ASSESSMENT OF THE GEOTHERMAL RESOURCES

OF KANSAS

Volume I - TEXT

Section 3

AS07-79ET27204

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REGIONAL INTERPRETATION OF KANSAS AEROMAGNETIC DATA

by

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INTRODUCTION

The Kansas Geological Survey (KGS) has recently completed a regional aeromagnetic survey of the state. This report documents the aeromagnetic mapping techniques used and presents a qualitative regional interpretation of the magnetic basement. The total intensity magnetic field contour map and some spectrally filtered magnetic maps are used in the interpretation. This study is a compilation and extension of earlier preliminary reports (Yarger, 1979, 1980 and 1981; Yarger et al, 1976, 1977 and 1978; Robertson et al, 1978). It is expected that more detailed studies of some of the larger anomalies, which make use of quantitative modeling and other interpretation schemes, will appear in future reports.

In addition to information presented in this report on basement composition and paleotectonics, the magnetic data should eventually prove useful for a variety of purposes such as petroleum, mineral and geothermal exploration, earthquake hazard evaluation, and other scientific studies. Sedimentary rocks that contain petroleum are essentially nonmagnetic. However, sedimentary rocks are usually underlain by magnetic basement rocks that

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produce magnetic anomalies. Magnetic data are sometimes useful for determining relief on the basement surface that may be directly related to structure favorable for accumulation of gas and oil in overlying sedimentary rocks. Regional aeromagnetic data can be used to estimate the depth to the bottom of the magnetic portion of the crust and thus to map the Curie isotherm surface. Regions of thin magnetic crust are promising areas for geothermal exploration. Recent research has indicated that some continental earthquakes in the U.S. occur near boundaries of large mafic igneous intrusions within the basement (McKeown, 1978). Aeromagnetic data provide an effective tool for locating and defining the boundaries of these mafic bodies.

BACKGROUND

The earth's main magnetic field is approximated fairly well by postulating a strong permanent bar magnet at the center of the earth inclined 11.5° from the geographic north-south axis. However, this explanation is highly unlikely since the temperature at the center is much too hot for any known material to be permanently magnetized. Therefore, different mechanisms that produce a field equivalent to that produced by a bar magnet, a dipole field, have been postulated. The theory best accepted, but not proven, is that of a self exciting hydrodynamic dynamo within the metallic liquid core of the earth which generates a large electric current much like dynamos in commercial power plants do (see for example, Stevenson, 1981).

Near surface crustal rocks, which are cool enough to be permanently magnetized, slightly distort the earth's main field. Measurement of the distortion of the main field yields information on the magnetic source rocks within the crust. The main field strength in the northern mid-latitudes is

typically 50,000 gammas (0.5 Oersted). Magnetic field strengths from crustal sources are typically hundreds of gammas and rarely exceed several thousand gammas so that the distortion of the main field by the magnetic crust is usually less than one or two per cent.

Magnetic methods have had a long and successful history of mapping the earth's crust for both basic and applied scientific objectives. Recent development in the past decade of more sensitive magnetometers capable of absolute measurements and digital recording have opened new vistas for magnetic exploration of the earth. Approximately fifty per cent of the U.S. is covered by available magnetic surveys conducted by federal agencies, states and academic institutions. Additional areas covered by private industry surveys are generally not available in the public domain. Probably less than ten per cent of the existing U.S. coverage is of high enough quality to glean maximum potential information from the data (Hinze, 1976). The specifications used in the Kansas aeromagnetic survey fall in this elite category.

DATA AQUISITION

Measurements of the total intensity of the earth's magnetic field were made with a Geometrics model G-806 proton precession magnetometer modified for airborne use. This instrument has a ± 1 gamma sensitivity and a two second sampling rate (since completion of the regional survey this instrument has been modified to ± 0.25 gamma sensitivity and one second sampling rate). The magnetic sensor, housed in an aerodynamically stabilized "bird", is trailed 30 meters behind the Twin Beech model D-18 aircraft used in flight operation. Other major components of the magnetometer system are a Geometrics model G-704 Data Acquisition System, a Cipher model 70 digital magnetic tape

recorder, a Sperry model RA-227 radar altimeter, an Automax model G-2 35mm camera with a 30 meter film magazine, and a solid state intervalometer designed by KGS personnel. This system digitally records on magnetic tape, at two second intervals, the magnitude of the total magnetic field, time, ground clearance, camera fiducial number and other bookkeeping information. The 35mm camera is triggered by the magnetometer at a rate appropriate for continuous or near-continuous coverage of the flight path. The fiducial number and time are recorded simultaneously on film and magnetic tape for subsequent correlation of flight path coordinates with magnetic field measurements.

Eastern Kansas was flown during the summer of 1975 and summer and fall of 1976. Western Kansas was flown during the summers of 1977, 1978 and 1979. In both eastern and western Kansas the flight lines were approximately 340 kilometers in length and were flown east or west with tie lines, approximately 345 kilometers in length, were flown north or south. The flight lines were spaced 3.2 kilometers (2.0 miles) apart. The tie lines were spaced 32 kilometers apart. In eastern Kansas the airplane was flown at a fixed barometric elevation of 762 meters (2500 feet) above sea level. In western Kansas the flight elevations were 915 meters (3000 feet) above sea level in the eastern portion and 1372 meters (4500 feet) above sea level in the westernmost quarter of the state. U.S. highway 283, which runs north-south through western Kansas was used as a visual landmark signal to the pilot to change elevations while flying the east-west flight line. The ground clearance, which averaged 366 meters (1200 feet), was measured by the radar altimeter and recorded on magnetic tape along with magnetic

measurements. Navigation was accomplished by visual siting along section roads. The northernmost flight line is located 1.6 kilometers (one mile) north of the Kansas-Nebraska border and the southernmost flight line is located 1.6 kilometers south of the Kansas-Oklahoma border. Normally a crew of three, the pilot, navigator and equipment operator, flew in the plane. As a back-up to the flight path camera, the navigator recorded the time the plane passed over predesignated checkpoints spaced along the flight line every 15 to 30 kilometers. During flight a 24 BCD (binary coded decimal) character record was digitally recorded on magnetic tape with a 7 track, 556 bits/inch tape drive.

To avoid excessive magnetic fluctuation due to solar wind disturbance, the magnetic activity k index (Lincoln, 1967) reported from the World Data Center A (NOAA) in Boulder, Colorado was required to be ≤ 3 before flight takeoff. For $k = 4$ or 5 the magnetic field was monitored on the ground for at least one half hour before takeoff. If the noise did not exceed ± 1 gamma the flight went as scheduled. For $k \geq 6$, flight was cancelled.

DATA REDUCTION

After each flight all records on the magnetic tape were edited for obvious noise and illegal characters. The original unedited data were saved on a permanent summary tape. The flight path film was used to identify landmarks spaced 10 to 15 miles apart on 1:125,000 scale county road maps. The longitude and latitude coordinates of landmarks (fiducial points) were digitized on a ± 0.001 inch x, y digitizing table and saved on digital tape. The fiducial coordinates tape was then merged with the magnetic field tape for final assignment of longitude and latitude to all magnetic measurements.

The resulting flight path map is presented in Figure 5-1.

The International Geomagnetic Reference Field (IGRF) 1975 was calculated at each measurement location at the appropriate epoch and subtracted from the total intensity.

The diurnal drift was removed by analysis of the tie line-flight line intersection mismatches of magnetic field values. This procedure, which does not require a recording base station, assumes diurnal drift during flight is a smoothly varying low order polynomial in time. The polynomial coefficients were determined by minimizing magnetic field residuals at flight line-tie line intersections (for further detail see Yarger, et al, 1978). Before least squares adjustment, the intersection residuals were "corrected" by searching for the minimum intersection residual within a 150 meter radius, the estimated uncertainty in the flight path recovery procedure, from the originally calculated intersection location. After 5th order adjustment to tie lines and flight lines the residuals were normally distributed about zero with an RMS of approximately 2.0 gammas. This residual distribution is adequately narrow to permit contouring at contour intervals of 5 gammas and greater.

A master grid for the state was prepared with 0.16 km (0.1 mile) east-west spacing and 3.2 km (2 mile) north-south spacing which is nearly equivalent to the original measurement spacing. The grid was determined by shifting magnetic field values from quasi-straight flight lines to nearby grid lines. The overall grid location was determined by minimizing (in the least squares sense) the difference between grid lines and the flight line coordinates. this procedure, which takes advantage of a regular grid flight line pattern

avoids smoothing that normally occurs when done by the available computer algorithms written primarily for arbitrary spaced data. The master grid, which represents the residual total intensity magnetic field, is useful for machine contouring over a wide range of scales and contouring intervals. It is also useful for most quantitative analyses since the gridding procedure preserved the original integrity of the data. Figure 5-2 presents the aeromagnetic map contoured by a CALCOMP contouring program at an original scale of 1:500,000 and 50 gamma contour interval.

SPECTRAL FILTERING

BACKGROUND

Several spectrally filtered versions of the original contour map (Figure 5-2) are used in this regional interpretation. The purpose of filtering a map is to remove certain unwanted characteristics and to enhance desirable characteristics depending on the interpretation objective. Because of the simple mathematical form most potential field filters have in the spectral domain, it is advisable to transform the original unfiltered map to the spectral domain, apply the filters, then transform the filtered map back to the spatial domain for use in interpretation (Gunn, 1976).

A suite of spectrally filtered magnetic maps has proven useful in this study of Kansas basement composition, paleotectonics, and age terranes. Certain composite filters reveal basement influence on the magnetic field, not readily apparent in the original contour map.

An ordinary contour map, where the contoured variable is a function of spatial coordinates, is said to be in the spatial domain. In Figure 5-2 the magnetic field, $M(x,y)$, is a function of the spatial coordinates x,y . The

units of x,y are in kilometers (or miles). The map, $M(x,y)$, in the spatial domain was transformed into a map, $M(u,v)$, in the spectral domain using the Fast Fourier Transform (FFT) algorithm (Singleton, 1969) where u,v are the orthogonal spectral domain coordinates. The units of u,v are in cycles/kilometer (or cycles/mile). After applying various filter combinations to the map, $M(u,v)$, in the spectral domain, the resulting filtered maps were transformed back to the spatial domain.

Cycles/kilometer refers to magnetic highs and lows per kilometer. The characteristic frequency, $[u^2 + v^2]^{1/2}$, of a positive (or negative) anomaly in $[2 \times \text{anomaly width}]^{-1}$. For example, an anomaly of width one-half kilometer has a characteristic frequency of one cycle/kilometer. For further discussion of spectral filtering see Nettleton (1976).

FILTER APPLICATION

The State was divided into two equal 216x216 grids for input into the FFT program. The grid cell size was approximately 1.6 kilometer on a side. The filtered maps were compiled using a variable black and white density scale instead of the more traditional contour lines. This format was chosen for several reasons. Density maps are considerably more cost efficient and time efficient to produce. Some of the filtered maps have a large dynamic range (i.e., the data range from very large numbers to very small numbers) or have sharp gradients which are difficult to contour. And finally, density maps make it much easier for the reader to see relative magnitudes.

A suite of seven filtered maps, which appear to be useful in enhancing basement features, are presented in Figures 5-3 through 5-9. These represent a subset of a much larger suite of filtered maps originally examined. The

filtered maps were derived from a combination of two or more filters presented in Table 5-1.

Figure 5-3 presents a map reduced to the pole and downward continued to 760 meters above sea level. Reduction to the pole removes the distortion caused by the earth's inclined magnetic field direction (which is approximately 65° from the horizontal in Kansas). This results in a slight migration to the north of anomaly locations and increases, in some cases, anomaly amplitudes. The western half of the map was downward continued to 760 meters above sea level which makes it comparable to the eastern half which was flown at 760 meters above sea level. This operation relates all anomaly magnitudes and gradients to the same base level of 760 meters above sea level. This is not the case for the original contour map in Figure 2 where anomaly magnitudes and gradients are somewhat attenuated in western Kansas relative to eastern Kansas because of the different flight elevations. In the remainder of the text all maps that have been downward continued to the eastern flight elevation of 760 meters above sea level are referred to as "leveled" maps. To summarize, Figure 5-3 is the same as Figure 5-2 except that it has been corrected for the earth's inclined field and for differences in flight elevation.

Figure 5-4 presents an aeromagnetic map reduced to the pole and upward continued to 9 kilometers above sea level. This map emphasizes deep seated long wavelength magnetic sources within the crust.

Figure 5-5 presents an aeromagnetic map reduced to the pole, and downward continued to 850 meters below sea level which corresponds roughly to the average elevation of the Precambrian surface. This map emphasizes magnetic

sources at or near the Precambrian surface.

Figure 5-6 presents an aeromagnetic map reduced to the pole, leveled and high frequency pass filtered. This filter passed all frequencies above 0.8 cycles/kilometer and attenuated lower frequencies. The attenuation function used, which is linear in radial-frequency, was $1.25[u^2 + v^2]^{1/2}$. This map emphasizes anomalies due to magnetic sources at or near the Precambrian surface to a greater extent than does the downward continued map (Figure 5-5). Note that negative amplitudes are not displayed in Figure 5-6. All amplitudes below +5 gammas appear as white. This choice was made to enhance several statewide magnetic trends evident in the original maps displaying the full spectrum of negative and positive amplitudes. There were no significant trends with negative amplitudes that are not also apparent in the positive amplitudes. Negative amplitudes in Figures 5-7 through 5-9 were also suppressed for the same reason.

Figure 5-7 presents an aeromagnetic map reduced to the pole, leveled, high pass filtered and trend pass filtered. This map is the same as Figure 6 except that an additional filter has been applied which passes anomalies trending northeast $\pm 45^\circ$. This map emphasizes anomalies due to magnetic sources at or near the Precambrian surface and also trending northeast $\pm 45^\circ$.

Figure 5-8 is the complement of Figure 5-7 and emphasizes anomalies due to sources at or near the Precambrian surface and also trending northwest $\pm 45^\circ$. Note that the simple addition of Figure 5-8 to Figure 5-7 would yield the original high pass filtered map in Figure 5-6.

Figure 5-9 presents the aeromagnetic map reduced to pole, leveled and the second vertical derivative calculated. This map emphasizes near-vertical

contacts between contrasting magnetization at or near the Precambrian surface.

REGIONAL INTERPRETATION OF AEROMAGNETIC DATA

BACKGROUND

Major variations in total magnetic field strength at or near the land surface are normally due to lateral changes in magnetic susceptibility of basement rock. Overlying sedimentary rocks have relatively low magnetic susceptibilities. Susceptibility is proportional to the amount of magnetite in the rock (Clark, 1966). The amount of magnetite in rock, to a rough approximation, is inversely proportional to silica content. For a given source rock volume and depth of burial, mafic rocks such as gabbro and basalt will produce larger magnetic anomalies than silicic rocks such as granite and rhyolite.

The relative total intensity magnetic map (Figures 5-2 and 5-3) depicts a rather complex crustal magnetization pattern in eastern Kansas. The dynamic range of the total magnetic field is almost 2000 gammas. The contour levels vary from 450 to 2350 gammas with an average value of approximately 1200 gammas. The base level of the map was established by arbitrarily adding 1500 gammas after subtraction of the IGRF from the absolute total intensity. Relative to the IGRF, the magnetic field in Kansas is anomalously low by some 300 gammas. If the IGRF accurately describes the large scale magnetic field intensity in the Midcontinent, then the net magnetization of the crust in Kansas is slightly below average.

DEPTH TO MAGNETIC BASEMENT

Comparison of the magnetic patterns (Figures 5-2 and 5-3) with the Pre-

cambrian relief map (Figure 5-10) reveals little obvious correlation. The Humboldt Fault, which has in some places over 600 meters of vertical displacement, is only weakly discernable. The correlation can be seen in the alignment of magnetic contours along the fault. This is evident in southern Nemaha, northern Pottawattomie and Waubaunsee Counties. The influence of the vertical displacement can also be seen in southern Morris County where the fault trace splits the north-northwest trending anomaly. The horizontal gradient of the anomaly on the high side (west side) of the fault is steeper than the gradient on the low side. It follows that the source rock for the anomaly was probably emplaced before vertical displacement along the fault took place. The presence of this anomaly across the fault also suggests that there has been no major (less than 500 meters) strike-slip movement along the fault. The difference of 50 gammas in magnitude of this anomaly on either side of the fault suggests that most Precambrian relief features in eastern Kansas will have less than a 50 gamma influence on the total magnetic field. This is normally the case in areas where the crystalline basement has a fairly thick sediment cover (see for example, Steenland, 1965). Most of the observed field is due to intrabasement rock lying below the Precambrian surface and above the depth corresponding to the Curie Point isotherm, which is normally 30 to 40 km below sea level. Suprabasement features such as relief and thin lenses of crystalline rock at the surface contribute only a small part to the observed field. Suprabasement anomalies are characterized by small magnitudes with sharp horizontal gradients and short wavelengths superimposed on large intrabasement anomalies with gentle horizontal gradients and longer wavelengths. Although not considered in this report, suprabasement anomalies are often useful

for estimating depth to basement (Chapter 15, Nettleton, 1976).

BASEMENT TERRANES

The total intensity aeromagnetic maps (Figures 5-2 and 5-3) exhibit a northwest trending grain consistent with the Precambrian surface terrane (Figure 5-10), which is interrupted in northeastern Kansas by a northeast trending linear positive anomaly flanked by adjacent linear negative anomalies. (The positive anomaly, caused by CNARS rocks of gabbroic composition, will be discussed in a later section.) The CNARS anomaly appears to terminate in central Kansas against a roughly linear trend of negative anomalies. This negative trend is defined by a near-continuous band across the state defined by total intensity amplitude <1200 gammas. The most prominent low is centered over Wichita with negative anomalies of lesser magnitude continuing west beyond the Colorado border. This trend can also be traced into Missouri (Missouri Geological Survey, 1943). The southern boundary of this band is clearly visible in the high frequency passed filtered map (Figure 5-6). This boundary corresponds to a fairly sharp magnetization contact suggesting contrasting rock types. This apparent contrast may correspond to a distinct boundary between the older mesozonal granitic terrane to the north and the younger epizonal granitic terrane to the south. This "spectral" boundary is caused by an abrupt attenuation of high frequency signal, from south to north, and presumably corresponds to the onset of the southern edge of the mesozonal granitic terrane or to some kind of transition zone between the two basement terranes. The northern boundary of the transition zone is not so sharply defined. Outside the CNARS the width of the transition zone varies from 25 to 50 km. The zone may correspond to

foundered granitic rock overlain by a Precambrian sedimentary or metasedimentary wedge. Alternatively, it could be a band of nonmagnetic granitic basement. The high frequency signal north of the transition zone and outside of CNARS appears similar to that of the southern terrane. The second vertical derivative map (Figure 5-9) emphasizes near vertical contacts between contrasting magnetizations. The boundary, which is clearly outlined in the high frequency pass filtered map (Figure 5-6), is not as prominent in the second vertical derivative map. Certain portions, however, are enhanced such as the southern edge of the Wichita low and areas in western Kansas. The boundary is also discernable in the upward continued map (Figure 5-4), which emphasizes the deep seated magnetic character of the crust.

INTRUSIVES

The extreme northeastern portion of the aeromagnetic map (Figures 5-2 and 5-3) shows a series of strong positive, roughly circular anomalies with diameters of approximately 15 km. Basement cores from two of these anomalies, located in Douglas and Miami Counties^{*}, yielded U/Pb zircon ages of about 1350 m.y. (Steeple and Bickford, 1981). Although these rocks are more coarse grained than rocks in the southern terrane, they are clearly epizonal granite and related to them (Bickford et al, 1981). The Miami County core^{*} contains about 2 per cent magnetite by weight (Steeple and Bickford,

* Referred to by township-range location in Blackwell and Steele, Chapter 5; by Department of Transportation County Code in Stavnes, Chapter 2; and by town near where hole is located in Kodama, Chapter 6.

1981), which may account for the positive magnetic anomalies. The close similarity of the circular magnetic anomalies makes it probable that most, if not all, of them are caused by intrusive bodies similar to those drilled in Douglas and Miami Counties. This suggests that the 1625 m.y. terrane in northeastern Kansas and northwestern Missouri is peppered with isolated shallow granite plutons, possibly related to the 1400 m.y. granitic terrane to the south, but younger by some 50 m.y. This series of circular magnetic highs along with similar highs in Missouri (Missouri Geological Survey, 1943) roughly track the boundary of the southern half of the Forest City Basin. These mid-Proterozoic granitic plutons may have been intruded along a zone of weakness that later influenced the formation of the late-Proterozoic Forest City Basin.

There are also at least six major near circular anomalies in western Kansas, five of which are closely associated with the granitic terrane boundary discussed previously. Over the entire state there are at least five circular intrusive bodies just to the north of the terrane boundary (Figure 5-6). These could possibly be the remnants of volcanic centers associated with Precambrian plate convergence along this boundary.

THE CENTRAL NORTH AMERICAN RIFT SYSTEM

The pervasive influence the Central North American Rift System had on the Kansas crust is perhaps best seen in Figure 5-7. This map, which emphasizes high frequency anomalies trending northeast, indicates that the rift system extends south across the entire state.

A magnetic quiet zone, the predominantly white area in Figure 5-7, surrounds the magnetic high along the mafic belt and corresponds to a basin

filled with clastic rocks, presumably of Keweenawan age. The magnetic quiet zone is due to the extreme depth to magnetic basement, presumably granite, which foundered during the extensional phase of the CNARS. Both the eastern and western boundaries of this Keweenawan basin are fairly sharply defined, suggesting that they may be fault bounded.

The magnetic lineations to the southwest of the magnetic quiet zone, which are the most prominent in Figure 5-9, probably correspond to block faulting and possibly mafic dike intrusion that occurred during the initial stage of rifting.

Apparently the rift in southern Kansas did not progress beyond the stage of block faulting and dike intrusion, whereas the rift in northern Kansas developed to a more mature stage of volcanic flows followed by foundered crust and clastic deposits. The fracture system in southern Kansas is probably representative of the crust throughout the CNARS during the early stages of rifting, before upwelling of Keweenawan volcanics occurred. This southwest-trending system indicates that the CNARS extends into Oklahoma.

The Humboldt Fault Zone (Figures 1-3, 1-4 and 5-10), which borders the eastern side of the Nemaha Ridge, closely parallels the CNARS across the state, suggesting that this apparent post-Mississippian fault may be a reactivated CNARS fault. This Proterozoic forerunner of the Humboldt Fault may have developed within the easternmost part of the CNARS crust that was not involved in subsequent foundering. Alternatively, the Humboldt Fault Zone may be a zone of Pre-Keweenawan crustal weakness that has been reactivated, or it may not have formed until Paleozoic time.

POSSIBLE BASEMENT FAULTS

The trend pass filtered maps (Figures 5-7 and 5-8) reveal significant magnetic lineations in both the northeast and northwest directions. The most prominent northeast linear trends correspond to the rift system through central Kansas, but there are also a number of northwest trends outside the rift, particularly in northwestern Kansas. Figure 5-8 exhibits northwest magnetic linears extending over large parts of the state, substantially interrupted however within the rift zone. This, of course, implies that the northwest grain is older than the rift.

Figure 5-11 presents the magnetic linears appearing in Figures 5-7, 5-8, and 5-9 superimposed on the Precambrian relief map. Determining what constitutes a magnetic linear trend is very subjective. The linears shown in Figure 5-11 represent what I consider "middleground". Another researcher, depending on his criteria and biases could easily identify more or fewer linears from the same maps. The linears I have chosen are at least 50 km long or belong to a trend of shorter segments at least 50 km long.

In addition to suites of northeast and northwest trending linears across the state (seen in Figure 5-11), there is a third suite of linears located primarily in southern Kansas that trend east-northeast.

Figure 5-11 reveals that the number of magnetic linears far outnumbers the heretofore mapped faults in the Precambrian. There are, however, a number of one-to-one correlations.

The northern half of the Humboldt Fault Zone, which borders the eastern side of the Nemaha Ridge, shows up clearly as a continuous magnetic linear. The northwest trending magnetic linear in Rush County matches the southwest

bounding fault of the Rush Rib. This fault (Merriam, 1963) lies along the postulated Precambrian age boundary (Figure 5-6) discussed earlier. There is also good correlation with the northeast trending fault segments in western Reno and Pratt Counties. The fault through Ellsworth County, which trends northwest along the southwest side of the Ellsworth Anticline, apparently serves as the northern boundary for several of the southwest trending magnetic linears within the rift zone.

The northwest trending fault in Pawnee County coincides with a magnetic trend that continues to the northwest up into Rush County. Part of the southwest trending fault bounding the northwest side of the Voshell Anticline coincides with a short magnetic linear at the intersection of McPherson, Reno and Harvey Counties.

Although the northwest trending magnetic grain in eastern Kansas parallels the Precambrian surface grain, there is little one-to-one correlation with mapped faults. One exception to this is the fault through Bourbon and Linn Counties which coincides with a magnetic trend that continues northwest into Anderson and Osage Counties.

Whether all magnetic linears correspond to basement faults is an open question. The fact that some of them correspond to known faults strongly implies that at least some of the remaining linears must also correspond to unmapped faults. The northeast trending magnetic linears within the rift zone surely must correspond to faulting in Keweenawan time. The post-Mississippian movement along the Humboldt Fault is most likely a reactivation of a Keweenawan rift fault.

Microearthquake results for the last four years (Steeple, 1980) indi-

cate that the Humboldt Fault Zone is still active. The northeastern magnetic trend through Washington, Republic and Cloud Counties, which corresponds to the postulated boundary between the rift sediments (Rice Formation) and the older granitic terrane, is seismically active (Figure 5-12). There is slight evidence (two events) that the eastern boundary between the rift sediments and granitic terrane is also seismically active. The only other significant recent seismic activity recorded within the state is located in Barber County and may be related to the southwest magnetic trend through Harper and Barber Counties.

SUMMARY AND DISCUSSION

The recently compiled aeromagnetic map of Kansas is proving to be very useful in studying the composition and paleotectonics of the Precambrian crust. Examination of the magnitudes and gradient of the total intensity magnetic field map and a suite of spectrally filtered maps coupled with existing geologic information, has yielded the following regional interpretation of the Precambrian crust in Kansas.

The postulated Precambrian terranes are summarized in Figure 5-13. There appears to be a rather distinct boundary between the northern 1625 m.y. old mesozonal granitic terrane and the southern 1400 m.y. old epizonal granitic and rhyolitic terrane, whose magnetic signature is a series of nearly contiguous lows trending west cross the state. The southern boundary of this band of lows is sharply defined by steep horizontal gradients and short wavelengths. The magnetic source of this band is not clear. Gravity measurements in this region, which are being taken by the KGS, along with potential field modeling should help to clarify this.

Drilling results from two of the 14 circular magnetic highs in northeastern Kansas suggest that the older 1625 m.y. old crust in northeastern Kansas is pockmarked with younger, 1350 m.y. old granitic plutons similar in composition to the southern, 1400 m.y. old terrane of epizonal granite and rhyolite. The one to two per cent magnetite, by weight, found in the two basement cores may account for the positive magnetic anomalies whose magnitudes range from 500 to more than 1000 gammas.

The CNARS extends through Kansas and probably into Oklahoma. Although it is clear that large volumes of mafic volcanics did not reach the Proterozoic surface in southern Kansas, there is strong magnetic evidence for block faulting and possible dike intrusion normally associated with initial stages of continental rifting. The extreme southern portion of the 1100 m.y. old rift that extends into the 1400 m.y. old crust in Kansas did not evolve into the more mature stages of deep rift valley formation accompanied by voluminous volcanics and clastics as did the main part of the rift to the north.

There are three main suites of magnetic linears of basement origin. Predominantly northwest trending linears are found in southeastern and northwestern Kansas, whereas central Kansas is dominated by north-northeast trending linears associated with the CNARS. Both of these trends are present in south central Kansas resulting in a system of roughly orthogonal intersecting linears. A third suite of east-northeast trending linears are present in southern Kansas.

Several of the magnetic linears correspond to previously mapped basement faults suggesting that at least a small fraction of the remaining linears

correspond to heretofore unknown faults. These remaining linears must be examined by other geophysical methods to establish which ones are faults.

The Humboldt Fault Zone, bounding the eastern side of the Nemaha Uplift, parallels the CNARS system suggesting that it may have developed in Keweenawan time and was reactivated in late Paleozoic time. Recent microearthquake results in Kansas indicate that the Humboldt Fault is still active. There is also some activity along two other magnetic linears within the CNARS.

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FIGURE CAPTIONS

- FIGURE 5-1: Flight paths for aeromagnetic map of Kansas.
- FIGURE 5-2: Aeromagnetic contour map of Kansas. Contour interval is 50 gammas.
- FIGURE 5-3: Aeromagnetic map reduced to pole and downward continued to 760 meters above sea level.
- FIGURE 5-4: Aeromagnetic map reduced to pole and downward continued to 9 kilometers above sea level. (The continuous line delineates a possible deep seated paleoplate boundary within the crust. The dashed lines outline the possible deep seated boundaries of the CNARS.)
- FIGURE 5-5: Aeromagnetic map reduced to pole and downward continued to 850 meters below sea level.
- FIGURE 5-6: Aeromagnetic map reduced to pole, leveled and high pass filtered. (The continuous line delineates a sharp high frequency boundary within the crust. Also delineated are shallow intrusive plutons.)
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- FIGURE 5-9: Aeromagnetic map reduced to pole, leveled and second vertical derivative calculated. (The continuous lines outline the suggested boundaries of the Keweenaw gabbros and the location of the Humboldt Fault Zone.)
- FIGURE 5-10: Configuration of the top of Precambrian rocks in Kansas. After Cole (1976).
- FIGURE 5-11: Magnetic lineations. (The lineations, which are superimposed on Figure 5-10, were derived from Figures 5-2 and 5-5 through 5-9.)
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- FIGURE 5-13: Precambrian terranes in Kansas. (Inferred from magnetic data and age data of Bickford et al, (1981).)

FLIGHT PATHS FOR AEROMAGNETIC MAP OF KANSAS

H. Taper, R. Robertson, J. Martin, R. M. S. Soudy and R. Woodland

OPEN FILE SEPT. 1, 1960

FIGURE 5-1

AEROMAGNETIC MAP OF KANSAS

H. Yarger, R. Robertson, J. Martin, K. Ng, R. Sooby and R. Wentland

FIGURE 5-2

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND DOWNWARD CONTINUED TO 760 METERS ABOVE SEA LEVEL

FIGURE 5-3

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND UPWARD CONTINUED TO 9 KILOMETERS ABOVE SEA LEVEL

FIGURE 5-4

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND DOWNWARD CONTINUED TO 850 METERS BELOW SEA LEVEL

FIGURE 5-5

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND HIGH FREQUENCY PASS FILTERED

FIGURE 5-6

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND TREND PASS FILTERED NORTHEAST $\pm 45^\circ$

FIGURE 5-7

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND TREND PASS FILTERED NORTHWEST $\pm 45^\circ$

FIGURE 5-8

AEROMAGNETIC MAP OF KANSAS

REDUCED TO POLE AND SECOND VERTICAL DERIVATIVE TAKEN

CONFIGURATION OF THE TOP OF PRECAMBRIAN ROCKS IN KANSAS

Virgil B. Cole
1976

FIGURE 5-10

CONFIGURATION OF THE TOP OF PRECAMBRIAN ROCKS IN KANSAS

Vogel & Cox
1915

FIGURE 5-11

AEROMAGNETIC MAP OF CENTRAL KANSAS

Reduced to pole and second vertical derivative taken

● Microearthquakes

8/18/77 to 6/30/80

Index Map

FIGURE 5-12

FIGURE 5-13

TABLE CAPTIONS

TABLE 5-1: Spectral filters applied to Kansas Aeromagnetic Data.

TABLE 5-1

<u>Spectral Filter Name</u>	<u>Function</u>	<u>Result</u>
Reduction to the Pole	Removes the effect of the earth's inclined magnetic field.	Improves the resolution and location of anomalies, particularly along north-south direction.
Downward Continuation	Recalculates the magnetic field at elevations below flight elevation.	Enhances anomalies due to near-surface sources.
Upward Continuation	Recalculates the magnetic field at elevations above flight elevation.	Enhances anomalies due to deep-seated sources.
High Frequency Pass	Attenuates low frequency (long wavelength) signals and passes high frequency (short wave length) signals.	Enhances anomalies due to near-surface sources.
Trend Pass	Removes spectral surface trends outside selected directions, passes trends within selected directions.	Enhances anomalies trending in selected directions.
Second Vertical Derivative	Calculates second vertical derivative of the magnetic field.	Delineates near-vertical magnetic contacts.

PALEOMAGNETIC RESULTS FROM THE OSAWATOMIE CORE
AND BIG SPRINGS CORE, KANSAS

by

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INTRODUCTION

In December 1979 the Kansas Geological Survey drilled into the Precambrian age basement rocks at an aeromagnetic high located near Osawatomie, Kansas. In March 1980 the Precambrian basement rocks were drilled at another aeromagnetic high near Big Springs, Kansas. Nine independently oriented samples from the Osawatomie core^{*} and four independently oriented samples from the Big Springs core^{*} were provided to this laboratory for magnetic studies. The primary motivation for the magnetic studies was to determine if the Precambrian age basement rocks were magnetic enough to produce the observed total field anomalies. Natural remanent magnetization (NRM) intensities measured for these rocks average 2.79×10^{-3} emu/cm³ ($\sigma = 1.41 \times 10^{-3}$ emu/cm³) for the Osawatomie core and 5.53×10^{-4} emu/cm³ ($\sigma = 2.92$

* Referred to by township-range location in Blackwell and Steele, Chapter 3; by Department of Transportation County Code in Stavnes, Chapter 2; by County in Yarger, Chapter 5.

$\times 10^{-4}$ emu/cm³) for Big Springs core. These rocks, based on their NRM intensities, are comparable in magnetic strength to a basalt (Nagata, 1961). The NRM directions from the Osawatomie core were somewhat unusual because they were nearly vertically downward (Appendix I.). Since these directions were parallel to the core axis, the possibility of a remanence acquired during drilling had to be considered. The NRM directions from the Big Springs core were not consistently vertically downward (Appendix I.).

Susceptibilities of the specimens from the Osawatomie core average 2736×10^{-6} cgs units ($\sigma = 522 \times 10^{-6}$) (Appendix I.) giving an average Königsberger ratio of 2.0 ($\sigma = 0.79$) for these rocks. The Big Springs specimens yield an average susceptibility of 2703×10^{-6} cgs units ($\sigma = 1337 \times 10^{-6}$) (Appendix I.), but since their average NRM intensity is smaller than for the Osawatomie core the average Königsberger ratio for the Big Springs core is 0.41.

A detailed paleomagnetic study of the samples was carried out so that their final demagnetized paleomagnetic directions could be compared to the local field directions predicted for this site by Irving and McGlynn's (1976) apparent polar wander path for the North American Precambrian. Radiometric age dating suggests that these rocks are 1355 m.y. (Steeple and Bickford, 1981). Based on Irving and McGlynn's (1976) apparent polar wander path for North America, Kansas would have been near the equator at this time and very shallow inclinations would be expected for these rocks (Figure 6-1).

In order to determine the stable remanent directions for these

rocks they must be magnetically cleaned by thermal and alternating field demagnetization techniques (Collinson and others, 1967, p.207-311; McElhinny, 1973). These methods remove spurious secondary magnetizations from the rocks by either randomizing the magnetizations of magnetic grains with low blocking temperatures or randomizing the magnetizations of magnetic grains with low magnetic coercivities.

The assumption made when using these techniques is that the magnetic grains with magnetizations which are stable at high temperatures or high coercivities have been stable for geologically long times ($\sim 10^9$ yrs.).

One aspect of the NRM's from the Osawatomie core which can be studied by demagnetization techniques is the steepness of the magnetic directions. If the Osawatomie samples acquired an isothermal remanent magnetization (IRM) from being exposed to highly magnetic drilling equipment, this type of magnetization would be easily removed by alternating field demagnetization (Gough, 1967; McElhinny, 1973). Alternatively, if the vertical magnetization were acquired by being exposed to a vertical field for a geologically long period of time (10^5 years or more) (in this case it would be called a viscous remanent magnetization (VRM)), it would be more easily removed by thermal demagnetization than by alternating field demagnetization (Dunlop, 1973). Although the acquisition of a vertical VRM is unlikely it should be considered as a possibility.

Ideally, when determining the paleomagnetic vector in a sample, the azimuthal and vertical orientation of the sample should be

known. In a core it is usually impossible to recover its absolute azimuthal orientation; however, a relative azimuthal orientation between pieces of the core is desirable and possible. This relative azimuthal orientation is available for the pieces of the Osawatomie core.

This laboratory has been supplied with three groups of three independently oriented samples from the top, bottom and middle of the core. Four pieces from the Big Springs core were also supplied; however, there had been no retention of the relative azimuthal orientations of these pieces. In the Osawatomie core it is possible to study variations in paleomagnetic directions along the core. This is not possible for the Big Springs core. In either core the absolute paleomagnetic declination is unrecoverable and only the paleomagnetic inclination can be used to tie into Irving and McGlynn's (1976) apparent polar wander path. This leads to some ambiguity (Figure 6-1) since an inclination of 50° , as an example, could indicate ages of 1150 m.y., 1225 m.y., 1475 m.y., 1725 m.y. or 1850 m.y. b.p. The paleomagnetic data will only indicate whether the inclination is consistent with the radiometric age and will not give an independent age for the core.

DEMAGNETIZATION DATA

Two specimens were drilled from each Osawatomie core sample, one was thermally demagnetized and one alternating field demagnetized.

Four specimens were drilled from each paleomagnetic sample from

the Big Springs core. Two of these specimens were thermally demagnetized and two were subjected to alternating field demagnetization.

THERMAL DEMAGNETIZATION

The thermal demagnetization experiments involved heating the specimens to a given temperature, cooling them in field-free space, measuring them, then repeating this procedure at progressively higher temperatures. The specimens were demagnetized in twelve steps up to 640°C (100°C , 200°C , 300°C , 400°C , 450°C , 500°C , 525°C , 550°C , 575°C , 600°C , 620°C , 640°C).

The thermally demagnetized specimens from the bottom (samples 1a, 1b, 1c) and middle (2a, 2b, 2c) of the Osawatomie core (Figure 6-2) maintain their steep inclinations up to 575°C , then they become scattered in direction. Samples from the top of the Osawatomie core (3a, 3b, 3c) (Figure 6-2) start at less steeply inclined directions and move toward shallow inclinations upon demagnetization.

The thermal demagnetization behaviour of the Big Springs specimens are different from that of the Osawatomie core specimens. In samples 1, 2, and 4 (bottom, second from the bottom, and top) the inclinations change from steep to intermediate (50° from the horizontal) with demagnetization up to 575°C . The NRM inclinations for sample 3 started at approximately 50°C and remained at that inclination; however, similar to the Osawatomie core the directions are well grouped up to 575°C and then scatter above this temperature. Sample 2 is interesting since it has reversed (upward) inclinations. This could indicate a geomagnetic field reversal, but it is more likely the result of an

upside-down piece of core.

The scattering of directions above 575°C for the specimens from both the Osawatomie and Big Springs cores is very suggestive of magnetite being the main, or only, magnetic mineral in these rocks (Curie Point 580°C) (Nagata, 1961; McElhinny, 1973). This is supported by the large decrease in magnetic intensity with thermal demagnetization (Figure 6-3) above 575°C.

ALTERNATING FIELD DEMAGNETIZATION

In alternating field demagnetization experiments a specimen is exposed to an alternating magnetic field which is decreased from some peak value to zero. The sample is then measured and this procedure is repeated with the sample being exposed to progressively higher peak fields. At least one specimen from each group of three samples from the Osawatomie core and one specimen from three Big Springs samples were progressively demagnetized in 5 mT to 10 mT steps up to a peak field of 100 mT (100 mT = 1000 gauss). This treatment indicated that only one component of magnetization was present in these rocks and that it resides in grains with coercivities that range from 50 mT to 70 mT. For the remainder of the specimens progressive demagnetization was carried out only until the stable final demagnetization direction was reached at about 60 mT.

The alternating field demagnetization results for the Osawatomie core were surprisingly quite different than the thermal demagnetization data (Figure 6-4). The final AF (alternating field) demagnetization directions derived from Zijderveld diagrams (Zijderveld, 1967) of specimens

from Osawatomie samples 1a, 1b, 1c (bottom of the core) and samples 3a, 3b, 3c (top of the core) all clustered around an arbitrary declination of 208.4° and an inclination of -20.5° ($\alpha_{95} = 6.6^{\circ}$). The vertically downward NRM directions were completely removed above peak alternating fields of 35 mT; however, greater than 95 per cent of the original NRM intensity was also removed at these peak demagnetization fields. The final AF demagnetization directions of specimens from samples 2a, 2b, 2c were quite different from samples 1 and 3 and cluster about an arbitrary declination of 135.9° and an inclination of -19.8° with a good deal more scatter ($\alpha_{95} = 19.1^{\circ}$). This anomalous demagnetized direction and the increased scatter of specimen directions could possibly be due to a quickly changing geomagnetic field during cooling through the Curie Point suggesting a geomagnetic field excursion; however, this seems highly improbable since it is more likely that the samples 2a, 2b, 2c were not properly aligned during reconstruction of the core after it was recovered from the drill hole. Based on very simplified calculation of the cooling rate for a body of this size (Lovering, 1935) it probably took several hundred to 1000 years for a core this length (7.6 cm) to cool through the Curie Point. Since a geomagnetic excursion itself is possibly as long as several hundred to one thousand years (Liddicoat and Coe, 1979), the core may not be long enough to have a geomagnetic excursion recorded in one part of it. More core material is being supplied to check the validity of the anomalous directions from samples 2a, 2b, and 2c. Paleomagnetic directions will be measured at 0.67 m intervals down the core and shifts in declination compared to the positions where the core was

broken during drilling.

The results from the alternating field demagnetization of the Big Springs core were similar to the results from thermal demagnetization (Figure 6-5). Since we have no relative azimuthal reference down the core only inclinations can be compared. Specimens from samples 1, 3 and 4 all demagnetized to an average inclination of 50.8° at peak fields of 50 mT. Specimens from sample 2 started with NRM directions which were pointing nearly vertically upward and demagnetized to an average inclination of -48.3° . Since even very short geomagnetic reversals may be 10^5 years in length and the Big Springs core is even shorter than the Osawatomie core (2.9 m), it is unlikely that there would be enough of a time interval between the cooling of sample 1 and sample 3 (2.1 m of separation along the core) to record a geomagnetic reversal. It is more likely that sample 2 was inadvertently turned upside down during core reconstruction. However, the possibility of a short reversal being recorded in the Big Springs core is being checked by measuring samples taken from a single piece of core from between samples 2 and 3.

The decrease in intensity of the magnetization with AF demagnetization for the Big Springs core is similar to that seen for the Osawatomie core with less than 5 per cent of the NRM intensity remaining at peak fields of 50 mT.

INTERPRETATION

By plotting the progressive demagnetization data for each specimen on a Zijderveld diagram (Zijderveld, 1967) (Figure 6-6) it is possible to determine a characteristic direction for that specimen. Characteristic

directions from the Osawatomie and Big Springs specimens (Figures 6-5 and 6-7) can be used to tie into Irving and McGlynn's (1976) apparent polar wander path for the North American Precambrian (Figure 6-1).

The Osawatomie core's mean inclination, based on specimens from sites 1 and 3, is -20.5° with an alpha 95 of 6.6° . If errors in Irving and McGlynn's data are $\pm 10^{\circ}$ the Kansas site could have been far enough south of the equator to produce the Osawatomie core inclinations in a normal polarity geomagnetic field at only two times during the Precambrian, 100 m.y. b.p. and 1300 m.y. b.p. If we consider the possibility that the field was of reversed polarity during the cooling of the Osawatomie core then the core's inclinations would be consistent with ages of 1050 m.y., 1275 m.y., 1425 m.y. and 1800 m.y. on Irving and McGlynn's apparent polar wander path. Since Bickford has obtained a good radiometric date of 1355 m.y. b.p. for the Osawatomie core (Steeple and Bickford, 1981), it is more likely that the core has a normal polarity direction with ages of 1275 m.y. or 1425 m.y. The Osawatomie core's paleomagnetic directions are consistent with its radiometric age.

Assuming that sample 2 from the Big Springs core has been turned upside-down, the mean inclination for this core is 51.5° . This inclination is close to the axial geocentric dipole inclination for this latitude ($I = 57.8^{\circ}$) and could be the result of present day magnetic overprinting. However, the stability of the magnetization to both thermal and AF demagnetization probably suggests that it is the primary magnetization of the rock. If this is true an inclination of 51.5° could correspond to ages of 1150 m.y., 1225 m.y., 1475 m.y., 1725 m.y. or 1850 m.y. b.p. on Irving

and McGlynn's (1976) apparent polar wander path. The most likely interpretation of the Big Springs magnetization is that it cooled through its Curie Point at either 1225 m.y. b.p. or 1475 m.y. b.p., as close to its radiometric age of 1355 m.y. b.p. (Steeple and Bickford, 1981) as possible. The paleomagnetic data does suggest that even though the Osawatomie and Big Springs cores give the same radiometric age the paleomagnetic data indicates that their cooling times probably differ by 50 - 80 m.y.

The Osawatomie specimens have a mean NRM magnetization intensity which is five times stronger than the mean NRM magnetization of the Big Springs specimens. Alternating field and thermal demagnetization experiments suggest that the Osawatomie specimens have suffered from an IRM, possibly during drilling. Some Big Springs specimens also may have acquired an IRM, but this seems to be less of a problem in this core. If samples with steep NRM inclinations in the Big Springs core did acquire an IRM, their NRM intensities should be higher than specimens whose demagnetized directions and NRM directions are nearly the same. Apparently this may be the case (Figure 6-8). NRM's of Big Springs specimens which appear to be unaffected by the hypothesized IRM are approximately two times weaker than those which may have an IRM. Since it appears that most or all of the Osawatomie samples have been affected by an IRM their measured NRM intensities could be somewhat stronger than the NRM intensity of the rock in situ. If it can be assumed that the magnetic mineralogy of the Osawatomie and Big Springs cores are similar, then the in situ NRM intensity of the Osawatomie rocks may be one-half of

its measured value.

CONCLUSIONS

Alternating field and thermal demagnetizations studies suggest that most of the Osawatomie core samples and some of the Big Springs core samples are affected by an IRM which may have been acquired during drilling. The in situ magnetic intensity of the Osawatomie core may be somewhat less than the measured NRM intensity, although the in situ magnetization is probably strong enough to account for the observed aeromagnetic anomaly at the drill site. The Osawatomie demagnetized paleomagnetic inclinations are consistent with the radiometric age of 1355 m.y. b.p. obtained for this rock. The demagnetized directions determined for the Big Springs core suggests that is older or younger than the Osawatomie core, and that there is probably a 50 - 80 m.y. age difference between the cooling of the two cores.

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FIGURE CAPTIONS

- FIGURE 6-1: Variation of normal polarity inclination as a function of age for eastern Kansas (lat = 38.4°N ; long = 95°W); based on Irving and McGlynn's (1976) apparent polar wander path for the Precambrian.
- FIGURE 6-2: Progressive thermal demagnetization of three representative specimens from the Osawatomie core. Solid circles are lower hemisphere. Data is plotted on a stereo net.
- FIGURE 6-3: Magnetization intensity normalized by NRM intensity (J/J_0) as a function of thermal demagnetization. Note the large decrease above 575°C .
- FIGURE 6-4: Progressive AF demagnetization of three representative specimens from the Osawatomie core. Open circles upper hemisphere; solid circles lower hemisphere. Data is plotted on a stereo net.
- FIGURE 6-5: Final demagnetization directions for the Big Springs core. These directions have been devised from Zijderveld (1967) plots.
- FIGURE 6-6: Zijderveld (1967) plots for an AF demagnetized specimen from the Osawatomie core and for a thermally demagnetized sample from the Big Springs core. Note that above 40 mT the Osawatomie sample tends to trend toward the origin. This indicates a final demagnetization (characteristic) direction. This is better seen in the thermal demagnetization data from 500°C to 575°C for Big Springs specimens 1b. Note that above 575°C the data does not trend toward the origin.
- FIGURE 6-7: Final demagnetization directions (based on Zijderveld plots) for the Osawatomie core.
- FIGURE 6-8: Plot of magnetization intensity versus inclination for the Big Springs core. The data may suggest that the steep NRM inclinations are a result of an IRM acquired perhaps, during drilling.

FIGURE 6-1

Thermal Demagnetization

Osawattamie Core

FIGURE 6-2

FIGURE 6-3

AF Demagnetization

Osawattamie Core

FIGURE 6-4

Osawattamie

Final Demagnetization Directions

all directions of demagnetization

FIGURE 6-5

FIGURE 6-6

Big Springs

Final Demagnetization Directions

FIGURE 6-7

○ ● AF Demagnetization
 △ ▲ Thermal Demagnetization

FIGURE 6-8

GRAVITY MEASUREMENTS IN KANSAS

by

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INTRODUCTION

Woollard (1958) compiled a statewide gravity map with a 5 milligal contour interval at approximately a 1:2,000,000 scale (Figure 7-1). His data, which were mostly from proprietary files and unavailable now, were typically spaced five miles apart. The Kansas Geological Survey (KGS) has been improving state gravity coverage over the past several years (Figure 7-2).

Area A (Figure 7-3) has been open-filed at a scale of 1:500,000 and contour interval of one milligal (Yarger et al, 1980). The somewhat variable coverage patterns for this map are east-west traverses with one to two mile spacing between stations and one to six miles between traverses. The sources for these data were several master's theses and earlier unpublished field work done by KGS staff. Gravity data in area B were acquired under this contract during the summer of 1980. Approximately 3300 points were measured in a regular pattern of east-west traverses with one mile spacing between stations along the traverse and four mile spacing between traverses.

Area B (Figure 7-4) has been open-filed at a scale of 1:500,000 and contour interval of one milligal (Yarger et al, 1981). Approximately 3300 points were acquired in area C under this contract during summer 1981. The

coverage pattern was the same as for area B. Also during summer 1981 under this contract, approximately 6600 points were acquired in area D. In this area the desirable coverage patterns of one mile spacing along the east-west traverses and two mile spacing between traverses was used. Due to a backlog of work on our digitizing table, compilation of contour maps for areas C and D will not be completed until fall 1982. The KGS plans to complete coverage of area E, with the same coverage used in area D, during summers 1982 and 1983. Long term plans are to go back into areas A, B and C to upgrade coverage to one mile east-west by two mile north-south station density.

DATA ACQUISITION AND REDUCTION PROCEDURES

The following paragraphs describe the procedures used for gravity data acquisition and reduction in areas B, C and D that were funded under this contract.

Three Lacoste-Romberg model G gravity meters were used. The measurement stations were usually located at section road intersections spaced one mile apart along east-west section lines. USGS 7.5 minute topographic quadrangle maps, with 10 foot contour intervals were used to record station location and to determine station elevations to an estimated ± 1 foot accuracy.

The station identification scheme used was an x, y coordinate system based on the regular system of section lines within the state. The x coordinate represents the number of sections (or approximate miles) from the Kansas- Missouri border.

The surveyed area was divided into blocks of 25 miles east-west by 16 miles north-south. One base station was centrally located within each block. All stations at the eastern and western edges were designated as "overlap" stations and were reoccupied during coverage of the adjacent block. Base

station readings were normally taken four times: the beginning of the day; before lunch; after lunch; and end of day. After correction for the earth's tidal variation (Longman, 1959), meter drifts were usually less than 0.05 milligals/hour with a range of 0.01 to 0.1 milligal/hour.

Absolute gravity values were determined by tying all the local base stations (one for each 25 mile by 16 mile block) to Department of Defense (DOD) base stations within the state. Two loops between the local base and DOD base were used which allowed two independent determinations of absolute gravity at the local base station. The root mean square of the difference (RMS) between the two values was usually less than 0.01 milligals. To monitor the daily meter operation, the base station readings were plotted on a graph along with the continuous theoretical tidal variation. The RMS between the measured and theoretical tidal variation was usually less than 0.05 milligals with a range of 0.005 to 0.15 milligals. After subtracting tidal drift, a linear meter drift rate was determined for each pair of base station readings. All regular measurement stations were then corrected for tidal drift and meter drift. Meter drift rates were usually less than 0.01 milligals/hour.

Overlap stations were used to check consistency of base levels between adjacent blocks. The independent measurements of the overlap stations typically agreed within 0.1 milligals with the worst case being approximately 0.3 milligals. In some cases the overlap discrepancies were used to make slight level adjustments to local bases to bring the data blocks into better overall internal consistency. Final latitude and longitude coordinates for each measurement station were determined by digitizing the station locations on the 7.5 minute quadrangles. After assignment of latitude and longitude the following five variables were plotted against longitude for each east-

west profile: elevation, absolute gravity, free air gravity, Bouger gravity and horizontal gravity gradient. These profiles were screened for unphysical gradients. Most of the problem points found in this screening process could be traced back to an earlier error such as incorrect meter reading punched from field sheets.

The final corrected data file was used as input to the Surface II contour program (Sampson, 1978). The data were gridded into one mile by one mile nodes. The RMS between the original data points and interpolated grid values was 0.46 milligals. The grid was contoured at a scale of 1:500,000 and a one milligal contour interval (Figure 7-4). The reduction procedures outlined above are also being applied to data taken in south-central Kansas and northwestern Kansas.

PRELIMINARY INTERPRETATION

Figures 7-3 and 7-4 show considerable improvement in the resolution of gravity anomalies compared to Woollard's earlier map (Figure 7-1). These new gravity maps in eastern Kansas bring out the prevailing northwest trending grain evident in the Precambrian relief map (Figure 5-10) and the aeromagnetic map (Figure 5-2).

The most prominent gravity anomaly is the northeast trending 60 milligal high in northern Kansas. The source for this is a trough of Keweenawan mafic igneous rocks, approximately 1.1 billion years old, that extend from central Kansas through the North American continent to the Lake Superior region. The flanking gravity lows are correlated with Precambrian clastic sediments. These mafic and associated clastic sedimentary rocks are interpreted to be the result of a Late Precambrian crustal rifting event (Halls, 1978). The gravity and magnetic anomalies associated with this rift are often referred

to as the Midcontinent Geophysical Anomaly (MGA). Recent interpretation of the aeromagnetic map of Kansas (Chapter 5, this report) indicates that the rift extends through central Kansas to the Kansas-Oklahoma border. Forthcoming gravity data from south-central and west-central Kansas should be very useful in further study of this major crustal rift.

A prominent circular gravity high, of ~10 milligal magnitude, is evident in Jewell County just west of the MGA. This suggests the existence of mafic intrusions within the crust underlying the Salina Basin. The relatively gentle horizontal gradients may be located well below the Precambrian subcrop surface.

A circular anomaly of similar size and magnitude also occurs in northeastern Kansas suggesting that the Forest City Basin may also be underlain by mafic intrusives at depth.

A large area in southeastern Kansas is characterized by a 30 to 40 milligal positive gravity anomaly and correlates well with a 1400 m.y. old rhyolite terrane (Bickford, 1979). This suggests that a sizeable volume of intermediate to mafic rock underlies the relatively low density rhyolite.

Another positive anomaly of large areal extent (Figures 7-3 and 7-4), with magnitudes ranging between 5 to 10 milligals, trends northwest from Miami and Johnson counties to Shawnee and Jackson counties. This gravity feature does not correlate with known basement rock type or with the magnetic map (Figure 5-2). It most probably represents a mass of deep seated rock that intruded, during Precambrian time, a northwest trending zone of weakness.

Although the main northwest trending gravity anomaly is not reflected in the magnetic map, certain local features within this trend do have correspond-

ing magnetic counterparts. The positive 5 to 6 milligal circular gravity anomaly located in northern Douglas County is coincident with a sharply defined 1000 gamma circular positive magnetic anomaly. This anomaly, which is located near the town of Big Springs, is part of a series of north-south trending circular magnetic anomalies. A similar circular magnetic anomaly in Miami County is approximately correlated with a south trending positive gravity nose, a local feature within the northwest trending gravity high.

A study of basement cores derived from drilling the Big Springs and Miami county anomalies (Steeple and Bickford, 1981) reveals that these rocks are epizonal granites emplaced approximately 1350 m.y. ago. Gravity and magnetic modeling of these bodies (Yarger, 1982) indicate that they are approximately 15 kilometers in diameter and extend from the Precambrian surface to a depth of 10 kilometers.

Apparent in Greenwood, Butler and Sedgwick counties (Figure 5-2) is a prominent negative magnetic anomaly elongate in the east-west direction. The source for this feature, which is often referred to as the Wichita magnetic low, is poorly understood. Gravity data in Greenwood County (Figure 7-4), which is located within the eastern end of the Wichita low, reveal two circular anomalies of opposite polarity. Completion of the gravity map of south-central Kansas should enhance our understanding of this geophysically complex region.

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FIGURE CAPTIONS

- FIGURE 7-1: Bouger gravity anomaly map of Kansas; 5 milligal contour interval (After Woollard, 1958).
- FIGURE 7-2: Index map of areas where gravity data has been acquired. The grid spacing for data points varies for areas A-E.
- FIGURE 7-3: Bouger gravity map of northeastern Kansas; one milligal contour interval.
- FIGURE 7-4: Bouger gravity map of southeastern Kansas; one milligal contour interval.

BOUGUER GRAVITY ANOMALY MAP OF KANSAS

by G. P. Woollard, 1958

BULLETIN 137 Plate 1

FIGURE 7-1

FIGURE 7-2

BOUGUER GRAVITY MAP OF NORTHEASTERN KANSAS

H. Yarger, K. Ng, R. Robertson, and R. Woods

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Bouguer Gravity Field of the Earth in Milligals
Contour Interval 1 Milligal
Lambert Conformal Conic Projection
Standard Parallels 33° and 45°
Standard Deviation for Station Measurement - 0.3 Milligals

The absolute gravity field was referenced to the
International Gravity Standardization Net 1971.
The Bouguer gravity field was calculated using
The Gravity Formula 1967 and a density of 2.67.

Supported principally by the Kansas Geological Survey.
Supported in part by the U. S. Nuclear Regulatory
Commission under Contract No. AT(49-28)-0256.

Index Map

FIGURE 7-3

BOUGUER GRAVITY MAP OF SOUTHEASTERN KANSAS

H. YARGER, C. LAM, R. SOOBY, A. MARTIN, G. ROTHE, D. STEEPLES

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International Gravity Standardization Net 1971
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The Gravity Formula 1967 and a density of 2.67.

Supported principally by the Kansas Geological Survey.
Supported in part by the Department of Energy under
Grant No. DE-AS07-19ET27204

Index Map

FIGURE 7-4

GEOTHERMAL MAPPING OF WESTERN KANSAS BASED ON CHEMICAL GEOTHERMOMETERS

by

Don Whittemore and Nelda Roehl
Kansas Geological Survey
Lawrence, Kansas

INTRODUCTION

A study of the geothermal potential of the United States based on silica geothermometer temperatures was made by Swanberg and Morgan (1979). The temperatures were calculated from dissolved silica concentrations in subsurface waters. The geothermometer equation used assumes that the water in the geothermal reservoir is in equilibrium with quartz and that no silica precipitation occurs as the water flows from the reservoir to the shallower sampling location. The silica geothermometer map did not include results for Kansas, however, because data was lacking at that time in the WATSTORE file of water-quality data used by Swanberg and Morgan.

In the last several years L. R. Hathaway of the Kansas Geological Survey has directed investigations of the geochemistry of groundwaters used for irrigation in Kansas. The approximately 1,200 wells sampled are from the broad, unconfined aquifers of Kansas, the Ogallala aquifer in the western third of the state, the Great Bend Prairie in south-central Kansas, and the Equus Beds in McPherson, Harvey, and Sedgwick counties (Figure 8-1). The Arkansas River valley was also included in the study area, from western Kansas where it separates the central and southern portions of the Ogallala aquifer, along the northern part of

the Great Bend Prairie, to the southern portion of the Equus Beds. Sampling of each aquifer area was conducted during the middle of the summer, the period of greatest irrigation pumpage. Thus, seasonal variations were minimized. Careful control of the quality of the analytical data was maintained during these investigations through the use of various types of duplicate samples. Only a small portion of the data are in the WATSTORE file. These analyses provided for the computation of geothermometer temperatures for approximately half of Kansas.

A conspicuous feature of Swanberg and Morgan's (1979) map is the region of high temperatures given by the silica geothermometer for central and western Nebraska. This area appears to be coincident with the location of the Ogallala aquifer in Nebraska. The aquifer extends from southern South Dakota to northwestern Texas and the eastern edge of New Mexico. Geothermal temperatures were not computed in Swanberg and Morgan's map for the Oklahoma and Texas portions of the Ogallala aquifer, as well as for Kansas, due to lack of data. A possible explanation for higher geothermal temperatures is the leaching of ash and feldspar in the sediments of the Ogallala aquifer and ash in Upper Cretaceous rocks. The ash is primarily vitric tuff and contains amorphous silica. In the Ogallala Formation some silica has been leached and precipitated as opal cementing the sediment. Concentrations of silica dissolved from ash, opal, and feldspar weathering can be appreciably greater than those in equilibrium with quartz.

Other chemical geothermometers have been used to estimate temperatures in geothermal reservoirs. Another silica geothermometer is based on chalcedony, which is more soluble than quartz. Therefore, the resul-

tant geothermal temperatures are less than those calculated from the quartz geothermometer for the same dissolved silica content.

Cation geothermometers include an equation involving the ratio Na/K. Fournier and Truesdell (1973, 1974) developed a Na-K-Ca geothermometer that reportedly gives better values than the Na/K geothermometer, especially at lower temperatures. Paces (1975a, 1975b) modified the Na-K-Ca geothermometer for groundwater with temperatures below 75°C and partial pressures of carbon dioxide above 10^{-4} atm.

Mineralogic controls on cation concentrations within the shallow portions of sedimentary aquifers are probably much more important than chemical characteristics inherited from waters circulating from depth. Calcium contents in Ogallala aquifer waters are generally in equilibrium with calcite. Sources and controls on sodium and potassium vary from contributions by deeper saline waters or the Arkansas River, to changes caused by ion exchange on clays, and to the weathering of feldspar. Thus, waters circulating from deeper, warmer strata could have lost their diagnostic chemistry as used in chemical geothermometers.

The objectives of this study were as follows:

1. Determine and compare geothermal temperatures using various chemical geothermometers and groundwater quality data from Kansas.
2. Correlate geothermometer temperatures with measurements of subsurface temperatures and calculated geothermal gradients.
3. Evaluate the relative importance of mineralogic controls within the aquifer versus geothermal effects on the composition of groundwater and, thus, temperatures derived from geothermometer calculations.

Towards the end of this study, a complete map of the heat flow of the United States based on the quartz geothermometer was published by Swanberg and Morgan (1981). An area of high heat flow is shown in northwestern Kansas. Although Swanberg and Morgan did not describe in the publication how they had treated data in the Great Plains, Swanberg personally communicated that data for wells shallower than 400 feet deep in the area of the Ogallala aquifer had been eliminated during the map preparation. This was based on an evaluation of the silica-geothermometer anomaly for Nebraska (Swanberg, 1980). The shallower well data give generally higher and more widely ranging temperatures than for the deeper wells. The map of Swanberg and Morgan (1981) appeared to have met objective (1) as stated above and its relation to the geothermal potential of Kansas. However, the other objectives were very useful for determining whether the area of higher heat flow below 400 feet affects the temperatures and geochemistry of the shallower strata. Also, an improved understanding of the mineralogic controls on the concentrations of dissolved constituents used in computing geothermal temperatures could allow improvement in the application and interpretation of geothermometer data for sedimentary systems.

PROCEDURE

Groundwater chemical analyses acquired by the Kansas Geological Survey as part of irrigation water studies (Hathaway, et al., 1975, 1977, 1978a, 1978b, 1979, 1981) were converted into the computer format used in the WATSTORE system. This system is managed by the U.S. Geological Survey and allows access to water resources data by federal, state, and other agencies.

Geothermal temperatures were calculated from the water quality data and five geothermometer equations. Two of the equations are based on the solubility of silica in the geothermal reservoir. The quartz geothermometer used by Swanberg and Morgan (1979, 1981) to construct silica temperature and heat flow maps of the United States assumes conductive cooling during the passage of the water to its nearer surface location and is applicable for temperatures of 125-250°C (Fournier, 1973, 1976),

$$T^{\circ}\text{C} = \frac{1315}{5.205 - \log(\text{SiO}_2)} - 273.15$$

where the concentration of SiO_2 is in mg/L. The chalcedony geothermometer of Fournier and Truesdell (1970) may be more applicable for lower temperatures.

$$T^{\circ}\text{C} = \frac{1015.1}{4.655 - \log(\text{SiO}_2)} - 273.15$$

The other three chemical geothermometers are based on cation concentrations. The Na/K geothermometer of White and Ellis (quoted in White, 1970) was reported to be applicable for temperatures of 100-275°C.

$$T^{\circ}\text{C} = \frac{855.6}{\log(\text{Na/K}) + 0.8573} - 273.15$$

where Na and K contents of the water are in mg/L.

Fournier and Truesdell (1973, 1974) formulated a Na-K-Ca geothermometer

$$T^{\circ}\text{C} = \frac{1647}{5.218 + \log(\text{Na}/\text{K}) + \beta \log([\sqrt{\text{Ca}}]/\text{Na})} - 273.15$$

where concentrations are in mg/L and $\beta = 4/3$ for temperatures of less than 100°C . Paces (1975a, 1975b) modified the Na-K-Ca equation for groundwaters with temperatures below 75°C and partial pressures of carbon dioxide above 10^{-4} atm.

$$T^{\circ}\text{C} = \frac{1647}{7.275 + \log(\text{Na}/\text{K}) + \beta \log([\sqrt{\text{Ca}}]/\text{Na}) - 0.253J} - 273.15$$

where, $J = \text{pH} - \log(\text{HCO}_3) - 4.22 \times 10^{-3}t - 3.54 \times 10^{-5}t^2$

t is the temperature of the groundwater samples in $^{\circ}\text{C}$ and concentration units are the same as for the Na-K-Ca equation. An activity coefficient of 0.93 was used to adjust the bicarbonate concentration to activity units.

Silica concentrations, the ratio of K to total dissolved solids, and all geothermometer temperatures except those based on the Na/K equation were plotted and contoured with the digital graphics programs TERRA-PLOT (FELIX) (McCullagh, 1979) and GIMMAP (Ross, 1981; Brentano, 1982) of the Kansas Geological Survey. The patterns of the temperature contour maps were compared with each other and a map of subsurface temperatures and two maps of geothermal gradients from Stavnes (Plates 2-1,

2-2, 2-4). Stavnes computed the subsurface temperatures for a depth of 1000 feet and geothermal gradients from oil and gas records for wells over 1000 feet. She also calculated geothermal gradients from her own temperature measurements below 400 feet in boreholes. The quartz geothermometer temperatures were also statistically compared with the subsurface temperatures and borehole geothermal gradients using linear correlation and regression. Graphs of the correlation were produced with the computer program SURFACE II (Sampson, 1978).

RESULTS AND DISCUSSION

COMPARISON OF TEMPERATURES FROM DIFFERENT GEOTHERMOMETERS

The geothermal temperatures computed for the two silica and three cation geothermometers are listed in Appendix I along with the well location and actual groundwater temperature during sampling. Ranges of the quartz and chalcedony geothermometer temperatures are 39.6-118.2°C and 4.6-88.1°C, respectively. Differences between the quartz and chalcedony temperatures range from 35-30°C from the low to the high values, and are consistent because the basic form of the equations is the same for both quartz and chalcedony solubility. The areas with higher silica geothermometer temperatures are located in the northwestern corner and the west-central part of Kansas (Figures 8-2 and 8-3). Nearly all of the quartz and chalcedony geothermometer temperatures were below 90°C and 60°C, respectively, in southwestern Kansas, the Great Bend Prairie and the Equus Beds, (see Figure 8-1 for location of aquifers). The region of higher heat flow indicated by Swanberg and Morgan's (1981) silica geothermometry map generally coincides with the areas of higher silica temperatures computed in this study, even though the data for their map was derived from water

samples below the Ogallala aquifer.

Temperatures calculated using the Na-K-Ca geothermometer range from 2.6-85.8°C and are both higher and lower than the chalcedony equation temperatures. The highest values ($>60^{\circ}\text{C}$) stretched along a west to east strip in northwestern Kansas along the border with Nebraska (Figure 8-4). Some higher temperatures were also present in the west central portion of the state and in alluvial valleys in western Kansas, particularly along the Arkansas River valley from the Colorado state line to Garden City. Except for the highs in the river valleys, the higher temperatures were in the same general areas as those for the silica geothermometer temperatures, even though the one to one correlation on a local basis within the high areas was low.

The modified Na-K-Ca geothermometer, (adjusted for dissolved carbon dioxide), gave the lowest temperatures (-39.0 to 30.9°C) of all five geothermometers. The below-zero temperatures indicate that this geothermometer is not appropriate for the aquifer systems investigated. The higher temperatures ($>20^{\circ}\text{C}$) were distributed mainly within the northwestern area and partly in the west-central portion in Kansas. The patterns were relatively similar to those for the Na-K-Ca geothermometer.

The Na/K geothermometer temperatures were unreasonably high (31.4 - 657°C). The Na/K equation has been found before to fail at temperatures below 100 to 120°C and to yield improbably high temperatures for solutions with high calcium concentrations (Truesdell, 1975).

CORRELATION OF GEOTHERMOMETER TEMPERATURES WITH TEMPERATURE MEASUREMENTS AND GEOTHERMAL GRADIENTS

Stavnes prepared contour maps of the geothermal gradients and

subsurface temperatures at a depth of 300 meters using bottom-hole temperatures (BHT) from oil and gas records (Plates 2-1 and 2-2 of Chapter 2 of this report). Although she stated that the data were subject to errors from drilling mud effects, and that the temperatures computed for extreme northwestern Kansas are not valid, the relative changes in the data were examined for patterns that could be associated with geothermometer temperatures. The BHT map shows temperatures range from 20-30°C in the western two-thirds of Kansas, except for a few isolated locations with temperatures above and below this range. Generally, larger areas of lower temperatures occur in the southwestern part of the state. There are no noticeable differences to distinguish the other aquifer areas studied, except for two small areas in the northwestern corner of Kansas which have temperatures greater than 32°C. No distinctive differences were observed on the geothermal gradient map for the western two-thirds of the state. Values range from 20-35°C.

The statistical correlations between the chalcedony geothermometer temperatures and BHT values interpolated for the same 1,200 points is highly significant. However, the correlation coefficient is 0.33, meaning that only 11 percent of the variation in the geothermometer temperatures is explained. A similar result is expected for a correlation between the geothermometer temperatures and the geothermal gradients computed from the BHT data.

Stavnes also prepared maps of the distribution of the geothermal gradients and subsurface temperatures at a depth of 300 meters from thermal logging of boreholes, 22 of which were located in the western two-thirds of the

state (Plates 2-3 and 2-5 in Chapter 2 of this report). Geothermal gradients and temperatures are relatively high ($42\text{--}59\text{ }^{\circ}\text{C}/\text{km}$ and $78\text{--}85\text{ }^{\circ}\text{C}/\text{km}$, respectively) in the northwestern and parts of west-central Kansas. In the rest of western and central Kansas gradients and temperatures are relatively uniform, fluctuating from $24\text{--}40\text{ }^{\circ}\text{C}/\text{km}$ and $22\text{--}25\text{ }^{\circ}\text{C}/\text{km}$, respectively.

The associations between the chalcedony geothermometer temperatures and both gradients and subsurface temperatures from borehole measurements are statistically highly significant. Correlation coefficients are 0.68 in both cases, giving coefficients of determination of 0.46. A graph of the 22 points for each correlation shows two general groups of points, one group of five at high geothermometer temperatures and gradients and subsurface temperatures, and the other group with little apparent correlation. Four of the points with higher values represent locations in northwestern Kansas, the other point is in west-central Kansas. The associations between the geothermometry and borehole data can also be observed visually by comparing the maps of both silica geothermometers with those for subsurface temperatures and gradients.

RELATIONSHIP BETWEEN GEOTHERMOMETER TEMPERATURES AND AQUIFER GEOCHEMISTRY

The areas of highest temperatures given by the quartz, chalcedony, and Na-K-Ca geothermometers are all located in northwestern Kansas and extend into the west-central regions of the state. Chemical data used for these areas of highs are for waters from the Ogallala aquifer. The sediments of this aquifer are composed mainly of arkosic gravel, sand, and silt of predominantly Pliocene age, although some Pleistocene sediments are present, especially in alluvial valleys. The sediments also contain calcite, volcanic ash, diatomaceous marl, opaline sandstone, and

bentonitic clay. The ash, opal, bentonite (indicating previous ash that has been weathered), and feldspar could be the major sources of higher concentrations of dissolved silica (Figure 8-5), rather than waters circulating from deeper strata with higher temperatures. The ash contains amorphous silica and the opal comprises hydrated, poorly-crystalline cristobalite, both of which are appreciably more soluble than quartz, the major component of the silts, sands, and gravels constituting the major aquifers of Kansas.

Volcanic ash was deposited in both the Pliocene and Pleistocene sediments of the aquifers. The ash layers are discontinuous, having been redistributed during erosion, mainly by water, into ponds and undrained depressions (Carey, et al., 1952). Thus, deposits are generally widely separated, commonly of lenticular shape, and vary in thickness up to nearly ten meters. The ash beds are often crossbedded and may show banding due to alternating coarse and fine layers. Locations of the larger beds are shown in Figure 8-6. Many of these deposits have been mined or listed as potential economic sources of ash. Average thicknesses of the economic lenses are generally between two and five meters at the center.

The ash beds of Kansas are classified predominantly as vitric tuff, at times containing trace amounts of quartz, sanidine, and biotite (Swineford and Frye, 1946; Swineford, et al., 1955). Differentiation of ash falls has been based on characteristics of the glass shards: index of refraction, particle size, shape, color, chemical composition, and presence or absence of second order vesicles. Pliocene ash is generally gray, has a greater specific gravity, and exhibits thin, slightly

curved, platy shards relatively free of vesicles compared to the nearly white Pleistocene ash which contains sharply curved shards with elongate vesicles.

Several petrographically distinct ash beds have been found in the Pliocene Ogallala Formation of Kansas (Swineford, et al., 1955). They occur primarily in the middle and lower members of the formation and comprise an estimated three percent of the total sediment volume. The deposits are located primarily in the northwestern part of the state (Carey, et al., 1952). Essentially all of the volcanic ash layers occurring in Pleistocene sediments were deposited within one stratigraphic member, but are distributed throughout much of Kansas as shown by Figure 8-6.

The source of the Pleistocene ash in Kansas has been attributed to volcanoes in north-central New Mexico (Swineford, 1949) and in the Yellowstone Park area of Wyoming and Idaho (Boellstorff, 1976). Landes (1928) found that coarser or heavier ash generally lies in the southwestern part of the state, while finer ash is located to the north and east, thereby suggesting a source to the southwest. Although little is known about the source area for pyroclastic material in the Ogallala Formation, most workers agree that the volcanic vents were west of the High Plains, probably in Wyoming, Colorado, or the Cordillera farther west (Stanley, 1976).

Silicified rock in the Ogallala Formation of Kansas can be directly linked to the Pliocene and Pleistocene ash. The rock consists of two major types: quartzite composed of sandstone and conglomerate with opaline cement, and chert consisting of opal, chalcedony, various

amounts of calcite and scattered sand grains (Frye and Swineford, 1946). The silicified rock is distributed widely with the largest deposits occurring in the northwestern and north-central parts of the state (Figure 8-6).

The quartzite occurs predominantly in the lower member of the Ogallala Formation. Irregular opal concretions and bentonitic clays are also present in the lower member. Opaline cement is widely distributed throughout the middle member of the Ogallala as discontinuous zones. Both the middle and lower members of the Ogallala contain most of the Pliocene ash. The leaching of this ash is thought to be the silica source forming the opaline cement in the quartzite. The water table is believed to have been high during the deposition of the Ogallala Formation (Frye and Swineford, 1946). Ash layers would have been subject to hydration and leaching shortly after accumulation. Subsequently, the dissolved silica precipitated as opaline cement. The presence of green quartzite containing ferrous iron in the lower Ogallala supports the theory of underwater formation of the opal. As the water table declined, the ash was often eroded, or, in some cases, an advanced state of leaching was reached before a return to normal groundwater conditions. Thus, much of the parent ash was removed.

The uppermost member of the Ogallala Formation contains discontinuous opal and chert composed of silt-sized clastics which are secondary replacements of calcium carbonate (Frye and Swineford, 1946). The source of this silica is considered to be the younger Pleistocene ash overlying the Pliocene sediments, the opal having been deposited by downward percolating waters in the vadose zone during a period of

arid climate in which caliche had formed.

The distribution of the dissolved silica concentrations in Figure 8-5 therefore appears to be consistent with the presence of volcanic ash and opaline cement. The higher silica concentration in groundwaters occur in the Ogallala aquifer, where the Pliocene ash and opal comprise a greater percentage of the sediment than in the Pleistocene deposits. The discontinuous nature of the ash and opaline cemented rocks could explain the variations in silica concentrations within regions of Kansas.

Although the main component of the volcanic glass constituting most of the ash is silica, relatively large amounts of potassium are present. For example, Swineford, et al. (1955) reported the mean silica content of 48 samples of late Tertiary ash deposits in western Kansas and western Nebraska to be 71.0 percent by weight (as SiO_2). The mean K_2O concentration of these samples is 5.53 percent which substantially exceeds the mean Na_2O content of 1.62 percent. Leaching of the ash could release much potassium. Although some of the potassium could be adsorbed by clays present in the sediments or formed from the ash weathering (bentonite), much would remain in solution due to competition for exchange sites by calcium, magnesium and sodium present in the groundwater. Feldspar in the Pliocene and Pleistocene sediments of Kansas is predominantly potassic and its weathering could also be a source of potassium as well as of dissolved silica in groundwaters. Therefore, the Na/K ratios derived from the ash and feldspar leaching would be higher in sediments with greater amounts of these materials and give high temperatures computed from the

Na/K and Na-K-Ca geothermometers.

A map (Figure 8-7) of the weight ratio of dissolved potassium to total dissolved solids (TDS) shows a distribution of high and low values somewhat similar to those for dissolved silica concentrations (Figure 8-5) and the Na-K-Ca geothermometer temperatures (Figure 8-4). Nearly all of the higher K/TDS ratios (>0.016) are located in northwestern and parts of west-central Kansas, with the highest values (>0.24) in a zone near the Nebraska border. Low ratios are found in the Arkansas River valley, the Equus Beds, and the eastern half of the Great Bend Prairie. Thus, the distribution of Na-K-Ca geothermometer temperatures could also be explained largely on the basis of sediment geochemistry rather than the circulation of deeper, warmer waters.

CONCLUSIONS

1. Geothermal temperatures computed from five chemical geothermometers for irrigation well waters from Kansas ranged widely. The chalcedony and Na-K-Ca geothermometers gave the most reasonable temperatures, ranging from $5-88^{\circ}\text{C}$ and from $3-86^{\circ}\text{C}$, respectively. Higher temperatures computed from both equations were distributed throughout northwestern Kansas and extended into the west-central part of the state. Quartz geothermometer temperatures were too high, Na/K equation temperatures much too high, and temperatures from a Na-K-Ca geothermometer modified for carbon dioxide generally much too low to be reasonable, including many values below 0°C .

2. The correlations between chalcedony geothermometer temperatures and both subsurface temperatures and geothermal gradients at 300 meters

derived from thermal logging of boreholes are statistically highly significant. Correlation coefficients are 0.68 in both cases. The distribution of the subsurface temperatures and geothermal gradients is similar to that for the geothermometer temperatures; higher values occur in northwestern and extend into west-central Kansas. The association between the chalcedony geothermometer temperatures and subsurface temperatures at 300 meters computed from bottom-hole temperatures of oil and gas wells is highly significant, but has a correlation coefficient of only 0.33.

3. The geochemistry of sediments in the aquifers, which are less than 200 meters in depth, appears to be the major control on dissolved silica and cation concentrations and, thus, the geothermometer temperatures computed from these concentrations. The Pliocene strata of the Ogallala aquifer generally contain a greater percentage of volcanic ash than the Pleistocene sediments across Kansas. Larger deposits of silicified rock cemented with opal (derived from ash leaching) occur in the northern part than elsewhere in the Ogallala Formation of western Kansas. The greater volumes of ash and opal (both containing silica more soluble than chalcedony and quartz) give rise to the higher silica concentrations in groundwaters of northwest and parts of west-central Kansas. Leaching of the potassium-rich ash and feldspar in the Ogallala aquifer could explain a similar distribution of higher ratios of dissolved potassium to total dissolved solids.

The areas of greater dissolved silica and K/TDS values also coincide with the regions of higher subsurface temperatures and heat flows under the Ogallala aquifer as determined from the measurements of Stavnes

(Chapter 2, this report) and the calculations of Swanberg and Morgan (1981), respectively. The higher temperatures underneath the northern half of the Ogallala may have increased the leaching of siliceous sediments. Thus, the effects of greater amounts of more soluble siliceous sediments and higher subsurface temperatures may have combined to give the areas of higher geothermometer temperatures. If the locations of larger ash and opal volumes in the aquifer sediments did not coincide with the region of higher temperatures, the distribution of geothermometer temperatures would be expected to conflict with the temperature distribution, for the sediment geochemistry is the more important control on groundwater composition.

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FIGURE CAPTIONS

- FIGURE 8-1: Area of study.
- FIGURE 8-2: Distribution of quartz geothermometer temperatures.
- FIGURE 8-3: Distribution of chalcedony geothermometer temperatures.
- FIGURE 8-4: Distribution of Na-K-Ca geothermometer temperatures.
- FIGURE 8-5: Distribution of dissolved silica concentrations.
- FIGURE 8-6: Volcanic ash, siliceous rock, and related deposits of Kansas. Information compiled from Jewett and Schoewe, 1942; Carey, et al., 1952.
- FIGURE 8-7: Distribution of the weight ratio of dissolved potassium to total dissolved solids.

GENERAL AVAILABILITY OF GROUND WATER IN KANSAS

FIGURE 8-1

QUARTZ GEOTHERMOMETER TEMPERATURES, °C

Western 2/3 of Kansas is shown
 Contour Interval 20°C
 Lambert conformal conical projection

0 10 20 30 40 50 Miles
 0 20 40 60 80 Kilometers

FIGURE 8-2

CHALCEDONY GEOTHERMOMETER TEMPERATURES, °C

Western 2/3 of Kansas is shown
 Contour Interval 20°C
 Lambert conformal conical projection

FIGURE 8-3

NA - K - CA GEOTHERMOMETER TEMPERATURES, °C

Western 2/3 of Kansas is shown

Contour Interval 20°C

Lambert conformal conical projection

FIGURE 8-4

SILICA CONCENTRATIONS, mg/L

Western 2/3 of Kansas is shown
Contour Interval 15 mg/L
Lambert conformal conical projection

0 10 20 30 40 50 Miles
0 20 40 60 80 Kilometers

FIGURE 8-5

VOLCANIC ASH, SILICEOUS ROCK AND RELATED DEPOSITS OF KANSAS

FIGURE 8-6

RATIO OF POTASSIUM, mg/L, TO TOTAL DISSOLVED SOLIDS, mg/L

0 10 20 30 40 50 Miles
0 20 40 60 80 Kilometers

FIGURE 8-7

CONCLUSIONS

Geothermal gradients measured for this report and data from oil well records indicate that geothermal resources in Kansas are of a low-grade nature. However, considerable variation in the gradient is noted statewide within the upper 500 meters of the sedimentary section; this suggests the feasibility of using groundwater for space heating by means of heat pumps.

The silica geothermometer data indicate an area of high dissolved silica content in northwestern Kansas that is consistent with silica content derived from volcanic ash deposits or, perhaps, from the siliceous Ogallala aquifer. The presence of a high temperature source for subsurface waters in northwestern Kansas cannot be inferred from their silica geothermometry.

The gravity and aeromagnetic data are valuable assets in basement geologic interpretation. Yarger has shown in his reports that a complex Precambrian history is recorded in the Kansas crust. His conclusions suggest that the Wichita aeromagnetic low and the southern extension of the MGA are possible future sites for deep geothermal exploration if the Hot Dry Rock Project is shown to have long-term profit potential.

Preliminary analyses of data from the Consortium for Continental Reflection Profiling (COCORP) indicate a probable thickness of as much as 3 to 4 km for the Rice Formation, a Precambrian arkosic unit that flanks the MGA. Yarger's modeling of gravity and aeromagnetic data indicates a similar thickness for the Rice Formation as the COCORP data. The possible development of the Rice Formation as a geothermal aquifer cannot be ruled out at this time. The water quality and transmissivity of the the aquifer are, however, unknown.

None of the presently available data lead us to believe that geothermal gradients below 1 km depth exceed 30 to 40 °C/km.

Additional conclusions are enumerated by individual authors.