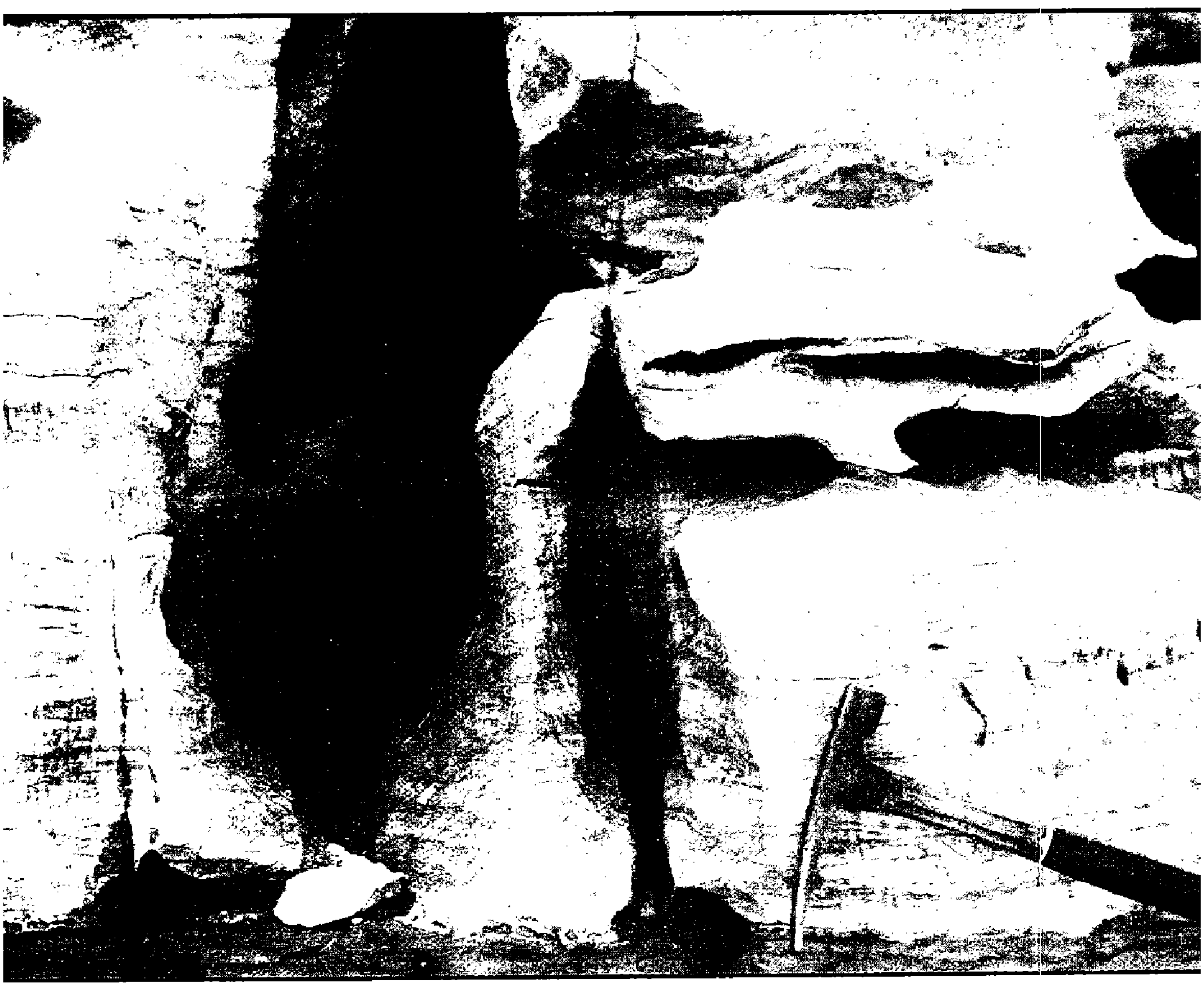
# LAHOMA GEOLOGY



Vol. 58, No. 5
October 1998

## *On The Cover —*

### Karst Features in Permian Gypsum

Gypsum is one of the most soluble of common rocks; it dissolves readily to form caves, sinkholes, disappearing streams, and other karst features that typically are found in limestones and dolomites, as well as in gypsums.

Gypsum deposits of Permian age are common in western Oklahoma, mainly in the Blaine and Cloud Chief Formations. On the cover is an outcrop of Cloud Chief gypsum with pronounced dissolution features along bedding planes and near-vertical joints. Such features are abundant in the gypsum beds of the Blaine Formation, making it a prolific aquifer in the Hollis irrigation district of southwestern Oklahoma. The feature article in this issue, "Demonstration and Evaluation of Artificial Recharge to the Blaine Aquifer in Southwestern Oklahoma" (p. 184), discusses the importance of artificial recharge to the karstic Blaine aquifer.

*Kenneth S. Johnson*

**OKLAHOMA GEOLOGICAL SURVEY**

CHARLES J. MANKIN
*Director*

KENNETH S. JOHNSON
*Associate Director*

**OKLAHOMA GEOLOGY NOTES**

*Editor*
Christie Cooper

*Associate Editor*
Tracy Peeters

*Cartography*
T. Wayne Furr, *Manager*
James H. Anderson
Charlotte Lloyd

*OKLAHOMA GEOLOGY NOTES,* ISSN 0030-1736, is published bimonthly by the Oklahoma Geological Survey. It contains short technical articles, mineral-industry and petroleum news and statistics, abstracts, notices of new publications, and announcements of general pertinence to Oklahoma geology. Single copies, $1.50; yearly subscription, $6. Send subscription orders to the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019. Short articles on aspects of Oklahoma geology are welcome from contributors; general guidelines will be sent on request.

This publication, printed by the Oklahoma Geological Survey, Norman, Oklahoma, is issued by the Oklahoma Geological Survey as authorized by Title 70, Oklahoma Statutes 1981, Section 3310, and Title 74, Oklahoma Statutes 1981, Sections 231–238. 1,500 copies have been prepared for distribution at a cost of $1,301 to the taxpayers of the State of Oklahoma. Copies have been deposited with the Publications Clearinghouse of the Oklahoma Department of Libraries.

ƆKLAHOMA GEOLOGY

# Notes



VOL. 58, NO. 5
OCTOBER 1998

# Demonstration and Evaluation of Artificial Recharge to the Blaine Aquifer in Southwestern Oklahoma

*Noël I. Osborn*[1], *Edward Eckenstein*[1], *and Robert S. Fabian*[1]

## Abstract

The Blaine Gypsum Groundwater Recharge Demonstration Project has demonstrated that artificial recharge using gravity-flow recharge wells in the cavernous Blaine aquifer is economically feasible, with a benefit-to-cost ratio greater than four to one. Artificial recharge provides an effective method in offsetting seasonal and long-term water-level declines in an aquifer that is heavily pumped for irrigation.

The aquifer was recharged with five gravity-flow recharge wells located near the town of Hollis in southwestern Oklahoma. The wells intercepted surface runoff and channeled the untreated water into solution cavities within the Permian-age Blaine Formation. An impoundment at one site diverted runoff into the recharge well.

From August 1993 through September 1996, the five recharge wells contributed an estimated 1,056 acre-ft of water to the aquifer, an average of 70 acre-ft per well, per year. Each recharge well replenished about half the amount produced from one irrigation well.

The amount of water recharged to the aquifer could be increased by installing additional recharge wells in appropriate locations. In order for recharge wells to have the most effect on replacing produced water and preventing irrigation wells from going dry, wells should be placed upgradient of, or within, irrigation pumping centers. Recharge wells placed in areas where the aquifer is permeable and where depth to water is >20 ft should have sufficient storage capacity. Wells with impoundments are most effective at capturing runoff.

No harmful effects of the project on the quality of water in the Blaine aquifer were detected. Although, occasionally, low levels of pesticides and volatile organic compounds were detected in ground water, they did not persist over time. The most commonly found pesticides were trifluralin and pendimethalin, which are herbicides used for preemergent control of grass and weeds. Concentrations of both herbicides were below regulatory levels.

A positive impact of the recharge operations was the short-term improvement of water quality of the aquifer, as fresh recharge water diluted the highly mineralized ground water. Statistical analysis of the general water quality indicates that concentrations of most parameters either decreased after recharge or did not significantly change. These changes reflect short-term effects after recharge and do not necessarily reflect long-term effects.

## Introduction

### Background

The Blaine aquifer is the primary source for irrigation of cotton, winter wheat, and other row crops in Harmon and Jackson Counties, in southwestern Oklahoma. During the 1960s, the water level of the Blaine aquifer declined, due to increasing

[1] State of Oklahoma Water Resources Board.

use of irrigation and to a series of droughts that occurred in the 1950s and 1960s. Some wells went dry, and water quality in other wells deteriorated due to induced infiltration of salt water from underlying strata and from the Red River.

In 1968, in response to these conditions, local farmers began to artificially recharge the Blaine aquifer. They formed the Southwest Water and Soil Conservation District (SWSCD) and constructed recharge wells, diversion channels, and impoundments.

### Project Description

*Purpose and Objectives*

The purpose of the Blaine Gypsum Groundwater Recharge Demonstration Project was to demonstrate the feasibility and effectiveness of recharging surface runoff into the cavernous Blaine aquifer with gravity-flow wells. The project expanded the SWSCD's existing recharge system by constructing five additional wells and an impoundment. Specific study objectives were:

1) to determine the volume of water artificially recharged to the aquifer during the study,
2) to determine the impact of artificial recharge on the water quality of the aquifer, and
3) to determine the economic feasibility of using gravity-flow recharge wells to recharge the aquifer artificially.

The project was one of 13 demonstration projects implemented by the Bureau of Reclamation and local sponsors, in cooperation with the U.S. Environmental Protection Agency (EPA) and the U.S. Geological Survey (USGS), under the "High Plains States Groundwater Demonstration Program Act" of 1983. The primary purpose of this act was to advance state-of-the-art ground-water-recharge techniques. The State of Oklahoma Water Resources Board (OWRB) sponsored the project in cooperation with the SWSCD.

*Study Area*

The study area is defined by the drainage basin for Sandy Creek, which encompasses the recharge areas for the project's recharge wells and the streams from which the recharged ground water is eventually discharged (Fig. 1). It covers 373 $mi^2$ in Harmon and Jackson Counties in southwestern Oklahoma and in Childress and Collingsworth Counties in the Texas Panhandle. The project area, which encompasses the five recharge sites, is located within 3 mi of the town of Hollis (Fig. 2).

## Hydrogeologic Setting

### Stratigraphy

The Permian-age Blaine Formation consists of a cyclic series of interbedded gypsums, shales, and dolomites. The formation is 135–255 ft thick; average thickness is 200 ft. Underlying the Blaine Formation is the Flowerpot Shale, which consists of red-brown shale interbedded with thin layers of gypsum, dolomite, siltstone, and green-gray shale (Johnson, 1990b). The Dog Creek Shale overlies the Blaine Formation in much of the study area. The Dog Creek consists of up to 200 ft

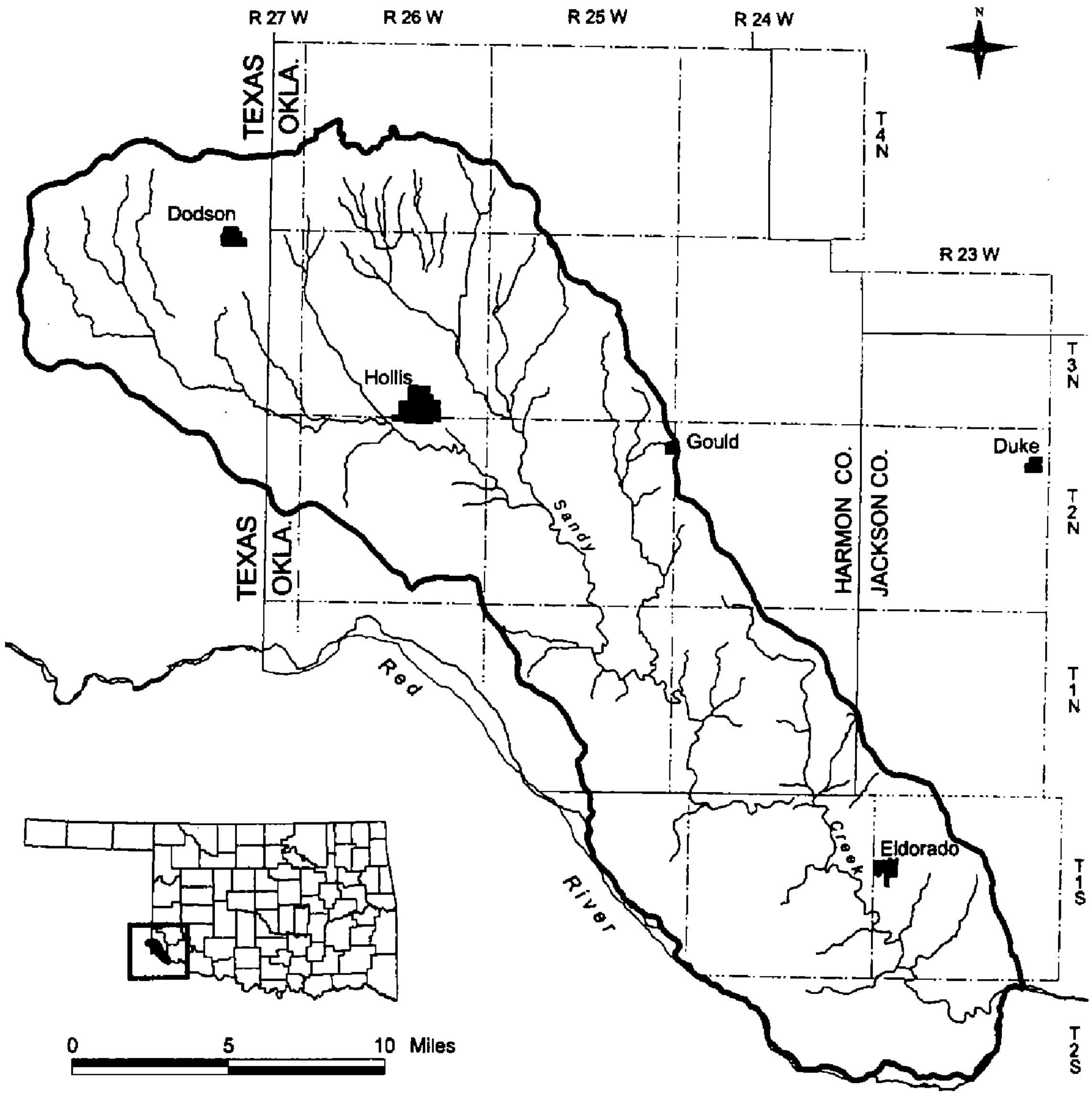



Figure 1. Study area of the Blaine Gypsum Groundwater Recharge Demonstration Project, defined by the drainage basin of Sandy Creek.

of red-brown shale with thin gypsum and dolomite beds in the lower 50 ft of the formation (Johnson, 1990b).

## Karst Development and Features

Water in the Blaine aquifer is obtained from cavities, solution channels, and fractures present in the gypsum and dolomite beds of the Blaine Formation. Solution openings are formed when percolating rain water and circulating ground water dissolve beds of soluble gypsum ($CaSO_4 \cdot 2H_2O$) and dolomite ($CaMg(CO_3)_2$) (Johnson, 1990a).

Karst features, such as caves, sinkholes, disappearing streams, and springs, occur within the study area. Karst features are most abundant near streams, where fresh water percolates into the gypsum. Karst development generally is greatest in areas where the overlying Dog Creek Shale is <60 ft thick and least where that for-

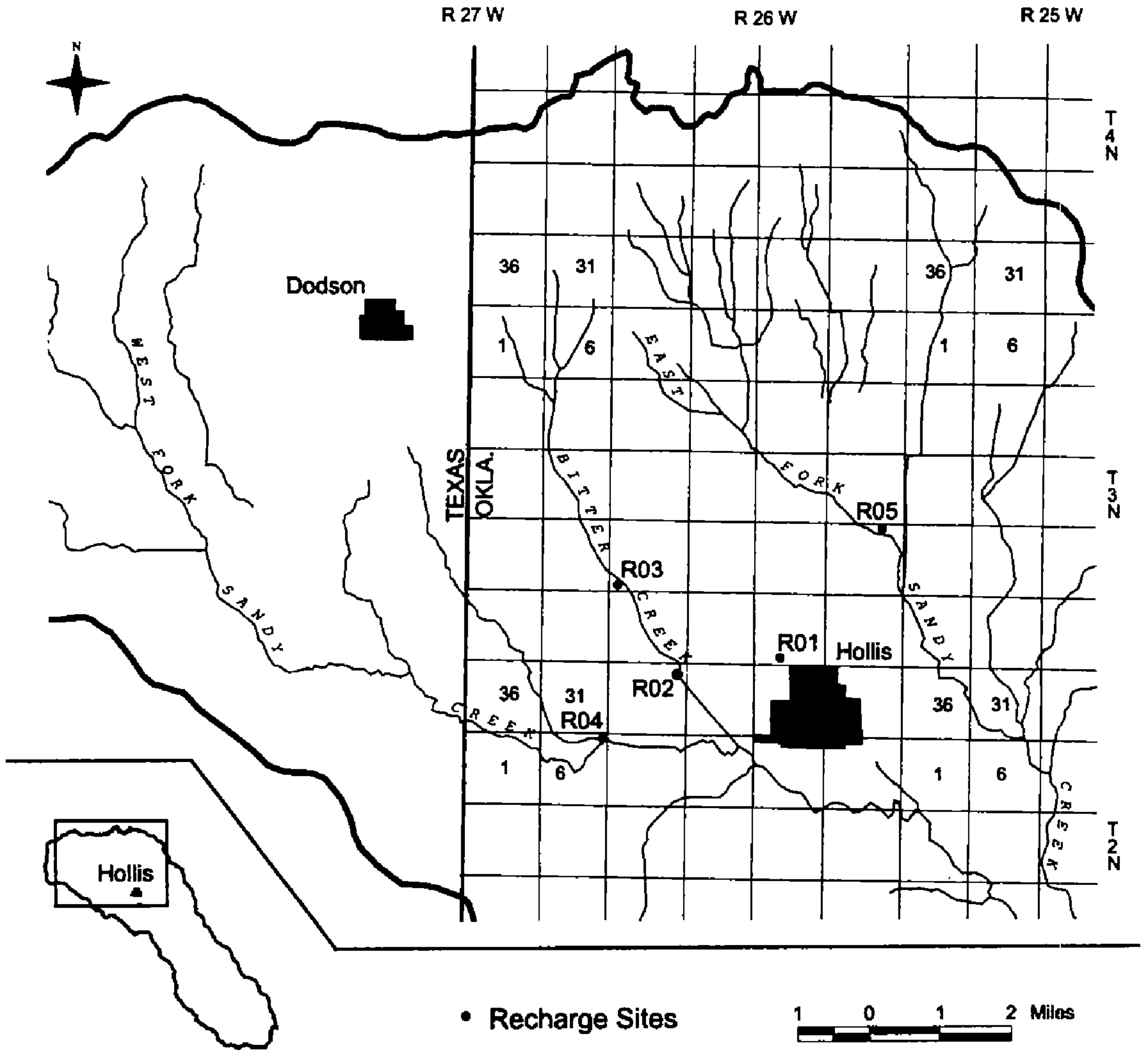



Figure 2. Project area showing the five recharge sites, R01–R05, near the town of Hollis.

mation is >100 ft thick. In areas where the Dog Creek Shale is thick, fresh water is not in contact with the Blaine Formation, and anhydrite ($CaSO_4$) may be present instead of gypsum (Johnson, 1990a; Runkle and McLean, 1995).

## Aquifer Characteristics

Hydraulic conductivity varies considerably in the aquifer. It is greatest where dissolution of gypsum and dolomite occurs, in areas of high recharge. Using a computer model to simulate ground-water flow of the Blaine aquifer, Runkle and McLean (1995) estimated a hydraulic conductivity value of 4.2 ft/d for areas of low recharge, and values of 17 ft/d and 71 ft/d for areas of high recharge. Where the full thickness of the Blaine aquifer is present, ~200 ft, transmissivities in the high recharge areas would be equivalent to ~3,400 $ft^2/d$ and ~14,000 $ft^2/d$ (Runkle and McLean, 1995).

Steele and Barclay (1965) evaluated water-level changes in areas of heavy irrigation pumping to estimate transmissivity and storage coefficient. By applying the Theis nonequilibrium equation to the pumping centers, they calculated transmissivities of approximately 16,000–61,000 $ft^2/d$. These values are higher than those estimated by Runkle and McLean (1995), suggesting that transmissivity is greater in local areas where cavern development is extensive.

Steele and Barclay (1965) estimated the storage coefficient in the pumping centers to range from 0.0004 to 0.03, with an average of 0.016. They estimated the average storage coefficient for the entire aquifer to be 0.001.

The Dog Creek Shale is considered a confining unit where its thickness overlying the Blaine aquifer is >100 ft; where it is <100 ft thick, karst features in its gypsum and dolomite units make it a leaky confining unit (Johnson, 1990a). The Blaine aquifer is unconfined where the Blaine Formation crops out, or where it is in communication with alluvial and terrace aquifers.

Natural recharge to the aquifer occurs from infiltration of precipitation and from streams that flow across sinkholes. Recharge is greatest where <60 ft of Dog Creek Shale overlies the aquifer. Average recharge to the aquifer is estimated to be 1.5 in./yr, or 6% of the average annual precipitation of 24 in. (Runkle and McLean, 1995).

Artificial recharge of the Blaine aquifer began in 1968, when the SWSCD was created. Many of the SWSCD's recharge projects consist of diverting surface drainage to sinkholes, caves, or other natural openings into the ground; for others, recharge wells or impoundments were constructed. The SWSCD had constructed 4 impoundments and about 70 recharge wells prior to the beginning of the demonstration project. In addition to the project's 5 wells, approximately 45 recharge wells are currently in operation.

Ground water from the Blaine aquifer discharges to Sandy Creek in the southern portion of the study area and to the Red River. The USGS used base-flow measurements taken in 1988 to determine that the Blaine aquifer discharged 15.9 $ft^3/s$ to Sandy Creek and 6.9 $ft^3/s$ to the Red River (Runkle and McLean, 1995), or, ~11,500 acre-ft/yr and ~5,000 acre-ft/yr, respectively.

Ground water in the study area is also discharged to wells for irrigation use. According to water-use reports filed by permitted water users (public records on file at the OWRB), an average of 17,130 acre-ft of water is pumped annually for irrigation.

## Project Activities

### Facilities

The project consisted of five recharge sites, identified as sites R01–R05 (Fig. 2). The sites each had one recharge well, identified as recharge wells R1–R5, and 3–7 monitoring wells.

An impoundment was built at the R01 site to divert runoff into the recharge well. The impoundment drains 369 acres and has a capacity of 25 acre-ft. It also provides flood control for Hollis.

### Recharge Wells

The project's recharge wells intercept surface runoff and channel the water into cavities and fractures within the Blaine Formation. Surface runoff is diverted to an inlet structure, where the untreated water flows by gravity into a recharge well. Screens around the inlet structures prevent large debris from entering the wells and damaging or clogging them. Slotted casing allows recharge water to enter the cavernous zones in the Blaine Formation. Figure 3 is a schematic diagram of a recharge well.

The OWRB and the SWSCD worked together to improve the design of recharge wells to be drilled for the project. Typically, only the first 90 ft of a SWSCD recharge well was cased, with 16-in. casing seated in cement; cement was also placed in the annular space at the surface, enclosing the inlet pipe. From a depth of 90 ft to the final total depth of the well, a 12-in. hole was drilled and left uncased. Over time, the gypsum in the uncased hole dissolved and SWSCD wells collapsed at or below 90 ft.

The project's recharge wells are cased with 12-in.-diameter casing to depths of 155–270 ft, to prevent the kind of dissolution and collapse that has occurred in SWSCD wells at or below depths of 90 ft. In order to prevent dissolution of the gypsum beds at depths above 90 ft (shallow zones), the OWRB incorporated three new features into the design for the project's recharge wells: (1) the annular space between the outer 16-in. casing and the wall of the hole is grouted with cement (under pressure) from a depth of ~90 ft to land surface; (2) an inner string of 12-in. cas-

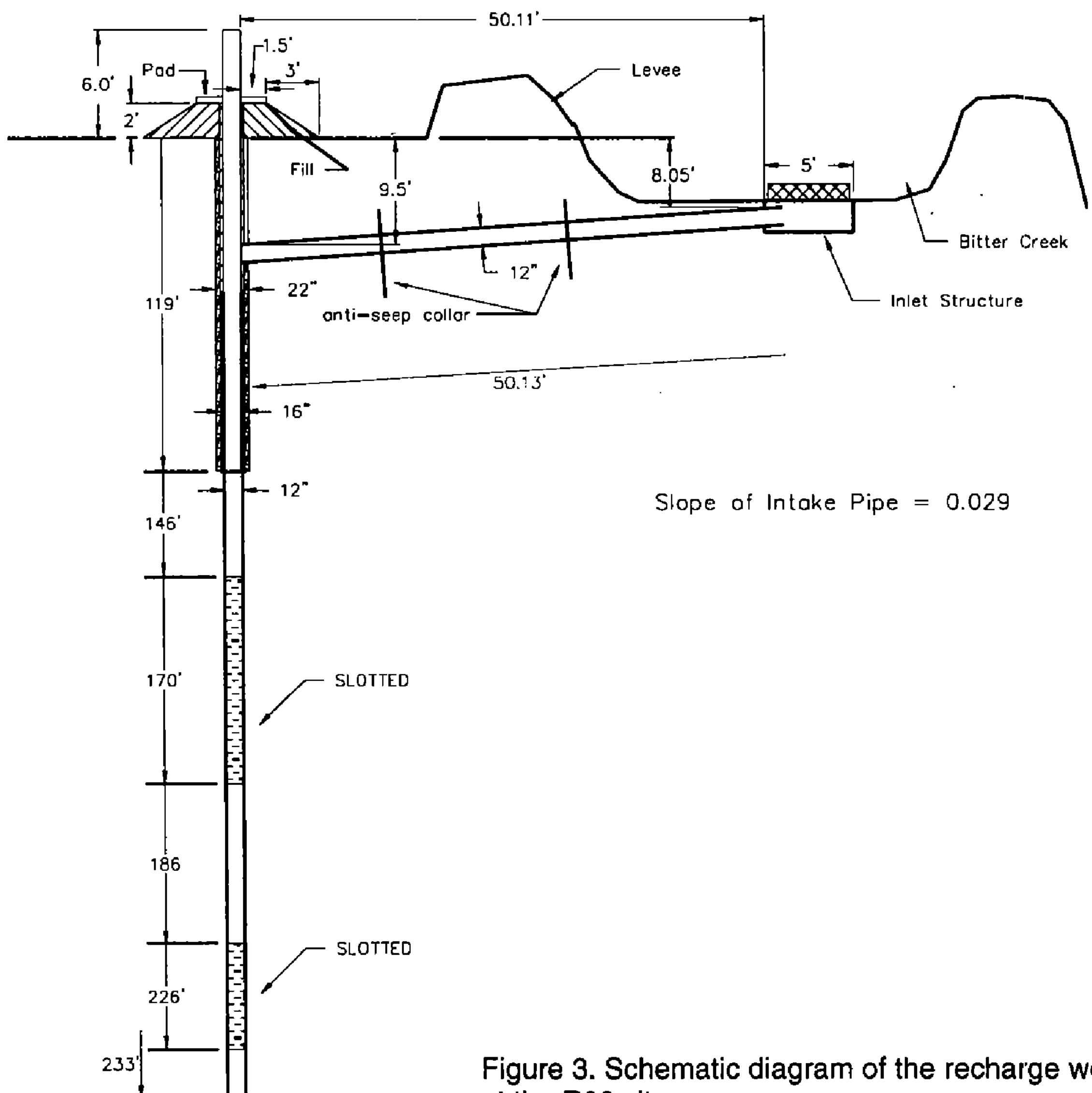



Figure 3. Schematic diagram of the recharge well at the R03 site.

ing is added; and (3) the annular space between the 12-in. inner casing and the 16-in. outer casing is grouted with cement from a depth of ~90 ft to land surface.

### Monitoring Wells

Twenty-four wells were installed to monitor water levels and water quality. Each monitoring well was drilled to the same depth as the associated recharge well and screened across the same interval as the recharge well. All of the monitoring wells were used to monitor water levels; 16 of the wells were also used for water quality sampling. Wells designed for monitoring both water quality and water level were constructed with 4-in. PVC casing; wells for monitoring only water levels were constructed with 2-in. casing. All of the sites had at least one upgradient and two downgradient 4-in. wells. The R01 site had three downgradient 4-in. wells.

### Operation and Maintenance

The recharge wells, which began operation in June 1993, were not operated on a schedule; they depended on runoff from precipitation in the normally dry creeks and ditches. The only maintenance required was the control of weeds and brush around the inlet structures, the control of burrowing animals around the well and inlet pipes, and the clearing of debris from the screens that cover inlet structures.

The total cost of operation and maintenance for the project's five wells and the impoundment was very low ($53 per month), largely because water treatment was not required. Debris screens around the entrances of the drop inlet structures provided coarse filtration. Formation clogging was not a problem in this karst aquifer.

## Findings and Results

This article summarizes project activities and findings. More information can be found in the final project report, *Blaine Gypsum Groundwater Recharge Demonstration Project, Final Report* (OWRB, 1997, unpublished), and in OWRB Technical Report 97-5: *Demonstration and Evaluation of Artificial Recharge to the Blaine Aquifer in Southwestern Oklahoma* (Osborn and others, 1997). A summary of water quantity and quality data is available in OWRB Technical Report 97-4: *Blaine Gypsum Groundwater Recharge Demonstration Project Data Report* (Osborn and Eckenstein, 1997). Copies of these reports can be obtained by contacting Susan Birchfield, Oklahoma Water Resources Board, 3800 N. Classen Boulevard, Oklahoma City, OK 73118; telephone (405) 530-8800. (See p. 212 for pricing.)

### Hydrology

*Monitoring*

Aquifer response to recharge and pumping was monitored with measurements of water level and precipitation. Water levels were measured from a network of 71 irrigation, recharge, stock, and observation wells located throughout the study area. The network consisted of 69 wells in Oklahoma that were measured monthly, and 3 wells in Texas that were measured semiannually. Water levels were recorded hourly on electronic water-level recorders installed in 24 monitoring wells located near the recharge wells. A stream gauge measured stream flows on Sandy Creek, and two tipping-bucket rain gauges recorded rainfall.

*Ground-Water Flow*

Figure 4 is a potentiometric map of the Blaine aquifer within the study area, based on the monthly water-level measurement for wells in February 1994 and on the altitudes of perennial streams that are in hydraulic connection with the aquifer. Ground water flows perpendicular to the water-level contours, from high to low elevations. As illustrated in Figure 4, ground water flows southeast, where it discharges into Sandy Creek and the Red River. The regional slope of the potentiometric surface, or the hydraulic gradient, is ~10 ft/mi, or 0.002. Depth to water ranges from just below land surface to >100 ft below land surface.

Ground-water velocity can be calculated by multiplying the hydraulic conductivity by the hydraulic gradient, and dividing by the average porosity (Driscoll, 1986). To calculate the regional ground-water velocity of the study area, a hydraulic conductivity of 71 ft/d, representing areas of high recharge (Runkle and McLean, 1995), was multiplied by the regional hydraulic gradient of 0.002. The product was then divided by 0.016, the storage coefficient calculated by Steele and Barclay

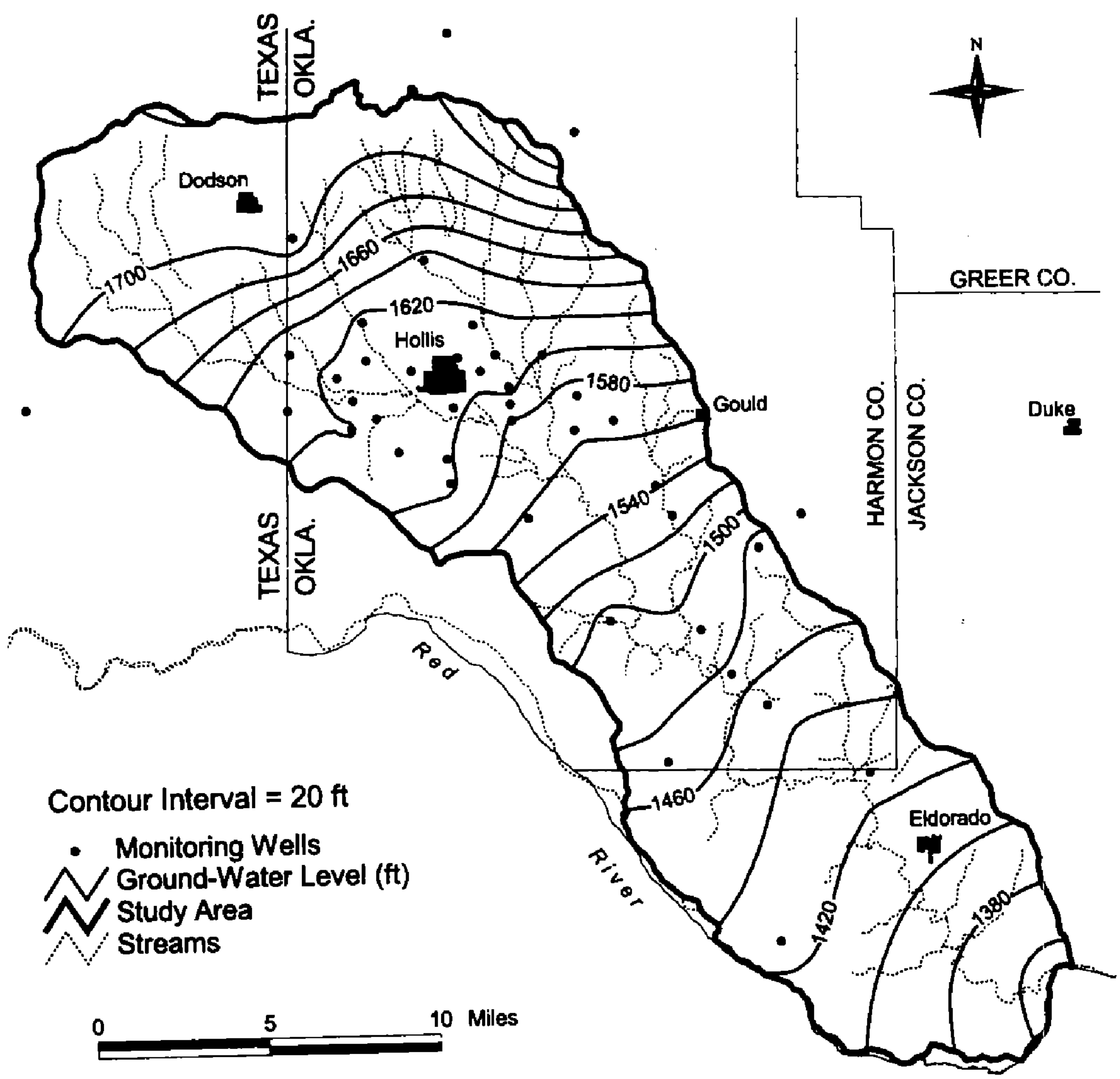



Figure 4. Potentiometric map of the Blaine aquifer in the study area, based on water levels measured in February 1994.

(1965) for the pumping centers. Based on these values, regional ground-water velocity is ~9 ft/d.

Locally, ground-water velocities can be very high. A dye-tracing test conducted at the R01 recharge site during an injection test resulted in a maximum ground-water velocity of ~2 mi/d and an average velocity of 1 mi/d (Osborn and others, 1997).

### *Water-Level Changes*

Water level in the Blaine aquifer fluctuates in response to recharge from precipitation and discharge from well pumping. Figure 5 is a hydrograph of an irrigation well located west of Hollis, showing water-level measurements collected annually during winter months from 1950 through 1997. The hydrograph is typical of hydrographs for other wells in the area and shows a gradual decline in the water level from 1950 to 1960. After a slight incline in 1961, the water level continued to decline to historically low levels between 1965 and 1968. The water level then increased to a high level between 1976 and 1978, followed by a decrease in the early 1980s. Water levels increased between 1985 and 1996.

From 1993 through 1996, precipitation was generally higher than average. The driest year was 1994, when precipitation was 3.71 in. below Hollis's average annual precipitation of 23.32 in.; the wettest year was 1995, when precipitation was 12.98 in. above average (NOAA, 1992–1996).

Figure 6 shows a daily hydrograph of a monitoring well and a precipitation graph of the rain gauge at the R03 site for January 1993 through September 1996. The water level decreases in the summer months, when irrigation pumpage is greatest, and recovers in the autumn. Most of the precipitation occurs during the

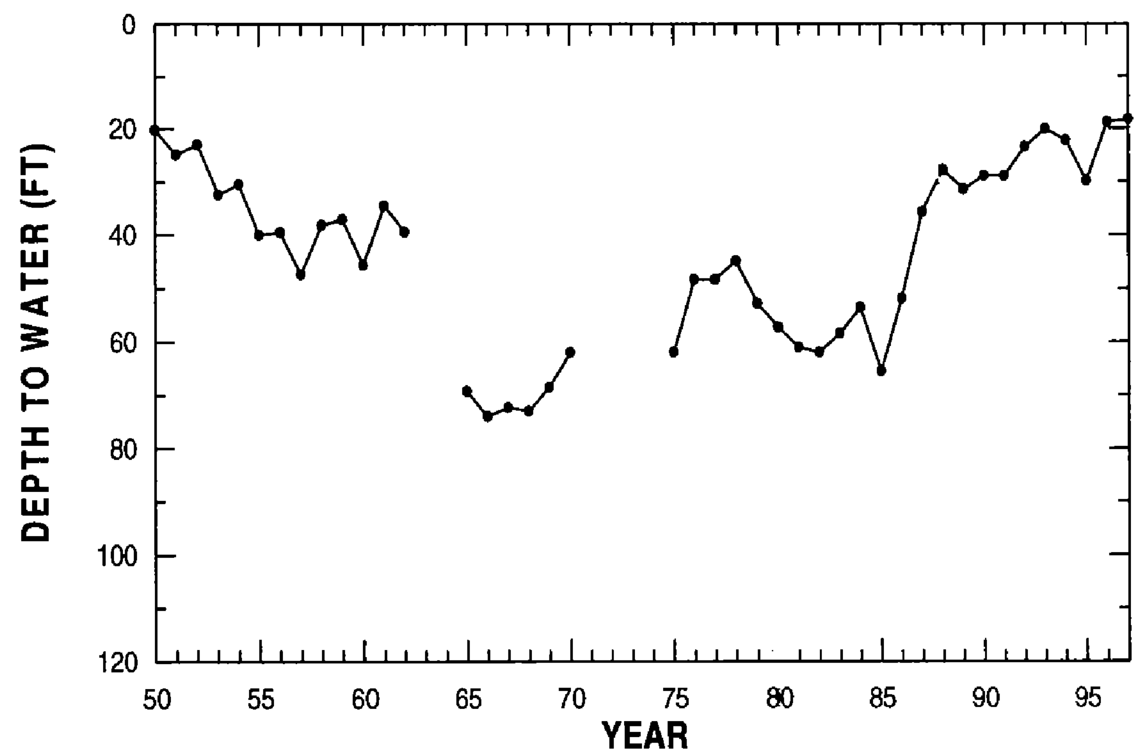



Figure 5. Hydrograph of an irrigation well located west of Hollis (sec. 5, T. 2 N., R. 26 W.), showing water-level measurements taken once a year between January and March. (No data for years 1963–64 and 1971–74.)

spring. Water level decreased significantly in August 1994 in response to pumping and increased suddenly in 1995 in response to heavy rains.

As can be seen in the hydrograph (Fig. 6), the water-level response to recharge is flashy, as is typical of karst aquifers. For example, on July 3, 1995, the water level rose 25 ft in one hour, and 37 ft in a 24-hour period.

Figure 7 displays potentiometric maps of the Blaine aquifer in the study area. The maps were constructed using a contouring package of the ARC/INFO geographic information system software (ESRI, 1997), and are based on monthly water level measurements from wells and on altitudes of perennial streams that are in hydraulic connection with the aquifer. Maps are displayed for four months in 1994, each month representing a different season. February represents winter months, when water levels are most stable; May represents spring, when recharge occurs; August represents summer, when effects of irrigation pumping are greatest; and November represents autumn, when water levels recover from pumping.

Areal changes in water level from season to season are best illustrated with maps of water-level change. The maps in Figure 8 are the result of taking the mathematical difference between the seasonal potentiometric maps in Figure 7 and show the seasonal changes in water levels in 1994. Between February and May, the water level rose slightly in the northern and central portions of the study area, and declined slightly over the rest. An extreme drop in water level occurred between May and August due to low precipitation and heavy irrigation pumping. Drawdown due to pumping created a regional cone of depression in the northern portion of the study area, where the water level declined as much as 60 ft. The least change was in the southern portion of the study area, where ground water is discharged, and in a small area south of Hollis, which may represent a natural-recharge area.

The map of water-level change for August to November, showing a significant rise in water level, is almost an inverse image of the map for May to August, which

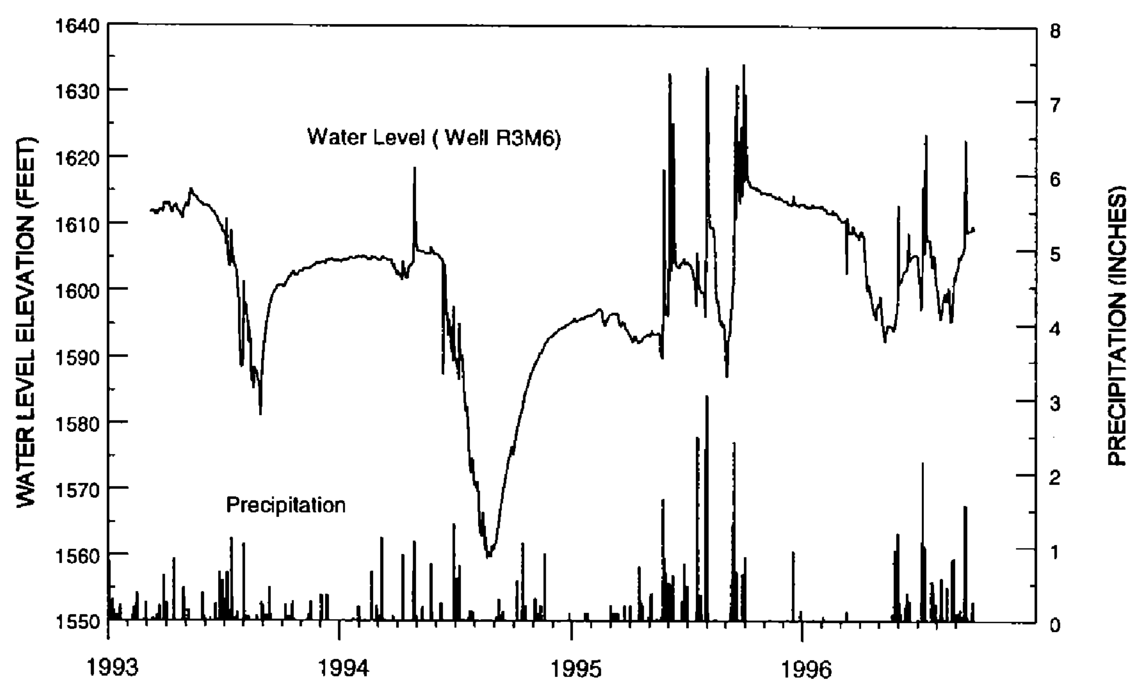
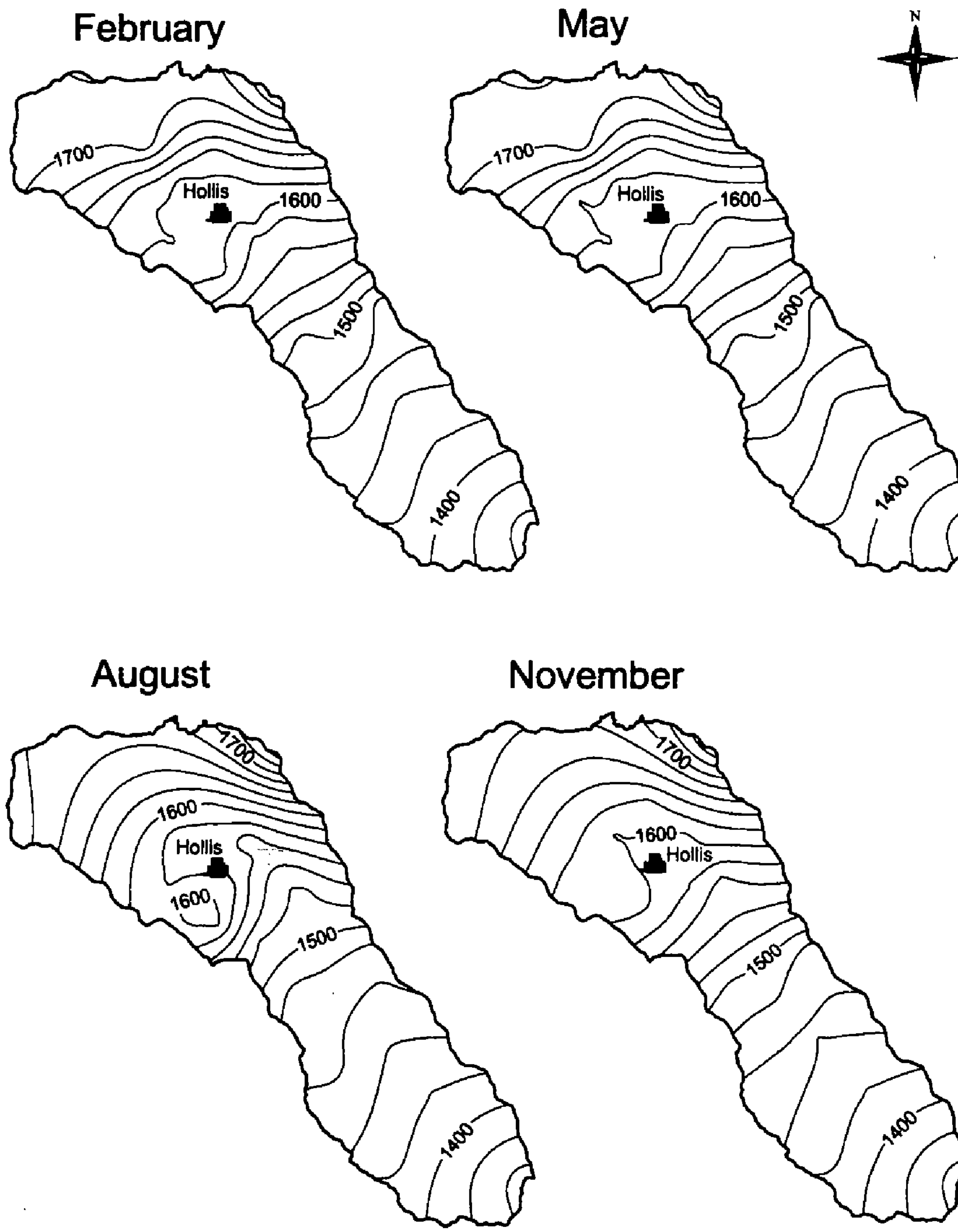



Figure 6. Daily hydrograph of a monitoring well and precipitation graph of the rain gauge at the R03 site, for January 1993 through September 1996.




Contour Interval = 20 ft

Figure 7. Potentiometric maps of the study area showing seasonal variation in the potentiometric surface during 1994. Each map is constructed for a single month, which represents the season in which it occurs. February represents winter; May represents spring; August represents summer; and November represents autumn.

shows a decline. Because little precipitation occurred from August to November, and irrigation pumping ceased, the rise in water level is attributed to recovery of the regional cone of depression. The greatest increase was in the northern portion of the study area, where drawdown had been greatest.

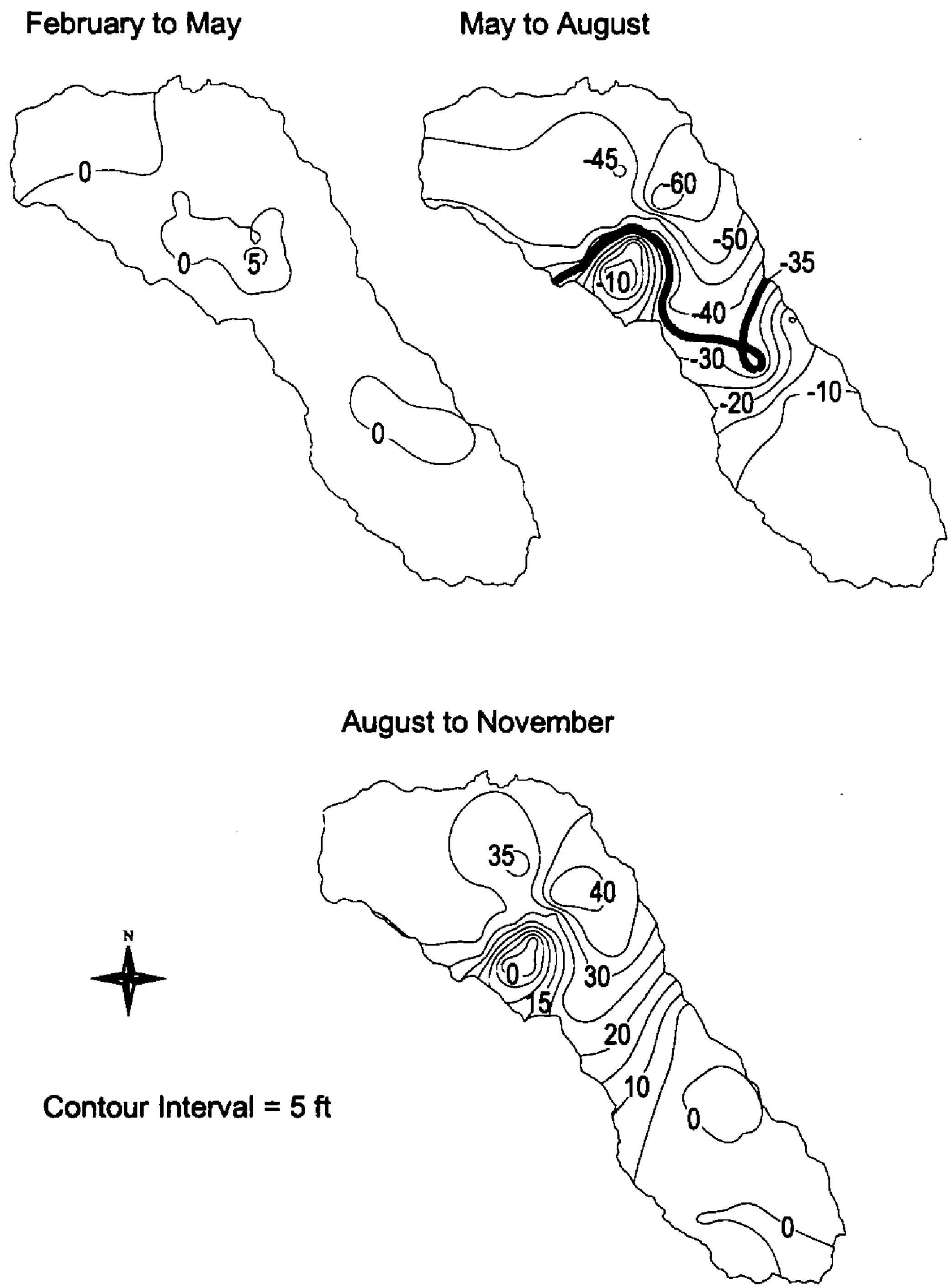



Figure 8. Maps of water-level change in the study area, showing seasonal variation in water level for 1994. The maps in Figure 8 are the result of taking the mathematical difference between the seasonal potentiometric maps in Figure 7.

## Recharge Water

### *Description*

The inlet structures to recharge wells at sites R02–R05 are located in intermittent streams and ditches. Water in the streams and ditches is derived from surface runoff and sometimes from irrigation tailwater. Streams contain water for short periods after rainfall, and then go dry. The inlet structure to the recharge well at the R01 site is fed by an impoundment, which drains 369 acres and has a capacity of 25 acre-ft.

Watersheds contributing to the five recharge wells are about 250–14,000 acres in size. The total drainage area for the project's five recharge wells is >23,000 acres.

A "recharge event" occurs when sufficient runoff has collected in the streams or the impoundment to flow into the inlet structures of the recharge wells. Recharge events occur rapidly and have short durations, lasting from a few hours to a few days. During the project, the number of recharge events per year varied from as few as 9 in 1994 to as many as 17 in 1995. During most recharge events, the inlet structures were covered by 2–4 ft of water; during large events, depths of up to 8 ft were observed.

*Water-Level Response to Recharge*

Water-level response to injection of recharge water is the inverse of its response to a pumping well. Pumping causes water levels to decline, whereas injection causes water levels to rise. Just as a cone of depression develops around a pumping well, a cone of impression (or recharge) develops around a recharge well (Driscoll, 1986).

An example of water-level response to a recharge event is illustrated in Figure 9, which is based on hourly measurements of a recharge event that occurred in September 1996 at the R03 site. Figure 9 shows graphically the recharge rate of the water entering the recharge well, the hydrograph of a monitoring well located 142 ft downgradient of the recharge well, and the amount of precipitation collected in the rain gauge at the site. During this event, 1.93 in. of rain fell in 19 hours, 11.7 acre-ft of recharge water was recorded entering the recharge well, and water level in the monitoring well rose 20 ft.

*Recharge Volume*

The amount of water recharged to the aquifer through a recharge well is controlled primarily by the volume of surface runoff, the amount of runoff captured by the well, well capacity, and aquifer storage capacity. Thus, variation in recharge volume from site to site is influenced by spatial variation in rainfall, by differences in the amount of runoff captured by the wells, and by local variations in aquifer storage capacity.

Due to limitations in methodology and equipment used in the project, the exact volume of recharge contributed by the project wells could not be calculated directly. To determine the amount of surface water entering the recharge wells, a pressure transducer was placed within each recharge well's inlet pipe to measure the depth of overlying water. Estimates of volumetric flow rates and recharge volumes were calculated from these measurements. The Manning equation for open-channel flow in a circular pipe (Janna, 1993) was used to calculate the volumetric flow rate for water depths of up to 1 ft, and the modified Bernoulli equation (Janna, 1993) was used to calculate full-pipe flow where water depths were >1 ft. An estimated recharge volume of 1,056 acre-ft of recharge water entered the aquifer through the five project wells from August 1993 through September 1996. An estimated 188 acre-ft were obtained from irrigation tailwater, as determined with field observations combined with analysis of the volumetric flow rates.

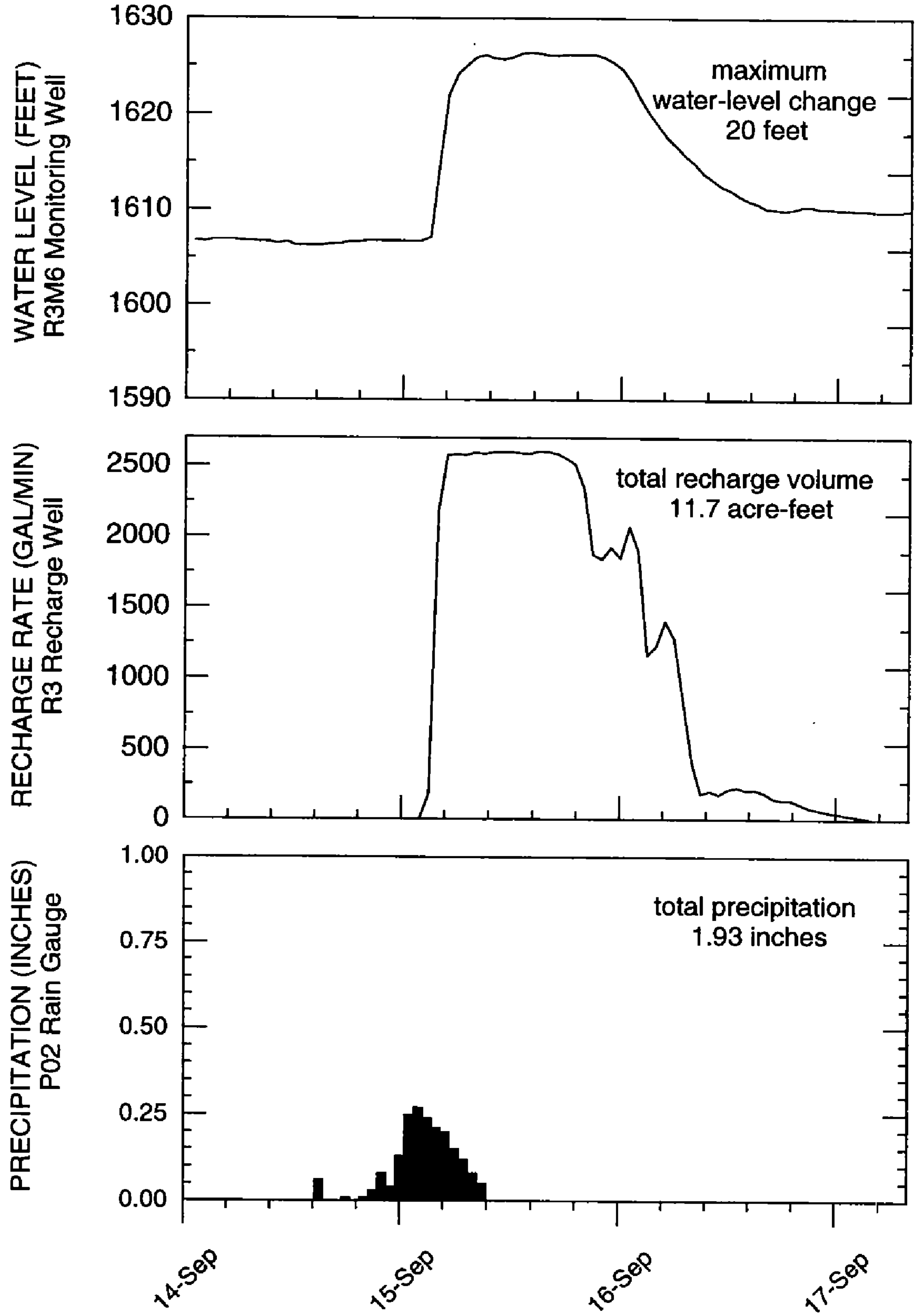



Figure 9. Graphs illustrating an example of water-level response to a recharge event. Precipitation, recharge rate, and water level in a monitoring well (142 ft downgradient from the recharge well) were measured hourly during a recharge event that occurred September 15–16, 1996, at the R03 site.

Figure 10 graphically displays the estimated recharge volume, by year, through the five project wells. The biggest annual recharge (726 acre-ft) occurred in 1995, when precipitation was greatest; the smallest annual recharge (72 acre-ft) occurred in 1994, when precipitation was least. The recharge volume for 1993 reflects only the events that occurred after July 1993.

The mean annual precipitation runoff was calculated for each of the five watersheds contributing water to the project's recharge wells using the Soil Conservation Service curve number method (USDA, 1989). A comparison of the calculated runoff with measured recharge volumes indicates that runoff captured by the wells can be greatly enhanced with an impoundment or retention structure (Osborn and others, 1997). This is demonstrated at the R01 site, where the impoundment enabled the well to capture all of the calculated runoff. The impoundment at the R01 site covers 5 acres, a small investment of land, considering the returns.

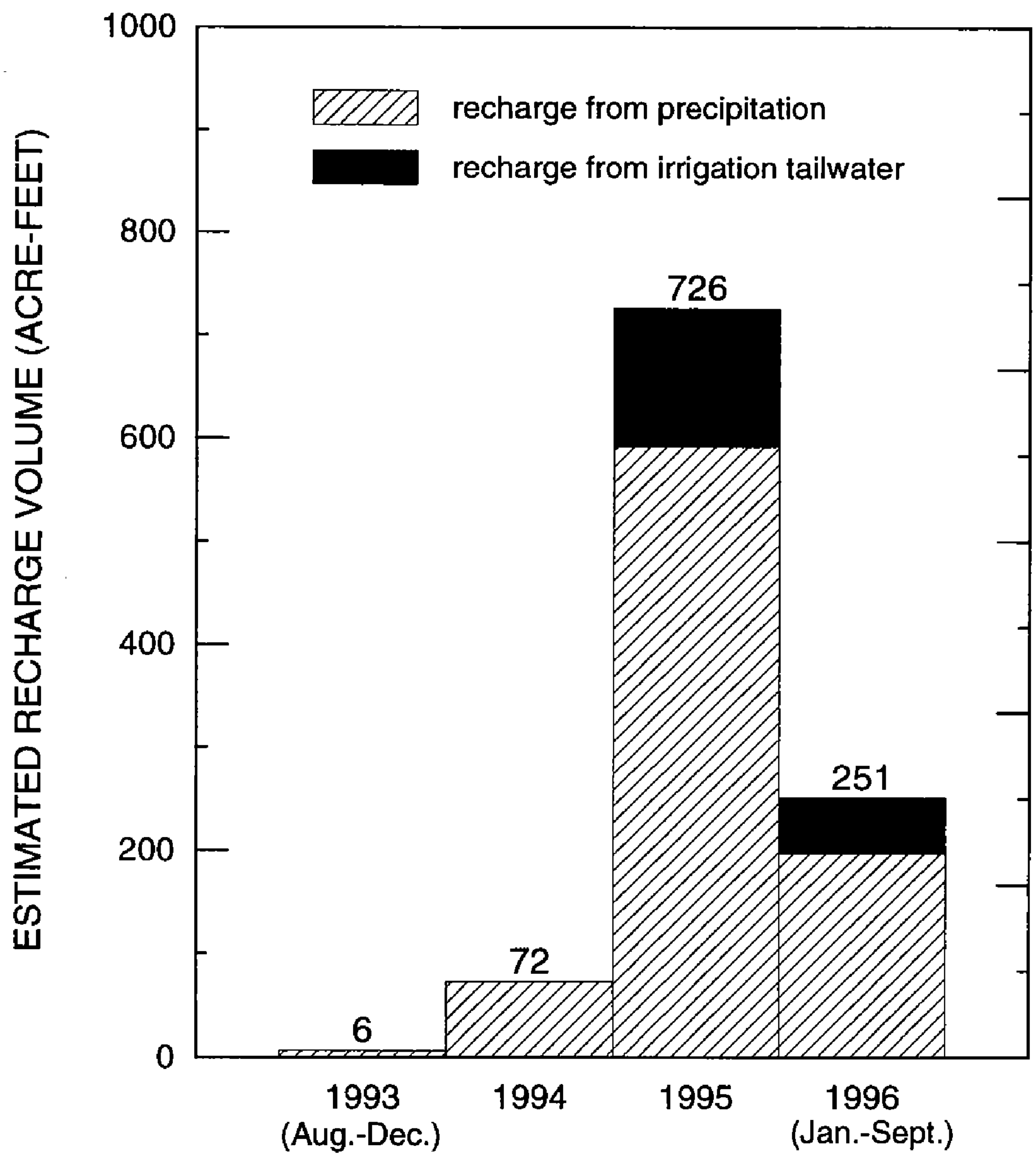



Figure 10. Estimated recharge volume, through the five project wells, by year (August 1993 to September 1996).

The average annual recharge volume per recharge well was 70 acre-ft, whereas the average annual pumpage per irrigation well was 142 acre-ft (from information in water-use reports by permitted water users, on file at the OWRB). Thus, each recharge well replenished about half the amount of water produced from one irrigation well.

Assuming that the performance of the SWSCD's recharge wells is equal to that of the project wells, then the SWSCD's 45 wells and the project's 5 wells contribute an average of ~3,500 acre-ft/yr of recharge water to the aquifer. This is about 20% of the average 17,130 acre-ft of irrigation water produced each year. If all of the water produced were to be replaced by recharge wells, ~195 additional recharge wells would need to be drilled. Of course, total replacement of produced water is unnecessary. The intended purpose of artificial recharge is to supplement the natural recharge to the aquifer in order to prevent wells from going dry in times of drought.

### Placement of New Recharge Wells

The amount of water recharged to the aquifer could be increased by installing additional recharge wells in appropriate locations. In order for recharge wells to have the most effect on replacing produced water and preventing irrigation wells from going dry, wells should be placed upgradient of, or within, irrigation pumping centers. Recharge wells placed downgradient of the main pumping areas would add water to the ground-water basin, but would not prevent irrigation wells from going dry. The shaded area in Figure 11 is the area most affected by irrigation pumping, which is defined as the area where the water level declined >35 ft between May and August 1994 (Fig. 8).

Recharge wells should also be placed in areas where the aquifer-storage capacity is good. Such areas generally occur where the aquifer is permeable; they correlate to areas where conditions are good for the dissolution of gypsum and dolomite and thus for cavern development. Dissolution is greatest in areas where the thickness of the overlying Dog Creek Shale is <60 ft (Runkle and McLean, 1995), and least where it is >100 ft (Johnson, 1990a). Figure 12 is an isopach map showing the 0-, 60-, and 100-ft contours of the Dog Creek Shale. The shaded areas correspond to areas where conditions are most favorable for good cavern development.

Another factor affecting aquifer-storage capacity is the elevation of the water table. Where the aquifer is unconfined and the water table is near the land surface, there is little room for additional storage. Figure 13 is a depth-to-water map for February 1994. The water table is near the land surface (that is, depth to water is low) in the southern portion of the study area, where ground water from the aquifer discharges to Sandy Creek. The water table is also near the surface in a few isolated areas near Hollis. Recharge wells placed where the depth to water is ≥20 ft, as shown in the shaded areas, should have sufficient aquifer storage for recharge.

Figure 14, generated with geographic analysis features of the ARC/INFO geographic information system, shows the area of overlap for the shaded areas in Figures 11–13. Thus, Figure 14 shows the optimal area in which to install new recharge wells. This area is upgradient of, or within, the irrigation-pumping center, and it has conditions favorable for cavern development, as well as depths to water of ≥20 ft.

### Water Quality

#### *Monitoring*

Water quality was monitored to assess the effects of the recharge on the quality of water in the Blaine aquifer. In order to determine baseline conditions, water

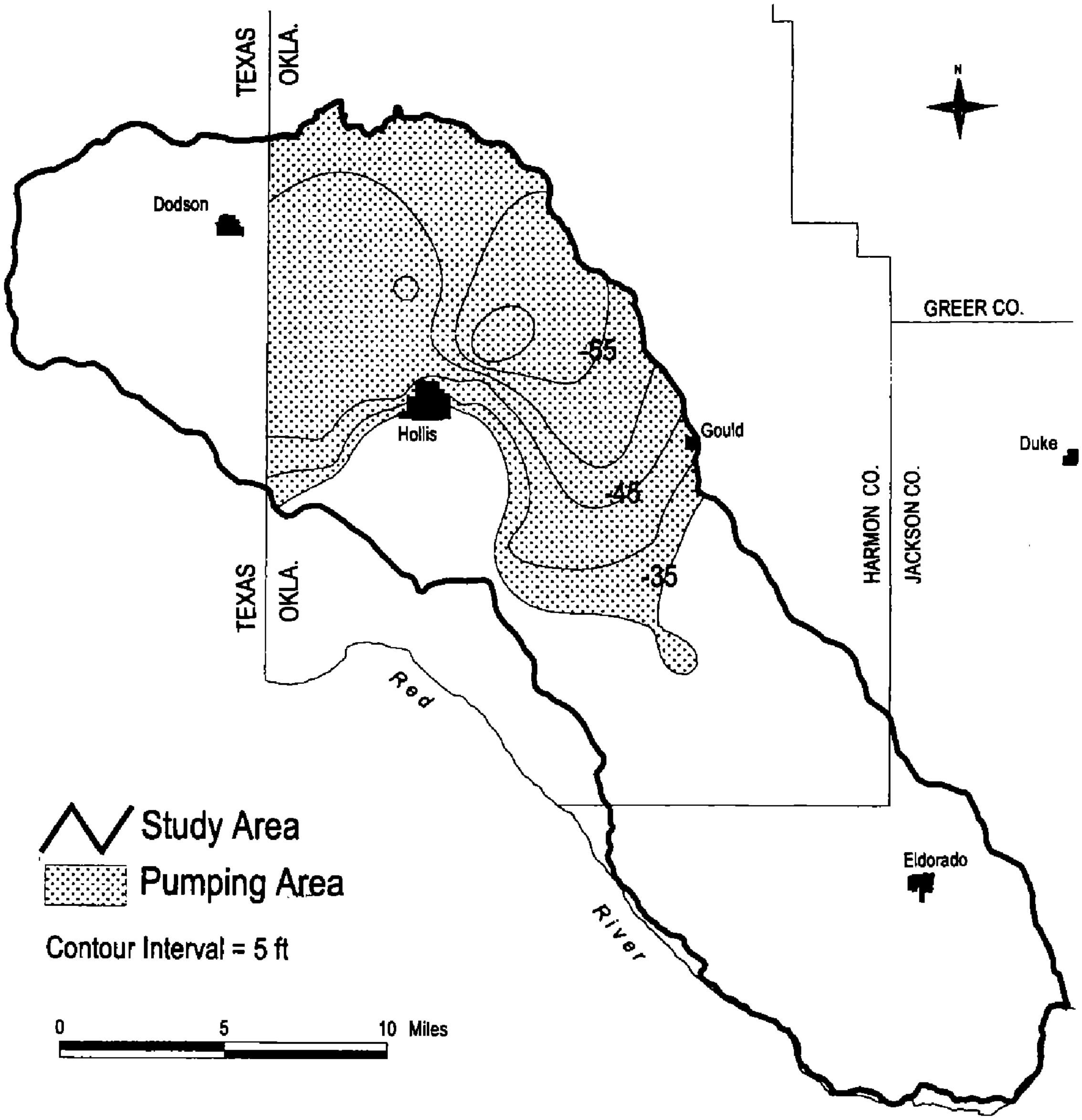



Figure 11. Map showing the irrigation pumping center (shaded), defined as the area in which the water level declined by >35 ft between May and August 1994 (Fig. 8).

quality was monitored for one year before the recharge wells began operation; monitoring continued after the wells began operation, to determine post-recharge conditions.

Samples were collected during three sampling periods each year: April 1–June 15; June 16–August 31; and September 1–November 15. These periods were selected because precipitation is greatest from April through October, the growing season for cotton is April to September, and pesticides are applied between April and September. Samples were not collected during the winter months when little agricultural activity or recharge occurs.

For baseline monitoring, ground-water samples were collected during the three sampling periods of 1992 from the upgradient monitoring well at each site. Post-recharge monitoring included sampling of injectate (recharge water) and ground water at upgradient and downgradient monitoring wells.

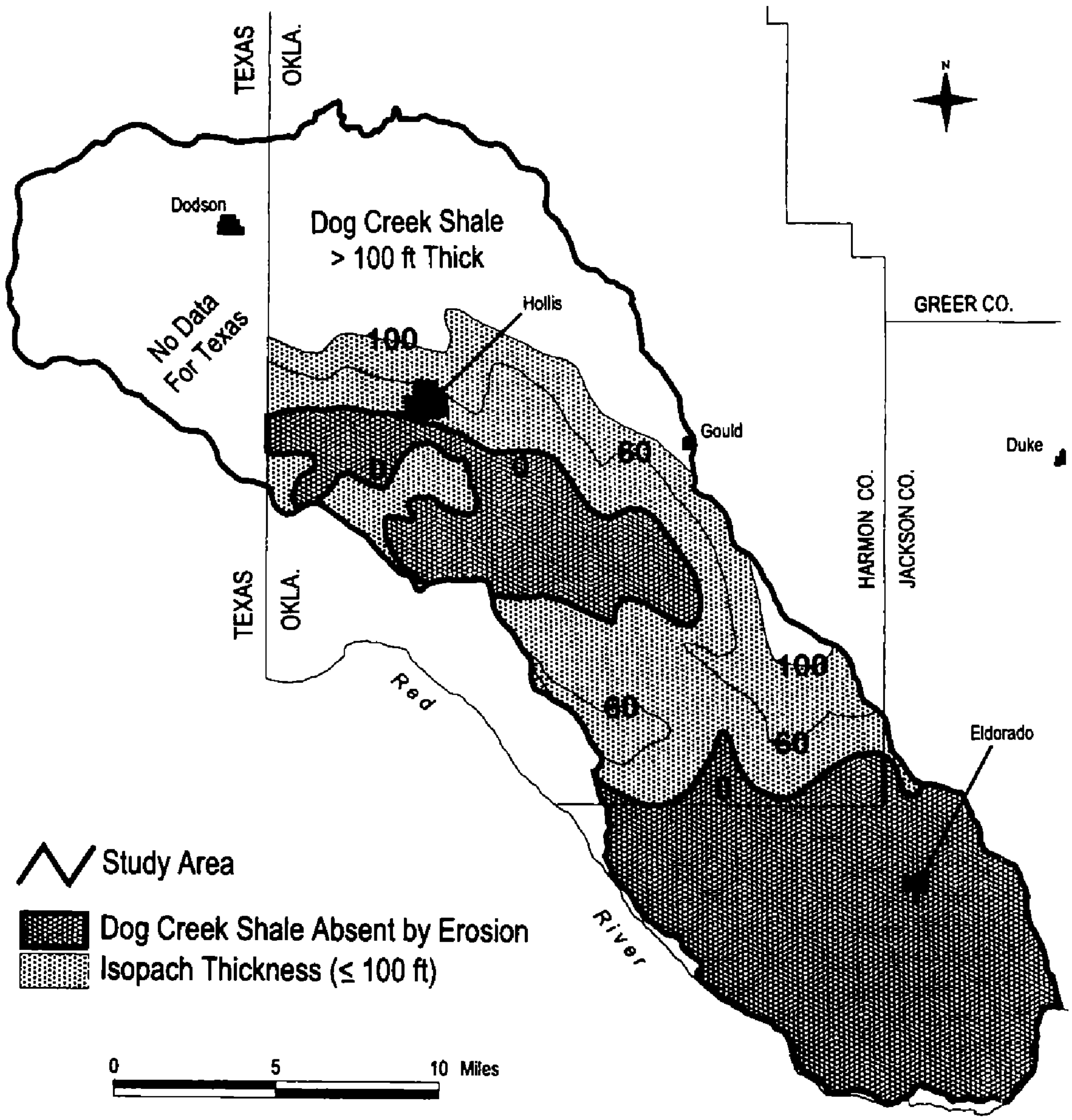



Figure 12. Isopach map of the Dog Creek Shale where the formation is ≤100 ft thick (modified from K. S. Johnson [Oklahoma Geological Survey], unpublished map of the thickness of the Dog Creek Shale in southwestern Oklahoma).

An automatic sampling unit was programmed to collect an injectate sample from the inlet pipe at each recharge well at the first recharge event during each of the three sampling periods. Injectate samples were not collected for sampling periods when no recharge event occurred. The number of injectate samples collected varied from site to site depending on equipment problems, number of recharge events, and resampling when contaminants were identified.

Ground-water samples were collected from all of the water-quality monitoring wells at a site within seven days of an injectate sample being collected in the associated recharge well. If, during a sampling period, a recharge event did not occur at a site, or if the recharge well was not in operation due to equipment problems, the upgradient monitoring well at the site was sampled by the end of the sampling period.

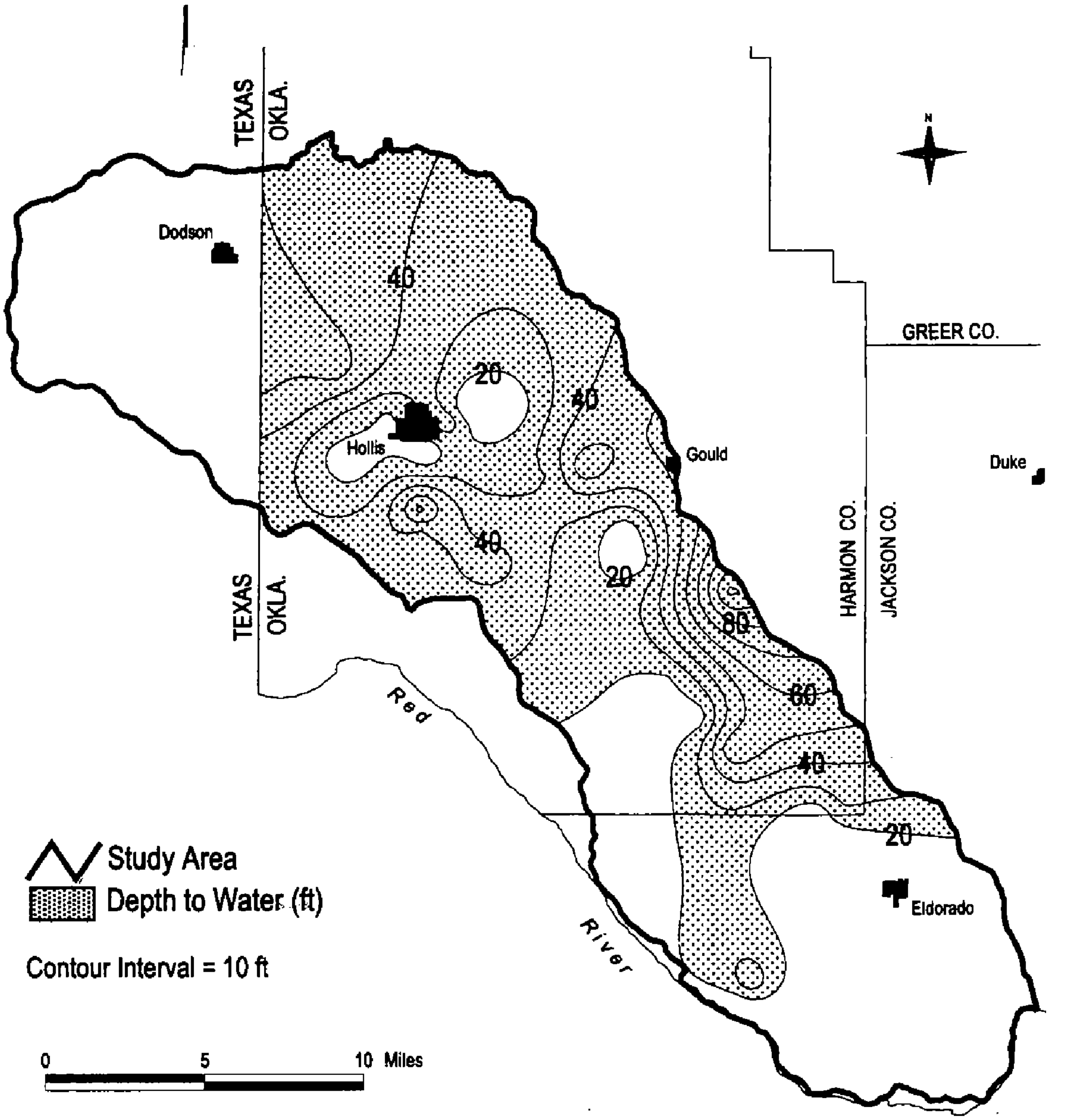



Figure 13. Map of the depth to water in the Blaine aquifer in the study area (constructed from water-level measurements made in February 1994), showing where the depth to water is ≥20 ft from the land surface.

All water-quality samples were analyzed for common ions, trace elements, organic compounds, and pesticides. Samples were analyzed for specific pesticides used in the study area: trifluralin, pendimethalin, ethephon, aldicarb, and methyl parathion. Injectate samples also were analyzed for cyanide.

*Ambient Quality*

The ambient quality of the Blaine aquifer is poor for drinking water but is suitable for irrigation water. It has high concentrations of total dissolved solids, sulfate, and other ions. The aquifer is generally a calcium-sulfate to sodium-sulfate type water, reflecting dissolution of gypsum and dolomite in the Blaine Formation. The highly mineralized aquifer is a potential source of drinking water, as defined by the EPA, but is not currently used as a drinking-water supply.

TABLE 1.— GENERAL WATER QUALITY OF GROUND WATER AND SURFACE WATER IN THE STUDY AREA

| | BLAINE AQUIFER[a] $n^c=10$ | | SANDY CREEK[b] $n=7$ | | RED RIVER[b] $n=4$ | |
|---|---|---|---|---|---|---|
| | Range | Median | Range | Median | Range | Median |
| Ca (mg/L) | 470–728 | 580 | 160–800 | 690 | 710–1,000 | 810 |
| Mg (mg/L) | <1–185 | 141 | 150–1,300 | 170 | 170–250 | 215 |
| $SO_4$ (mg/L) | 1,470–2,037 | 1,817 | 2,000–2,400 | 2,000 | 2,500–3,600 | 2,900 |
| Cl (mg/L) | 110–2,625 | 306 | 2,400–3,800 | 2,600 | 7,800–12,000 | 8,550 |
| TDS[d] (mg/L) | 2,941–35,630[e] | 3,636 | 7,250–9,450 | 7,740 | 1,640–22,900 | 19,675 |

[a]Blaine aquifer samples include two sample sets collected by the USGS and the OWRB in 1987.

[b]Samples from Sandy Creek and the Red River were collected by the USGS during low-flow periods between 1986 and 1988 (Runkle and others, 1997).

[c]n = number of samples analyzed. Note: Samples for common ions had cation/anion balances of ±10%. Because TDS is independent of the cation/anion balance, a greater number of samples was used to analyze TDS.

[d]TDS = total dissolved solids.

[e]TDS was determined from 16 samples; some of the additional samples had higher ion concentrations than the 10 samples with cation/anion balances of ±10%.

Table 1 summarizes the general water quality of the ground water and surface water in the study area. In water collected from the Blaine aquifer, the concentration of total dissolved solids (TDS), which is an indicator of water quality, is 2,941–35,630 mg/L. Leakage from the underlying Flowerpot Shale, which locally contains gypsum and some bedded or disseminated salt (halite, NaCl) and is high in TDS, may increase the TDS of the aquifer in some areas. The concentration of sulfate in water from the Blaine aquifer is 1,470–2,037 mg/L. These concentrations of TDS and sulfate in the Blaine aquifer are well above the secondary maximum contaminant levels of 500 mg/L and 250 mg/L, for TDS and sulfate, respectively.

The waters of Sandy Creek and the Red River also are highly mineralized, which reflects discharge of the mineralized ground water. The concentration of TDS in water from Sandy Creek is 7,250–9,450 mg/L, and the concentration in water from the Red River is 1,640–22,900 mg/L. The concentration of chloride in water from the Red River (7,800–12,000 mg/L) is higher than in water from the Blaine aquifer or from Sandy Creek. The source of the chloride in the Red River is natural-brine springs located upstream in Texas (Johnson, 1990a).

### *Impacts from Recharge*

The general water quality of the aquifer appears to improve after recharge. Statistical analysis of TDS, total suspended solids (TSS), and common ions in water

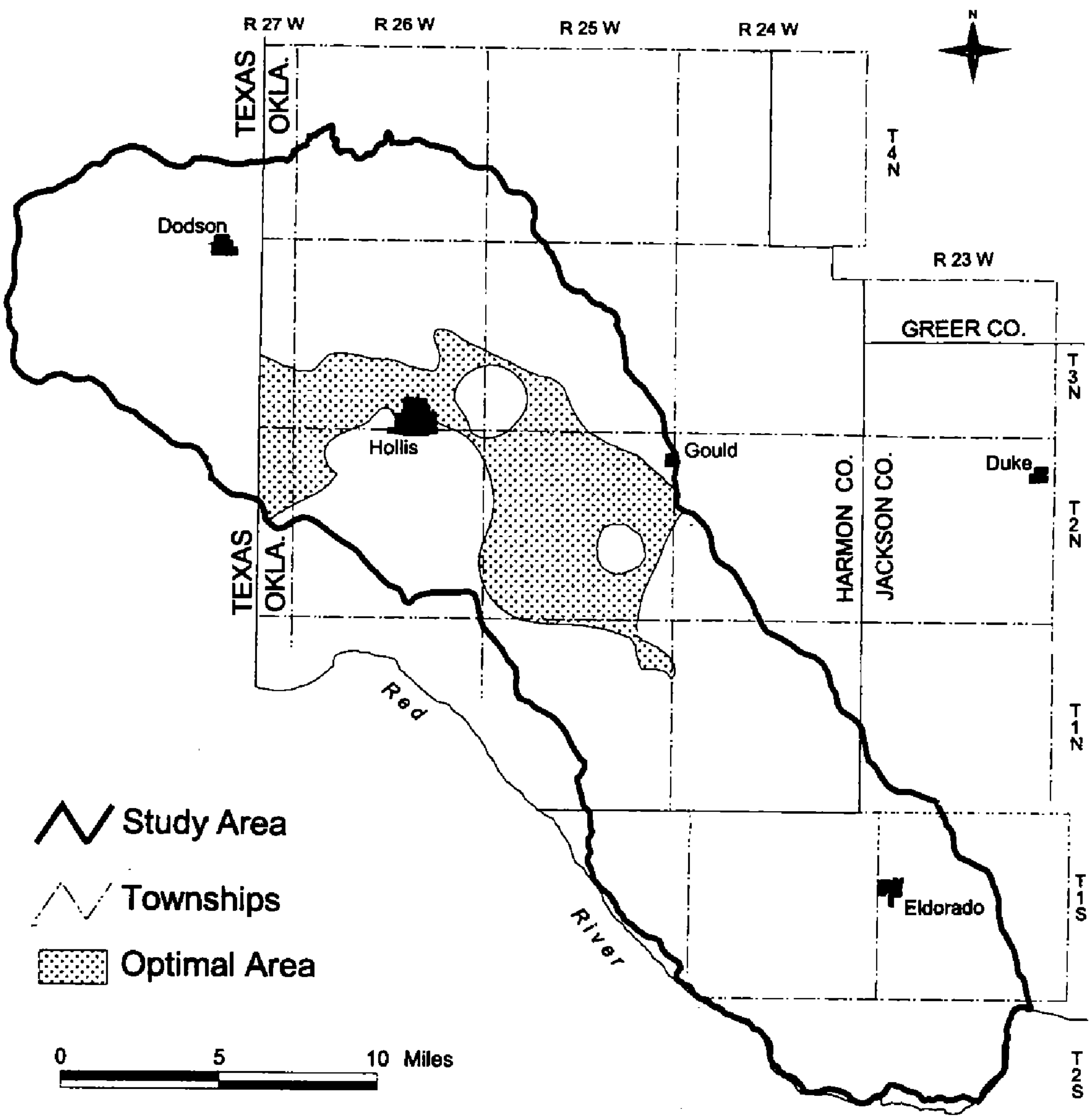



Figure 14. Map of the study area showing the optimal area (shaded) for installation of new recharge wells. The shaded area on this map represents the overlap of the shaded areas shown in Figures 11–13.

samples from the monitoring wells at the five recharge sites indicates that concentrations of most parameters either decreased after recharge or did not significantly change. TDS decreased at all five recharge sites, by as much as 1,000 mg/L. The decrease in TDS was statistically significant at four of the sites.

A decrease in nitrate occurred at all five sites, but was statistically significant only at two sites. A few parameters (TSS, phosphorus, calcium, and potassium) increased after recharge at some sites. The increase of phosphorus at four sites may have been due to adsorption to suspended solids.

Because most of the post-recharge samples were collected within seven days of a recharge event, these changes reflect short-term dilution effects on the aquifer and do not necessarily reflect long-term effects. As fresh recharge water is introduced into the mineralized ground water, gypsum and dolomite dissolve slowly, causing calcium, magnesium, and sulfate concentrations to increase until the water becomes saturated with respect to gypsum and dolomite, and returns to equilibrium.

Several trace elements exceeded their maximum contaminant level (MCL) in ground water and injectate samples. Samples with the highest concentrations of trace elements also had high TSS, which suggests that the elements were bound to suspended clay particles and were not mobile in water.

Low levels of pesticides were occasionally detected in injectate and in ground water. The most commonly found herbicides were trifluralin and pendimethalin, which are used for preemergent control of grass and weeds. Concentrations of both herbicides were below regulatory levels. Methyl parathion, an organophosphorus insecticide, was detected twice (in a single ground-water sample from each of two wells).

Low levels of volatile organic compounds (VOCs) were also detected occasionally. Toluene, xylene, 1,2,4-trimethylbenzene, 1,1,1-trichloroethane, and chloroform were detected in a few ground-water and injectate samples. Concentrations were significantly below the MCLs.

Cyanide, from unidentified sources, was detected in some samples. Cyanide concentrations exceeded the MCL once in the baseline ground-water samples and twice in post-recharge injectate samples. Discrepancies in concentrations from duplicate samples suggest laboratory error is the cause for some results.

In summary, no harmful effects of the project on the quality of the Blaine aquifer were detected. Although low levels of pesticides and VOCs were occasionally detected in ground water, they did not persist over time. A positive impact of the recharge operations was the short-term improvement of water quality of the aquifer as fresh recharge water diluted the highly mineralized ground water.

### Economic Feasibility

Using gravity-flow recharge wells to augment ground-water supplies is very cost effective, largely because water treatment is not required. Therefore, operation and maintenance costs are very low. The average annual cost of recharge (including the cost of construction, operation, and maintenance) is $2,899 per well, over an expected 20-year life for the wells. The estimated average annual recharge volume per well is 70 acre-ft, resulting in an average cost of $42.50 per acre-ft of water recharged.

Assuming 100% recovery of the recharged water for irrigation purposes, 70 acre-ft of water will result in $11,980 of irrigated cotton production, based on the 1995 market value of cotton (Oklahoma Agricultural Statistics Service, 1995). Based on these assumptions, the value of irrigation water is $171.14 per acre-ft of water pumped. Thus, the benefit-to-cost ratio for the use of gravity-flow recharge wells is greater than four to one.

Additional consideration of pumping, fertilizers, and other farming costs would reduce the value of the irrigation water. However, it is clear from the comparison of the cost of recharge to the value of irrigation water that it is economically beneficial to use gravity-flow recharge wells for storing water for irrigation use.

## Conclusions

The Blaine Gypsum Groundwater Demonstration Project was an operational success. It demonstrated the feasibility and effectiveness of using gravity-flow wells to recharge surface runoff water into the Blaine aquifer. The project met its specific objectives.

1. The volume of water artificially recharged to the Blaine aquifer during this project was estimated to be 1,056 acre-ft, or, an average annual recharge volume per well of 70 acre-ft.

2. Water quality in the Blaine aquifer was monitored throughout the project, and no harmful effects were detected. Although, occasionally, low levels of pesticides and VOCs were detected in ground water, they did not persist over time. A positive impact of the recharge operations was the short-term improvement of the water quality of the aquifer, as fresh recharge water diluted the highly mineralized ground water.

3. The project demonstrated that artificial recharge using gravity-flow recharge wells in the Blaine aquifer is economically feasible, with a benefit-to-cost ratio of greater than four to one. Operation and maintenance costs were very low, largely because water treatment was not required.

4. The project advanced the state-of-the-art technology in artificial recharge through development and implementation of new design features for recharge wells, as well as through its operational success.

In conclusion, artificial recharge to the Blaine aquifer provides an effective method in offsetting seasonal and long-term declines in water level. Recharge wells augment ground-water supplies in an aquifer that is heavily pumped for irrigation. In times of drought, this management technique could help prevent wells from going dry or from deteriorating in water quality through induced infiltration of salt water from underlying formations. Recharge wells capture surface runoff that otherwise would leave the area and eventually flow into the Red River.

## Acknowledgments

We would like to extend thanks to the Southwest Water and Soil Conservation District and to individuals in Harmon, Jackson, and Greer Counties who have provided information and permitted access to their land. We thank Jamie Schlottmann Norvell (USGS) for her assistance with the statistical analysis of the water quality data. Also, thanks to Kenneth S. Johnson (Oklahoma Geological Survey) for his technical assistance regarding information on the Blaine Formation. We would like to acknowledge the assistance of OWRB staff Mark Belden, Henry Elling, Kim Sullivan, and Kent Wilkins. We are especially grateful to Mike Sughru for his assistance with the geographic information system analysis and displays.

This manuscript is published with the understanding that the United States Government is authorized to reproduce and distribute reprints for governmental purposes. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either express or implied, of the U.S. Government. Research was supported by the U.S. Department of the Interior, Bureau of Reclamation, under Bureau Cooperative Agreement O-FC-60-01170.

## References Cited

Driscoll, F. G., 1986, Groundwater and wells (second edition): Johnson Filtration Systems, Inc., St. Paul, Minnesota, 1089 p.

ESRI (Environmental Systems Research Institute, Inc.), 1997, ARC/INFO version 7.1.1: Redlands, California.
Janna, W. S., 1993, Introduction to fluid mechanics: PWS Publishing Co., Boston, Massachusetts, 786 p.
Johnson, K. S., 1990a, Hydrogeology and karst of the Blaine gypsum-dolomite aquifer, southwestern Oklahoma: Oklahoma Geological Survey Special Publication 90-5, 31 p.
_____1990b, Standard outcrop section of the Blaine Formation and associated strata in southwestern Oklahoma: Oklahoma Geology Notes, v. 50, p. 144–168.
NOAA (National Oceanic and Atmospheric Administration), 1992–1996, Climatological data, annual summary, Oklahoma 1992–1996.
Oklahoma Agricultural Statistics Service, 1995, Oklahoma agricultural statistics, 1995, 104 p.
Osborn, N. I.; and Eckenstein, Edward, 1997, Blaine gypsum groundwater recharge demonstration project data report: Oklahoma Water Resources Board Technical Report 97-4, 310 p.
Osborn, N. I.; Eckenstein, Edward; and Fabian, R. S., 1997, Demonstration and evaluation of artificial recharge to the Blaine aquifer in southwestern Oklahoma: Oklahoma Water Resources Board Technical Report 97-5, 136 p.
Runkle, D. L.; and McLean, J. S., 1995, Steady-state simulation of ground-water flow in the Blaine aquifer, southwestern Oklahoma and northwestern Texas: U.S. Geological Survey Open-File Report 94-387, 92 p., 1 diskette.
Runkle, D. L.; Bergman, D. L.; and Fabian, R. S., 1997, Hydrogeologic data for the Blaine aquifer and associated units in southwestern Oklahoma and northwestern Texas: U.S. Geological Survey Open-File Report 95-50, 213 p.
Steele, C. E.; and Barclay, J. E., 1965, Ground-water resources of Harmon County and adjacent parts of Greer and Jackson Counties, Oklahoma: Oklahoma Water Resources Board Bulletin 29, 96 p.
USDA (United States Department of Agriculture, Natural Resources Conservation Service Division), 1989, Engineering field handbook, chapter 2: Estimating runoff and peak discharges, p. 2-1–2-91.

**GUIDEBOOK 31.** ***Geology of the Hartshorne Formation, Arkoma Basin, Oklahoma,*** by Neil H. Suneson. 73 pages. Price: $6.

This guidebook and its companion volume, the special publication described below (SP 98-7), are outgrowths of two well-received OGS programs: detailed geologic mapping in the Arkoma basin and Ouachita Mountains (COGEOMAP and STATEMAP programs), and the fluvial-dominated deltaic (FDD) oil reservoir project. STATEMAP and COGEOMAP in southeastern Oklahoma consisted of new geologic mapping at a scale of 1:24,000 with an emphasis on resource (gas, coal, limestone, sand and gravel) and environmental (waste-disposal siting, abandoned coal mines) issues. The FDD project, funded partly by the U.S. Department of Energy, was designed to identify and analyze all FDD light-oil reservoirs in Oklahoma and "to implement an information- and technology-transfer program to help the operators of FDD reservoirs learn how to increase oil recovery and sustain the life expectancy of existing wells." Eight plays were studied and the results were presented in a series of workshops held in 1995–97.

Prepared for a two-day field trip first held by the OGS in fall 1998, the guidebook describes 19 outcrops of the Hartshorne Formation throughout the Arkoma basin. Most of the strata are delta-front deposits, but others are pebble conglomerates eroded off the Ouachita Mountains, incised channel-fill deposits, and delta-front coals and crevasse-splay sandstones. It focuses on the depositional environment of the Hartshorne Formation and relating outcrops to electric-log signatures. It also contains a historical review of Hartshorne nomenclature, distribution, petrology and chemistry, provenance, and resources. Guidebook author Neil H. Suneson was also the leader of the field trip.

This publication is also a companion volume to two recently published OGS guidebooks: *Stratigraphy and Resources of the Krebs Group (Desmoinesian), South-Central Arkoma Basin, Oklahoma* (Guidebook 30), and *Geology and Resources of the Eastern Ouachita Mountains Frontal Belt and Southeastern Arkoma Basin, Oklahoma* (Guidebook 29).

**SPECIAL PUBLICATION 98-7.** ***The Hartshorne Play in Southeastern Oklahoma: Regional and Detailed Sandstone Reservoir Analysis and Coalbed-Methane Resources,*** by Richard D. Andrews, Brian J. Cardott, and Taylor Storm. 90 pages, 6 full-color plates. Price: $12.

Produced for a one-day workshop held by the OGS in fall 1998, OGS SP 98-7 focuses in detail on the natural gas and coalbed-methane resources of the Hartshorne play in Oklahoma. The Hartshorne Formation was chosen as the topic for the workshop and a related two-day field trip (see the description for Guidebook 31 above) because it is one of the most important gas-producing horizons in the Arkoma basin of southeastern Oklahoma.

The first and largest section of the publication, by OGS petroleum geologist Richard Andrews, provides an overview of the Hartshorne play with an Oklahoma emphasis. It covers stratigraphy, regional cross sections, structure, a depositional model, regional Hartshorne mapping, and includes in-depth studies of the Cabaniss NW and Kiowa NW fields.

The second section, by Brian Cardott, OGS coal geologist, describes the role of coal as a gas-source rock and reservoir for methane in the Hartshorne Formation of Oklahoma. This section discusses the composition of gas from the Hartshorne coal, coalbed-methane resources, Hartshorne coal chemistry, and fracture (cleat) patterns in Oklahoma coal. It also reports the findings of a study of Hartshorne coalbed methane in the Spiro SE gas field.

The third section, by Taylor Storm of West Virginia University, provides an overview of the Hartshorne Formation in Arkansas, where interest in gas production has been stimulated by a recent change in field-spacing rules to allow 40-acre production units.

The publication also includes a glossary of terms and a set of core descriptions, well logs, and digital images of select rock intervals from two gas wells in Oklahoma.

The Hartshorne workshop and field trip have been offered by the OGS in cooperation with the Southern Midcontinent Petroleum Technology Transfer Council (PTTC). They are part of a continuing series that provides information and technical assistance to Oklahoma's oil and gas operators.

**SPECIAL PUBLICATION 98-4.** ***Oklahoma Resources for Economic Development***, edited by Hans-Joachim Späth, Gary L. Thompson, and Henry Eisenhart. 265 pages. Price: $12.

Within the brief span of a century, Oklahomans have created and sustained a diverse economy and a supportive human-resource base that have generated a positive image of the State nationally. This volume, conceived and coordinated by members of the University of Oklahoma's Department of Geography, takes a look at Oklahoma's accomplishments in its first century of statehood and its possibilities for the next century.

Compiled to provide basic information for planning in both private industry and State government, the publication profiles the State's assets at the close of the 1980s and the beginning of the 1990s. Its 15 chapters were written by experts in a wide range of disciplines, and cover the following areas: natural environment, population, energy, water, wheat farming, transportation and communication, education, recreation, health care, forests and minerals, utilities and industries, environmental regulation, finance industries, the fine arts, and the cities and the land.

Editor Hans-Joachim Späth is a professor of geography at the University of Oklahoma. Gary L. Thompson is the former chair of the OU Department of Geography. Henry Eisenhart is professor and chair of the Department of Recreation and Leisure Studies at Georgia Southern University.

OGS **Guidebook 31**, **SP 98-7**, and **SP 98-4** can be purchased by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; fax 405-325-7069. To mail order, add 20% to the cost for postage, with a minimum of $1 per order. All OGS publications are sold over the counter at the OGS Publication Sales Office, 1218-B W. Rock Creek Road, Norman; phone (405) 360-2886, fax 405-366-2882.

# OGS TEACHERS' COLLECTION EXPANDS

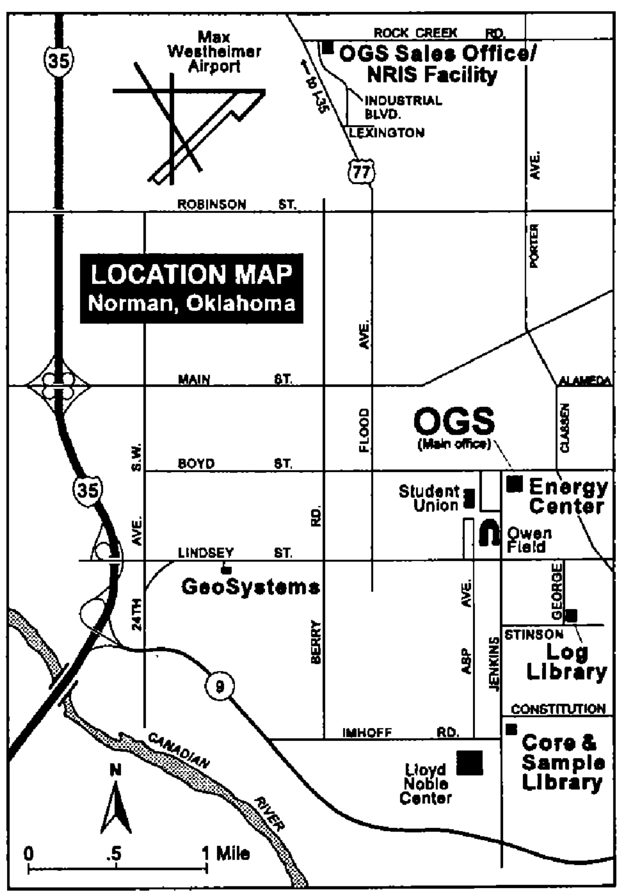
The Oklahoma Geological Survey houses a valuable resource for the State's earth science teachers—the "Teachers' Collection Room" in the OGS Core and Sample Library in Norman (see map below). One of the Survey's most-used facilities, this room contains more than 100 bins and boxes of rocks, minerals, and fossils, most of which are from Oklahoma. The specimens are very useful as teaching aids and are available, free, to Oklahoma earth-science teachers and educators. Because the cost to mail the specimens to all those who wish to have them is prohibitive, the OGS merely asks that teachers who want specimens visit the Core and Sample Library and help themselves to the samples they want.

Over time, the Teachers' Collection becomes depleted in certain specimens, particularly fossils. Recently, Mr. Granville Morgan, a long-time member of the Oklahoma Mineral and Gem Society of Oklahoma City, donated hundreds of specimens to replenish the collection. He and his wife, Minnie Lee, an avid mineral collector, have acquired specimens from most of the United States for almost 40 years. Both have a keen interest in introducing their hobby to young people.

Mr. Morgan donated nearly 20 boxes of material to the OGS. Thanks to his generosity, the OGS now has ample supplies of crinoid bulbs, rose rocks, pieces of petrified wood, quartz crystals, and specimens of jasper to give to Oklahoma teachers. It should be noted that this is not the first time Mr. Morgan has acted to benefit earth-science educators. A fossil collection he donated to the OGS last year will be used to build fossil kits for students in grades 1–12 (see *Oklahoma Geology Notes,* v. 58, p. 21).

The OGS welcomes donations from rockhounds and fossil and mineral collectors for the OGS Teachers' Collection. Although the collection focuses on Oklahoma materials, we welcome good specimens of nearly any rock, mineral, or fossil. If you have a large collection and have run out of room to store it, please consider donating it to the OGS. We will be sure it gets into the hands of teachers for their use in exciting Oklahoma schoolchildren about earth science.

—*Neil H. Suneson*




The Oklahoma Geological Survey Core and Sample Library is at 2725 S. Jenkins in Norman, phone (405) 325-4386. It is open from 8 a.m. to noon and 1–5 p.m. on weekdays.

**Waterflood Workshop,** November 19, 1998, Oil and Brine Museum, Smackover, Arkansas. Information: Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 or (800) 330-3996, fax 405-325-7069.

**Interstate Oil and Gas Compact Commission, Annual Meeting,** December 6–8, 1998, Salt Lake City, Utah. Information: Interstate Oil and Gas Compact Commission, P.O. Box 53127, Oklahoma City, OK 73152; (405) 525-3556, fax 405-525-3592; e-mail: iogcc@oklaosf.state.ok.us.

**American Association of Petroleum Geologists, Southwest Section Meeting,** February 28–March 2, 1999, Abilene, Texas. Information: AAPG Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 560-2679, fax 918-560-2684.

**Geological Society of America, South-Central Section, Annual Meeting,** March 15–16, 1999, Lubbock, Texas. *Abstracts due December 15, 1998.* Information: James Barrick, Dept. of Geosciences, Texas Tech University, Lubbock, TX 79409; (806) 742-3107; e-mail: ghjeb@ttu.edu.

## OCGS to Host Layton–Osage Layton Play Workshop

The Oklahoma Geological Survey will cooperate with the Oklahoma City Geological Society to sponsor a half-day workshop, "Fluvial-Dominated Deltaic Oil Reservoirs in Oklahoma: The Layton and Osage-Layton Play," on **December 8** from 1 p.m. to 5 p.m. It will be held at the Home Builders Association of Greater Oklahoma, 625 West Interstate 44 Service Road, Oklahoma City. The cost is $30 for members of the OCGS, $35 for nonmembers. To register, please contact the OCGS reservation lines at (405) 236-8086 or (405) 235-3648, ext. 40. If you have questions regarding the workshop, call Carol Jones at (405) 236-8086, ext. 11.

## *OGS Computer Facility Demonstrations Are "Free-for-All"*

Presentations demonstrating computer access to Oklahoma petroleum data and highlighting the use of that data in various software packages are currently being offered once a month at the OGS NRIS Facility, 1218-B W. Rock Creek Road, Norman, Oklahoma. Held on selected Fridays from 1:30 to 4:30 p.m., each "Friday Free-for-All" provides several informal demonstrations plus a chance for attendees to try out the facility's equipment and software.

The South Midcontinent Region of the Petroleum Technology Transfer Council and the OGS sponsor the program. The University of Oklahoma's Geo Information Systems prepares the demonstrations.

The next Friday Free-for-All is **December 4.** Sessions are free and reservations are not required. Come and go as you please.

*Call the NRIS facility, (405) 360-2886, or GeoSystems, (405) 325-3131, for more information and presentation dates.*

### *Demonstration and Evaluation of Artificial Recharge to the Blaine Aquifer in Southwestern Oklahoma*

The activities and findings of the Blaine Gypsum Groundwater Recharge Demonstration Project are described in this report by N. I. Osborn, E. Eckenstein, and R. S. Fabian. The project's purpose was to demonstrate the feasibility and effectiveness of recharging surface runoff into the cavernous Blaine aquifer with gravity-flow wells. Specific study objectives were to determine: (1) the volume of water artificially recharged to the aquifer, (2) the impact of artificial recharge on the water quality of the aquifer, and (3) the economic feasibility of this method of artificial recharge. The project was conducted in cooperation with the U.S. Bureau of Reclamation, U.S. Geological Survey, U.S. Environmental Protection Agency, and Southwest Water and Soil Conservation District. (See feature article, p. 184, this issue.)

Order Technical Report 97-5 from: Susan Birchfield, Librarian, Oklahoma Water Resources Board, 3800 N. Classen Blvd., Oklahoma City, OK 73118; phone (405) 530-8800. Cost is $15. Also available are an 18-page executive summary (Technical Report 97-5S; cost $3) and a compilation of the hydrologic data collected for the project (Technical Report 97-4; cost $15).

### *Hydrogeology, Water Quality, and Geochemistry of the Rush Springs Aquifer, Western Oklahoma*

The hydrogeology, water quality, and geochemistry of the Rush Springs aquifer in western Oklahoma are described in this 37-page USGS water-resources investigations report by Mark F. Becker and Donna L. Runkle. The project's purpose was to fulfill a legislative mandate for the Oklahoma Water Resources Board (OWRB) to describe the aquifer and to prepare a numerical model on the ground-water flow of the Rush Springs aquifer, an important source of water for irrigation, livestock, industrial, municipal, and domestic use. Agriculture is the primary industry in the study area. Information provided in this report was collected and compiled through a cooperative project of the Oklahoma Geological Survey, OWRB, and the USGS.

Order WRI 98-4081 from: USGS, Water Resources Division, 202 NW 66, Building 7, Oklahoma City, OK 73116, telephone (405) 810-4400, fax (405) 843-7712. A limited number of copies are available free of charge.

### *Steady-State Simulation of Ground-Water Flow in the Rush Springs Aquifer, Western Oklahoma*

A simplified, steady-state model of the ground-water hydrology of the Rush Springs aquifer is presented in this 88-page water-resources investigations report by Mark F. Becker. The report was intended to provide the Oklahoma Water Resources Board (OWRB) with a model that will allow it to determine changes in storage from a transient simulation. Also in the report are the general geologic setting, boundaries, input data to the model, and final model output.

Order WRI 98-4082 from: USGS, Water Resources Division, 202 NW 66, Building 7, Oklahoma City, OK 73116, telephone (405) 810-4400, fax (405) 843-7712. A limited number of copies are available free of charge.

### *Estimated Predevelopment Discharge to Streams from the High Plains Aquifer in Northwestern Oklahoma, Southwestern Kansas, and Northwestern Texas*

Estimates of the amount of water discharged from the High Plains (Ogallala) aquifer prior to large-scale irrigation development are presented in this 28-page USGS water-resources investigations report by Richard R. Luckey and Mark F. Becker. The High Plains aquifer supports a large amount of irrigation in northwestern Oklahoma and is a water source for a rapidly growing swine industry. The estimates cover the Oklahoma Panhandle and the adjacent parts of Kansas and Texas.

Order WRI 97-4287 from: USGS, Water Resources Division, 202 NW 66, Building 7, Oklahoma City, OK 73116, telephone (405) 810-4400, fax (405) 843-7712. A limited number of copies are available free of charge.

### *Ground-Water-Quality Assessment of the Central Oklahoma Aquifer, Oklahoma—Geochemical and Geohydrologic Investigations*

Ground-water samples, core samples, and hydrologic measurements were obtained in the Central Oklahoma Aquifer as part of the pilot National Water-Quality Assessment Program. This USGS water-supply paper examines ground-water recharge and discharge, the potentiometric surface, the chemical and isotopic composition of ground water, and the abundances and textures of minerals in core materials to determine the rates and directions of ground-water flow and the geochemical reactions occurring within the aquifer. D. L. Parkhurst, S. C. Christenson, and G. N. Breit wrote the 101-page report, which supersedes open-file report 92-642.

Order W 2357-C from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone (303) 202-4210. Cost is $7, plus $3.50 per order for handling.

### *Geohydrology and Simulation of Steady-State Flow Conditions in Regional Aquifer Systems in Cretaceous and Older Rocks Underlying Kansas, Nebraska, and Parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming*

Three regional aquifer systems are the basis for describing the geohydrology of bedrock aquifers in the central United States. The Great Plains aquifer system, composed of Lower Cretaceous sandstone, generally contains brackish water; the Western Interior Plains aquifer system of lower Paleozoic rocks contains saline water and is laterally adjacent to the freshwater-bearing Ozark Plateaus aquifer system composed of rocks of the same age. Written by D. C. Signor, J. O. Helgesen, D. G. Jorgensen, and R. B. Leonard, this USGS professional paper contains 105 pages.

Order P 1414-C from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone (303) 202-4210. Cost is $14, plus $3.50 per order for handling.

### *Water-Quality Assessment of the Ozark Plateaus Study Unit, Arkansas, Kansas, Missouri, and Oklahoma; Habitat Data and Characteristics at Selected Sites, 1993–95*

S. R. Femmer is the author of this 44-page USGS open-file report.

Order OF 97-0236 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone (303) 202-4210. Cost is $7.50 for a paper copy or $4 for microfiche, plus $3.50 per order for handling.

The Oklahoma Geological Survey thanks the American Association of Petroleum Geologists and the Geological Society of America for permission to reprint the following abstracts of interest to Oklahoma geologists.

## The Municipal Water Supply of Nichols Hills, Oklahoma: Wellhead Protection Program

*TRISTA S. CUSTER*, 4700 N.W. 40th, Oklahoma City, OK 73122

The Wellhead Protection Program, established in 1986, was designed to protect potable groundwater supplies. For a given well or well-field, compliance with regulations requires the delineation of areas where contaminants are reasonably likely to reach the potable water supply. The City of Nichols Hills, located in northwest Oklahoma City, is currently delineating a wellhead protection area. Nichols Hills obtains water from the Garber-Wellington aquifer that consists of massive cross-bedded sandstone units interbedded with shale, that range in depth from approximately 250–325 meters.

Geologic cross-sections, based on drillers' logs from the municipal water well-field, illustrate the complexity of the aquifer; specifically, flow through the aquifer primarily occurs in discrete layers. Modeling groundwater flow through a complex system, such as the Garber-Wellington aquifer, requires the use of a three-dimensional groundwater model, so that the system can be separated into multiple layers. In such a model, the effects of partially screened wells and vertical fluxes can be considered. The USGS program, MODFLOW, is used to develop a three-dimensional model for the Garber-Wellington aquifer that explicitly considers external stresses, including recharge and evapotranspiration.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 4.

## Magnetic Surveys at the Norman, OK, Landfill Site

*JUDSON L. AHERN*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Several geophysical investigations have been carried out as part of a multidisciplinary and multi-institutional collaborative study of migration of a waste plume at the Norman, OK, landfill research site. Included among these were detailed, total-field magnetic surveys carried out at 3 locations being considered as sites for soil borings. The sites were just south of the toe of the landfill, between the land fill and the Canadian River. At each location, a 20-foot square area was surveyed at a grid spacing of 2 feet using a proton-precession magnetometer with sensor ("bottle") 4.5 feet above the (flat) ground.

The three repeat readings at each station generally agreed to within 1.0 nT, the resolution of the instrument. The central and west sites had significant anomalies, probably due to buried, ferrous waste. These anomalies were marked by large standard deviations—up to hundreds of nT—indicating a strong gradient across sensor and therefore an extremely shallow source. The anomaly at the west site consists of a 1000 nT high

just south of a 500 nT low. A model of this anomaly is consistent with a small drum or similar object with a magnetic susceptibility 0.04 cgs buried at a depth of about 3 feet. The magnetic surveys proved to be an inexpensive means to avoid invading a potentially hazardous object.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 1.

## Soil Magnetic Susceptibility Anomalies at the Norman Landfill: Investigating Their Occurrence and Origin

*MONIKA COGOINI, R. DOUGLAS ELMORE*, and *BODO KATZ*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Previous studies have documented a connection between hydrocarbons and authigenesis of magnetite. Magnetite, therefore, might be expected to form in the methane producing environment of a landfill. In this study we tested whether soil magnetic susceptibility (SMS) could detect methane seepage at the Norman Landfill, Oklahoma.

Several cores extracted from the clay cap of the landfill show high SMS values in the lower part compared with control samples. Rock magnetic and optical observations suggest the addition of magnetite in the cap soil. Gas chromatographic analyses within the lower part of the core indicate that methane is present in the zone of elevated SMS. Methane is produced within the sand layer underneath the cap and is seeping into the cap. Additionally, SMS decreases along transects away from the landfill in the migration direction of a contaminant plume. A decrease in magnetite content with distance from the landfill is consistent with the hypothesis that exposure to hydrocarbons causes changes in SMS. However, the magnetic characteristics and grain size analyses indicate variations of SMS with sediment type. Although the presence of the plume may affect the soils, the preferred interpretation is a grain size control on the magnetic signal.

The results suggest that SMS can be used as a rapid, nearly non-invasive and inexpensive tool for the tracing of methane seepage at and around landfills, if sediment types are not significantly different. Furthermore, the landfill offers an opportunity to study the processes that cause authigenesis of magnetite in a hydrocarbon producing environment.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 3.

## Biogeochemical and Geohydrologic Processes in a Landfill-Impacted Alluvial Aquifer, Norman, Oklahoma

*I. M. COZZARELLI, S. C. CHRISTENSON, J. S. NORVELL, J. E. LUCIUS, R. J. BISDORF, R. P. EGANHOUSE*, and *T. E. REILLY*, U.S. Geological Survey, 202 N.W. 66th St., Oklahoma City, OK 73116; *J. M. SUFLITA, S. K. HARRIS*, and *G. ULRICH*, Dept. of Botany and Microbiology, University of Oklahoma, Norman, OK 73019; and *R. W. PULS*, U.S. Environmental Protection Agency, National Risk Management Research Laboratory, P.O. Box 1198, Ada, OK 74820

The Norman landfill research site is a multidisciplinary and multi-institutional collaborative study of the natural migration of a mixed-waste plume in an area affected by ground-water/surface-water interactions. This site offers a unique opportunity to study the interaction between hydrologic and biogeochemical processes which will result in a unified understanding of the processes controlling contaminant distribution and migration.

A leachate plume has migrated in the direction of ground-water flow at least 300 meters southwest of the landfill and beneath a small freshwater slough. Geophysical and geochemical data show that contaminants have migrated beneath the slough and the plume is spread out throughout the entire 13-meter thickness of the alluvial aquifer. Sharp chemical gradients exist in the alluvial aquifer. Dissolved organic carbon concentrations decrease from 101 mg/L to 33 mg/L over a 20 meter distance in shallow ground water downgradient from the toe of the landfill. Over this same distance dissolved sulfate concentrations vary by 3 orders of magnitude (from <1 mg/L to 483 mg/L).

Controls on the distribution of plume constituents include degradation of the DOC by in situ microorganisms. Laboratory microcosms, incubated with sediments at this location, indicate that sulfate reduction is the dominant terminal electron accepting process. The reduction of sulfate and the cycling of sulfate and iron are important biogeochemical processes that influence aquifer geochemistry downgradient of the landfill mound. The heterogeneous availability of electron acceptors and mixing of the contaminant plume with oxygenated water at the plume boundaries have resulted in significant variations in the chemical character of the water and the aquifer.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 4.

## Seismic Refraction Investigations

*WILFRED B. HASBROUCK, JEFFREY E. LUCIUS*, and *MICHAEL H. POWERS*, U.S. Geological Survey, Box 25046, Federal Center, MS 964, Denver, CO 80225

Seismic refraction data collected on and near the Norman landfill have determined thickness of the alluvium and attitude of the water table beneath the main landfill cell. The seismic refraction technique measures the travel times of seismic waves in the subsurface. The transverse-transverse shear-wave refraction technique was useful in measuring depth to bedrock. Where the seismic refraction data have been collected, the bedrock surface is relatively flat at an elevation of about 320 meters above seal level (approximately 10–12 meters deep). The compression-wave refraction technique is sensitive to the saturated zone and measured the slope of the water table beneath the main cell. The saturated zone forms a mound about six to eight meters high under the main cell. The water table mound slopes about three to four degrees on all sides. The information interpreted from the seismic data supplements the well data and provides data where wells cannot be drilled.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 7.

## Luminescence Dating of Canadian River Sediments at the Norman Landfill Toxics Site, Cleveland County, Okla.

*SHANNON A. MAHAN* and *JOHN WHITNEY*, U.S. Geological Survey, Box 25046, Federal Center, MS 963, Denver, CO 80225

Thermoluminescence and infrared stimulated luminescence dating techniques are being used for geochronological reconstruction of the Quaternary fluvial sediments of the Canadian River system in the vicinity of Norman, Okla. Luminescence dating can be used to obtain burial ages on silt-sized quartz and feldspar. The fluvial sediments were cored, and silt samples for luminescence analyses were collected from eight cores that contained at least several inches of mud layers between the massive sand deposits. Normal sample collection techniques could not be routinely employed, so several experimental procedures were implemented.

Thermoluminescence results indicate a variety of potential complications with the technique at this location. Perhaps due to sample collection or the unusual man-made contaminants that percolated throughout the sediments. However, the infrared stimulated luminescence ages were consistent with stratigraphic relations and with available radiocarbon data on carbonized plant remains. Modern fluvial and eolian samples exhibit only 2 to 5 percent of the infrared stimulated signal observed in the youngest (1 to 2 ka) mud layers, indicating effective resetting of infrared stimulated luminescence during sediment transport. Fifteen samples with ages ranging from 150 to more than 50,000 years provide a framework to estimate timing of geomorphic processes in the evolution of present valley fill, potential for physical erosion and flood recurrence.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 10.

## Seismic Shear Wave Surveys at the Norman Landfill Site

*JORGE HOYOS, ROGER YOUNG*, and *JUDSON AHERN*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The United States Geological Survey has begun an interdisciplinary study to assess concerns about a leachate flow from an old, closed landfill located near the Canadian River in Norman, Oklahoma.

The present geophysical work is part of this study. One goal of the survey is to obtain the depth to the bedrock below the alluvium at the landfill.

Shear waves propagate at slower velocities than P-waves do. Properly oriented sensors do not record surface waves which are noise for this case. A later arrival time for the shear reflection produces a good separation between it and noise that is present in the shear wave record. Additionally P-wave reflections from the bedrock are swamped by surface waves. Therefore the use of an SH-wave survey for this case gives better signal to noise ratio than a P-wave survey does.

Reports by the USGS (Denver and Oklahoma City offices) on previous refraction surveys and on hydrological studies at the landfill allowed a simple velocity/depth model to be established in order to compute synthetic seismograms. These were used to guide the survey design.

Three multifold (4 and 6) reflection lines with lengths 47, 57 and 87 m were collected at the Norman landfill using a 24-channel Geometrics Strataview seismograph, 10 Hz horizontal geophones, and an SH-wave source.

A principal result thus far is the identification of a strong and continuous reflection at a depth of 10–12 m, with a very gentle dip. The identity of this reflector is determined to be the top of the Hennessey Group by tying the seismic sections to a lithology log from a nearby borehole.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 8.

## Geophysical Exploration Strategy at the Norman Landfill

*ROGER A. YOUNG*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019; and *JEFFREY E. LUCIUS*, U.S. Geological Survey, Box 25046, Federal Center, Denver, CO 80225

Geophysical investigation at the Norman Landfill began with EM induction and direct current resistivity surveys of the alluvial aquifer beneath the Landfill mound. These surveys established the presence of a shallow water table contaminated by leachate flowing toward the Canadian River in the uppermost part of the aquifer. These methods also established the areal extent and vertical stratification of the plume.

Ground penetrating radar had been successful in mapping the base of the alluvium a mile upstream (Sun and Young, 1996), but this method proved unable, over a wide range of frequencies, to penetrate to the base of alluvium at the Landfill. This is due to a high conductivity layer .01 to 1 m in thickness that occurs at a depth of 3–6 m.

Seismic shearwave refraction profiles interpreted by delay time methods give consistent depths to the base of the alluvium and show a relatively flat boundary, dipping slightly toward the Canadian River. Seismic shearwave reflection sections show a strong event from the base of the alluvium that coincides with refraction-determined depths. Soil borings show this boundary to be the contact between the alluvium and the underlying Hennessey Group consisting of shales.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 35.

## Imaging Beneath Overthrust Blocks: A Raytracing Study

*ROGER A. YOUNG* and *ZHI-MING LIU*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Seismic raytracing in a simplified overthrust model compares the images possible from the normally used primary reflections and from fault plane reflections, an unconventional mode. Velocities chosen for basement and underlying sediments in the model correspond broadly to those for igneous rocks, clastics, and carbonates of the Anadarko Basin, Oklahoma. Modeling shows that in the presence of a vertical velocity gradient it is possible to generate diving rays that reflect first from the underside of the thrust plane before illuminating sediments beneath the basement block. This fault plane reflection images further under the fault overhang than the primary reflection. It also has reverse moveout that may aid in separating it from other events, and it can have higher amplitude than the primary reflection. This suggests that special acquisition design to record the fault plane reflection may be useful in some cases in imaging beneath an overthrust block.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 35.

## Heat Flow and Thermal History of the Anadarko Basin, Oklahoma

*LARRY S. CARTER*, Marathon Oil Co., 909 ESE Loop 323, Suite 500, Tyler, TX 75713; *SHARI A. KELLEY*, Dept. of Earth and Environmental Sciences, New Mexico Institute of Mining and Technology, Socorro, NM 87801; *DAVID D. BLACKWELL*, Dept. of Geological Sciences, Southern Methodist University, Dallas, TX 75275; and *NANCY D. NAESER*, U.S. Geological Survey, MS 926A, National Center, 12201 Sunrise Valley Dr., Reston, VA 20192

New heat-flow values for seven sites in the Anadarko basin, Oklahoma, were determined using high-precision temperature logs and thermal conductivity measurements from nearly 300 core plugs. Three of the sites are on the northern shelf, three sites are in the deep basin, and one site is in the frontal fault zone of the northern Wichita Mountains. The heat flow decreased from 55 to 64 $mW/m^2$ in the north, and from 39 to 54 $mW/m^2$ in the south, due to a decrease in heat generation in the underlying basement rock toward the south. Lateral lithologic changes in the basin, combined with the change in heat flow across the basin, resulted in an unusual pattern of thermal matu-

rity. The vitrinite reflectance values of the Upper Devonian–Lower Mississippian Woodford formation are highest 30–40 km north-northwest of the deepest part of the basin. The offset in highest reflectance values is due to the contrast in thermal conductivity between the Pennsylvanian "granite wash" section adjacent to the Wichita uplift and the Pennsylvanian shale section to the north. The geothermal gradient in the low-conductivity shale section is elevated relative to the geothermal gradient in the high-conductivity "granite wash" section, thus displacing the highest temperatures to the north of the deepest part of the basin.

Apatite fission-track, vitrinite reflectance, and heat-flow data were used to constrain regional aspects of the burial history of the Anadarko basin. By combining these data sets, we infer that at least 1.5 km of denudation has occurred at two sites in the deep Anadarko basin since the early to middle Cenozoic (40±10 m.y.). The timing of the onset of denudation in the southern Anadarko basin coincides with the period of late Eocene erosion observed in the southern Rocky Mountains and in the northern Great Plains.

Burial history models for two wells from the deep Anadarko basin predict that shales of the Woodford formation passed through the hydrocarbon maturity window by the end of the Permian. The Late Pennsylvanian–Early Permian section in the deep basin moved into the hydrocarbon maturity window during Mesozoic burial of the region. Presently, the depth interval of the main zone of oil maturation (%$R_o$ = 0.7–0.9) is approximately 2800–3800 m in the eastern deep basin and 2200–3000 m in the western deep basin. The greater depth to the top of the oil maturity zone and larger depth range of the zone in the eastern part of the deep basin are due to the lower heat flow associated with more mafic basement toward the east. The burial history model for the northern shelf indicates that the Woodford formation has been in the early oil maturity zone since the Early Permian.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 82, p. 291, February 1998.

## Structure and Exploration Significance of the Precambrian Basement of the Southwestern U.S.

*G. RANDY KELLER* and *KATE MILLER*, Dept. of Geological Sciences, University of Texas at El Paso, El Paso, TX 79968

Exploration efforts need to begin with an understanding of the Precambrian basement. Basement structures often exert considerable influence on younger features and late Proterozoic rocks can even be exploration targets themselves. We have much to learn about the basement of the southwestern U.S. because there are few outcrops and penetrations by drilling are shallow and concentrated in a few areas such as the Central Basin platform. Many seismic reflection lines in the area display reflectivity within the basement which can be readily interpreted. Some of the seismically defined layering in the basement is due to volcanic rocks, but some of it is due to Proterozoic sedimentary rocks and good source rocks of this age are known to exist in the Grand Canyon region. When combined with drilling and seismic data, gravity and magnetic data provide a cost-effective way to look at basement structure. For example gravity data show that the reflective basement beneath the Hardeman basin is most easily interpreted to consist of relatively low density and thus porous rocks. The symmetry of the gravity anomaly crossing this inferred basin, the Wichita uplift and the Anadarko basin suggests the Proterozoic basin is nearly as deep as the 45,000 ft deep Anadarko basin. However, care should be taken to remember that all layered rocks are not sedimentary. For example, a drill hole on the Central Basin platform penetrated 15,000 ft of layered mafic intrusions in the basement. Another area where basement structure is particularly important is along the Ouachita orogenic belt which follows the Paleozoic margin of Paleo North America. Here many subthrust targets are suggested by gravity and deep seismic data because anomalies due to basins along this margin extend far to the south and southeast beneath the known Ouachita thrust front.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 82, p. 526–527, March 1998.

## A Shallow Drilling Solution to a Global Scale Problem

*M. C. GILBERT* and *J. P. HOGAN*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Proposals by the plate reconstruction community suggest that a portion of southern Laurentia was removed in the Late Neoproterozoic/Early Paleozoic and is now found in the Precordillera of Argentina. Currently most of the evidence for this is paleontologic. This connection, if correct, fundamentally limits possible global plate models. Further, two competing views of tectonics of separation exist: clean break or stretched out. A firmer basis on which to make specific connections and decide mode of separation would be to characterize basements of the breakout areas in southern Laurentia and in the Precordillera. Unfortunately, only part of this Laurentian basement is exposed, but, fortunately, much of it is accessible to core holes of 300–2000 m depth. A series of shallow drill holes placed from southern Oklahoma to the Llano region (SOAL Project) would almost track one once coextensive mutual margin of these 2 plate pieces. Sufficient characterization of the basement can yield both detailed timing and tectonics of separation. Further, calibration of crustal geophysical signatures can provide distinctive piercing points critical to the correct reparation of the Argentine block.

Targeted drilling areas utilize Pennsylvanian upthrust tectonics to bring presently enigmatic basement, such as the Tillman Group, within reach of the drill: Wichita Uplift, Muenster Arch, Red River Uplift, Bend Arch.

Reprinted as published in the Geological Society of America *1997 Abstracts with Programs*, v. 29, no. 6, p. A-433.

## The Southern Oklahoma Aulacogen and Mid-Proterozoic AMCG Complexes: Are They Related?

*J. P. HOGAN* and *M. C. GILBERT*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The Cambrian Southern Oklahoma Aulacogen (SOA) and anorthosite-mangerite-charnockite-granite (AMCG) complexes exhibit striking similarities that suggest formation under similar petrogenetic and tectonic environments but under different emplacement environments. Igneous rocks comprising the SOA include: (1) voluminous anorthositic gabbro, (2) aluminous biotite-bearing gabbro, (3) A-type rhyolite/granite (±rapakivi texture), and (4) Fe-, Ti-, and P-rich diabase dikes. Nearly all SOA units have counterparts within AMCG complexes. An exception is the absence of coarse grained massif-type anorthosite with high-Al orthopyroxene megacrysts. This distinction likely reflects crystallization conditions: AMCG complexes form at higher P (middle crust) whereas the SOA is formed in a low-P near-surface setting. At mid-crustal levels assimilation of Al-rich crust may operate more efficiently, and AMCG complexes typically exhibit isotopic evidence supportive of assimilation. Lack of isotopic evidence for significant crustal contamination in SOA igneous rocks, and the near-surface crystallization conditions, suggest these magmas were rapidly transported to the emplacement level, thus inhibiting large scale crustal assimilation.

Petrologic and geophysical evidence support the presence of a large mid-crustal mafic root within the SOA that may be related and have a similar source. We speculate that, if exposed, this mid-crustal mafic complex would be a typical AMCG complex. Conversely, tectono-magmatic provinces similar to the SOA may have overlain mid-Proterozoic AMCG complexes and were subsequently removed by erosion.

Reprinted as published in the Geological Society of America 1998 *Abstracts with Programs*, v. 30, no. 3, p. 8.

## Timing of the Final Breakout of Laurentia

*J. P. HOGAN* and *M. C. GILBERT*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Plate reconstruction models for the Late NeoProterozoic–Early Paleozoic are in a state of flux. Radiometric dating of igneous events, tied to petrologic and tectonic setting, provides one of the best controls on timing, and to some degree position, of plate splitting. Review and interpretation of dating, some new, give a clearer picture of the evolution of the margin of southern Laurentia; particularly the separation of the Argentine Precordillera ('Texas Plateau' of Dalziel). Final breakout of Laurentia from Rodinia/Pannotia started about 600 Ma in SE Canada/NE USA and is well documented in the Sept Iles intrusion (570–564 Ma) and in the Catoctin Greenstone (570 Ma). New dating in the Southern Oklahoma Aulacogen's Wichita Mountains Igneous Province (a continental LIP) shows a concentrated series of strongly bimodal mafic-felsic events at 535–530 Ma. Alkaline magmatism is recorded in southern New Mexico (Florida Mtns.) at 505–500 Ma. Thus, these events show a two- or three-stage breakout with about 30 Ma time steps rather than a continuous plate separation process. If plume-related, this episodicity may indicate a shift in plates relative to plume centers. Younging of rifting from NE around the margin to SW argues for plate rotation.

Reprinted as published in the Geological Society of America 1997 *Abstracts with Programs*, v. 29, no. 6, p. A-432.

## Mapping within the Eastern Wichita Mountains, Oklahoma

*JONATHAN D. PRICE* and *M. CHARLES GILBERT*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

A recently completed EDMAP project of a portion of the Wichita Mountains reveals finer-scale complexities associated with rift environments and uplifted basement blocks. The 1:12,000 scale geologic map of the Mount Scott Area covers Oklahoma township and range coordinates T3N R13W secs. 1–24 and R14W secs. 13–17 and 20–24 on the Mount Scott, Meers, and Quanah Mountain U.S.G.S. 7.5′ quadrangles. This map provides new details of Mount Scott Granite (MSG) pluton emplacement and the nature of linear fractures within the area.

The MSG pluton is a large (55 km × 17 km × 0.5 km) tabular body emplaced at a depth ~2 km into and along the base of the ~coeval Carlton Rhyolite. This study documented that MSG emplacement was immediately preceded by the intrusion of fractionated MSG magma, which gave rise to the Unit B and Medicine Park granites. The emplacement of these paired granites, the MSG and these adjacent, coeval, consanguineous plutons, should be commonplace to rift intrusion. However, these could easily escape observation because of the small exposure area of the fractionated granite plutons. Intrusion produced minor amounts of contact metamorphism. Small, irregularly spaced outcrops of altered rhyolite (Unit F, Davidson metarhyolite) are interpreted to be intrusion-hornfelsed local portions of Carlton Rhyolite. Intrusion did not create a completely uniform contact aureole; some rhyolite in contact with the granites remained unaltered.

Mapping has also resolved the nature of many long (several km) linear fractures and are prevalent within the eastern Wichita Mountains. Commonly, these fractures focus water flow, and therefore erosion, reducing them to crevasses, valleys, and topographical boundaries. Because of their effect on topography, previous workers have attributed fault characteristics to these features. However, most linears within the study area show no evidence of offset or brecciation. Even those linears that roughly follow lithological contacts lack evidence of faulting, but rather show features indicative of magmatic boundaries.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 30.

## Paired Granites—An Example from the Wichita Mountains, Oklahoma

*J. D. PRICE, J. P. HOGAN*, and *M. C. GILBERT*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Recent field and geochemical evidence points to the existence of paired granites, two distinct but consanguineous granite bodies that are emplaced almost simultaneously, within the Cambrian Wichita Igneous Province of southwestern Oklahoma. This paired granite series is comprised of a less evolved parent, the Mount Scott Granite, in contact with a suite of more evolved daughter products, the Medicine Park Suite.

The two members appear to have been emplaced nearly simultaneously adjacent to one another. Xenoliths of the Medicine Park Suite within the Mount Scott Granite imply that portions of the Medicine Park Suite are relatively older than the Mount Scott Granite. However, other contacts between the units may be sharp, but intimate in pieces, or very diffuse and gradations implying both granites were liquid simultaneously.

The less evolved member is the Mount Scott Granite, whose partially crystallized magma rose from a ponded depth of 7–8 km to a depth of 1.5 km to form a widespread sheet (55 km × 17 km × 0.5 km exposed) of compositionally homogeneous porphyritic granite. The homogeneity has puzzled workers as to why such a large mass fails to show any fractionation products, while such products may be observed elsewhere within the Wichita Igneous Province.

The fractionation products are the rocks of the Medicine Park Suite. The suite varies slightly in mineralogical composition, and greatly in texture and composition. However, all appear to be interrelated and are the daughter products of Mount Scott Granite. Assuming Rb to be largely incompatible, chemical data point to the fractionation of orthoclase, plagioclase, and zircon. With increasing Rb, all samples have roughly equivalent K/Rb, nearly identical REE profiles, except for an increasing negative Eu anomaly, and decreasing Zr/Nb. Fractionation processes might include crystal settling at the ponding level, but flow differentiation, combined with variable crust-conduit undercooling within the individual ascent conduits, may best explain the spatial separation of the Medicine Park Suite. The degree of differentiation would vary with differences in conduit size, shape, and thermal pathway.

Paired granites illustrate the complex daughter-parent relationships within evolved systerms producing distinct granites that appear compositionally and temporally unrelated without careful observation of fine-scale variations.

Reprinted as published in the Geological Society of America *1997 Abstracts with Programs*, v. 29, no. 6, p. A-390.

## Permian Drainage Patterns in the Eastern Wichita Mountains: An Integrated Remote Sensing–Geographic Information Systems Study

*CAROL LINN MILLER* and *M. CHARLES GILBERT*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Permian period drainage patterns in the eastern Wichita Mountains can be recognized in the paleo-terrain as younger Permian formations are eroded. Cambrian granites, rhyolites, and gabbros form the bedrock for most of the paleo-drainage. These old drainage courses serve as a test of the ability of the Thematic Mapper sensor to locate and map such features. The modern drainage system is superimposed on the Permian terrain. The location of some Recent streams corresponds to prominent lineaments. Discriminating the paleo-drainage from "younger" superimposed drainage is part of the problem.

The foundation of this study is a subset of a seven band Landsat 5 Thematic Mapper image, Path 28, Row 36, taken on October 10, 1990, which covers most of the Wichita Mountains and the area in the Lawton quadrangle. Raw digital data was employed for all image processing procedures using ERDAS 7.5, ERDAS Imagine 8.2 and 8.3. Red, green, blue composite images of bands 7, 5, and 1, and bands 7, 5, and 2, respectively, were used to create and analyze thematic maps of the geology, streams and lakes, roads, and lineaments using the geographic information system Arc/Info versions 7.0.3 and 7.1.1. Thematic Mapper (TM) band 7 (2.08–2.35 μ) covers the absorption band for carbonate ($CO_3^{-2}$); band 5 (1.55–1.75 μ) includes absorption bands for $OH^-$.

Discrimination of different carbonate formations was improved using bands 7, 5, and 2, rather than bands 7, 5, and 1.

A thematic map of Permian drainage was produced from analysis of 7.5 minute topographic maps, a hand digitized version of a geologic map of the Lawton quadrangle, and by using the analysis and overlay functions of Arc/Info.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 12.

## Origin of the Permian Meers Valley, Wichita Mountains, Southwestern Oklahoma

*R. NOWELL DONOVAN*, Dept. of Geology, Texas Christian University, Fort Worth, TX 76129

The Meers Valley separates the Wichita Mountains and the Slick Hills. The Valley is floored by Pleistocene and Permian sediments that rest on Cambrian ultrabasic rocks. Formation of the valley is linked to differential erosion across the WNW-ESE–trending Meets fault. In the Cambrian this fault helped to define the Southern Oklahoma aulacogen. Subsequently the fault was reactivated in the Pennsylvanian when it facilitated a stratigraphic separation of 7–9,000 feet (down to northeast) between the Slick Hills and Wichita Mountains. Initial drainage and erosion off the Wichitas to the northeast (into the Anadarko basin) removed a thick Lower Paleozoic sedimentary section plus the Carlton Rhyolite Group and the Mount Scott Granite. Definition of the Meers Valley as a subsequent drainage pattern controlled by the fault trace began when ultrabasic rocks beneath the granite were rapidly eroded. The northern front of the Wichita Mountains evolved as a fault line scarp, retreating to the southwest. Permian facies in the valley are compatible with drainage to the ESE. Permian rejuvenation of the Meers fault with a reversed throw is recorded by megaclast breccias on the northern edge of the valley. Extreme aridity in the Permian preserved the land forms of the area.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 82, p. 525, March 1998.

## On Granophyre Fragments and Variations in Siliciclastic Grain Size—A Tectonic Spike of Late Cambrian Age in the Slick Hills of Southwestern Oklahoma

*R. NOWELL DONOVAN, STEVEN J. JUSCZUK, DAVID TRICE,* and *MATTHEW C. WALTERS,* Dept. of Geology, Texas Christian University, Fort Worth, TX 76129

A well-exposed record of the late Cambrian (Franconian) history of the Laurentian craton is preserved in the eastern Slick Hills of southwestern Oklahoma. This area forms part of the Palaeozoic Southern Oklahoma aulacogen, a linear basin that presently trends ESE-WNW, but "originally" trended NNE-SSW and lay a few degrees south of the equator. Initial definition of the aulacogen involved the emplacement of a bimodal suite of both extrusive and intrusive igneous rocks. Following thermal subsidence, a major late Carmbrian (Franconian) transgression was followed by redefinition of the aulacogen as a relatively rapidly subsiding depocenter in which a great thickness of mostly carbonate sedimentary rocks was deposited. The principal stratigraphic units that mark this stage are the late Cambrian Timbered Hills Group and the Cambro-Ordovician Arbuckle Group.

Most siliciclastic detritus in the two Groups is derived from either the late Cambrian Carlton Rhyolite, which forms the local basement, or from a Precambrian cratonic (Laurentian) source. The latter grain population is a mineralogically mature population dominated by monocrystalline quartz grains.

This paper describes a singular *ad hoc* unit in the upper part of the Timbered Hills Group—the "Big Quartz Spike"— that introduces a third potential source of detritus. In particular, grains of highly weathered epizonal granophyre and granite can be matched most closely with acidic intrusives within the aulacogen. If true, this match suggests that active faulting and deep weathering and erosion of the igneous basement of the aulacogen took place prior to the Franconian transgression. This interpretation implies the local removal of as much as 1,200 meters of acidic extrusives.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 5.

## Stratigraphic Sequences as Records of Sealevel Change in the Lower Ordovician Arbuckle Group at Ardmore, Oklahoma

*R. E. WILBORN* and *B. H. WILKINSON,* Dept. of Geological Sciences, University of Michigan, Ann Arbor, MI 48109; and *C. N. DRUMMOND,* Dept. of Geosciences, Indiana-Purdue University, Fort Wayne, IN 46805

Inference of sealevel change from epicratonic carbonate sequences has commonly relied on conjecture that distinctly different scales of stratigraphic variation reflect the influence of high frequency glacio-eustatic and low-frequency tectono-eustatic processes. We have measured and described 2161 lithologic units in one such sequence along I-35 about 10 km north of Ardmore, Oklahoma. This 811 m succession spans an approximately 10 Ma portion of the lower Ordovician Arbuckle Group, and includes a wide variety of distinct lithologies ranging from primarily calcitic intraclastic to oolitic to biogenous grainstones and thrombolitic bioherms, through sandy to silty flaser-bedded ribbon rocks, to increasingly dolomitic and occasionally desiccation-cracked crypt-algal laminates, with rare exposure collapse breccias and minor amounts of terrigenous silt and sand as either disseminated grains and discrete beds occur within shallower peritidal carbonate units.

Statistical assessment of lithologic order indicates a near-total absence of higher-frequency Markov dependence among lithofacies transitions, or for upsection transitions to comprise upward-shallowing lithofacies associations. Assessment of size-ordering indicates a similar absence of higher-frequency order among stratal element thicknesses; at scales of consideration spanning up to several dozens of stratal elements, lithofacies successions in the Ardmore sequence are nearly random, and embody little if any influence of Milankovitch-band sealevel change.

Conversely, compositions and sizes of stratal elements both exhibit a significant longer-term component of statistical nonstationarity manifest as low-frequency variation lithofacies recurrence frequency and thickness; at stratigraphic scales in excess of several dozens of stratal elements, lithofacies successions in the Ardmore sequence may well embody a significant control of low-frequency sealevel change. However, it is very unlikely that amplitude of this change was in excess of several tens of meters over the roughly 10 million years of accumulation represented by this peritidal carbonate sequence.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 2, p. 78.

## Arbuckle Granitoids: An Orogenic or Arc Magmatism Along the Southern Margin of the Proterozoic North American Craton?

*EDWARD G. LIDIAK*, Dept. of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, PA 15260; and *RODGER E. DENISON*, Program in Geosciences, University of Texas at Dallas, Richardson, TX 75083

The midcontinent region of the United States in middle Proterozoic time was the site of widespread anorogenic igneous activity 1,500–1,340 Ma ago. Granitoids in the Arbuckle Mountains of eastern Oklahoma have traditionally been included as part of this extensive anorogenic terrane. However, voluminous granitoids of intermediate composition (granodiorite, tonalite, quartz diorite, quartz monzodiorite) as well as abundant granites in the Arbuckles indicate that these igneous rocks differ from anorogenic granitoids exposed in the St. Francois Mountains, in the Wolf River batholith, and at widespread localities in the midcontinent. Major and trace element compositions of the earlier Arbuckle granitoids (Burch granodiorite, Troy granite, Blue River gneiss) have distinct calc-alkaline chemical signatures. On plots such as $SiO_2$ versus $K_2O$, $SiO_2$ versus FeO + (FeO+MgO), and Y+Nb versus Rb, compositions lie within the fields of orogenic granitoids. Radiogenic isotopic ratios are indicative of magma derivation from crustal reservoirs that are distinct from the anorogenic sources.

The geochemical variations are consistent with a tectonic setting where plate convergence occurred. A preferred tectonic model for the Arbuckles involves initial development of an Andean type magmatic arc along the southern margin of the North American craton 1,400–1,390 Ma ago. Magmatism terminated in the Arbuckles with the emplacement of the geochemically evolved Tishomingo granite at about 1,375 Ma. Further subduction along the craton margin and a possible reversal in arc polarity resulted in the docking of an island arc terrane now preserved in the Llano Uplift as the Big Branch gneiss (1,327–1,304 Ma) and Coal Creek igneous complex (1,292–1,275 Ma) of the Coal Creek domain (Roback et al., 1994; Mosher, 1995). Accretion was followed by collision-related deformation, metamorphism, and granitic igneous activity. An alternative model assigns the Arbuckle granitoids to the anorogenic granite-rhyolite terrane and part of a passive southern margin of Laurentia. Accretionary activity was confined to the Proterozoic rocks of the Llano Uplift and adjacent areas.

Reprinted as published in the Geological Society of America *1997 Abstracts with Programs*, v. 29, no. 6, p. A-433.

## Lead Isotope Ratios of Proterozoic Granitoids, Arbuckle Mountains, Oklahoma

*EDWARD G. LIDIAK*, Dept. of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, PA 15260; and *A. K. SINHA*, Dept. of Geological Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

Geochemical and mineralogical data indicate that the granitoids of the Arbuckle Mountains of eastern Oklahoma were part of a magmatic arc that developed along the southern margin of the Laurentian craton in Mesoproterozoic time. The granitoids display progressive arc maturity with time and range in composition from tonalite, quartz diorite, and granodiorite to quartz monzodiorite and abundant granite. A preferred tectonic model for the Arbuckles involves initial formation of an Andean-type arc accompanied by emplacement of three of the four main lithologic units (Blue River gneiss, Burch granodiorite, Troy granite) along the craton margin 1,400–1,390 Ma ago. Magmatism terminated in the Arbuckles with the emplacement of the geochemically evolved Tishomingo granite at about 1,375 Ma.

Whole rock lead isotope data from all major rock types show a linear pattern in $^{206}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$ diagram with a slope equivalent to a $^{207}Pb/^{206}Pb$ age of ~1,550 Ma. The close similarity between radiometric ages and the low inferred $\mu$ ($^{238}U/^{204}Pb$) suggest that the Arbuckle Mountain granitoids represent derivation of juvenile material from a mantle source. In comparison with other cratonal lead isotope data, the Arbuckle Mountain region is very similar to the Adirondack massif (New York) and the Llano region of Texas but significantly different from the outboard Grenville terranes of the central and southern Appalachians. Continued lead isotope mapping of crustal reservoirs along the southern and eastern margin of North America supports our tectonic interpretation of the accretion of "non-Laurentian" basement rocks to the Laurentian craton during the Grenville orogenesis.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 10.

## Speculations on Disappearance of Paleoproterozoic Cratonic Basement in the Eastern and Southern Midcontinent Region

*W. R. VAN SCHMUS*, Dept. of Geology, University of Kansas, Lawrence, KS 66045

Precambrian basement beneath the eastern and southern midcontinent is either 1470 Ma Eastern Granite–Rhyolite Province (EGRP) or 1370 Ma Southern Granite–Rhyolite Province (SGRP). These were thought to have formed from melting of Paleoproterozoic crust that is southward and eastward extensions of the 1650 to 1600 Ma Central Plains orogen. Recent studies have shown that rhyolite and granite from parts of EGRP and SGRP have Nd TDM ages less than 1550 Ma, indicating derivation from juvenile crust only slightly older than the granite and rhyolite themselves. Thus, a boundary has been defined separating 1470 and 1370 Ga granites and rhyolites having late Paleoproterozoic TDM ages from ones with younger ages (TDM <1550 Ma). The boundary runs NE from SE Oklahoma through SE Missouri, S Illinois, Indiana, SE Michigan and into SW Ontario. Its SW extension is not defined, but is probably close to the NW boundary of the Llano Province. Underlying crust SE of this boundary is Mesoproterozoic, whereas that to the NW is Paleoproterozoic, representing its SE limit in Laurentia. Nd data from Oklahoma NW of the boundary suggest that Paleoproterozoic crust below

SGRP could be younger than 1650 Ma. The nature and origin of ca. 1500 Ma juvenile crust under EGRP and SGRP SE of the boundary is not known, but it is assumed to be Mesoproterozoic accretionary terranes. The sharp nature of the boundary, plus absence of ages between 1600 Ma and 1500 Ma, suggests that it formed as a rifted margin in this interval, perhaps during breakup of a larger late Paleoproterozoic continent. If this is the case, a rift-to-convergence transition must have occurred within 100 my. to juxtapose ca. 1500 Ma juvenile crust against pre-1600 Ma crust under the EGRP. Data for the midcontinent are not easily compatible with post-1500 Ma rifting, but suggest renewal of terrane accretion from ca. 1500 Ma until Grenville collision ca. 1100 Ma.

Reprinted as published in the Geological Society of America 1997 *Abstracts with Programs*, v. 29, no. 6, p. A-432.

## Potential Boundary Stratotype and Horizon for the Lower Ordovician (Ibexian) Cassinian Stage for Southern Laurentia

*JAMES D. LOCH*, Dept. of Earth Sciences, Central Missouri State University, Warrensburg, MO 64093

The Lower Ordovician Cassinian Stage of Flower (1964) is ill defined by present standards, lacking formal statements of boundary stratotype and horizon. Restudy of the trilobites of the Fort Cassin Formation of New York State and Vermont, the basis of Flower's Cassinian concept, by Brett and Westrop (1996) now permits the formal definition of the Cassinian Stage and its correlation across the continent. Unfortunately, the Fort Cassin is bound by unconformities and is unsuitable as a boundary candidate.

Several trilobite species from the Fort Cassin and correlative Catoche Fm in Newfoundland, Canada, have been recovered from conformable sections in the Kindblade Formation (Arbuckle Group) of southern Oklahoma. Within the Kindblade, *Isoteloides peri* and *Petigurus* sp. A of Boyce appear immediately above taxa typical of the underlying Jeffersonian Stage. I suggest that a measured section of the Kindblade along Interstate 35 in the Arbuckle Mountains be selected as the boundary stratotype. Further, the base of the Cassinian should be defined at the lowest occurrence of *Petigurus* sp. A at 210 m (691 ft) above the base of the Kindblade Formation.

The Cassinian and underlying Jeffersonian Stages are applicable only to the southern Laurentian margin due to the geographic restriction of trilobite and, to a lesser extent, conodont taxa southeast of the Transcontinental Arch. These stages are equivalent to, in part, the Tulean and Blackhillsian Stages of Ross et al. (1993, 1997) but lack the trilobites characteristic of Ross' stadial concepts. The notion of globally applicable stadial terms based upon trilobite faunas through this portion of the Lower Ordovician is questionable.

Reprinted as published in the Geological Society of America 1998 *Abstracts with Programs*, v. 30, no. 3, p. 10.

## Paleomagnetic Dating of Fluid Flow Through the Reagan Sandstone

*CARRIE L. KIENENBERGER*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Dating the fluid flow through the Reagan sandstone in the Arbuckle Mountains of Oklahoma can be accomplished by testing for the presence of remagnetization and by looking at when the remagnetization took place. This can be completed by conducting a conglomerate test and a fold test. The conglomerate test showed the Reagan was remagnetized. The age of remagnetization was found to occur during the folding based on results from an incremental fold test. The best groupings of directions was at thirty percent folding and the pole position gives an age of fluid flow in the Pennsylvanian.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 9.

## Glacial-Eustatic Sea Level Curve and Sequence Stratigraphic Analysis of Upper Carboniferous and Lower Permian Strata from the North American Midcontinent

*DARWIN R. BOARDMAN II*, School of Geology, Oklahoma State University, Stillwater, OK 74078; *BRUCE W. WARDLAW*, U.S. Geological Survey, MS 970, National Center, Reston, VA 22092; and *MERLYND K. NESTELL*, Dept. of Geology, University of Texas at Arlington, Arlington, TX 76019

Sequence stratigraphic analysis of outcropping uppermost Carboniferous and Lower Permian Admire, Council Grove Group and Chase strata of the North American Midcontinent strongly suggest a distinctive hierarchy of stratigraphic forcing. Fourth order depositional sequences from the Admire Group represents the latest highstand sequence sets of a composite third order sequence (1–10 m.y.) that includes the majority of Virgilian sequences. These fourth order depositional sequences are comprised of between two and three fifth order depositional sequences (.01–0.1 m.y.) each.

The Council Grove Group comprises one composite third order depositional sequence (1–10 m.y.), and is divisible into nine fourth order depositional sequences (0.1–1 m.y.). Each fourth order depositional sequence contains between two to eight high frequency fifth order depositional cycles (.01–0.1 m.y.) that form the parasequences that stack into the retrogradational transgressive systems tract, and the aggradational to progradational highstand/forced regressive systems tracts. In total, thirty-eight widely correlatable fifth order depositional sequences are present in the Council Grove Group.

The Chase Group comprises one composite third order depositional sequence (1–10 m.y.), and is divisible into five fourth order depositional sequences (0.1–1 m.y.). Each fourth order depositional sequence contains between two to three high frequency fifth order depositional cycles (.01–0.1 m.y.) that form the parasequences that stack into the retrogradational transgressive systems tract, and the aggradational to progradational highstand/forced regressive systems tracts. Only the lower three of the fourth order depositional sequences are included in this study.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 2.

## The Pennsylvanian-Permian Boundary in the Midcontinent, U.S.A.: Some Historical Perspectives

*JAMES R. CHAPLIN*, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019

Placement of the Pennsylvanian-Permian boundary in the stratigraphic section of the Mid-continent U.S.A. has been the subject of controversy for more than 100 years. The boundary placement has vacillated stratigraphically from as low as the top of the Brownville Limestone, upper Wabaunsee Group to as high as the Carlton Limestone Member of the Wellington Formation, spanning an overall stratigraphic thickness of nearly 1,200 feet.

Unnecessary confusion and debate in terms of interbasinal as well as intercontinental correlation efforts have resulted because of some of the following problems and practices:

(1) Lack of agreement among Russian geologists as to what constitutes the Permian in the type area. (2) Chronostratigraphic boundaries were defined at regional disconformities, rather than on paleontological criteria. (3) A general lack of integrated biostratigraphic analyses using lineages of conodonts, fusulinids, ammonoids, etc. (4) Confused taxonomic nomenclature of inflated schwagerinids and their significance to zonal definitions. (5) First appearances of fauna elements differ stratigraphically and geographically. (6) Misidentification of marker beds in terms of stratigraphic position, lithology, and faunal composition has resulted in miscorrelations.

In the final analysis for placement of the Pennsylvanian-Permian boundary the following observations are deserving of consideration: (1) Is there continuous sedimentation across the boundary or is most of geologic time contained within regional hiatuses? (2) Are faunas penecontemporaneous on a global basis? (3) Do significant faunal changeovers occur at major cycle boundaries? (4) Is the boundary represented by a single lithostratigraphic horizon in the rock record? (5) Have objective stratigraphic sections been established in which there is no question as to proper superpositional order? (6) Have taxonomic collections been made from cored intervals where stratigraphic sequence and completeness are maximized to increase the fossil data base for the integration of independently based zonal data?

Hopefully, with these problems and practices in mind, the eventual placement of the boundary will serve as a practical basis for interbasinal as well as intercontinental correlations.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 3.

## Evolution of the Late Triassic Chinle Basin, Western United States

*S. G. LUCAS*, New Mexico Museum of Natural History, Albuquerque, NM 87104; and *A. B. HECKERT*, Dept. of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131

In the western United States, Upper Triassic nonmarine sliciclastic red beds as much as 600 m thick belong to the Chinle Group. These strata are of Late Carnian–Rhaetian age (about 228–208 Ma) and crop out in Wyoming, Idaho, Nevada, Utah, Colorado, Arizona, New Mexico, Oklahoma, and West Texas over an area of about 2.3 million km$^2$. Chinle Group strata were deposited in a single vast depositional basin with a paleoslope down to the N/NW located about 15–30°N of the paleoequator near the western shoreline of Pangea. Source areas of Chinle sediment were primarily to the south and southeast of the basin, especially the rift shoulder of the then opening Gulf of Mexico basin. A volcanic arc west of the Chinle basin was well outboard of the continental margin and had a negligible effect on Chinle sedimentation.

The Chinle Group is an unconformity-bounded tectonosequence that contains two, basinwide intragroup unconformities that reflect significant base level changes within the Chinle depositional basin. The lower two of the three Chinle Group sequences delimited by these unconformities have a similar facies architecture indicative of early aggradation of coarse bedload river systems followed by broad development of muddy floodplains culminated by extensive pedogenesis and landscape stability. The youngest Chinle Group sequence reflects rapid base level rise overprinted by an extreme drying in climate that produced regional eolian deposition. Near the center of the Chinle basin (Four Corners), terminal Chinle wadi, dunal and interdunal deposition may have continued into the Liassic.

Reprinted as published in the Geological Society of America *1997 Abstracts with Programs*, v. 29, no. 2, p. 37.

## Stratigraphic Architecture of Lower Permian, Cyclic Carbonate Reservoirs (Chase Group) in the Mid-Continent USA, Based on Outcrop Studies

*S. J. MAZZULLO*, Dept. of Geology, Wichita State University, Wichita, KS 67260

Seven depositional sequences, each of which consists of two intermediate-order cyclothems, compose outcrops of the Chase Group (Permian, Wolfcampian) in the mid-continent. Principal reservoir analog facies are restricted mainly to the highstand systems tracts of cyclothems. These facies include subtidal lime sands, deposited mainly in downdip distal ramp settings, and peritidal dolo-mudstones deposited farther updip on the ramp. The stratigraphic and depositional architecture of the section was controlled by the interplay among paleobathymetry, glacio-eustasy, and periodic syndepositional tectonism.

Porous lime sands dominate in the lower part of the Chase Group. The forced regressive, unconformity-bounded sequences within which they occur were deposited during relatively high-magnitude eustatic fluctuations that resulted in marine accommodation increases great enough to preclude peritidal deposition. Porous peritidal facies instead dominate in the upper part of the Chase Group. The sequences within which these normal-regressive deposits are present were deposited during lower magnitude eustatic fluctuations and decreased marine accommodation, which allowed for their eventual progradation across the ramp. Complex porosity heterogeneity is evident within individual depositional sequences and component cyclothems, as well as vertically within the Chase Group.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 82, p. 464, March 1998.

## Nuclei of Phosphatic Concretions from Carboniferous Dysoxic and Anoxic Shales of Midcontinent North America

*R. B. DALTON, R. H. MAPES*, and *D. L. KIDDER*, Dept. of Geological Sciences, Ohio University, Athens, OH 45701

The occurrence of phosphatic concretions in Carboniferous Midcontinent anoxic and dysoxic shales is well known; however, little analysis of the concretion contents has been recorded. A suite of 350 concretions from three localities were analyzed after breaking the concretions parallel to the bedding plane. The contents of each concretion were identified using a standard dissecting microscope. Two of the concretion data sets are of Mississippian age (M. Chesterian), one from near Ada, Oklahoma (Caney Fm.–Sand Branch Mb.), and the other from the Fayetteville Fm., near Durham, Arkansas. These units are essentially time-equivalent and are geographically separated by 280 km. The third concretion date set is from the Anna Shale at Tulsa, Oklahoma, which is part of a classic Pennsylvanian age (Desmoinesian) cyclothem. Field observations suggest the Tulsa locality was lower in oxygen than the Durham locality since the Anna Shale contained no observed benthic organisms and the Durham locality contained a low diversity benthic fauna limited to foraminifera and pyritised sponge spicules. Water depths are unknown. Planktonic bivalves such as Caneyella are commonly observed in the shale but are never recorded in the nuclei of the concretions.

The nuclei of the concretions are predominantly coprolites (78%) from unknown organisms. Presumably the fecal material was rich in phosphorus, which provided a microenvironment in the mud that selectively allowed calcium phosphate to be deposited on the nuclei. Contents in the coprolites include: cephalopod mandibles (8.50%), ammonoid shells (9.30%), acanthodian scales and bones (3.88%), bactritoid cephalopods (3.88%), and arthropod fragments (0.78%). Since all the shales that yielded these concretions are interpreted as strongly dysoxic to anoxic, we believe that the coprolites are from organisms that swam or floated in the mid to upper part of the water column. Thus, the fossil debris in the coprolites provides insight into a significant part of the food web that lived in low oxygen marine environments.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 2, p. 12.

## Geoscience Reference Materials for Information Specialists

*D. F. HANSON,* Edwin G. Schwartz Health Sciences Library, Cook Children's Medical Center, 801 Seventh Ave., Fort Worth, TX 76104; and *A. STROUT-DAPAZ,* Mary Couts Burnett Library, Texas Christian University, Fort Worth, TX 76129

Geoscience information occurs in a wide variety of formats, and a thorough research project will employ a variety of reference materials. The usual resources such as encyclopedias, subject bibliographies and indexes (e.g., the *Bibliography and Index of Geology,* and its elecronic counterpart, *GeoRef*), dictionaries (e.g., the *Glossary of Geology*), and directories (e.g., the *Directory of Geoscience Departments*) are all important. Some of the more unusual resources include indexes for geologic field trips (e.g., the *Union List of Geologic Field Trip Guidebooks of North America*) and for state and federal government publications. Geologic map indexes are extremely valuable (e.g., Oklahoma Geological Survey Map GM-21, *Index to Surface Geologic Mapping in Oklahoma through 1976*). Indexes for B.S. and M.S. theses can be just as important as doctoral dissertation indexes (e.g.,the *Bibliography of Geoscience Theses of the United States and Canada*). Resources that provide access to older literature and maps (1700s and 1800s) are sometimes as valuable as access to the current literature. Resources that provide access to electronic data sets such as topographic data, geochemical data, and geophysical data are also important (e.g., the *Digital Atlas of Oklahoma,* U.S. Geological Survey Open-File Report 97-23). Internet access offers a wealth of opportunities for finding and accessing geoscience information (e.g., access to digital geospatial data set collections from the U.S. Geological Survey). For additional assistance in locating literature guides and resources, contact a nearby geoscience librarian or a member of the Geoscience Information Society.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 6–7.

## Oklahoma Geological Survey's (OGS) Statemap Program: 1:100,000 Digital Geologic Maps

*T. WAYNE FURR,* Oklahoma Geological Survey, Norman, OK 73019; *MARK S. GREGORY,* Dept. of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078; and *NEIL H. SUNESON,* Oklahoma Geological Survey, Norman, OK 73019

The OGS has participated in the U.S. Geological Survey's (USGS) STATEMAP Program since its inception in FY93. In FY96, the Watonga and Foss Reservoir quadrangles were mapped to test OGS compilation efforts and digital capabilities. In November 1996, the OGS proposed to map the Oklahoma Panhandle because of increasing transportation-infrastructure needs, numbers of stockyards and meat-processing plants, and to complement ongoing studies of the area by the Oklahoma Water Resources Board and Water Resources Division of the USGS. The new digital geologic maps will form the basis for a new 1:500,000 geologic map of Oklahoma.

OGS procedure for producing the 1:100,000 digital geologic maps is: I.—OGS geologist (1) Conducts library research and compiles all existing modern geologic maps at 1:100,000; (2) Supplements compilation and resolves different geologic maps with air-photo interpretation and/or reconnaissance field checking; (3) Drafts by traditional "pen and ink" methods the geologic data on to a stable 1:100,000 mylar greenline base; (4) Prepares description and correlation of units, symbols, title block, etc. II.—OGS cartographic staff (5) Separates geologic data by scribing methods, assuring edge-match and latitude/longitude registration; (6) Prepares geologic color selections and map-sheet layout; (7) Makes photo-positive of map sheet. III.—GIS specialist (8) Scans geologic map sheet at 400 dots per inch and converts scanned (raster) image to vector polygons; (9) Plots vector data and visually compares with original map sheet to ensure completeness and precision of scanning and data conversion; (10) Creates polygon topology, attributes each polygon twice, and performs a series of quality-control checks; (11) Exports digital base-map data in standard USGS DLG-3 Optional format and imports into Arc/Info 7.0.3; (12) Writes and executes Arc Macro Language to utilize the polygons as part of the geologic map complete with title, legend, text, etc.; (13) Exports digital geologic data in Arc/Info export format (.e00); (14) Places USGS and Arc/Info files on a network server for World Wide Web or file transfer protocol availability.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 3, p. 6.