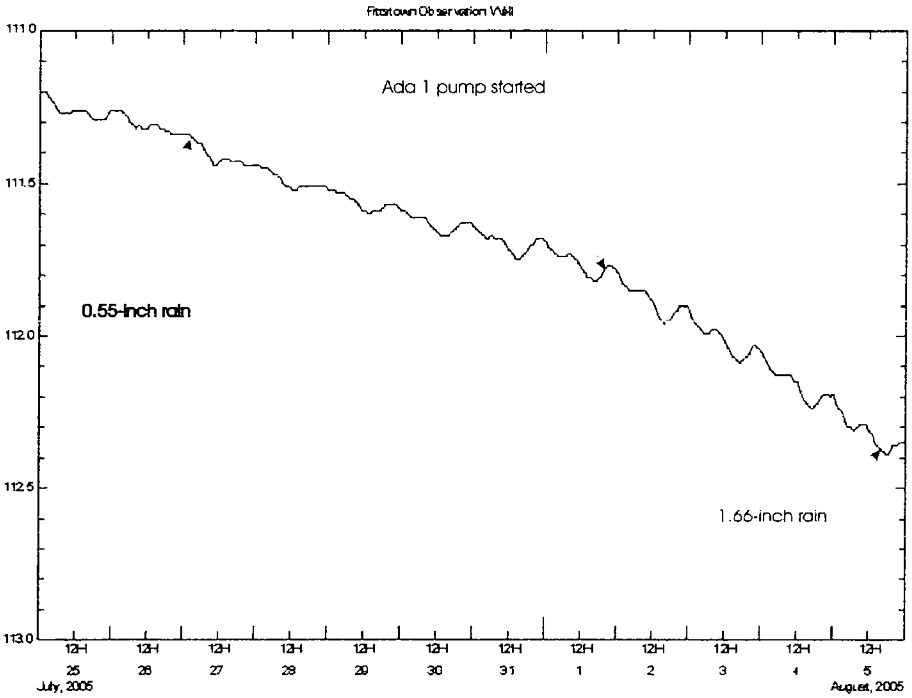


Hydrographs showing daily water level measurements for representative wells in the Arbuckle-Simpson aquifer.

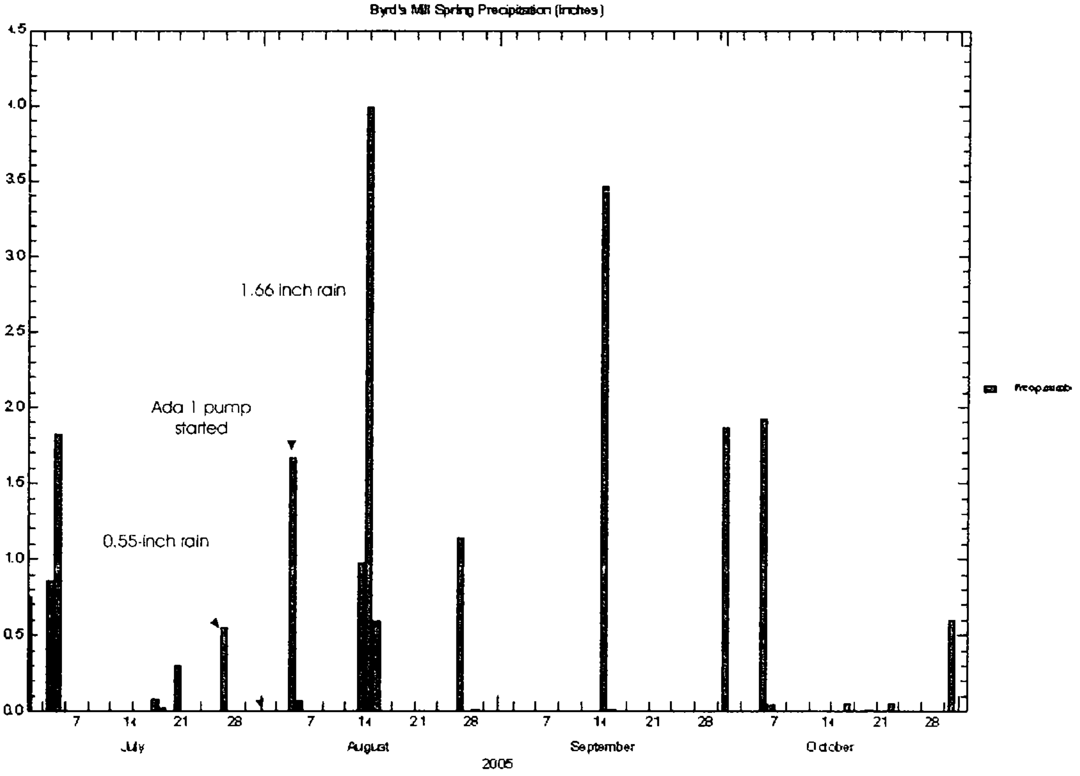


Potentiometric surface from water-level measurements collected June 22-23, 2005 of the Hunton Anticline portion of the Arbuckle-Simpson aquifer (20-feet contour interval).

Preliminary analysis of data collected from an aquifer test conducted on the City of Ada's well field shows the effects of Earth tides on water levels. Analyzing the water level's response to pumping will be much more complicated because of the Earth tides, but it is possible that the Earth tides will yield independent estimates of aquifer hydraulic parameters



Response of Fittstown observation well to City of Ada well 1 aquifer test

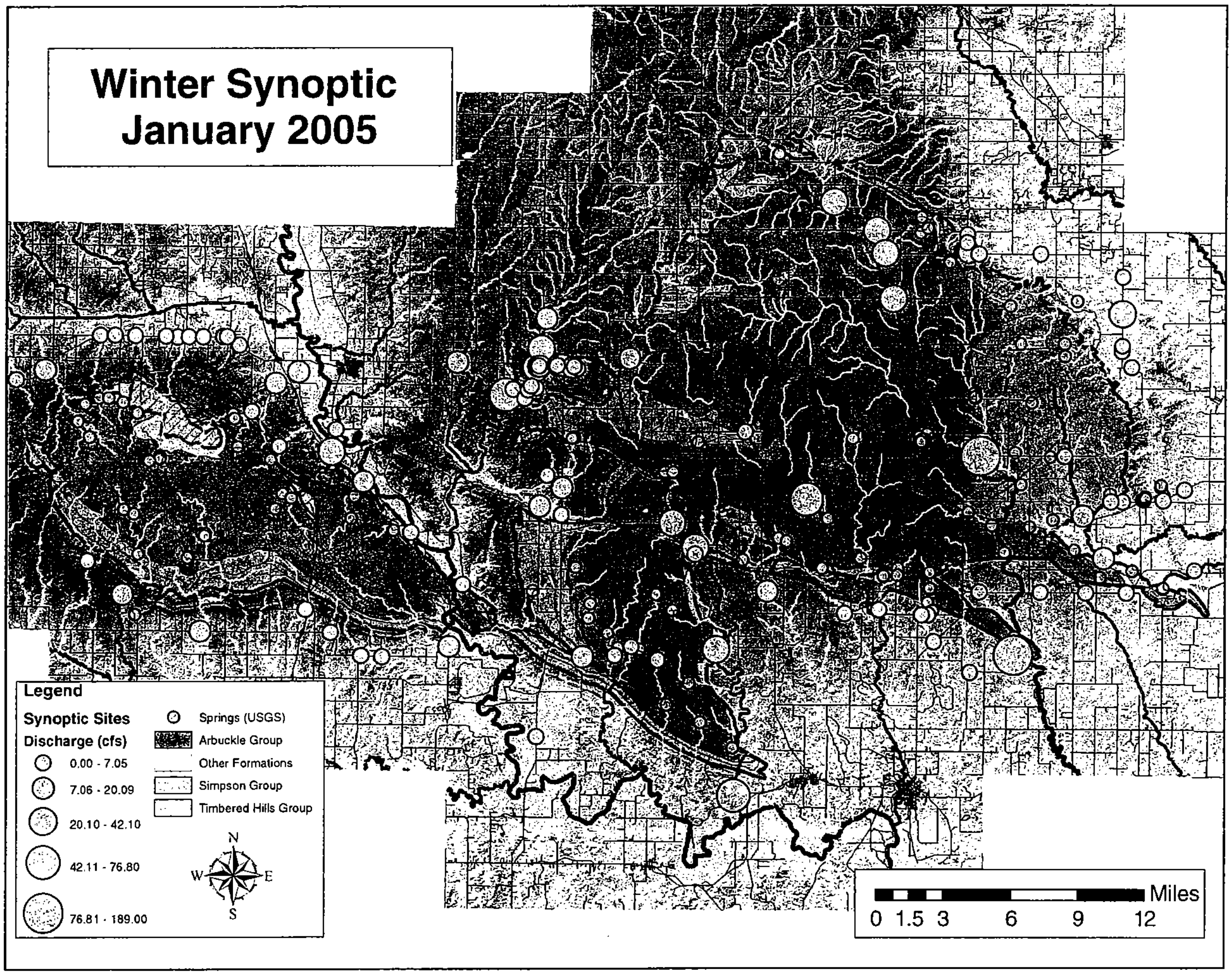


Streamflow

Three USGS stream gages have been installed for the study: Blue River near Connerville, Pennington Creek near Reagan, and Honey Creek below Turner Falls. These are in addition to other USGS gages at Byrds Mill Spring, Antelope Spring, and Rock Creek at Sulphur. To provide additional precipitation data for the study, USGS installed rain gages at the Pennington Creek, Honey Creek, Byrds Mill Spring, and Blue River stations.

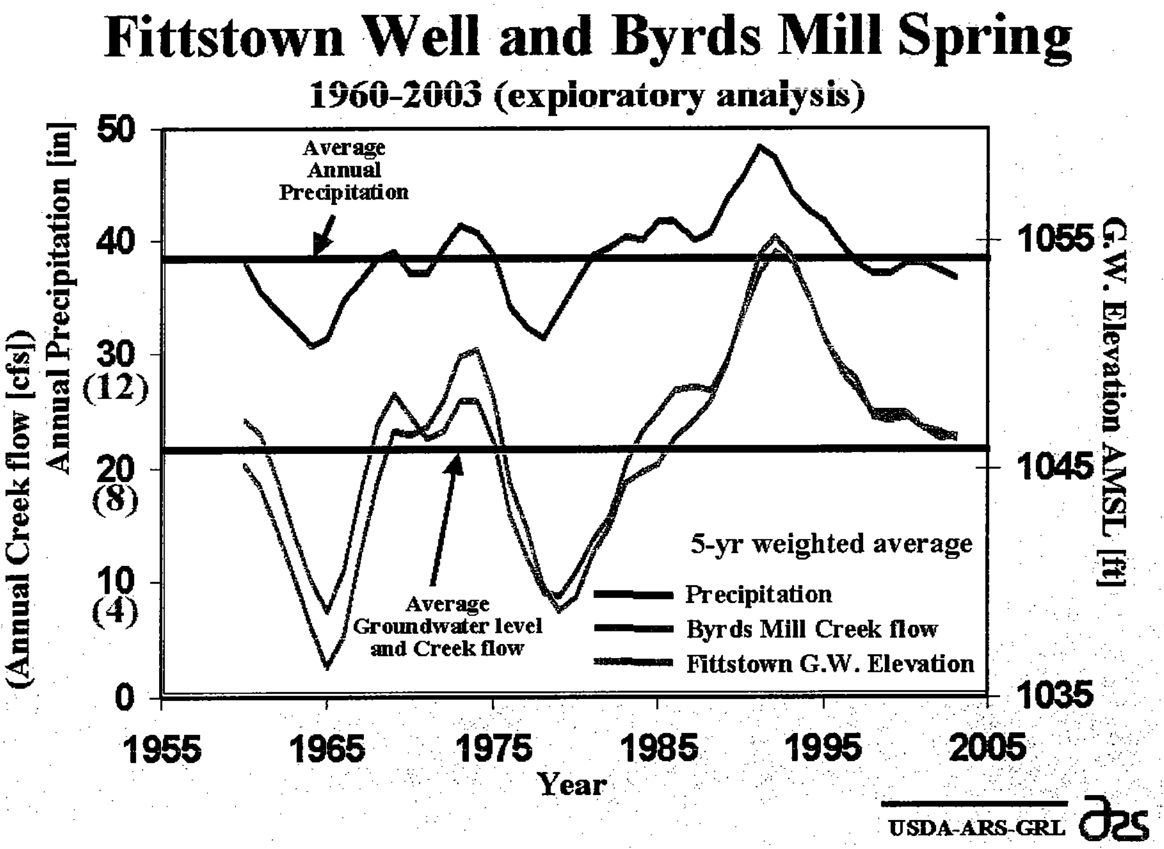
OWRB conducts periodic monitoring of 12 stream stations on Blue River and Delaware, Honey, Mill, Oil, and Pennington Creeks. Nine sites are equipped with wire-weight gages installed on bridges, and three sites are equipped with staff gages or tape-down points. Point discharge measurements and field parameters are measured during a variety of flow conditions to develop rating curves. One station, located on the upper reach of Blue River, conducts continuous monitoring.

OWRB also conducts seepage runs during base-flow conditions, when there is no surface runoff. Data obtained from these investigations will be used for model calibration and for determining the water budget.



Long-Term Trends

Garbrecht and Schneider (2004) plotted the five-year moving average for the groundwater levels from the Fittstown Well, mean annual spring flow of Byrds Mill Spring, and annual precipitation of the south central climate division. The graph shows a close correlation between groundwater levels, spring flow, and precipitation. Groundwater levels and spring flow were high from 1985-1997 (during the wettest period on record), and since 1992, both have followed the declining trend of precipitation. If precipitation returns to the record normal, Byrds Mill Spring should return to the flows experienced during the 1960 and 1970s.



Five-year moving average of the annual mean groundwater level at the Fittstown Well, mean annual flow at Byrds Mill Spring, and annual precipitation of the south-central climate division.

References

Garbrecht, J.D. and Schneider, J.M., 2004, Long-term variability of Oklahoma precipitation and water resources availability: Proceedings from Oklahoma Water 2004, Stillwater, OK, November 18-19, Environmental Institute Oklahoma State University, 7 p.

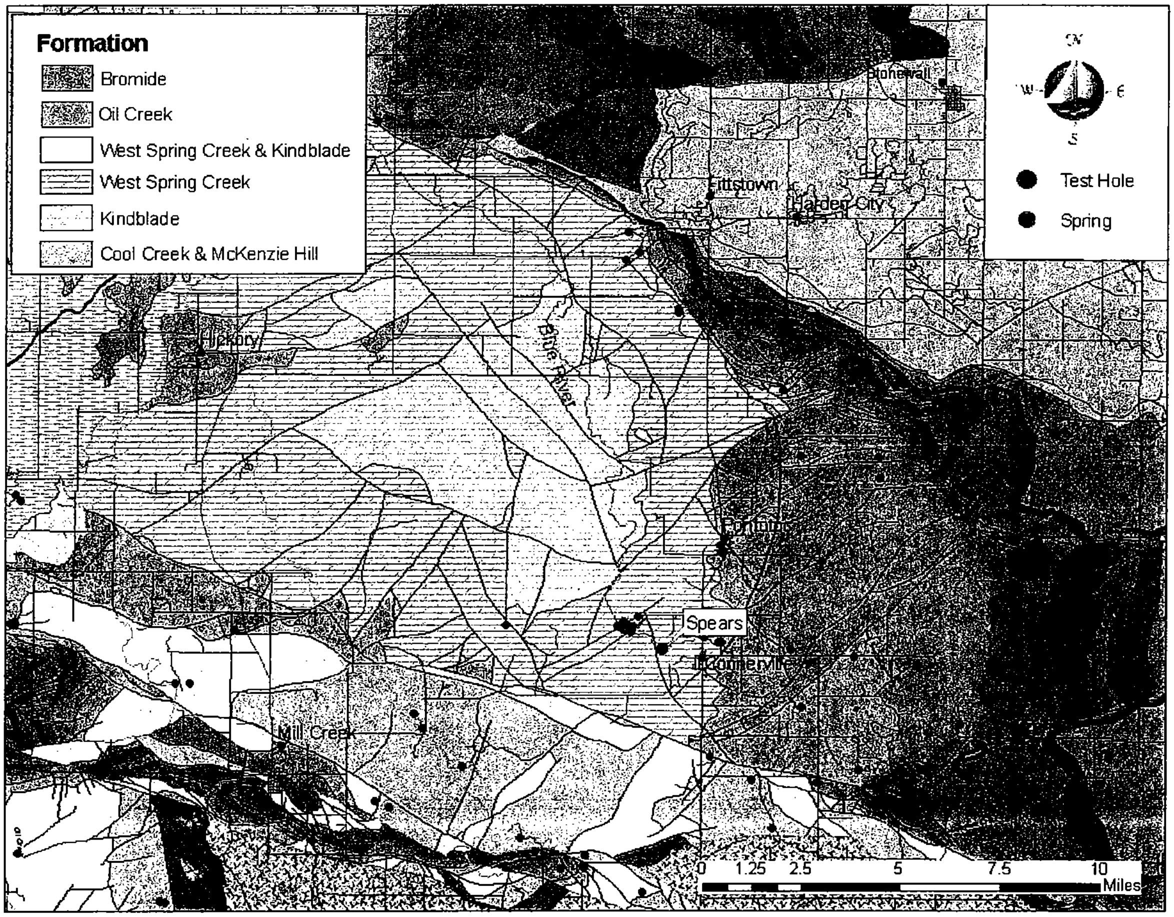
Stop 5
Spears Ranch

Deep Test Hole

Background

The purpose of drilling and testing the well was to gain information regarding reservoir characteristics, stratigraphy, aquifer properties, vertical flow gradients, and geochemistry. A deep test hole was especially needed to collect information on the lower portion of the Arbuckle-Simpson aquifer (1,000-4,000 ft) in order to determine the full extent of the fresh-water zone and the base of the aquifer. The drilling site was selected based on the study's needs, hydrogeology, and the model simulations. Model simulations indicated that the best location for determining vertical flow gradients is at the down-gradient end of the regional flowpath.

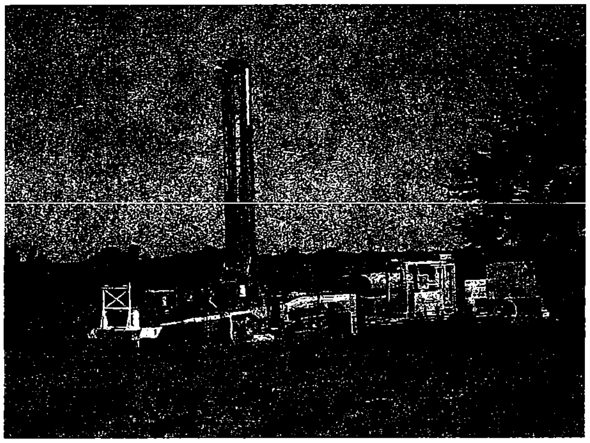
The selected site is located on the Spears Ranch in section 23-01S-06EI, Johnston County, and is approximately 1,300 feet from Blue River. The West Spring Creek Formation of the Arbuckle Group is exposed at the surface.

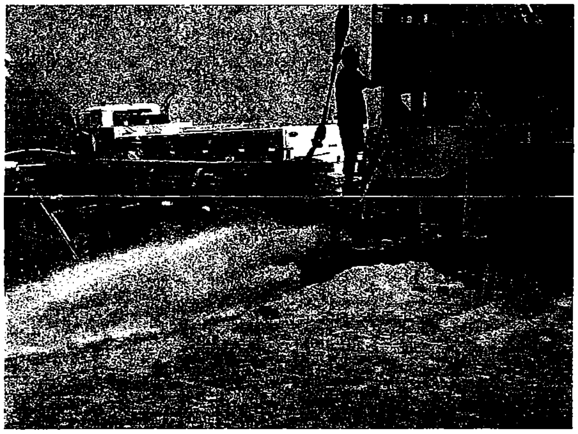


Spears deep test hole site

Drilling Summary

USGS Research Drilling Project out of Denver, Colorado was contracted to drill the well to a maximum depth of 3,000 ft, which is the approximate limit of the Gardner-Denver 17-W rig. Two air compressors were used to supply air for the drilling of the well: a rig deck-mounted 750 cfm, 350-psi compressor, and an auxiliary 900 cfm, 350-psi compressor. In addition, a 1,800 cfm, 1,000 psi-booster compressor was used to increase the air pressure so that drilling could continue to greater depths than what could otherwise be achieved.


USGS drill rig and support equipment at the Spear Ranch


Drilling produced large volumes of water

USGS began drilling the Spears Test Hole #1 on September 14, 2005. The well was drilled with air rotary to 80 ft, where $6^{5/8}$-in surface casing was set and cemented. A 6-in diameter hole was then drilled through the casing using a 5-in percussion hammer. A fractured zone at 364-366 ft made approximately 300-350 gpm of water, which created substantial backpressure against the hammer and greatly decreased its efficiency. In an effort to seal the fracture zone, approximately 280 pounds of cement were pumped into the hole. However, the cement flowed laterally into the zone and failed to seal the fracture or decrease the amount of water being produced. Drilling continued using a new 6-in pneumatic hammer. The tight clearance between the hammer body and the drill bit did not allow larger cuttings to be adequately removed from the hole which, in turn, began to cause the bit to bind and torque in the hole. After struggling with this problem, the driller recommended abandoning the 628-ft hole on September 24, and starting over with a new, larger-diameter well.

On September 25, drilling commenced on the Spears Test Hole #2, located about 200 ft east of the initial test hole. A 12¼ -in hole was drilled to 35 ft, where $8^{5/8}$-in surface casing was set and cemented. An 8-in diameter hole was drilled below the casing using the 6-in pneumatic hammer. The well steadily gained water (>300 gpm), until about 645-700 ft, where a heavily fractured zone was encountered and the well made an estimated 800-1,000 gpm of water. Drilling with the air hammer continued to a depth of 875 ft, where excessive backpressure again decreased the hammer efficiency to the point where bit penetration virtually stopped. Drilling continued using standard air rotary methods with a $6^{3/4}$-in carbide-tipped rollercone bit to a depth of 1,473 ft, at which point an overheating problem with the drill rig engine resulted in the need for major repair work.

Drilling resumed on November 16. At a depth of 1,540 ft, as a test, the drilling crew attempted to drill with hydraulic rotary using the rig's 200-gpm duplex mudpump and a portable shaker tank. However, due to the large number of fractures in the well, water was lost into the formation and circulation of fluid to the surface could not be achieved. They concluded that with lost circulation, drilling with water was not feasible, and drilling with mud and lost circulation material would be cost and time-prohibitive. The crew resumed drilling with air, and continued until November 30, when budgeted funds were exhausted. Total depth was 1,820 ft. Produced water was estimated to be between 1,000 and 1,200 gpm at this depth.

Drilling of the two test holes was hampered by several mechanical and technical problems, the primary of which was the pneumatic hammer's inability to effectively drill when large volumes of water were encountered. Drilling was able to continue to greater depths using standard air rotary techniques, but with much slower penetration rates than those achieved using the pneumatic hammer.

Geochemical Sampling

Plans are to sample the well for the same suite of constituents sampled for the fall 2004 geochemical reconnaissance (including major cations and anions, trace metals, nutrients, bacteria, oxygen and hydrogen isotopes, carbon-14, noble gases, and tritium). The chemical composition of water samples pulled from various depths in the well will show how water has evolved along the flow path and if water is stratified by depth. Age dating of water samples can be used to determine ground-water velocities and recharge rates.

The initial plan was to sample 5-6 zones as the hole was drilled using single conductor packer tests. When a test interval was reached, USGS stopped drilling to retrieve the drill string, insert the single-packer system, inflate the packer, and test the interval between the packer and the bottom of the test hole. Testing consisted of measuring the hydraulic head and collecting water-quality samples.

Three zones were sampled in this manner. However, after pumping the well 9-10 hours prior to collecting the last sample (916-960 ft), there was still drilling foam in the water. Concerned that the water samples were contaminated by air from the drilling, the sampling for the well was not performed as planned. Other methods are under consideration both to deepen the Spears test hole or drill a different deep well, and to collect depth-stratified samples that are not contaminated with drilling fluid.

Geophysical Logging

Dr. Randall Ross (EPA, Robert S. Kerr Laboratory) will run geophysical logs including natural-gamma, spontaneous-potential, normal-resistivity (64 in. long-normal; 16 in. short-normal), lateral-resistivity (48 in.), single-point resistance, 3-arm caliper, P-wave sonic, acoustic televiewer, fluid-temperature, fluid-resistivity, and electromagnetic borehole flowmeter. Dr. Halihan will conduct downhole electric resistivity imaging of the wells. Data obtained from geophysical logging will be used for stratigraphic correlation with logs of numerous petroleum wells in the area; to determine physical properties of the rock matrix and the contained fluids; to characterize fractures; and to obtain hydraulic properties.

Fracture characterization by the correspondence between geologic mapping and Ground Penetrating Radar imaging

Carlos Russian and Roger A. Young

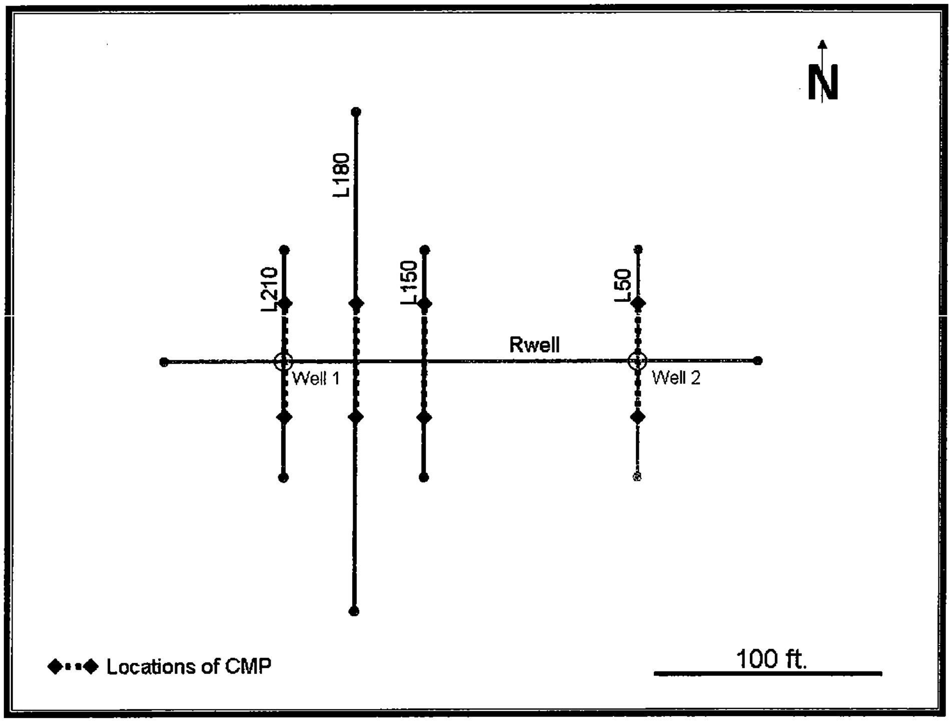


Figure 1: Location of Profiles including CMP's. In total, 9 profiles were acquired.

Figure 2: Acquisition of the profiles shown in Figure 1.

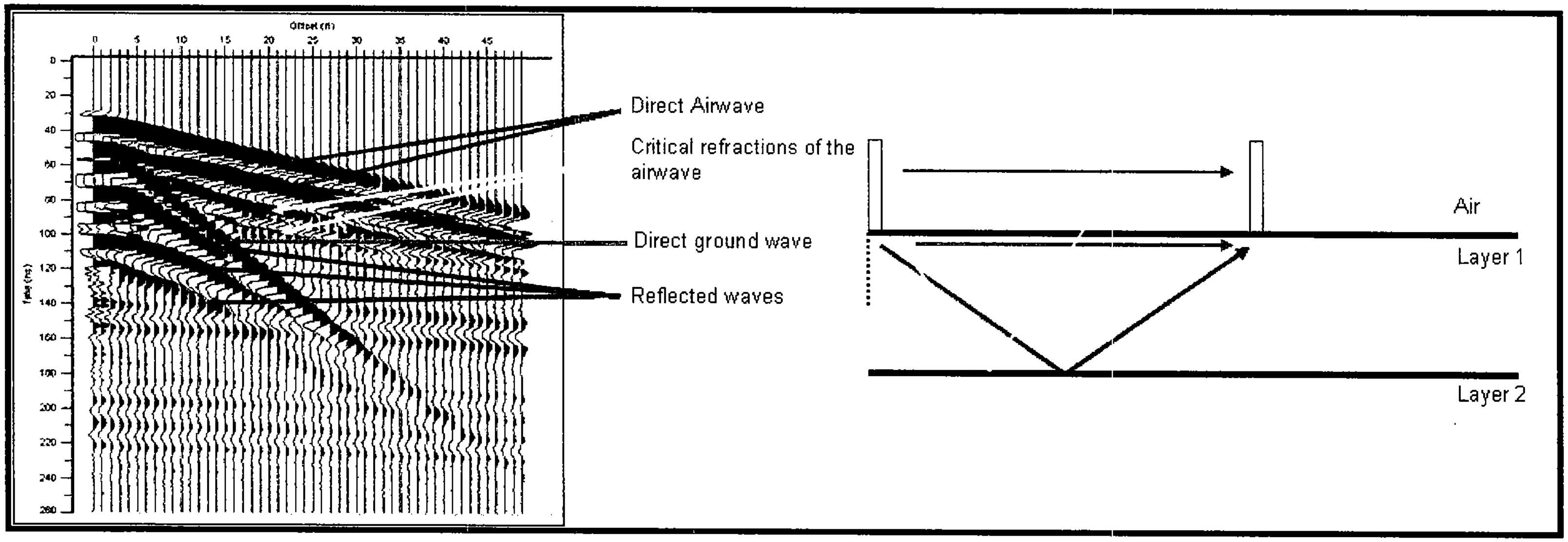


Figure 3: CMP gather CMP4. Associated signal travel times. The air wave and the critical refractions of the air wave travels at a velocity of 0.980 ft/ns (speed of light in air), and the direct ground wave (asymptotic to reflections) has an apparent velocity of 0.249 ft/ns.

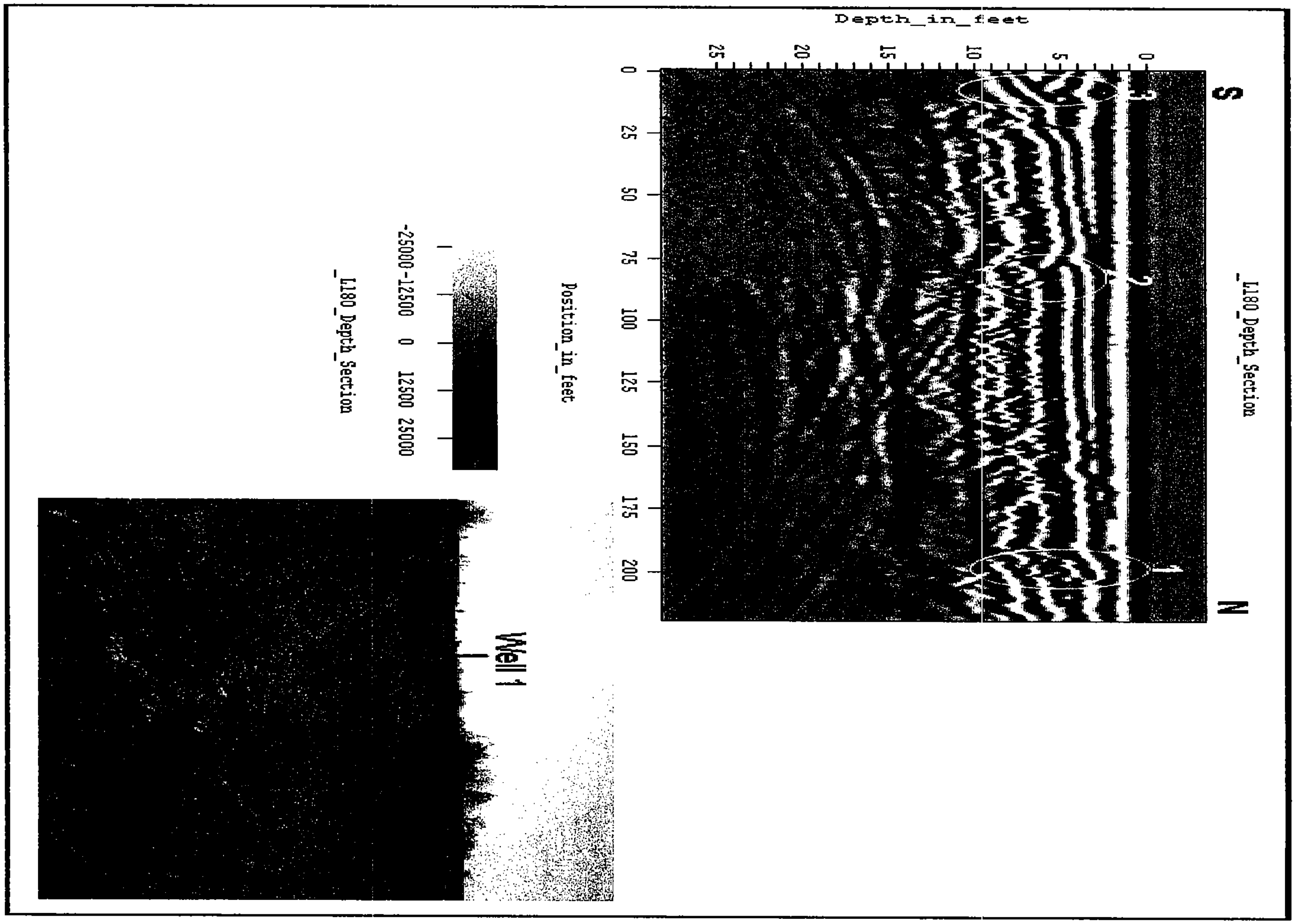


Figure 4: Profile Line L180. Important geological events are shown and highlighted in yellow. Circle 1 corresponds to the northern part of Profile L180 in which a fine layer of sandstone outcrops.

OUTCROP FRACTURE CHARACTERIZATION IN THE ARBUCKLE-SIMPSON

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Characterizing the faults and fractures in the Arbuckle-Simpson presents some unique challenges. The extreme thickness of the aquifer makes deeper fracture characterization very difficult, and the surface is highly eroded. This leaves a few good sources of data. Quarries can be used for one set of data, however, these have been found to be limited as the walls and floors have poor quality surfaces that have significant additional fracturing from the mining process. So, we are left with three other sources, lineament studies, stream traces and surface exposures. These are being used to evaluate the fracture domains in the region.

Introduction

Lineaments are mappable features on the surface that can reflect subsurface characteristics that are distinctly different from adjacent features. They can be created by topography, soil cover, vegetation, and streams. Lineaments have been studied for exploration of both oil and water. Studies have shown that the use of lineaments can be a useful tool in both cases. Using streams as lineaments is a tool that has been under utilized. Streams are morphological features that are easy to detect but have not been fully utilized when analyzing subsurface fracture characteristics. Stream patterns have the potential to provide important insight to the effect of faulting on subsurface characteristics. Stream density, length, and orientation can be analyzed and compared with hydrologic and geophysical data to correctly determine if a correlation can be made.

The Arbuckle-Simpson aquifer in southern Oklahoma, which is heavily faulted, provides an ideal focus area for this research. With the help of GIS, nodes of each stream segment were obtained, creating over 60,000 data points over the Arbuckle-Simpson study area. The method allows a large number of data points used to observe these lineaments allowing for a detailed unbiased study. By obtaining lengths and orientations, trends can be observed in the stream patterns.

Background

The Arbuckle-Simpson aquifer outcrops over an area of over ~500 mi^2. It lies beneath the Murray, Carter, Johnston, Pontotoc, and a small portion of western Coal County (Figure 1). The Arbuckle-Simpson aquifer includes formations from the Arbuckle Group (Upper Cambrian to Lower Ordovician) and the Simpson Group (Middle Ordovician). The aquifer is composed of mostly limestone, dolomite, and sandstone. Much of the rocks have been folded and faulted due to major uplifts in the area during Early to Late Pennsylvanian time (Fairchild et al., 1990). Secondary porosity is created by fractures, joints, and solution channels (Fairchild et al., 1979).

Purpose of Study

This study will allow for a better characterization of the Arbuckle-Simpson aquifer. It will describe the relationship between stream characteristics and subsurface fracture characteristics. The data used for this study was obtained from a GIS streams layer; it was processed by the Department of Primary Industries and Resources, South Australia. The methods introduced will allow for a rapid, unbiased, and cost effective method when assessing aquifers. The use of GIS allows for a massive amount of data to be gathered and analyzed using quantitative methods. Using GIS to analyze streams as lineaments is a method that can not only be applied regionally, but globally as well. The cost effective methods introduced in this study will provide future studies across the globe with a tool to assess aquifers.

Expected Results

Expected results are that a quantitative correlation will exist between streams and subsurface characteristics. A regional trend in orientation (Figure 2) will be seen and allow for a correlation to be made to subsurface fracture characteristics. The orientation trends will indicate flow boundaries and preferential flow paths. The length and density of the stream segments will delineate regions of higher permeability and more continuous fractures in the Arbuckle-Simpson aquifer, identifying high recharge areas.

Creating the smaller grid will enable stream characteristics to be observed in differing lithologies. Varying lithology will cause stream characteristics to be distinct allowing the aquifer system to be analyzed. Results may indicate which lithologic unit in the aquifer system creates continuous flow paths and which unit serves as flow boundaries.

The results will also identify characteristics in the underlying basement rock as some fractures and faults have been found to be propagated upward from the subsurface. Using streams as lineaments will allow a delineation of subsurface characteristics and thus allow for a better understanding of the hydraulic properties of the aquifer. The results found will allow for a better quantification of the aquifer characteristics, which can be used as a management tool for the Arbuckle-Simpson aquifer.

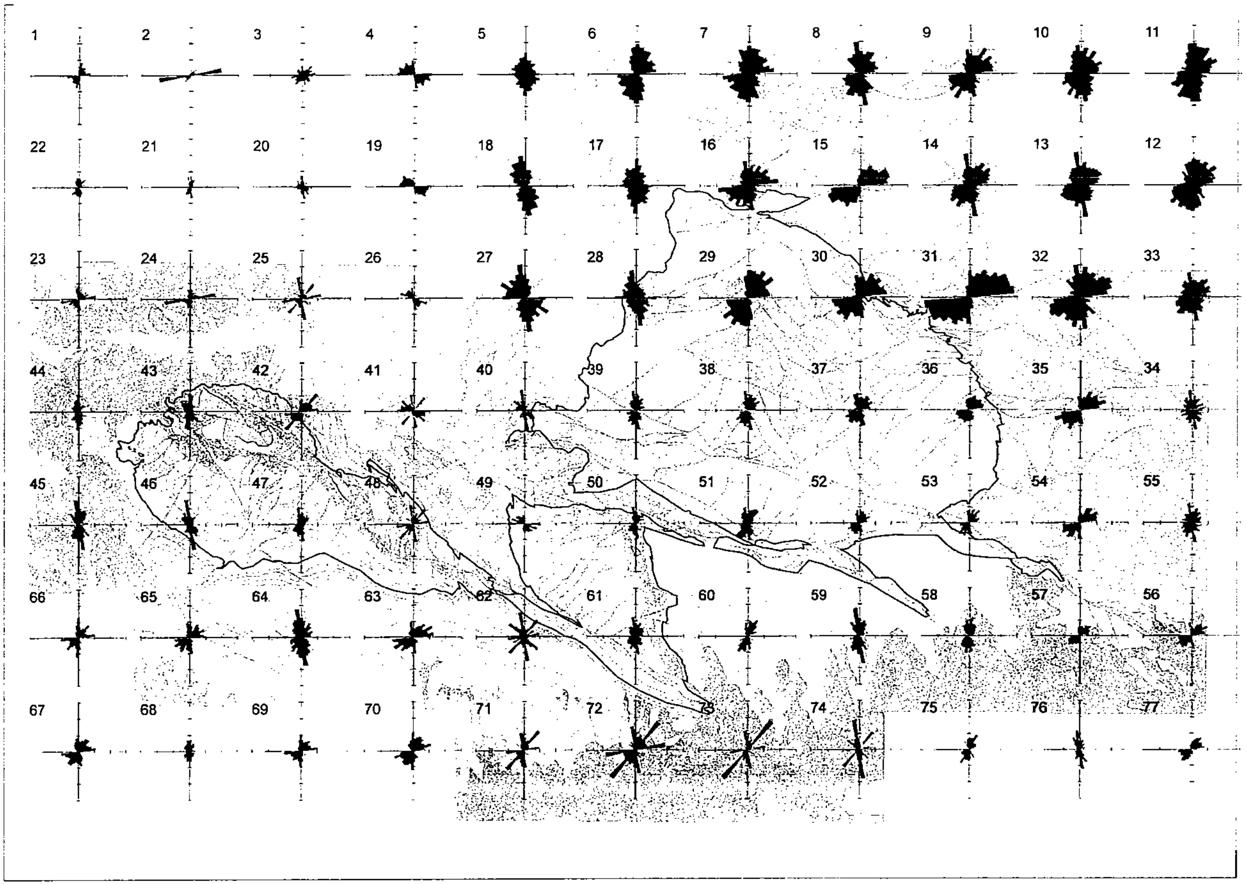


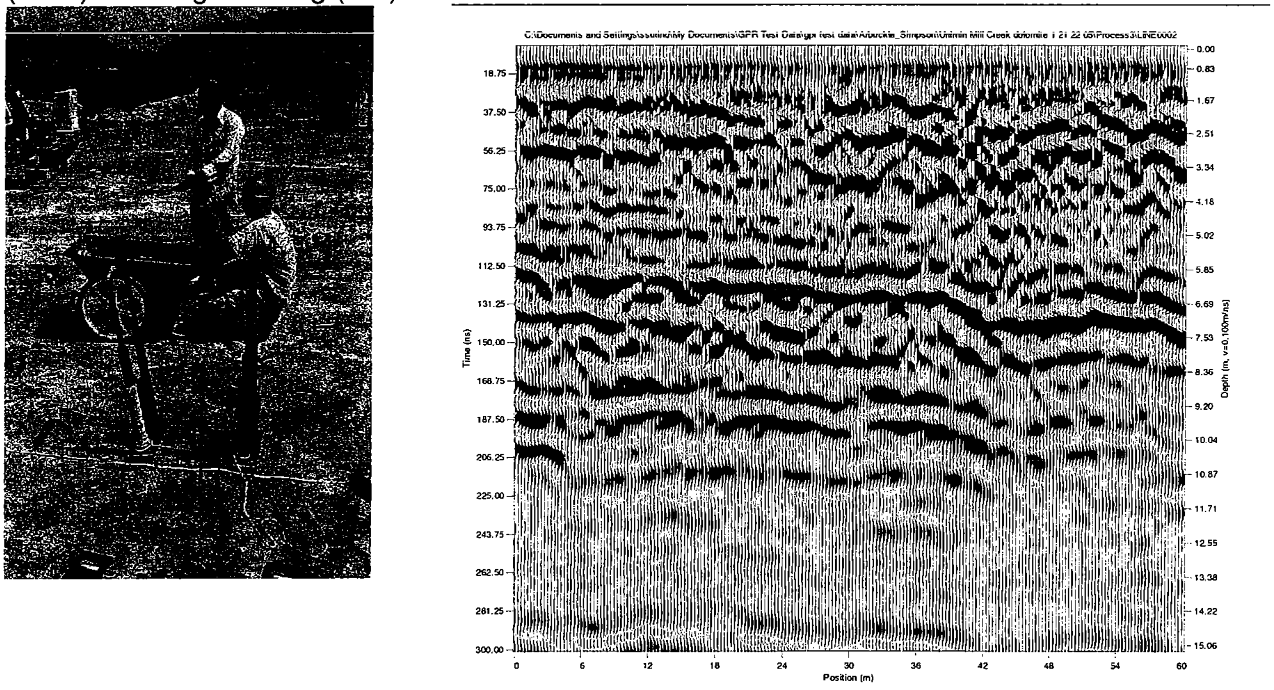
Figure 2. On a regional scale stream orientation trends over the Arbuckle-Simpson aquifer can be observed.

GEOPHYSICAL CHARACTERIZATION IN THE ARBUCKLE-SIMPSON

The size and extent of the Arbuckle-Simpson aquifer makes geophysical techniques an attractive approach for characterizing the heterogeneity of the aquifer. Through a range of funding mechanisms, several methods have been applied to study the aquifer. Small scale work has been conducted using ground penetrating radar (GPR) and electrical resistivity imaging (ERI). Intermediate scale work has been conducted with ERI and gravity methods. Large scale work is underway using gravity and reflection seismic data. The methodologies and results to date are discussed by technique.

Ground Penetrating Radar

GPR work has been conducted at both dolomite and sandstone quarries in the area. Analysis is still occurring for the datasets. This work is being performed by Surinder Sahai (OSU) and Roger Young (OU).



Left image: Field GPR work at dolomite quarry in the Arbuckle-Simpson. Right image: Migrated GPR data from the quarry.

Electrical Resistivity Imaging

Electrical Resistivity Imaging (ERI) has been made possible by advancements in both instrumentation and software developed over the past 15 years. Electrical resistivity is one of the oldest methods utilized by geophysicists, but ERI is a modification made possible by advanced in equipment and software. ERI surveys rapidly collect thousands of measurements to allow for use as a subsurface imaging tool. This tool is similar to seismic surveys for the oil industry in allowing a "picture" of the subsurface.

OSU School of Geology was tasked by OWRB to try this technique on the Arbuckle-Simpson aquifer to determine how well the method would assist in the development of a conceptual model for the aquifer. This required building equipment appropriate to imaging a very thick, fractured rock or karstic aquifer and testing the aquifer to determine the data quality available in the study area.

A 1500 ft (460 m) borehole electrical resistivity imaging (BERI) cable was constructed and installed on a trailer with a reel to allow for deep borehole imaging. The borehole system was tested in two wells in the aquifer. Since no available test well could be found that was known to intercept a faults, a surface images of fault were taken.

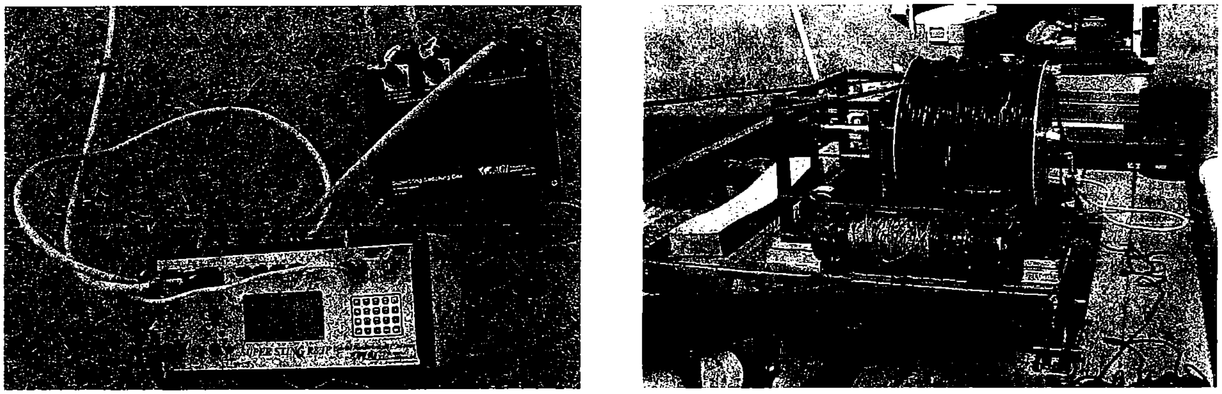
The borehole method has proven difficult to apply to the aquifer due to a lack of suitable borehole locations to test. Few deep boreholes exist and those that do exist have problems accommodating even a small diameter cable. Surface surveys work well in the aquifer, but are limited to how deep they can easily image.

The method has shown a repeatable presence of a shallow conductive zone that is often about 30 feet (10 m) thick. This zone is interpreted as an epikarst zone that could hold significant amounts of water. The images have also shown significant vertical conductivity zones. These features are interpreted as fracture zones which can transmit water to depth in the aquifer. These features extend more than 100 ft (30 m) into the subsurface. Finally, the method has been shown to be effective at imaging faults in the area. The conductive nature of the Mill Creek fault would be interpreted as a conductive zone suitable for transmitting fluids.

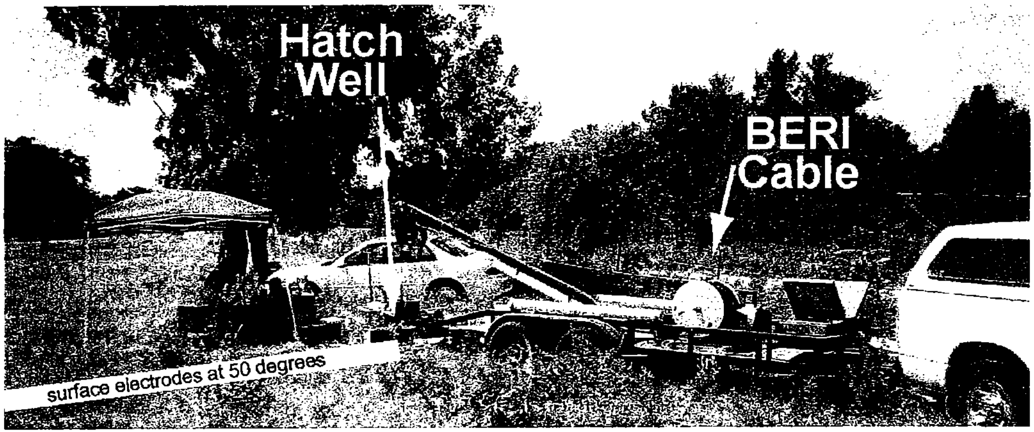
Overall, ERI is a suitable technique to assist with characterizing the Arbuckle-Simpson aquifer. The aquifer has a range of conductivities that are suitable for imaging and the images have illustrated features that would be difficult to characterize using other available techniques.

ERI Equipment

The equipment used for ERI data collection consists of a measurement and datalogging unit and electrodes on cables to connect to the earth. The modification for this aquifer was the application of deep electrodes on a 1500 foot cable.



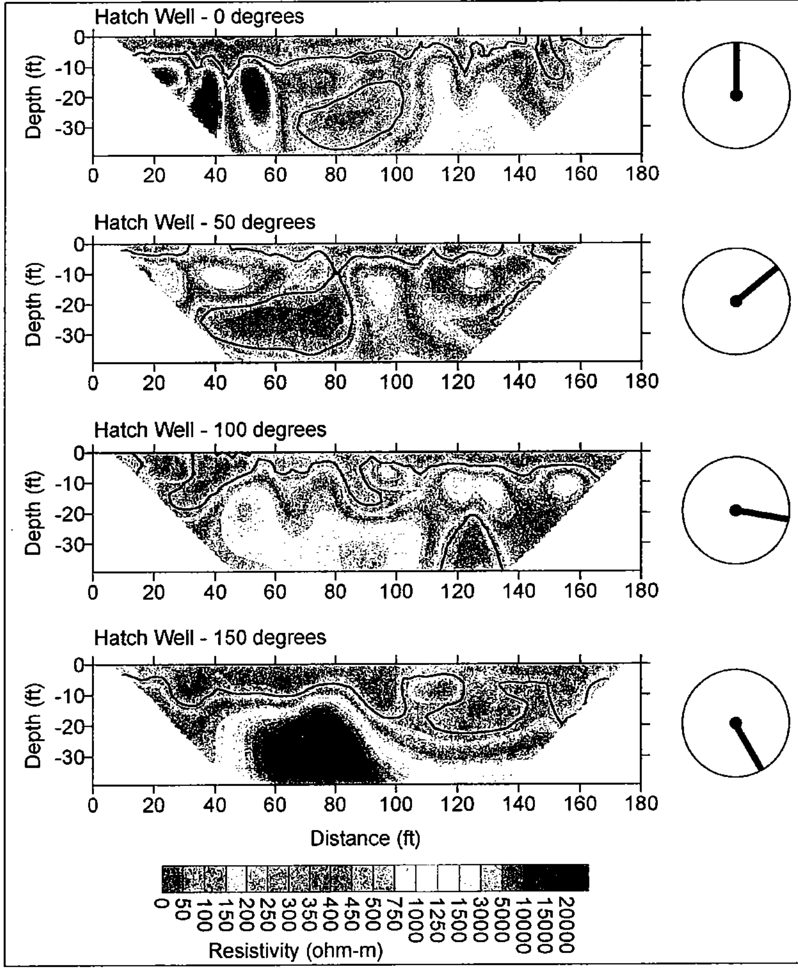
SuperSting 8-channel resistivity instrument and borehole switchbox. BERI cable used for borehole surveys on trailer at site Wingard 2.



Equipment setup at Hatch well site for ERI image at orientation of 50 degrees. Picture is taken from the north looking south.

Epikarst data

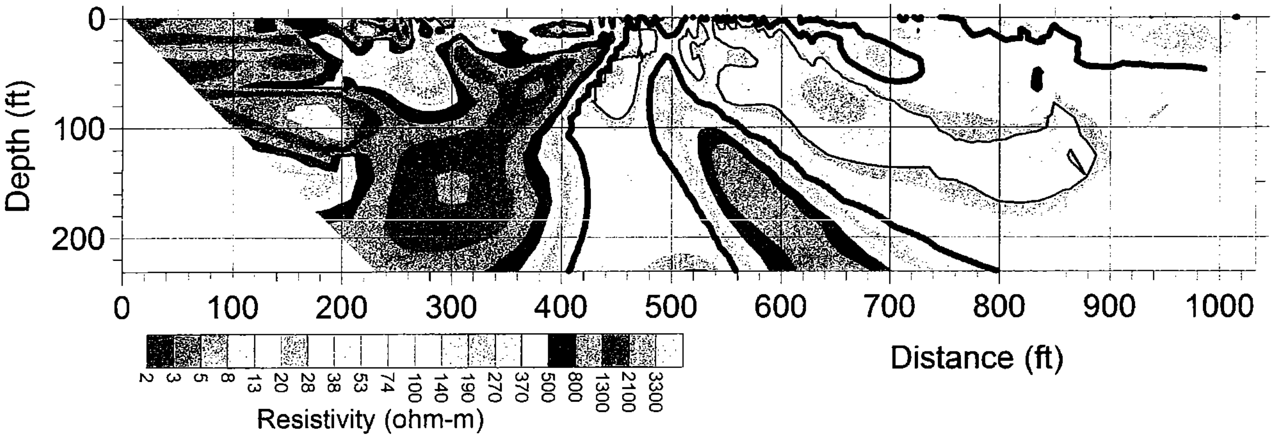
ERI datasets are being employed to calibrate hydraulic properties of many sites in the world. The high resolution imaging of the surface properties can be used to help characterize the epikarst zone of the Arbuckle-Simpson. Combined with shallow hydraulic measurements such as infiltration tests and direct push hydraulic conductivity testing, ERI should provide an ability to understand the heterogeneity of the epikarst zone of the Arbuckle-Simpson.



Surface ERI survey results at the Hatch well site. The images are scaled identically and the "clock" figure at the right indicates the orientation of each image relative to the well with north at 12 o'clock. Note the irregular boundary in the subsurface between the soil and bedrock.

Faults

ERI has provided one of the best technique to date for characterizing faults in the Arbuckle-Simpson. The imaging can be done to several hundred feet, but little is know about the limits of the technique. Work is ongoing to attempt to determine the orientation and hydraulic properties of the faults.



Plot of WATSONall3 using Conductive Stepped Sequential Color Scheme

This ERI image of the Sulphur fault indicates a significant conductivity contrast occurs across the fault. The dip of the bedding is also apparent on the right (north) side of the fault. The north side of the fault also appear to be a much better candidate for fluid flow than the left (south) side of the fault.

Wells

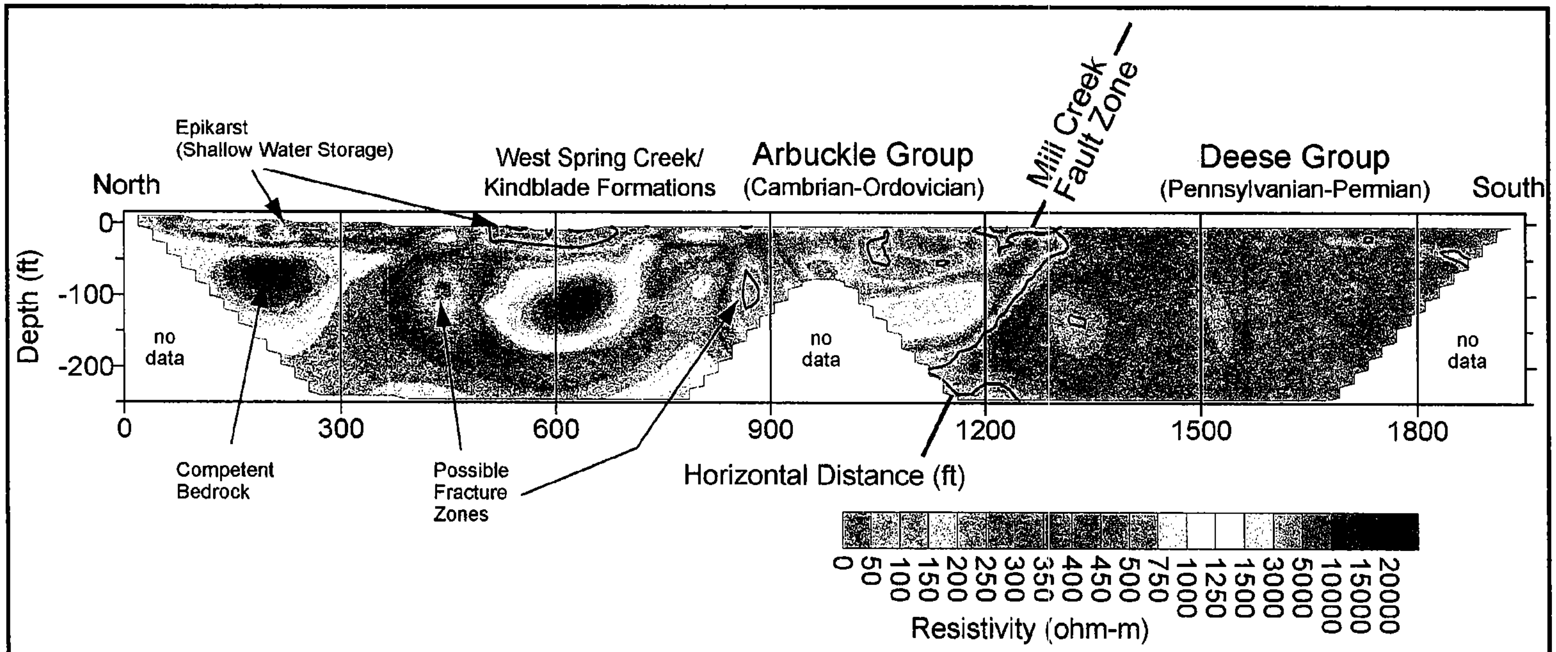
ERI datasets such as the one for Vendome well have indicated that the images provide good data on the lithology of the subsurface. Work continues to calibrate the images to hydraulic data for the area.

Results to date

The preliminary images from the Arbuckle-Simpson aquifer indicate that ERI can be a useful tool to develop conceptual models of the aquifer. The data that can be collected in this area is of high quality and provides useful information about the variability of the aquifer. In some bedrock settings, the high resistivity of the lithology makes ERI difficult to employ, but the resistivity of the Arbuckle-Simpson is highly variable and provides some very conductive areas which are easier to image with the technique.

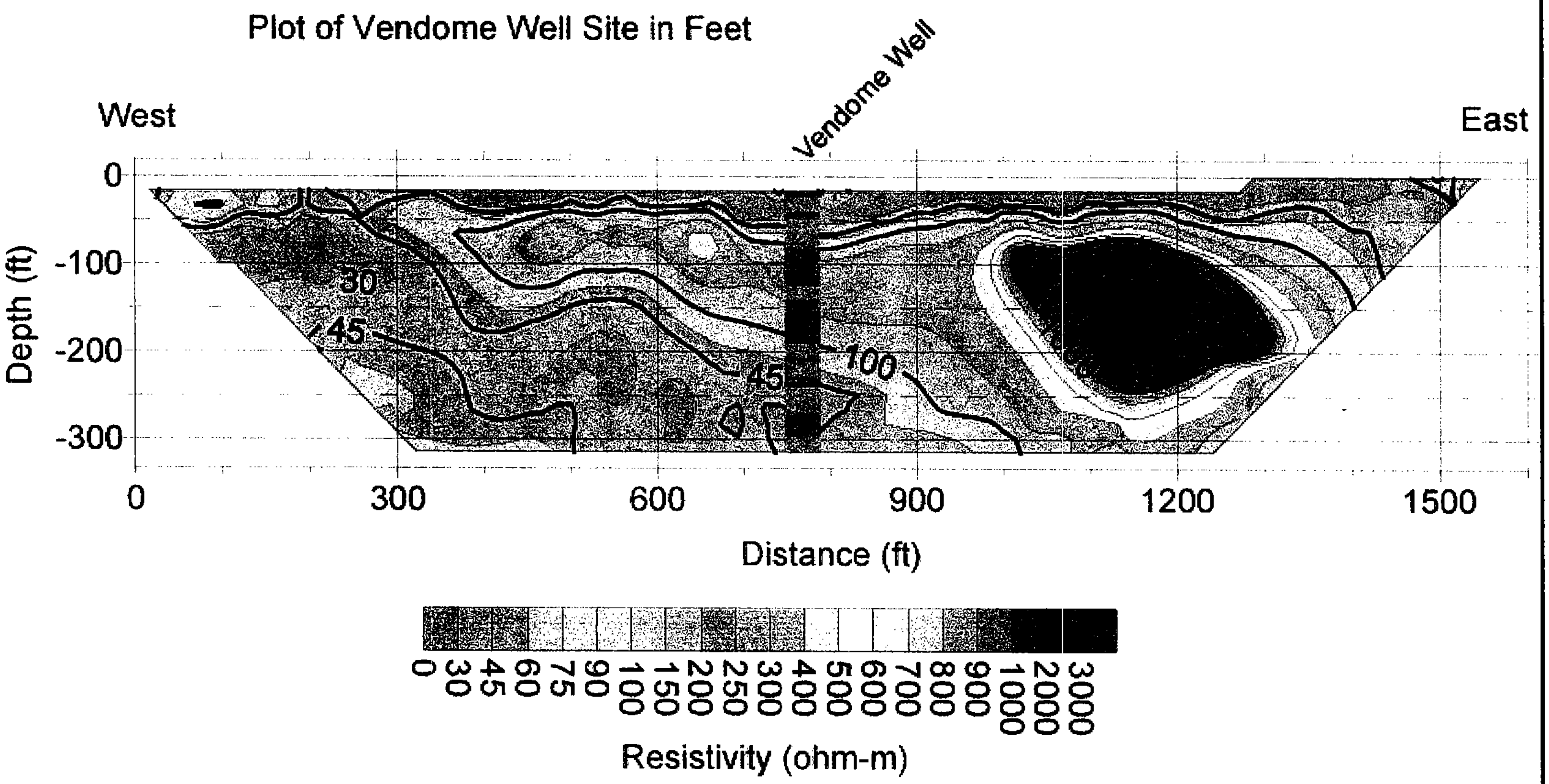
Surface imaging can provide information on fault location along with data about the thickness of soil zone and the soil/bedrock interface or epikarst zone. This will be important for constructing the storage properties of the aquifer in the shallow areas in the ground water model. With hydraulic testing, the conductive faults and vertical fractures can be confirmed as hydraulically conductive zones capable of transmitting fluids in the aquifer.

Borehole imaging of the aquifer provides a similar image to the surface images and indicates that vertically conductive zones may exist for large distances into the subsurface. Inversion software improvements and modified field procedures can improve the borehole imaging datasets, but good borehole imaging sites are the more difficult portion of the work. The limited number of deep undamaged, unused wells limits the ability to obtain good quality data about the structure of the aquifer at depth.



This ERI image provoked some controversy over the properties of the faults in the Arbuckle-Simpson. The image indicates a northward dipping fault, but “everyone knows” that faults are vertical in the Arbuckle-Simpson. This led to a reevaluation on field data that is available to support the dips shown in geological cross sections of the formations.

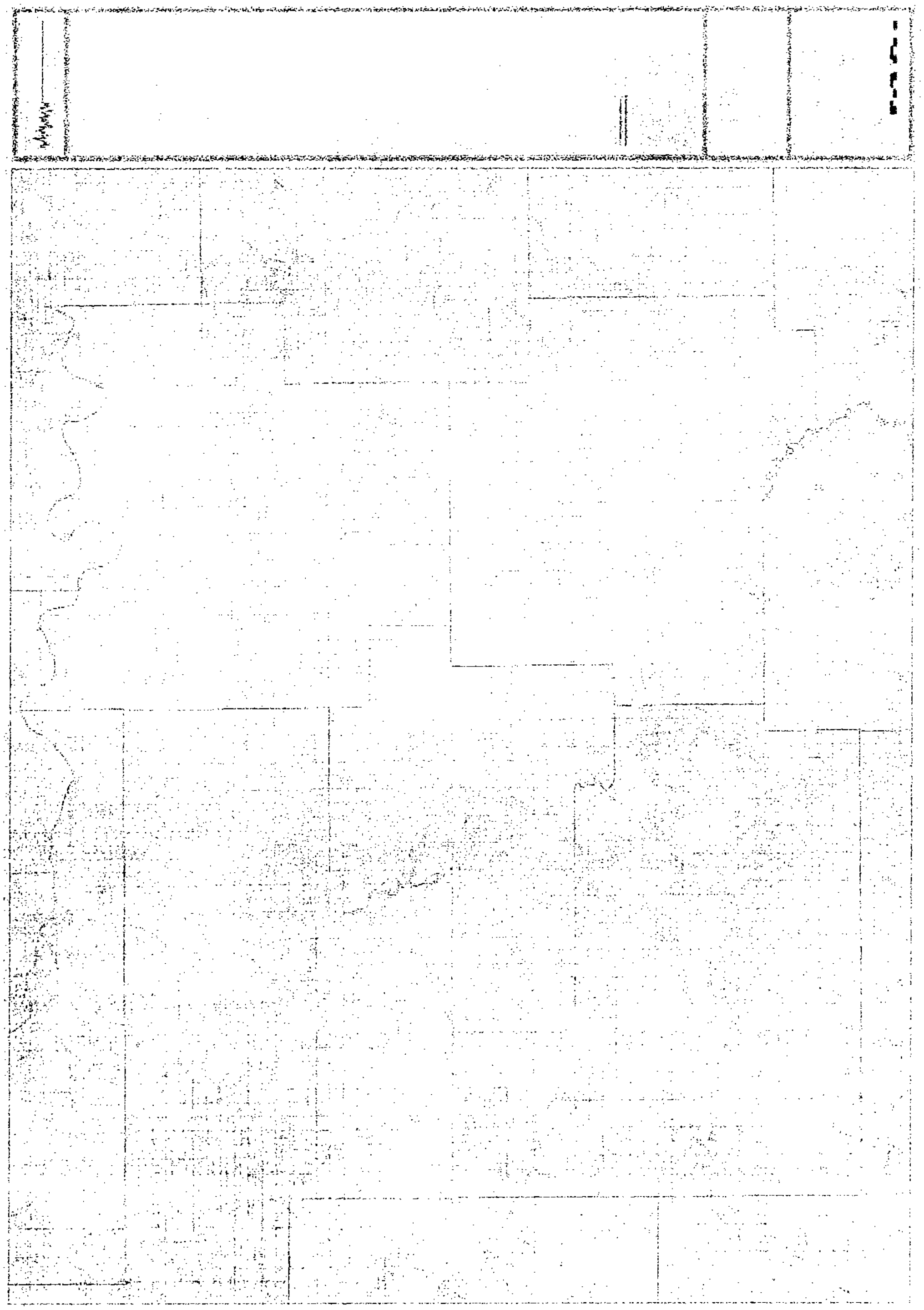
Field and modeling efforts are being conducted to determine how well a fault angle can be determined from this technique. The technique is sufficiently new that this data is not available.



The Vendome Well image presents another common feature in these images, a significant vertical conductor. This indicates that the surface water-ground water connections may extend to deeper depths of the aquifer than previously hypothesized.

Seismic Data

A significant amount of seismic data has been collected in the Arbuckle-Simpson area. Unfortunately, almost no data is collected over the Hunton Anticline area. A limited dataset of 5 lines (1 digital) is available for the study area. These are being evaluated for the location of bedrock and to determine if any information about the faults in the area can be delineated from the dataset. This work is being performed by Surinder Sahai (OSU) and Roger Young (OU).

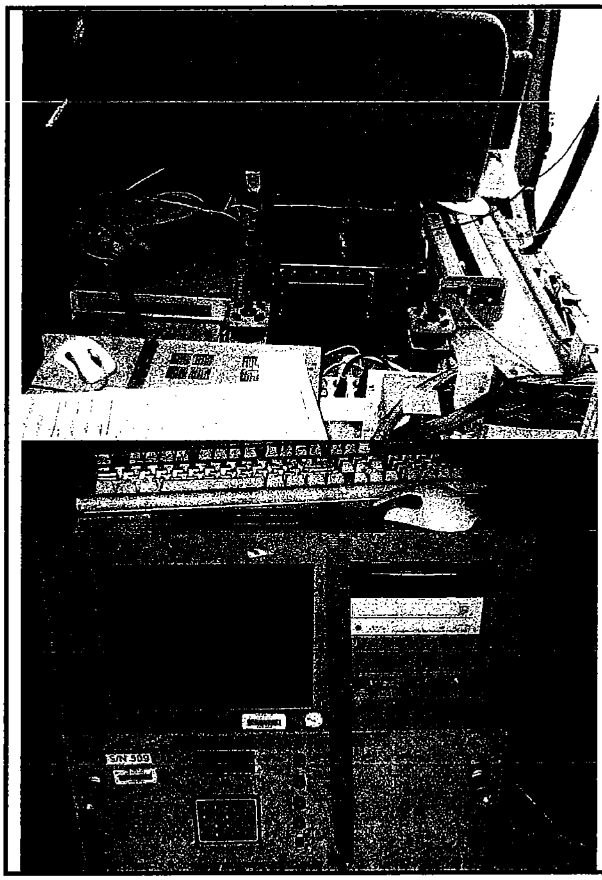


Gravity

Gravity work is being conducted by Dan Scheirer of the U.S. Geological Survey. Using standard gravity instruments, and continuous gravity measurements, the bedrock depth and orientation of the faults surrounding the Chickasaw National Recreation Area is being investigated.

Equipment

An oceanographic gravity instrument was adapted to terrestrial surveys as part of this project. This enabled continuous gravity profiling in a vehicle traveling between 10 and 30 mph. Differential GPS was utilized to determine the location as the profile was being collected.

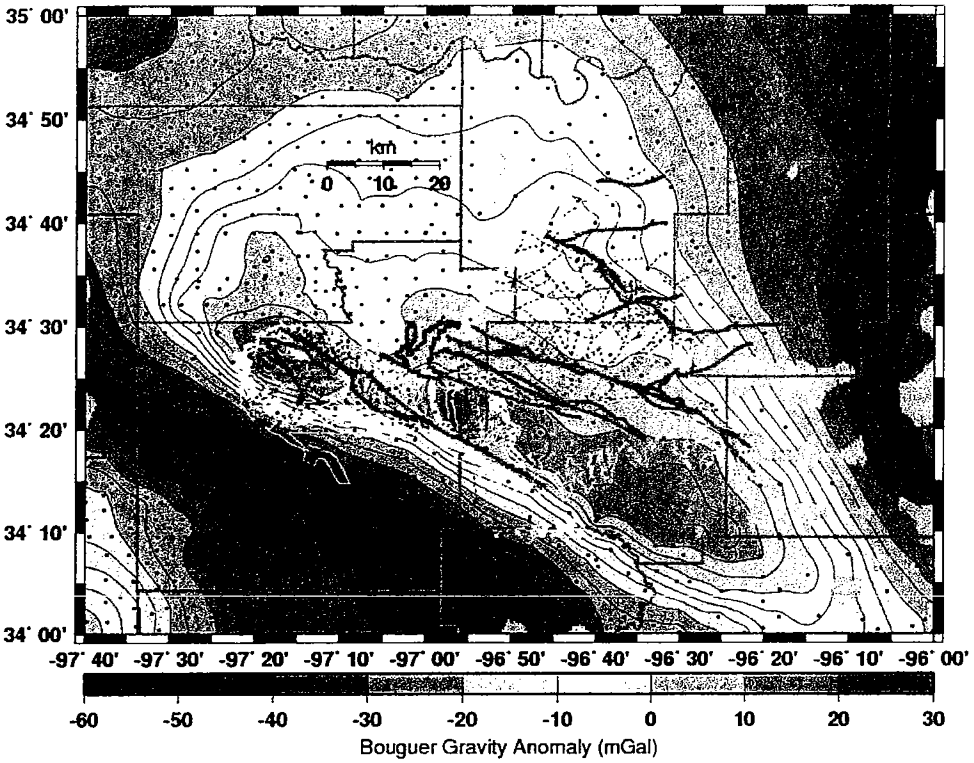


To left: Continuous gravity instrument mounted in survey vehicle. The black box in the upper left is the instrument consisting of a floating magnet that monitors voltage required to keep the magnet stable. This is proportional to the gravitational acceleration. Above: A differential GPS antenna is being established for corrections for the dataset.

Gravity Lessons

- Correlations of gravity and faults are imperfect; hard to extend faults beneath Vanoss cover
- Sulphur Syncline is a relative gravity low; Belton Anticline is a relative high; Tishomingo Anticline is a much larger high
- General gravity gradient from high values beneath Arb/Simp outcrop in Hunton Anticline region to lower values to the west

- What component of gravity variation is due to basement topography??



Paces Regional Gravity for study area.

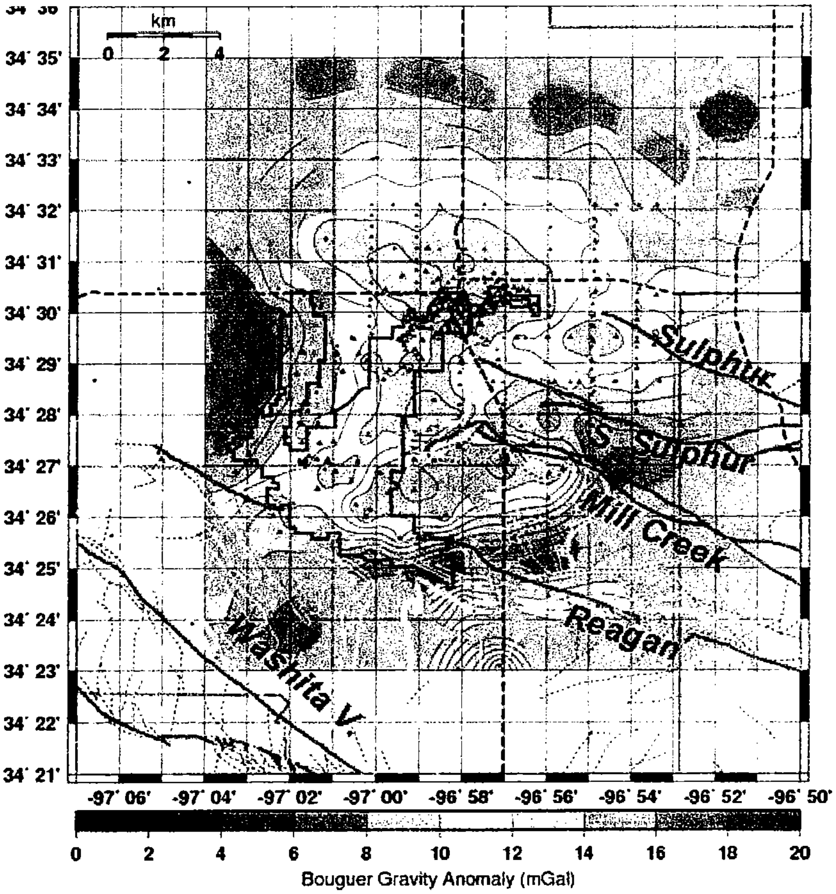
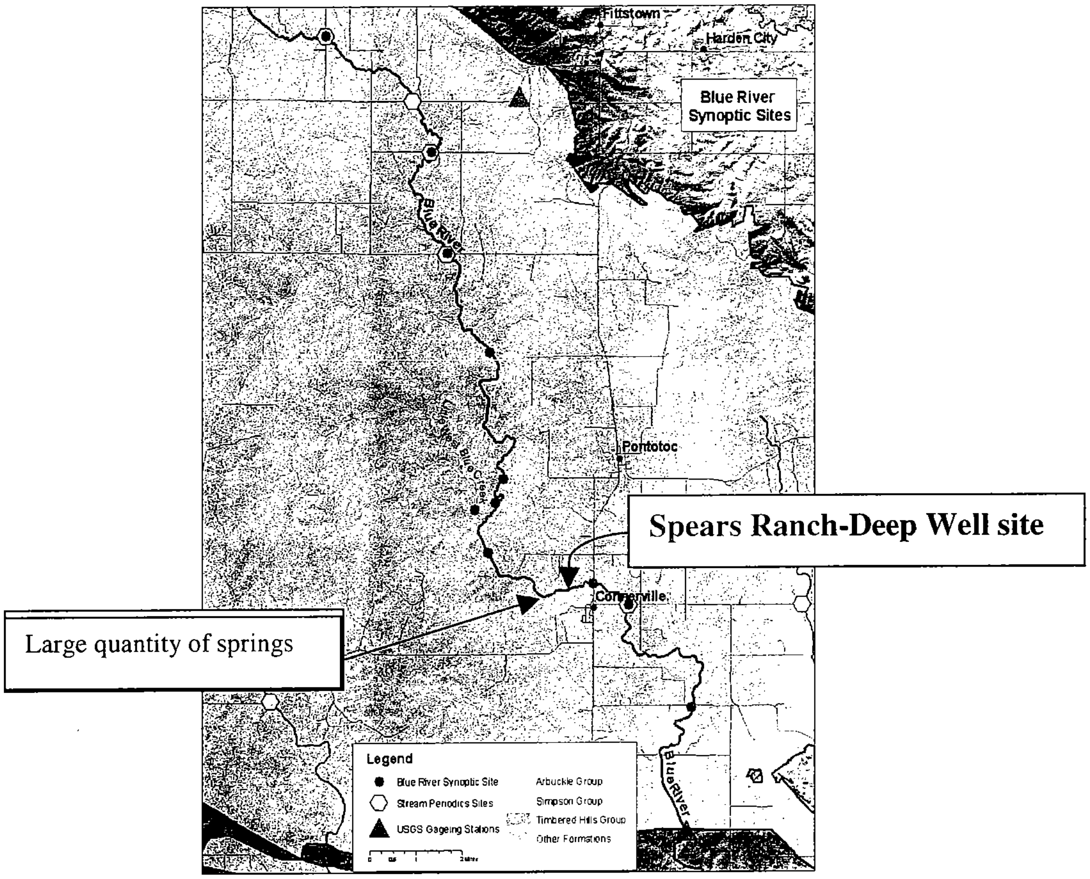


Figure P1. Prior gravity stations (black circles) and gravity stations collected by Steven Cates (black triangles), by the USGS in June 2004 (red triangles) and in April/May 2005 (blue triangles). Contour interval is 1.0 mGal.

BLUE RIVER

Where are you along Blue River?



Spears Ranch-Deep Well site

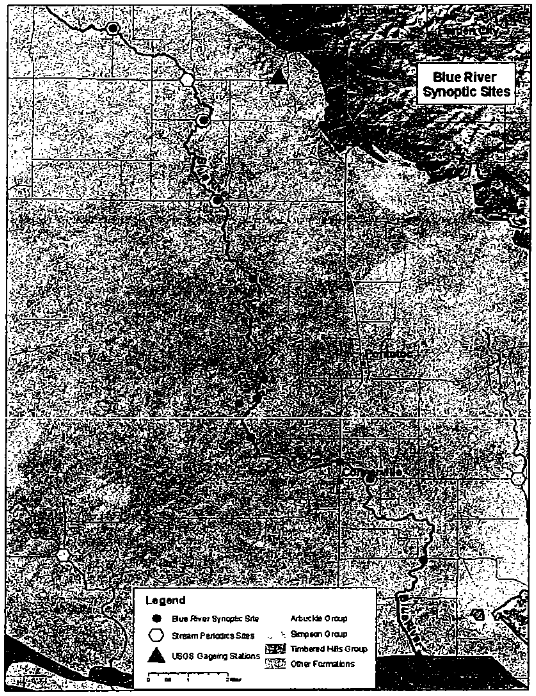
Large quantity of springs

Current Location-Spears Ranch

Nelson Spring

Getting a closer look

Blue River Public Hunting and Fishing Area



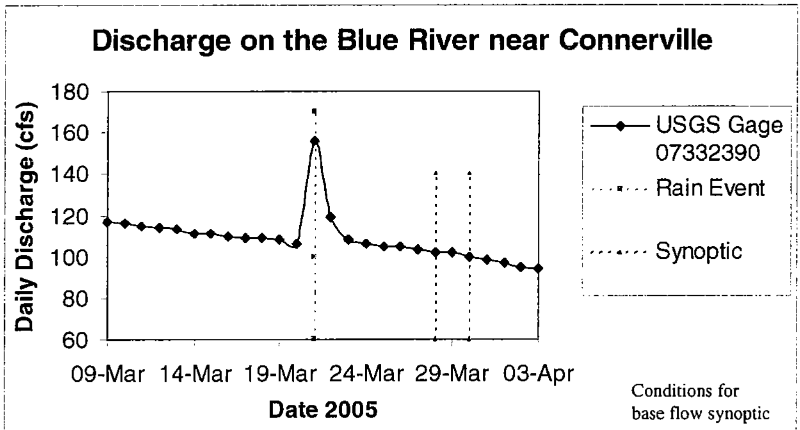
Blue River Synoptic March 2005

12 Synoptic Sites

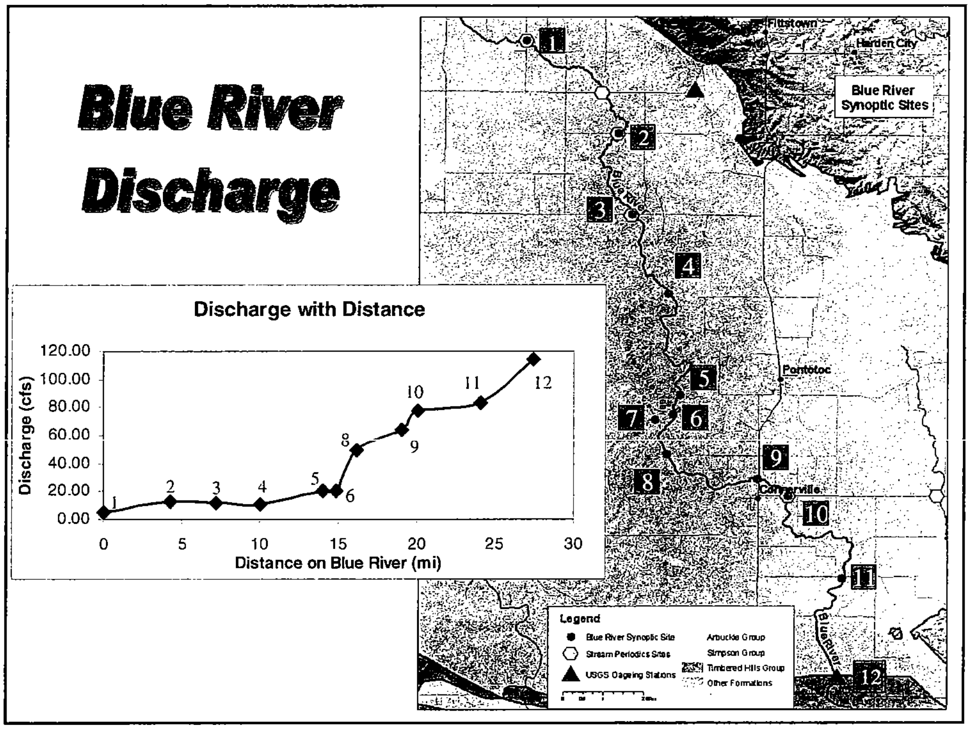
11 - Blue River
1 - West Little Blue Creek

4 Periodic measurement sites
1 USGS Gage Station

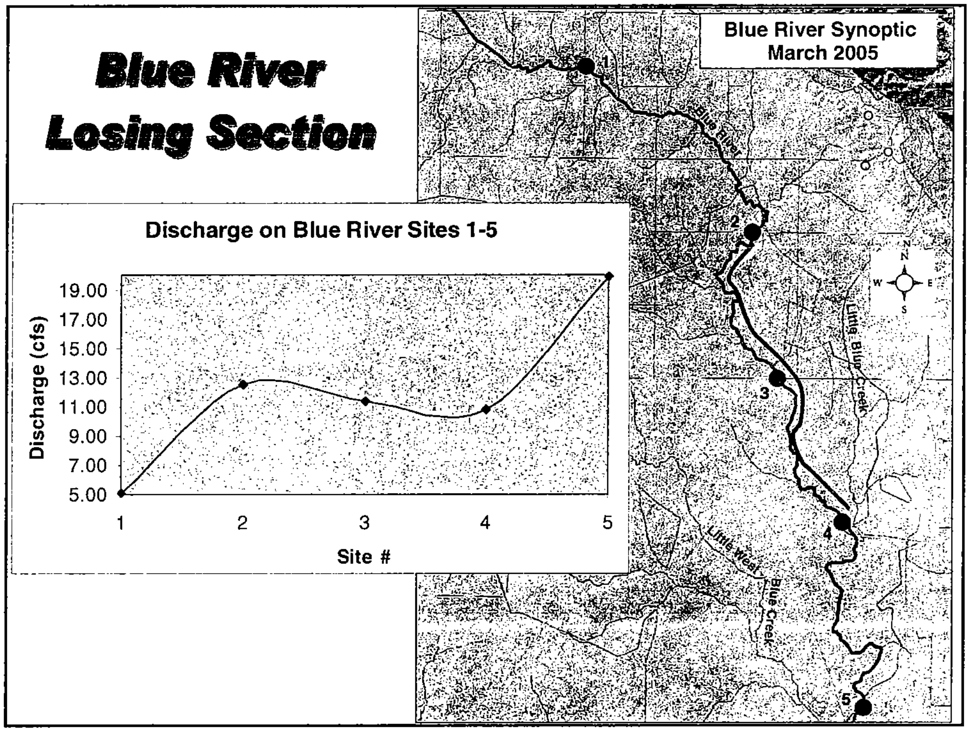
USGS Gage



Conditions for
base flow synoptic



Blue River Discharge



Blue River Losing Section

The Arbuckle-Simpson Hydrology Study

Management and Protection of an Oklahoma Water Resource

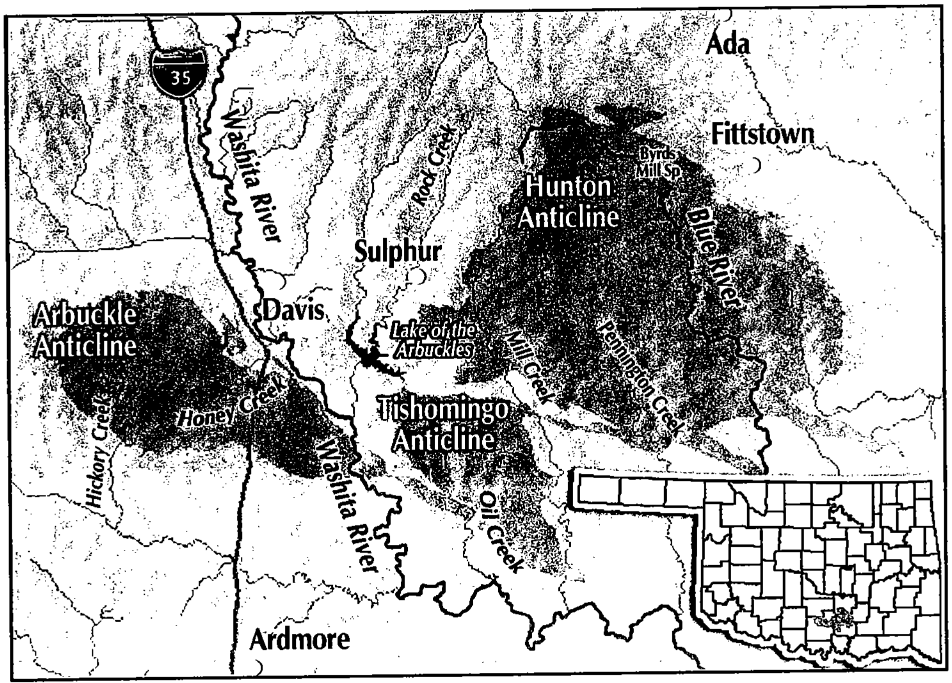
THE OKLAHOMA WATER RESOURCES BOARD
November 2003

Background

The Arbuckle-Simpson aquifer, which underlies more than 500 square miles in south central Oklahoma, is the principal water source for approximately 39,000 people in Ada, Sulphur, and others in the region. The aquifer is also the source of a number of important springs in the region, including Byrds Mill Spring, Ada's primary drinking water source, and those in the Chickasaw National Recreation Area, the destination for about 3.4 million visitors each year. The U.S. Environmental Protection Agency has designated the aquifer's eastern portion as a Sole Source Aquifer, a mechanism to protect drinking water supplies in areas with limited water supply alternatives.

Local, federal, and state agencies and organizations have been lobbying for a comprehensive study of the Arbuckle-Simpson aquifer for more than a decade. However, recent requests for water use permits from the aquifer have generated sufficient concern to make the study a reality. Early in 2002, the Central Oklahoma Water Authority (COWA), consisting primarily of communities in Canadian County seeking future supply, proposed to pump as much as 80,000 acre-feet of water per year from the aquifer and transport it to central Oklahoma.

Although Oklahoma water law considers groundwater the private property of the landowner, local residents, citizens' groups, and the National Park Service are concerned that large-scale withdrawals of water from the Arbuckle-Simpson aquifer will result in declining flow in streams and springs and cause groundwater levels to decline. As a result, the state will also investigate development of a management strategy that would protect the aquifer's current and future benefits yet comply with the basic precepts of Oklahoma water law.



The general outcrop area of the Arbuckle-Simpson aquifer extends some 500 miles between Ada and Ardmore in south central Oklahoma.

Senate Bill 288

Senate Bill 288, passed by the State Legislature in May 2003, imposes a moratorium on the issuance of any temporary groundwater permit for municipal or public water supply use outside of any county that overlays, in whole or in part, a "sensitive sole source groundwater basin." (The Arbuckle-Simpson aquifer is the only such groundwater basin in Oklahoma.)

The moratorium prohibits municipal and political subdivisions outside the basin from entering into contracts for use of the water and it applies to both pending applications and any revalidation of existing temporary permits. The moratorium will remain in effect until the OWRB completes its study of the Arbuckle-Simpson and approves a maximum annual yield that will not reduce the natural flow of water from springs or streams emanating from the aquifer.

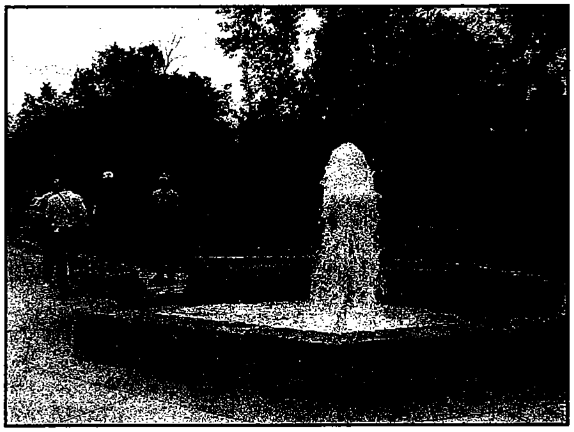
SB 288 also adds another requirement for groundwater permit approval for use within the basin: the Board must find that the proposed use is not likely to degrade or interfere with springs or streams emanating from the aquifer. Because current Oklahoma water law does not take into account the hydrologic interaction between surface and groundwater, the legislation sets a new precedent in the OWRB's permit approval process.

Plan of Study

State and federal water experts agree that information garnered from previous studies of the Arbuckle-Simpson aquifer--concentrating primarily on its geology and hydrology at or near the surface--is inadequate to address the aquifer's complex geology and management issues confronting local users. Investigation of the deeper portion of the aquifer (greater than 1,000 feet) is needed to understand the full extent of the fresh-water zone and the volume of water in storage in the aquifer. In addition, no sufficient information exists to predict the response of springs and streams to groundwater withdrawals. Critical to future study of the aquifer is an understanding of the formation's "plumbing system" that controls the interactions between groundwater levels and springflows.

To understand, as well as quantify, the region's complex geology and hydrology, the investigation will require five years for completion. Funded through a 50/50 state/federal cost-share agreement with the U.S. Bureau of Reclamation, the investigation will be the most intensive analysis of surface and groundwater relationships ever conducted in Oklahoma. Most importantly, study results will provide state and local decisionmakers with the necessary information to determine how water resources in the region should best be utilized while protecting area springs and streams.

The Arbuckle-Simpson study will be coordinated by the OWRB, but will involve participation from dozens of agencies and organizations, as well as private citizens. A technical peer review team consisting of experts from the U.S. Geological Survey, Oklahoma Geological Survey, Oklahoma State University, and EPA will review the scope of work and provide advice to ensure the use of sound science and appropriate methods.



Vendome Well, an artesian well in the Chickasaw National Recreation Area

> *The goal of the Arbuckle-Simpson study is to acquire understanding of the region's hydrology to enable development and implementation of an effective water resource management plan that protects the region's springs and streams.*

Study Objectives

1. Characterize the Arbuckle-Simpson aquifer in terms of geologic setting, aquifer boundaries, hydraulic properties, water levels, groundwater flow, recharge, discharge, and water budget.
2. Characterize the area's surface hydrology, including stream and spring discharge, runoff, base flow, and the relationship of surface water to groundwater.
3. Construct a digital groundwater/surface water flow model of the Arbuckle-Simpson aquifer system for use in evaluating the allocation of water rights and simulating management options.
4. Determine the chemical quality of the aquifer and principal streams, identify potential sources of natural contamination, and delineate areas of the aquifer that are most vulnerable to contamination.
5. Construct network stream models of the principal stream systems for use in the allocation of water rights.
6. Propose water management options, consistent with state water laws, that address water rights issues, the potential impacts of pumping on springs and stream base flows, water quality, and water supply development.

Methods

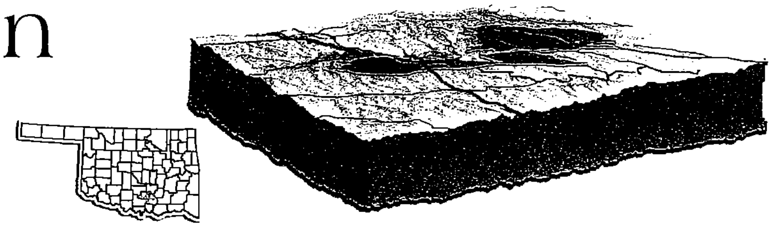
A variety of methods will be used to characterize the aquifer, including evaluation of petroleum-related information, test well drilling, groundwater and surface water modeling, geochemistry, isotopic age dating of groundwater, and various other methods depending upon findings as the study progresses, as well as available funding. The first year of the investigation will consist of reviewing literature, compiling and reviewing existing data, conducting field investigations, initiating groundwater flow model simulations, and identifying data needs. As a vital tool to furthering understanding of the aquifer and assisting in the water resource decision-making process, development of the digital groundwater flow model will be a key component of the study.

Fieldwork will include installation of two stream gages (on the Blue River and Pennington Creek), updating the current inventory of water wells and springs, and collecting measurements from wells, springs, and streams in the area. A variety of hydrologic tests will be performed, with special emphasis on deep wells. The second and third years will be devoted primarily to field investigation, the fourth year to model development, and the fifth year to reviewing various management options.

Input from the public, especially those residing in the Arbuckle-Simpson aquifer region, will be integral to the study. Landowners and other interested parties will be counted on to provide vital information related to the location of springs, streams, wells, and other components of the aquifer's complex surface/groundwater system. The OWRB will hold public meetings to update citizens on the study's progress and results. In addition, the agency will publish regular Arbuckle-Simpson study newsletters and share the latest study developments through its Web site.

Arbuckle-Simpson Hydrology Study

Newsletter



THE OKLAHOMA WATER RESOURCES BOARD January 2006

Surface Water Committee to Balance Science, Policy

The Surface Water Subcommittee of the Arbuckle-Simpson Technical Peer Review Team has been created to evaluate surface water needs and impacts to flows in the study area. Among various tasks assigned to the group is the investigation of potential instream flow regimes that could be implemented to minimize impacts to the springs and streams. The Subcommittee will seek to balance legal and public policy considerations with technical findings of the ongoing Arbuckle-Simpson Hydrology Study.

Chaired by Derek Smithee, chief of the OWRB's Water Quality Division, the Subcommittee also includes representatives of the U.S. Geological Survey (USGS), Oklahoma Department of Environmental Quality, Department of Wildlife Conservation, U.S. Fish and Wildlife Service, Oklahoma State University, and area landowners.

Members of the Surface Water Subcommittee met for the first time on January 31 at the Chickasaw National Recreation Area near Sulphur.

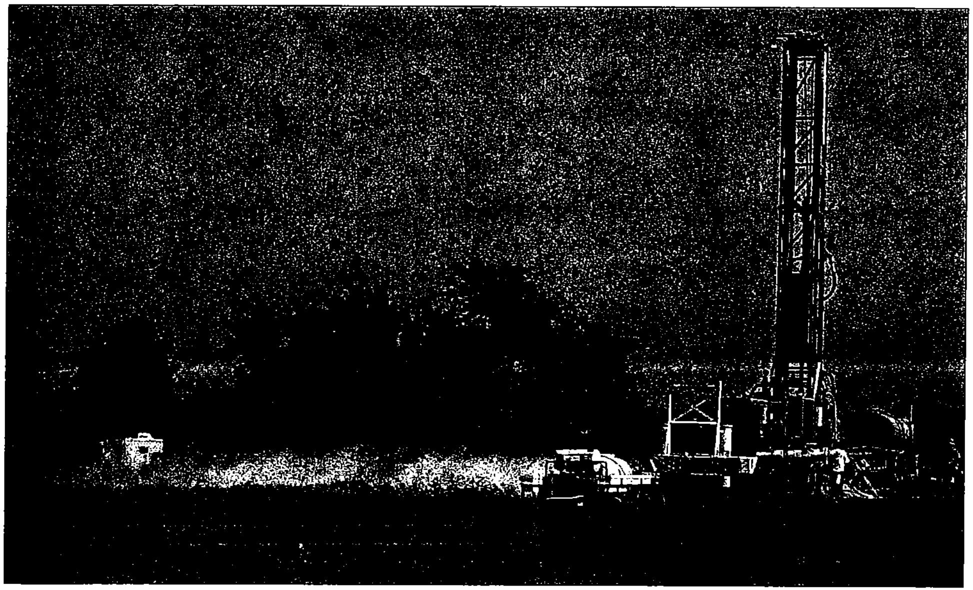
Deep Well Drilling Halted

On September 14, the USGS began drilling a deep test well near the Blue River, just west of Connerville. The well was drilled to collect information on the lower portion of the Arbuckle-Simpson aquifer, for which information is currently sparse. The plan was to drill to a maximum depth of 3,000 feet, the approximate limit of the USGS drilling rig, and to collect water samples at varying depths.

Information on the deeper portion of the aquifer, the depth generally ranging from 1,000 to 4,000 feet, is needed to understand the full extent of the fresh-water zone and the volume of water in storage in the aquifer. It is essential to determine the base of the aquifer, which is defined by the base of the fresh-water zone or basement (granite). Although information from petroleum wells is abundant on the flanks of the aquifer, it is sparse directly over the aquifer. Members of the Arbuckle Study Technical Peer Review Team believe that the only way to determine the base of the aquifer and to obtain critical information, such as vertical flow gradients and water chemistry, is to drill several deep test holes.

Unfortunately, the drilling project experienced several difficulties, especially the enormous volumes of water produced from numerous fractured zones. The volume of water produced--estimated at up to 1,200 gallons per minute--forced the drillers to switch from an air hammer drill to much slower air rotary methods. When budgeted funds were exhausted, drilling ceased on November 30 at a depth of 1,820 feet. In addition, planned geochemical sampling was not performed because of fear that the water samples were adversely affected by air from the drilling.

Other methods are under consideration both to deepen the test hole or drill a different deep well and to collect depth-stratified samples that are not contaminated with drilling fluid. Additional deep drilling operations in the Arbuckle-Simpson aquifer will depend upon future funding and partnering opportunities.



USGS drilling rig at test well. While drilling the deep test hole, air lifted up large volumes of water estimated at up to 1,200 gallons per minute.

Water Levels Reflect Unusual Weather

In June 2004, the OWRB began installing water-level recorders in wells in the Arbuckle-Simpson aquifer as part of the Arbuckle-Simpson Hydrology Study. These water-level recorders, which measure the depth to groundwater, can be used to determine the aquifer's seasonal fluctuation and response to recharge from precipitation and discharge from pumping. A longer period of record is available from the Fittstown Well, which has been monitored by the U.S. Geological Survey (USGS) since 1958.

The amount of recharge to the aquifer depends on several factors, including rate and intensity of rainfall, soil moisture, evaporation, and depth to the water table. The magnitude and response time to a precipitation event in a particular well is partially dependent on aquifer characteristics--the amount of fractures, karst features, porosity, and permeability. Although water level responses have varied from well to well, the data show a correlation between water levels and the timing and amount of precipitation.

During 2005, rainfall totals in the region were low (14.42 inches below normal) and most of the year's rain occurred atypically in the winter and summer. The heavy late summer rains in 2005 had little effect on groundwater levels, because recharge is significantly lower in the summer when there is higher loss of moisture to evaporation and transpiration through plants (see hydrograph below). Following one of the driest years on record, water levels are again on the decline.

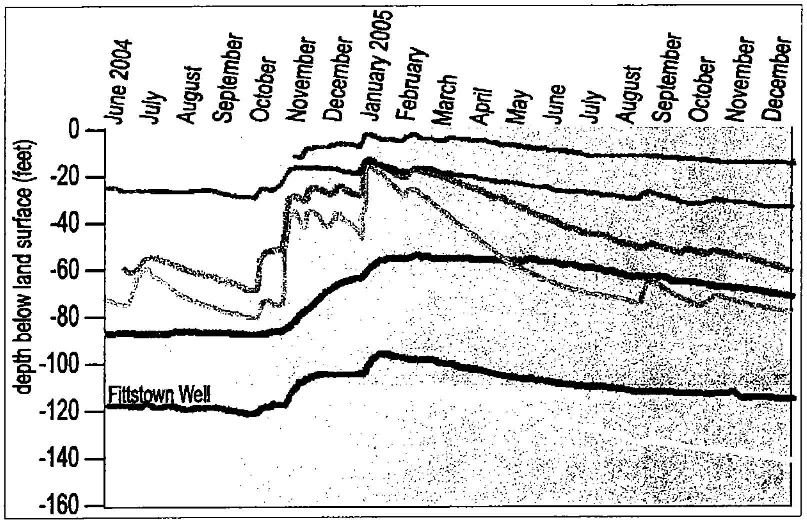
Although water levels are low, historically they have been lower, as illustrated at the Fittstown Well (see hydrograph below at right), which reached its lowest recorded depth in 1967 at 128 feet below surface. Currently, the water level is 118 feet, which is 26 feet lower than the same time last year. It is not yet as low as January 2004, when it was 122 feet below surface. Real-time water-level measurements from the Fittstown well can be viewed on the USGS Web site at http://waterdata.usgs.gov/ok/nwis/current/?type=gw.

Why Springs Bubble

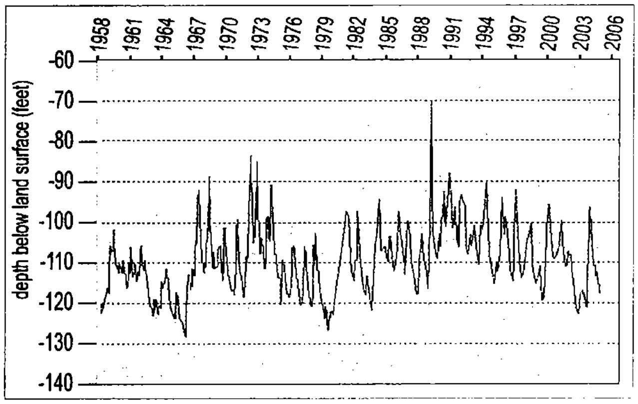
Many Arbuckle springs are bubbly. To determine the source of the bubbles, Dr. Andrew Hunt of the USGS Noble Gas Laboratory in Denver, Colorado, sampled bubbles emanating from Buffalo Spring at the Chickasaw National Recreation Area. Results indicate that the bubbles are composed primarily of nitrogen and carbon dioxide with trace amounts of argon and other gases. Small amounts of nitrogen gas occur naturally in the aquifer as a result of atmospheric nitrogen contained in precipitation.

Bubbles are most commonly observed at springs with pooled water and sandy bottoms. Dr. Hunt speculates that the groundwater degasses as temperature and hydrostatic pressure change. As groundwater discharging from the aquifer passes through sand in the spring pool, the sand provides nucleation sites for the gas to exsolve and form small lightly trapped pockets. When the gas pressure in the pockets overcomes the hydrostatic pressure in the spring pool, the gas bubbles out.

Andrew Hunt, USGS, samples Buffalo Spring.



Water levels recorded in observation wells from June 2004 to December 2005. The water level in one well rose 34 feet in 5 days in response to 3.78 inches of rain that fell in the area January 2-5, 2005. However, after 6.66 inches of rain August 14-16, 2005, water levels in the same well rose only 9 feet in 5 days.



Water levels at the Fittstown well from 1958 to present. The lowest recorded water level was 128 feet in April 1967, and the highest recorded level was 70 feet in May of 1990. Currently, the water level is at 118 feet.

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To join the Arbuckle-Simpson Study mailing list, call the OWRB at 405-530-8800.

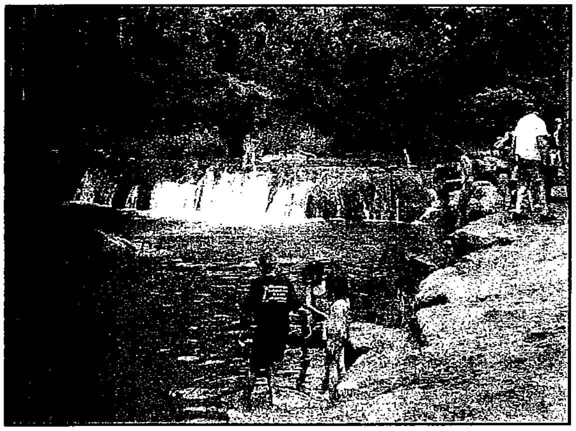
For more information, visit the OWRB's Web site at www.owrb.state.ok.us.

Hydrogeologic Setting

The Arbuckle-Simpson aquifer is contained within several rock formations. Rocks of the Arbuckle Group consist of limestones and dolomites that were deposited between 520 and 480 million years ago in Late Cambrian and Early Ordovician time. The carbonate sediments were deposited on a vast, shallow-water platform that extended from northeast New Mexico into northeast Canada. Rocks of the Simpson Group consist of sandstone, shale, and limestone that were deposited 480 to 460 million years ago in Middle Ordovician time.

Rocks of the Arbuckle and Simpson Groups are exposed at the land surface in three prominent uplifts separated from each other by large, high-angle faults. The southwestern outcrop is on the Arbuckle Anticline, a geological structure that was formed 300 million years ago when intensive folding and faulting of a thick sequence of Paleozoic rocks formed the ancestral Arbuckle Mountains. Originally rising several thousand feet above the surrounding plains, the mountains have been eroded to their present-day maximum relief of 600 feet. Topography over the steeply dipping strata is very rugged. Road cuts along Interstate 35 provide unique views of the thick sequence of Paleozoic rocks and complex structure of the Arbuckle Anticline.

The eastern outcrop is on several structural features, of which the Hunton Anticline is the most prominent. The central outcrop is on the Tishomingo Anticline. The Structural deformation on these two anticlines is much less pronounced than on the Arbuckle Anticline, and the topography consists of gently rolling plains formed on relatively flat-lying rocks.



Springs from the Arbuckle-Simpson Aquifer provide base flow to Travertine Creek, a popular recreation spot in the Chickasaw National Recreation Area.

Four (Five) Points of State Groundwater Law

In Oklahoma, surface water is considered public water while private property rights govern the use and ownership of groundwater. Prior to the OWRB's approval of a groundwater use permit, Oklahoma water law dictates that four points must be satisfied:

1) the applicant must own or lease the overlying land;
2) the land must overlie the groundwater basin;
3) the proposed purpose must be for a beneficial use; and
4) the water must not be wasted.

Senate Bill 288 would add a fifth precept to Board approval:

5) the proposed use is not likely to interfere with streams and springs emanating from a sensitive sole source groundwater basin.

Groundwater

The complex geologic features of the aquifer affect how water moves through the aquifer. Features such as folds, faults, bedding planes, and solution channels may have local influences on groundwater flow paths and flow rates. The numerous faults affect the movement of water through the aquifer because they can act as barriers to groundwater flow or as conduits through which water travels. The rate at which water moves through the aquifer can vary greatly. Water moves slowly through fine fractures and pores and rapidly through solution-enlarged fractures and conduits.

About two-thirds of the aquifer consists of carbonate rocks (limestones and dolomites), which are soluble. Infiltrating water slowly dissolves the rock, leading to the formation of solution channels and cavities along bedding planes, fractures, and faults. Karst (solution) features, such as sinkholes and caverns, are most common where fractures and bedding planes have enhanced groundwater circulation.

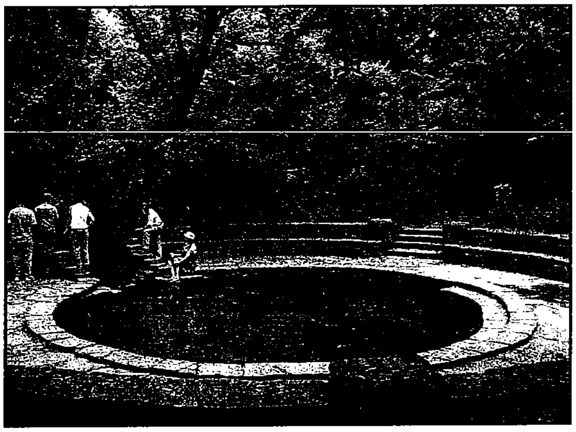
The Arbuckle-Simpson aquifer receives water from infiltration of precipitation and from losing streams that cross the outcrop area. Most of the discharge from the aquifer is to streams, rivers, and springs and some is to well withdrawals, outflow to adjacent aquifers, and to evapotranspiration.

Generally, groundwater flows from topographically high areas to low areas, where it discharges to springs and streams. Groundwater flow in the Arbuckle Anticline region appears to radiate from the crest of the anticline. Regional groundwater flow in the Hunton Anticline region is southeast, but a small component is southwest. Where the Arbuckle-Simpson aquifer dips beneath rocks of lower permeability, the aquifer is confined, and wells that penetrate below the confining layer may be artesian. Several artesian wells flow in the valley of Rock Creek, near Sulphur. The most well known of these wells is Vendome Well in the Chickasaw National Recreation Area.

Groundwater and surface water interact in different ways. In some areas of the Arbuckle-Simpson aquifer, streams gain water from aquifer discharge, and in other areas, streams lose water to the aquifer. Where the altitude of the water table is higher than the altitude of the stream-water surface, groundwater discharges into the stream channels. The groundwater component of streamflow is known as base flow. About 60 percent of the streamflow in the outcrop area of the Hunton Anticline is base flow from the aquifer. Where the altitude of the water table is lower than the altitude of the stream-water surface, surface water recharges the aquifer. In karst aquifers, losing segments of streams commonly occur where streams cross sinkholes or highly fractured rock.

Hydrologic Budget

Understanding the hydrologic budget is important for managing and understanding the water resources of the Arbuckle Mountains. The U.S. Geological Survey developed a hydrologic budget of the Hunton Anticline region for a period of record in the 1970s. During this time, 80 percent of the average annual precipitation (38.4 inches) was returned to the atmosphere by evapotranspiration. The remaining 20 percent discharged from the area as surface runoff, of which 12 percent was base flow and 8 percent was direct runoff from land surface. Recharge to the aquifer was estimated from base flow to average 4.7 inches/year.



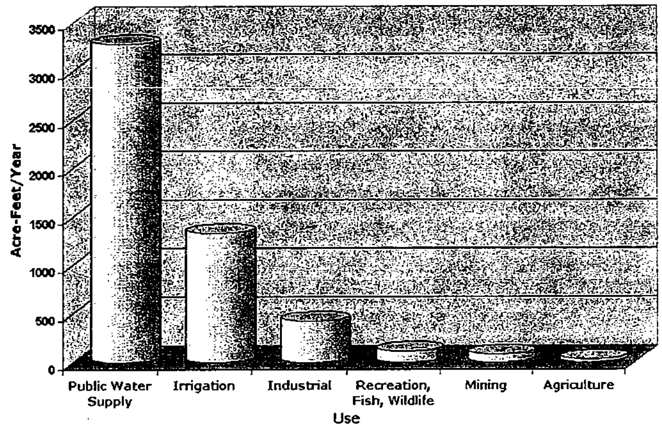
Buffalo Spring, part of the national park, is a freshwater spring originating from the Arbuckle-Simpson aquifer.

Water Use in the Arbuckle-Simpson

Wells in the Arbuckle-Simpson aquifer commonly yield 25 to 600 gallons per minute (gpm) of water, and deep wells have been known to yield as much as 2,500 gpm. To date, water in the aquifer has been produced in small amounts for municipal, irrigation, industrial, mining, agricultural, stock, and domestic purposes. Permit holders reported using about 5,000 acre-feet of groundwater in 2000, of which 62 percent was for municipal use and 25 percent was for irrigation.

Springs and streams receiving flow from the aquifer supply additional water for municipal, irrigation, industrial, mining, fisheries, recreation, and wildlife conservation purposes. Durant receives its water supply from the Blue River, Tishomingo from Pennington Creek, and Ada from Byrds Mill Spring.

Arbuckle-Simpson Aquifer 2000 Water Use



Surface Water

Major streams emanating from the aquifer are the Blue River and Delaware Creek, which flow into the Red River, and Mill, Pennington, Honey, Hickory, and Oil Creeks, which flow into the Washita River. These streams are sustained throughout the year by groundwater discharge to springs and seeps.

At least 100 springs are known to discharge water from the aquifer to streams that drain the outcrop area. The largest is Byrds Mill Spring, located in the northeastern margin of the Hunton Anticline region, about 12 miles south of Ada. The spring flows an average 20 cubic feet per second (cfs) or 9,000 gallons per minute (gpm) and is the primary source of water for the City of Ada.

Also of importance are the freshwater and mineralized springs in the Chickasaw National Recreation Area. The two principal freshwater springs are Antelope and Buffalo Springs. These springs provide the primary source of flow in Travertine Creek, a popular recreation spot. The water is chemically similar to Arbuckle-Simpson water, and recharge to the springs is most likely from the outcrop of Arbuckle-Simpson rocks to the east. Several springs in the park and Vendome Well produce mineralized water, once valued for its medicinal qualities. Some of the waters have a strong sulfur odor, which is characteristic of hydrogen sulfide. The mineralized water–with large concentrations of sodium, chloride, and sulfate–appears to be a mix of fresh water from the Arbuckle-Simpson aquifer and saline water derived from a regional and/or deeper source.

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For digital data sets, visit the USGS Web site at wwwok.cr.usgs.gov.

For more information, visit the OWRB's Web site at www.owrb.state.ok.us.

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