Paleomagnetism of granitic intrusives from the basement under eastern Kansas

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Abstract

The Precambrian basement under east-central Kansas was drilled at two circular aeromagnetic positives, one at Osawatomie and one at Big Springs. The core retrieved from these sites is a coarse- to medium-grained granite which has been dated by U-Pb to be 1,350 m.y. old. The paleomagnetism of these azimuthally unoriented cores was studied to see if a technique which uses low-coercivity, low-temperature magnetization components to orient the cores would allow an independent confirmation of the core's mid-Proterozoic age. Orthogonal-projection plots of the alternating field (af) and thermal-demagnetization data show that the magnetization of these cores is relatively simple. Both cores have a low-temperature/low-coercivity magnetization with steep positive inclinations. The Osawatomie core's characteristic magnetization has a shallow, negative inclination, and the Big Springs core has a positive, moderate-inclination characteristic magnetization. If the declination of the low-temperature/low-coercivity component is aligned parallel to the present field declination, the characteristic directions may be azimuthally oriented. This allows the calculation of paleomagnetic poles for the Big Springs core (lat. = 4.5°S, long. = 29.9°E) and the Osawatomie core (lat. = 20.2°N, long. = 39.3°E), which are consistent with Irving's (1979) apparent polar-wander path for Laurentia at about 1,300-1,400 m.y.

Introduction

A recently completed aeromagnetic survey of Kansas (Yarger, 1981) shows a series of very striking circular aeromagnetic highs about 15 km (9 mi) in diameter in northeastern and central eastern Kansas. In late 1979 and early 1980, the Kansas Geological Survey successfully drilled into the Precambrian basement at two of these aeromagnetic anomalies, one at Osawatomie and one at Big Springs, Kansas (Steeples and Bickford, 1981; fig. 1). The original objectives of this project were to determine if the basement rocks at the aeromagnetic highs were magnetically susceptible enough to produce the observed anomalies, to study the rocks' petrography, and to radiogenically date the basement. Even though unoriented core was collected at these sites, it was hoped that by using the rock's present field-magnetic overprints (Van der Voo and Watts, 1978), the core could be oriented. If this technique were successful, it might allow independent confirmation of the approximately 1,350-m.y. U-Pb ages of these samples. A more complete report on this study, including rock-magnetic results, is published in the Geophysical Journal of the Royal Astronomical Society (Kodama, 1984).

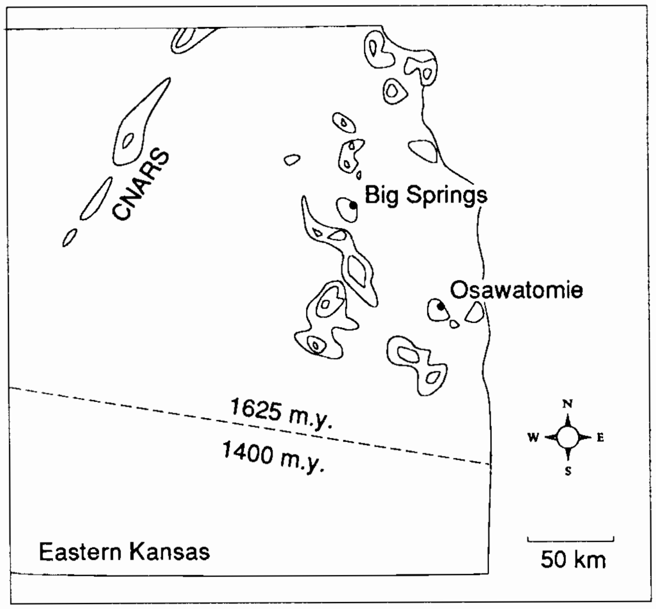


FIGURE 1—Map, adapted from Yarger (1981), of eastern Kansas showing location of aeromagnetic positives and Kansas Geological Survey drill sites. Dashed line shows postulated boundary between 1,625-m.y. and 1,400-m.y. basement rocks. CNARS, Central North American rift system. All contours show total magnetic field 1,600 nT from Yarger's (1981) map; contour interval 200 nT.

Geology

The Precambrian basement of Kansas is divided into two terrains; an older terrain of mesozonal granitic rocks (1,625 m.y.) which underlies the northern half of the state and a younger terrain (1,400 m.y.) of epizonal granitic and silicic volcanic rocks to the south (Van Schmus and Bickford, 1981). The Kansas Geological Survey drill cores suggest that the aeromagnetic highs are caused by granitic, intrusive bodies emplaced in the older, northern terrain. The 1,339±12 m.y. U-Pb age for the Big Springs core and 1,361±6 m.y. age for the Osawatomie core (Steeples and Bickford, 1981) indicate that these granitic bodies are approximately the same age as the southern terrain. Some authors have suggested that the boundary between the southern and northern terrains marks a mid-Proterozoic (~1,300 m.y.) convergence zone (Van Schmus and Bickford, 1981). This boundary is marked geophysically by a northwest-trending, linear band of aeromagnetic lows (Yarger, 1981). The Central North American rift system (Ocola and Meyer, 1973), a possible aborted Keweenawan-age rift (~1,100 m.y.), trends southwest-northeast about 120 km (72 mi) to the west of the aeromagnetic highs.

Petrographically, the Osawatomie core is coarse grained with microcline-perthite, plagioclase, quartz, biotite, and some muscovite (Steeples and Bickford, 1981). It has 2% magnetite by weight (Steeples, 1980). The Big Springs core is medium grained and mineralogically almost identical to the Osawatomie core, except that it lacks large microcline-perthite grains (Steeples and Bickford, 1981).

Sampling and measurement

A 7-m (22-ft)-long core of Precambrian basement was successfully retrieved at the Osawatomie drill site. The top of this core was drilled at a depth of 658.1 m (2,171.7 ft) below the surface. Nine samples (6.4 cm diameter by 5.2 cm long [2.6 x 2.1 inches]) were provided for paleomagnetic studies. The nine samples were taken from the core in three groups of three samples; one group from the top of the core, one at a depth of 4.6 m (15.2 ft) in the core, and one at the bottom of the core (fig. 2). In each three-sample group, the samples were cut from the core directly adjacent to each other and were given a relative azimuthal orientation. The three separate groups of samples were not oriented azimuthally with respect to each other.

For remanence-measurement and demagnetization studies, at least two 2.5-cm (1-inch)-diameter by 2.5-cm (1-inch)-long specimens were drilled from each sample, one for thermal demagnetization and at least one for alternating-field (af) demagnetization. If more than two specimens were drilled, the additonal specimens were af demagnetized.

At Big Springs, Kansas, a 3-m (10-ft)-long core of Precambrian basement was retrieved from a depth of 905 m (2,987 ft) below the surface. Seven 8.6-cm-diameter by 5-cm-thick (3.2 x 2-inch) samples were provided for paleomagnetic studies. Samples 1, 2, 3, and 4 were taken at relatively evenly spaced intervals from the core and were not oriented azimuthally with respect to each other (fig. 2). Samples A1, A2, and A3 were cut from a 1.1-m (3.6-ft)-long segment of core between samples 2 and 3 and could therefore be azimuthally oriented with respect to each other. Sample A1 was directly adjacent to sample 2, and A3 was directly adjacent to sample 3. Four specimens were drilled from each sample, two for af demagnetization and two for thermal demagnetization.

In addition to remanence, bulk susceptibility was measured for samples from the Osawatomie and Big Springs cores. One 2.5-cm-diameter by 5-cm-long (1 x 2 inch) specimen from each of the nine Osawatomie samples and from Big Springs samples 1, 2, 3, and 4 were used for these studies.

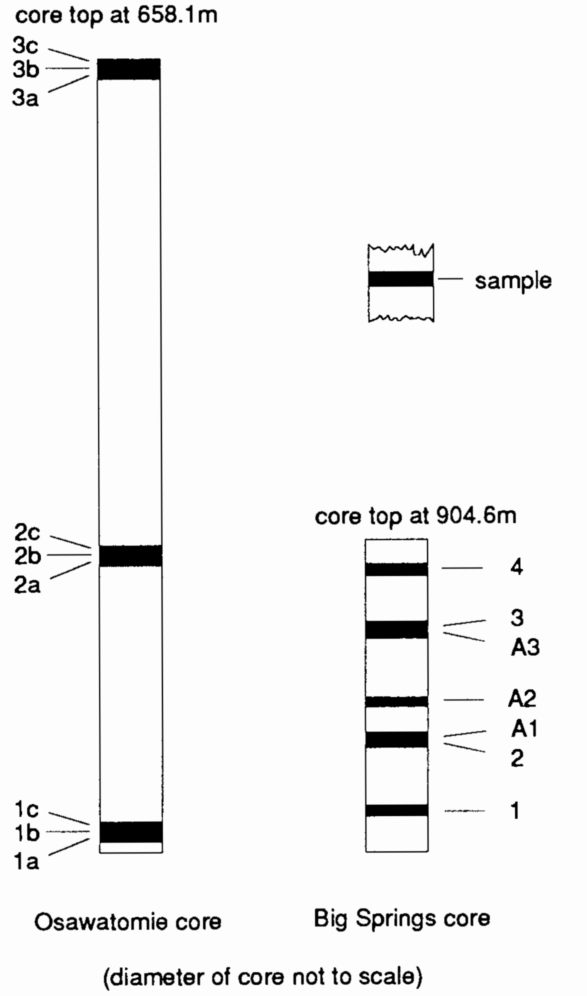


FIGURE 2—Sample localities in the 7-m (23-ft)-long Osawatomie core and in the 3-m (10-ft)-long Big Springs core.

Remanence measurements were made on both Digico and homemade digitized, fluxgate-spinner magnetometers. Thermal demagnetization was conducted with a mu-metal shielded oven where the ambient magnetic field was less than 5 nT. Af demagetization was carried out with both a Schonstedt GSD-1 and a two-axis, tumbling Inductrol-controlled apparatus. When the tumbling af demagnetizer was used to demagnetize the natural remanent magnetization (NRM), a sample was redemagnetized and remeasured at each demagnetization step after being rotated in the demagnetizer reference frame to average out the effects of rotational remanent magnetization (RRM). In the rock-magnetic experiments, a sample was only demagnetized once at each demagnetization step. Susceptibility measurements were made with a Bison susceptibility bridge.

Magnetization

All magnetizations were measured in an arbitrary, horizontal reference frame; however, since the cores were drilled within 5° of vertical (Don Steeples, personal communication, 1982), the vertical axis of each sample was known. The orthogonal projections (Zijderveld, 1967) that were used to analyze the sample's demagnetization behavior were therefore plotted in a reference frame in which the Z axis does represent the true vertical, but the horizontal axes have an unknown orientation with respect to north. In an orthogonal projection, if the points which represent the heads of magnetization vectors at different demagnetized steps trend univectorially to the origin, this suggests that only this magnetization remains in the rock. This characteristic direction may be calculated by vector subtraction or by a least-squares fit of points defining a univectorial decay to the origin. The directions of the secondary magnetic components may also be calculated by vector subtraction of the points which define a straight line that does not trend toward the origin. These techniques were used to analyze the data.

The susceptibility and NRM intensity data have relatively high values for these granitic intrusives (Osawatomie, K = 0.0344 SI units, NRM = 2.81 A/m; Big Springs K = 0.0340 SI units, NRM = 0.516 A/m; table 1). Average Koenigsberger ratios for the Osawatomie and Big Springs material are 2.05 and 0.38, respectively. The unoriented NRM directions for the Big Springs core have inclinations that range from nearly vertically downward to +45°, whereas the Osawatomie's NRM's are almost all vertically downward (fig. 3).

Alternating field demagnetization of the Osawatomie samples does not show the complex multivectorial behavior typical for rocks of this age. The magnetization of these samples is essentially dominated by two components, a low-coercivity component, which has steep positive inclinations, and the characteristic magnetization which has shallow, negative inclinations (fig. 4). The steep, low-coercivity magnetization is generally removed by demagnetization fields of approximately 30 mT; the characteristic magnetization is removed by fields between 40 mT and 80 mT and is isolated only after 95–99% of the NRM is removed (fig. 4). These two magnetizations are seen consistently in almost every sample. Some specimens (five out of 14) show an intermediate-coercivity magnetization (20–40 mT), but this magnetization varies in direction from specimen to specimen (fig. 4). Occasionally samples contain a very low coercivity component of magnetization (fig. 4).

Thermal demagnetization was only able to remove the steep, positive-inclination NRM directions from three of the nine Osawatomie samples. In these three cases (one sample from each group of three samples), the high-temperature (~525°C; ~977°F) characteristic directions agreed with the

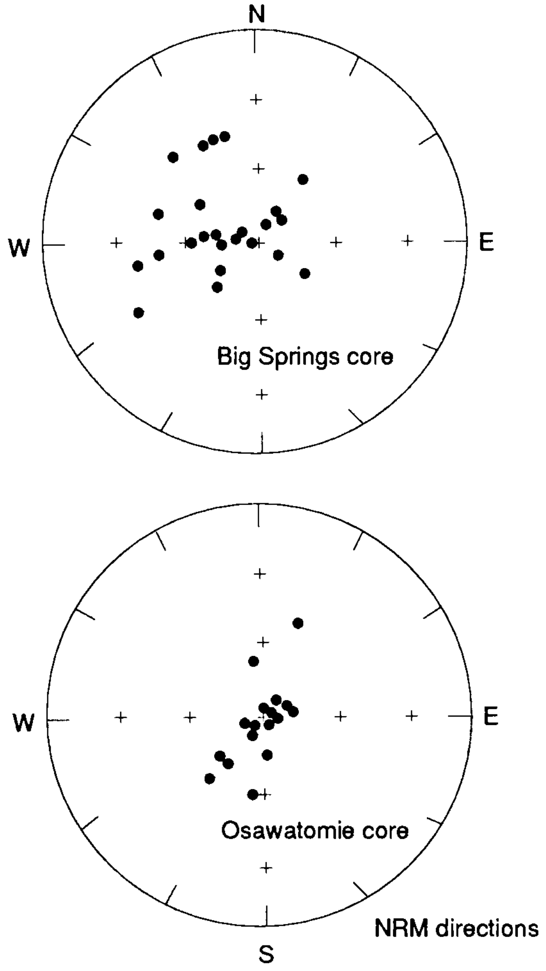


FIGURE 3—NRM DIRECTIONS MEASURED IN ARBITRARY REFERENCE FRAMES. Note that the Osawatomie core has much steeper NRM directions than the Big Springs core.

TABLE 1—Bulk-susceptibility and NRM-intensity data for the Osawatomie and Big Springs cores.

Sample	Bulk susceptibility X 4π (SI units)	NRM intensity (A/m)
	Osawatomie core	
1a	3.146-3	5.82
1b	2.400-3	2.60
1c	2.676-3	3.69
2a	2.988-3	3.00
2b	1.907-3	1.75
2c	2.869-3	2.80
3a	2.944-3	2.16
3b	3.576-3	2.29
3c	2.118-3	1.18
	Big Springs core	
1	3.936-3	8.83-1
2	2.209-3	1.81-1
3	1.044-3	2.78-1
4	3.622-3	7.20-1

sample's af demagnetization characteristic giving shallow, negative inclinations. These samples lost all their magnetization at about 580°C (1076°F). Low-temperature components that were removed between 100°C (212°F) and 300°C (572°F) for eight samples agreed in direction with what had been identified as their low-coercivity magnetizations.

In each group of three samples which had relative azimuthal orientations, there was directional agreement between the low- temperature and low-coercivity components within a sample (K 40.2; alpha 95 = 11.6°) and between the samples (K 72.8; alpha 95 = 11.4°). The thermal- and af-characteristic directions between the three samples in a group also agreed. The same declination difference between the mean characteristic direction and the mean low-coercivity/low-temperature component in a group was observed in each of the three groups. The high-temperature/high-coercivity characteristic components have declinations which are about 30° clockwise from the low-temperature/low-coercivity component declinations (fig. 5).

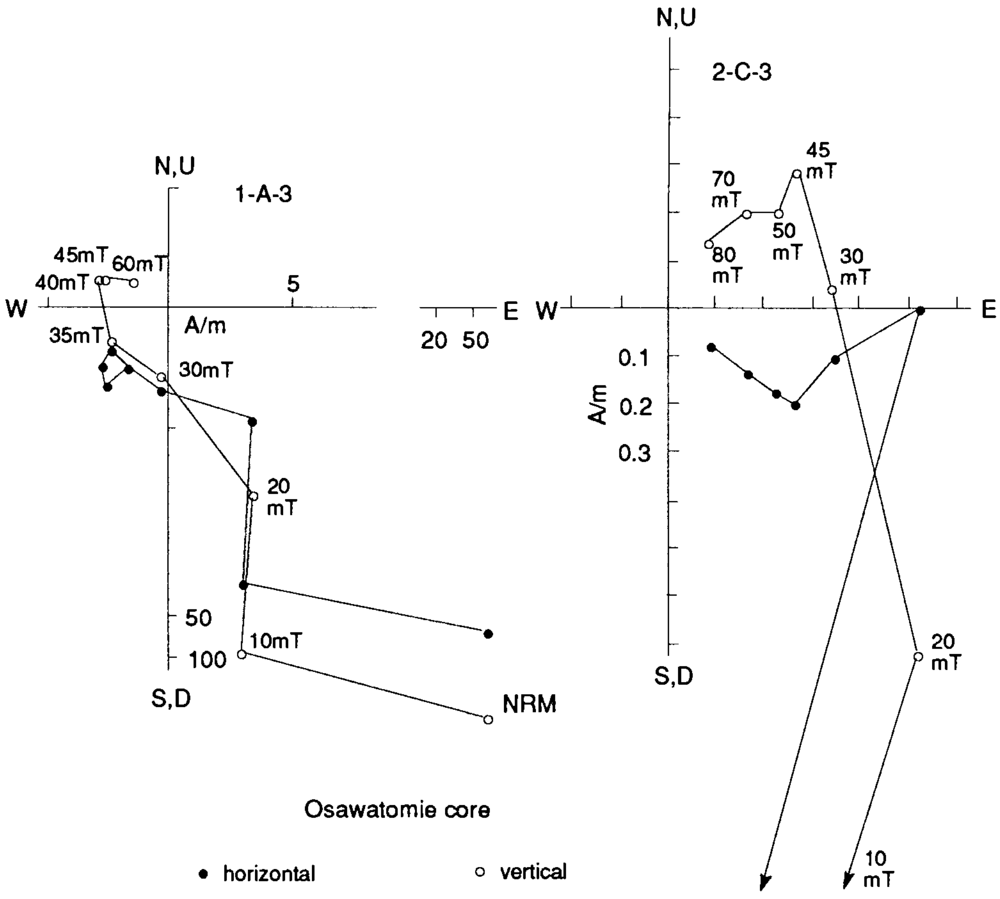


FIGURE 4—Orthogonal projections (Zijderveld, 1967) of af demagnetization data from the Osawatomie core. Sample 1-A-3 shows a very low coercivity component from 0 to 10 mT, probably acquired during storage; the present field component removed between 10 mT and 20 mT; an intermediate coercivity component removed between 20 mT and 40 mT, which does not represent a direction consistently seen in all samples; and the characteristic magnetization removed from 45 to 60 mT. Sample 2-C-3 shows only the present field component (20–45 mT), the characteristic magnetization (45-80 mT), and a storage field (20 mT). Azimuthal orientation of these samples is arbitrary. Note low, negative inclinations for characteristic directions.

Af demagnetization of the Big Springs core produced relatively simple orthogonal projections (Zijderveld, 1967), in which low-coercivity and high-coercivity components of magnetization are evident (fig. 6). The high-coercivity component is the characteristic direction and has positive inclinations of about 45° to 50°. It is removed by af fields from 10 mT to 60 mT and comprises only 1–5% of the NRM. The low-coercivity component generally has steeper positive inclinations (65–80°) and is removed by fields less than 10 mT. In some samples a very low coercivity component (specimen A–3–1 and A–1–1, fig. 6) was removed by fields smaller than 2.5 mT.

Thermal demagnetization produced results similar to af demagnetization for the Big Springs core. The characteristic directions were removed by temperatures from 300°C to 575°C (572–1067°F) and had +45° to +50° inclinations. The af- and thermal-characteristic directions agreed within one sample (see specimens 1–C–1 and 1–B, fig. 6). A steep-inclination, low-temperature component also was evident in these samples. This low-temperature component was removed by temperatures ~300°C (572°F) and had the same direction as the low-coercivity magnetization in a sample (specimens 1–C–1 and 1–B, fig. 6). The Big Springs samples lost all their magnetization when heated to temperatures above 580°C (1076°F).

Paleomagnetic poles for the Osawatomie and Big Springs cores

Since these cores are not azimuthally oriented, the only information about the location of the paleomagnetic poles for these rocks would be that they lie on small circles centered on the sampling sites with radii calculated from the cores' average inclination (eg., Kean and Swingen, 1976). Since simple arithmetical averaging of inclinations tends to underestimate the inclination (Peirce, 1976), the mean inclination values used for the small circle calculations (Big Springs core [+49°] and Osawatomie core [-32°]) were obtained using the method of Briden and Ward (1966). The small circles calculated intersect Irving's (1979) apparent polar-wander (apw) path for Laurentia at times which correspond to the U-Pb ages for the cores (fig. 8). Since the apw in the mid-Proterozoic loops back on itself four times, there is an obvious ambiguity in this result.

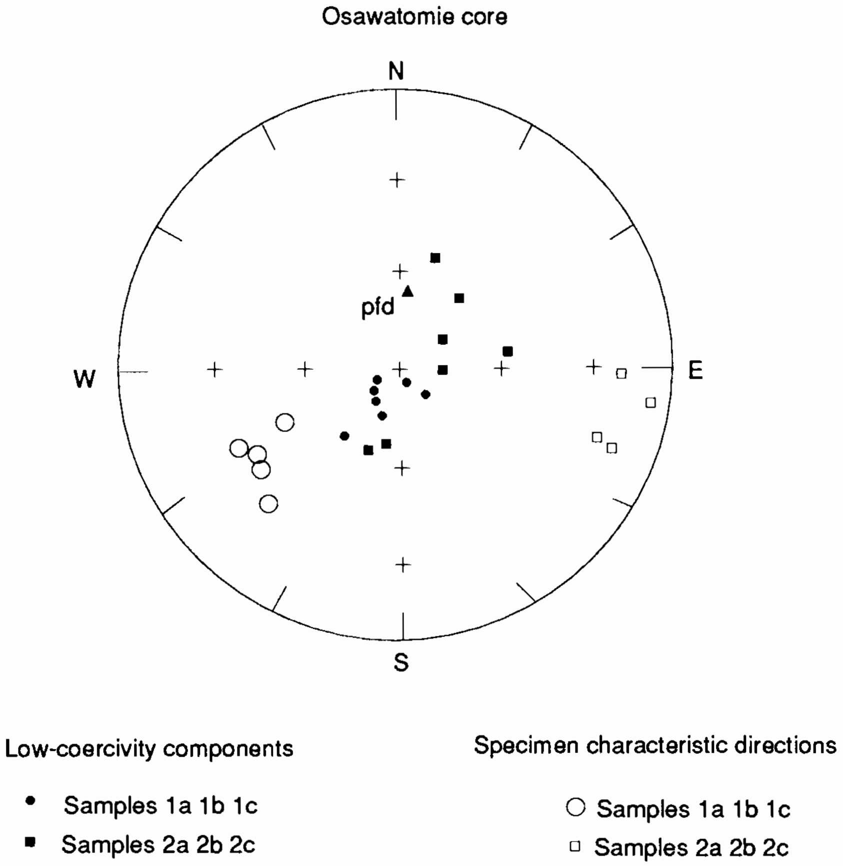


FIGURE 5—Relationship between low-coercivity magnetization components and characterisitic directions for sample groups from the Osawatomie core. Note that the characteristic magnetizations have declinations about 30° clockwise from the low-coercivity components. Open symbols are upper hemisphere, closed symbols are lower hemisphere, pfd = present field direction.

In order to maximize the information contained in the data, the low-coercivity/low-temperature components isolated during demagnetization were assumed to be present field direction (I = 68°, D = 8°) magnetic overprints (Van der Voo and Watts, 1978). Using this procedure the cores may be oriented in the horizontal plane.

As pointed out in the previous section, the low-temperature/low-coercivity mean direction for each relatively oriented group of three samples in the Osawatomie core has a declination approximately 30° less than the declination for the group's mean characteristic direction. When the declination of the low-temperature/low-coercivity component for each group is aligned parallel to the present field declination, it is possible to orient the characteristic directions for this core and arrive at a mean direction of I = -31.9°, D = 44.8° (K =24.3, α5 = 9.5°, N = 9; fig. 7). This mean direction has parameters which agree closely with estimates based on the method of Briden and Ward (1966; I = -32°, K = 22) calculated from inclination data. The direction corresponds to a paleomagnetic pole of lat. = 20.2°N., long. = 39.3°E. (δm = 10.7, δp = 9.0; fig. 8).

The use of this technique to orient the Big Springs core was not as straightforward. Samples 1, 2, 3, and 4 from the Big Springs core were demagnetized within four months of the core's drilling. Sample 3's low-temperature/low-coercivity magnetization had very low inclinations, so it was assumed that it could not have been acquired parallel to the present field at Kansas. Samples 1, 2, and 4 had high, positive-inclination low-temperature/low-coercivity magnetization components. When the declinations of these magnetizations were aligned parallel to the present field declination, the characteristic directions clustered near to D = 245°.

Samples A1, A2, and A3 were not demagnetized until 1.5–2 yrs after the core was drilled. They had been stored in random orientations for 1 yr during this period. These three samples had been oriented relative to each other when cut from the core; however, the directions of their low-temperature/low-coercivity components were different and would not align these samples' characteristic directions with the characteristic directions of samples 1, 2, and 4.

Samples A1, A2, and A3, then, could not be oriented by their low-temperature/low-coercivity magnetizations. Since sample A1 was cut from the core directly adjacent to sample 2, these two samples could be oriented relative to each other by a driller's scratch mark. Samples 2, A1, A2, A3, and 3 now had relative azimuthal orientation, but their absolute

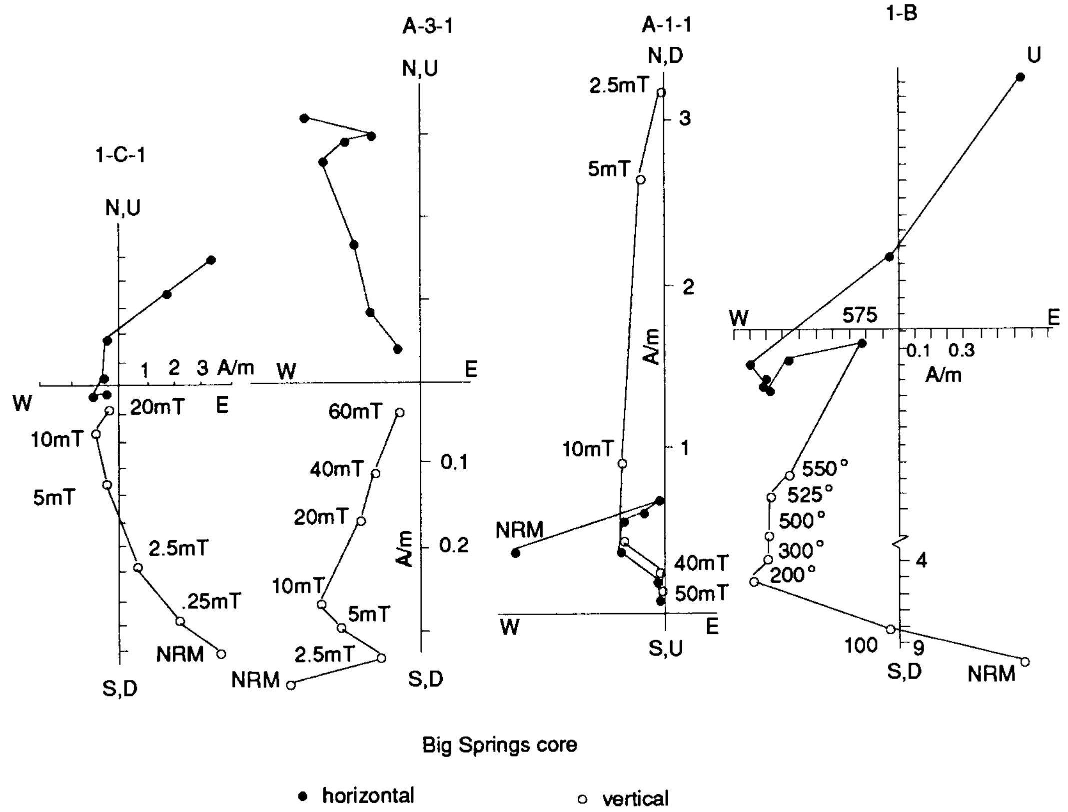


FIGURE 6—Orthogonal projections (Zijderveld, 1967) for demagnetization data for the Big Springs core. Both thermal and af data show the same horizontal component relationship between low-temperature (20–200°C; 68–392°F T_B)/low-coercivity (2.5 nT–10 mT H_{CR}) magnetizations, and characteristic magnetizations, i.e. the present field magnetizations have declinations which point 90° clockwise from the final directions.

orientation was based only on the low-temperature/low-coercivity magnetizations of sample 2. So as not to weight too heavily the present field directions of sample 2 in calculating the final mean direction for the Big Springs core, the mean direction of samples 2, A1, A2, A3, and 3 was combined with the characteristic directions of samples 1 and 4. This hierarchial averaging scheme gave a Big Springs magnetization direction of I = 49.0°, D = 249.6° (K = 51.4, $\alpha 5$ = 11.3°; fig. 7), agreeing with Briden and Ward's (1966) inclination estimate of 49° and having a K which lies within the error bounds of the K estimated by the Briden and Ward method (K = 79±66). The paleomagnetic pole corresponding to the mean direction is located at lat. = 4.5°S., long. = 29.9°E. (δm = 14.9°, δp = 14.1°; fig. 8).

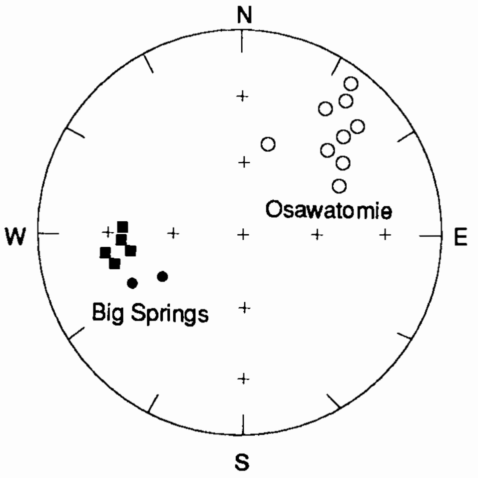
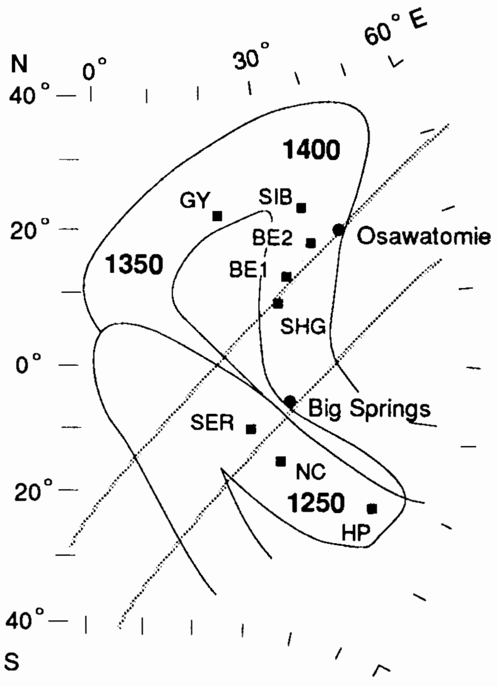


FIGURE 7—Characteristic magnetizations azimuthally oriented by aligning the declination of low-field, low-temperature magnetizations parallel to the declination of the present field at Kansas.



awp from Irving (1979)

FIGURE 8—Location of the Osawatomie and Big Springs paleomagnetic poles on Irving's (1979) mid-Proterozoic apparent polar-wander path for Laurentia. Small circles trending northeast-southwest are the locus of points on which the Osawatomie and Big Springs poles could lie given just the inclination information in the cores. Other poles are from Irving (1979). SIB, Sibley Group red beds; BE1 and BE2, Belt Series, Alta.-Montana; SHG, Sherman granite, Colorado; SER, Seal Lake Group red beds; NC, Nain Anorthosite Complex, Labrador; HP, Harp dikes, Labrador; and GY, Grand Canyon Supergroup, Arizona.

Discussion

The relatively high Koenigsberger ratio for the Osawatomie core ($Q_n = 2.05$) may suggest that it has a greater paleomagnetic stability than the Big Springs core ($Q_n = 0.38$); however, this interpretation is probably oversimplified. Since this core has the largest crystalline grain size of the two cores, its Q_n would be expected to be lower than the Big Springs Q_n because the Osawatomie probably contains more coarse-grained, multidomain magnetite. The average susceptibilities of the two cores are nearly identical (Osawatomie, K = 0.00344 SI units; Big Springs, K = 0.00340 SI units). The difference in Koenigsberger ratio comes entirely from the higher average NRM intensity for the Osawatomie core. This makes the Osawatomie NRM intensity suspect.

In addition to its high intensity, the Osawatomie's NRM has very steep inclinations which are removed by af demagnetization fields of 10 mT but are not removed by thermal demagnetization as high as 580°C (1076°F). The Big Springs material has NRM inclinations which are close to the present field-direction inclination (~68°). They are removed easily by both af and thermal demagnetization. This disparity in behavior would suggest that the Osawatomie core acquired a remanence during drilling parallel to the core axis.

One possible explanation for the secondary vertical component in the Osawatomie core is that it is a piezoremanent magnetization (PRM). Carmichael (1968) has shown for single-crystal magnetite rods that the resistance of PRM to af demagnetization is greater than that of an IRM. In addition, the PRM is generally larger than the IRM for the same direct field. Rock-magnetic experiments (Kodama, 1984) show that the Osawatomie overprint behaves as an IRM but is much more resistant to af demagnetization than IRM's which are experimentally induced in fields that might be expected to be caused by the drilling apparatus. The presence of the PRM does not invalidate the use of the Osawatomie low-coercivity/low-temperature component to azimuthally orient the core since a PRM applied exactly parallel to the core's axis would not affect the horizontal component of the low-coercivity/low-temperature present field magnetization. Declination information would still be retrievable; however, its accuracy may be decreased if the PRM was not applied exactly parallel to the core axis. It is not clear why the Osawatomie core acquired a PRM during drilling and the Big Springs core did not. Petrographically, the Osawatomie core is much coarser grained than the Big Springs core. This would suggest different magnetic grain-size distributions for the two cores and the potential for different magnetic behavior.

If the Osawatomie high NRM intensity is due primarily to a PRM overprint, its true Q_n is probably closer to that of the Big Springs core. This low Q_n (~0.38) is more consistent with the medium to coarse crystalline grain size for these rocks, which suggests a large multidomain component in the NRM. However, the resistance of a small part of the remanence (1–5%) to af demagnetization fields as high as 60–80 mT for both cores would suggest that the characteristic direction is carried by a very fine grained magnetic fraction which has high paleomagnetic stability.

The declination of the low-temperature/low-coercivity component was aligned parallel to the present field declination (D = 8°) rather than to the axial dipole declination (D = 0°) to orient these cores for the following reason: specimens which were demagnetized four months after the core was drilled had recognizable present-field, low-temperature/low-coercivity magnetization components; specimens demagnetized nearly 2 yrs later did not. This would suggest that the low-temperature/low-coercivity components have relaxation times of only 1 yr and they are more properly identified with present-field overprints. The very low coercivity component (~2.5 mT) seen in some samples (A–1–1 and A–3–1) is probably a viscous magnetization picked up during storage.

No tilt corrections were made to the characteristic directions when paleomagnetic poles were calculated because the early Paleozoic section directly above the Precambrian granitic basement has dips of <1°, indicating no major tectonic events in the Phanerozoic. Major tilting probably did not occur in the Precambrian because the granitic intrusives are undeformed and have been interpreted as having been emplaced in an anorogenic environment (Van Schmus and Bickford, 1981).

The paleomagnetic poles calculated for the Big Springs core and the Osawatomie core are nearly 25° apart, yet their radiogenic ages differ only by 22 m.y. If the pole positions and U-Pb ages are correct, this would necessitate a very high rate of polar wander at this time. It is more likely that the orientation technique was not totally accurate and that the poles should fall closer together. The small circles calculated from the inclination data are only 12° apart, which could reduce the required dipolar-wander rate. It is likely that the Osawatomie core's declination value may be slightly in error due to the PRM overprint the core probably acquired during drilling. Since the Big Springs core apparently did not acquire a PRM, its pole position is probably closer to the value that would be obtained from a conventionally oriented core.

The Big Springs paleomagnetic pole (1,339 m.y.) falls near several poles of the same age, the Seal Lake Group red beds (~1,350 m.y.; Roy and Fahrig, 1973); the Nain Anorthosite Complex, Labrador (~1,400 m.y.; Murthy, 1978); and the Harp Dikes, Labrador (~1,350 m.y.; Irving et al., 1977; fig. 8).

The Osawatomie pole (1,361 m.y.) should probably lie closer to the Big Springs pole for the reasons discussed above; however, it does fall close to several poles of nearly the same age, the Belt Series poles (BE1 and BE2 of Irving [1979]), which are estimated to be 1,400 m.y., the Sibley

Group red beds (1,370 m.y.; Robertson, 1973), the Grand Canyon Supergroup (~1,380 m.y.; GY of Irving, 1979), and the Sherman granite, Colorado (~1,410 m.y.; Eggler and Larson, 1968).

If Irving's (1979) polarity interpretation for the Proterozioc apw path is correct, Kansas was in the southern hemisphere during most of Keweenawan time. This implies that the Osawatomie core carries a normal polarity direction and the Big Springs core is reversed polarity. The presence of polarity reversals gives added support to the assumption that the characteristic directions are primary.

Conclusions

This study demonstrates that it can be possible to obtain reasonably accurate paleomagnetic poles from azimuthally unoriented core using a technique first described by Van der Voo and Watts (1978). Apparently, if demagnetization studies are conducted soon after drilling, the low-coercivity/low-temperature components of magnetization will allow a maximum amount of paleomagnetic information to be extracted from partially oriented cores. The data could aid in the age dating and correlation of the core materials and would be an important supplement to data typically collected on unoriented cores.

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