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PALEOMAGNETIC AND ROCK MAGNETIC PROPERTIES OF SANTA FE GROUP SEDIMENTS IN THE 98TH STREET CORE HOLE AND CORRELATIVE SURFACE EXPOSURES, ALBUQUERQUE BASIN, NEW MEXICO

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Abstract—Paleomagnetic and rock-magnetic results of upper to middle parts of the Neogene Santa Fe Group retrieved in the 457-m 98th Street core, west Albuquerque, were used to assess their age of deposition and their possible contributions to observed magnetic anomalies. Potentially correlative surface exposures in Arroyo Ojito, 40 km north of Albuquerque, were sampled to complement studies on the core material. For the 98th Street core, over 330 cube specimens (one per stratigraphic interval) were subjected to alternating field and limited thermal demagnetization to identify magnetic components and interpret polarity. For most Santa Fe materials, a phase of moderate coercivity, probably magnetite, carries the principal component of magnetization. The polarity of the interval retrieved is mainly normal, but specimens of reverse polarity cluster over three main intervals. A total of 21 apparent polarity zones are defined by at least two adjacent specimens of the same polarity. In the absence of independent age control, comparison of core polarity zonation to the geomagnetic polarity time scale does not yield a unique correlation. The dominance of normal polarity may be consistent with the sampled interval being part of several, closely spaced normal polarity subchrons that spanned 1–2 m.y. in middle Miocene to Pliocene time. Variation of magnetic properties within the core gives insight into potential contrasts of total magnetizations that control the aeromagnetic expression. Within the 98th Street core, magnetic susceptibility (MS) varies greatly, both in logs of whole-core MS (8.9E-5 to 6.7E-2 SI) and in individual specimens extracted from the core (4.8E-5 to 1.5E-2 SI). Likewise, natural remanent magnetization (NRM) intensity varies from 8.4E-4 to 2.7E-1 A/m. Both MS and NRM generally correlate with sediment grain size; the coarsest grained rocks have highest susceptibility and NRM intensity. Plots of both initial NRM and anhysteretic remanent magnetization (ARM) intensity versus MS define essentially single, continuous trends, implying a relatively uniform type of magnetic mineralogy that varies principally in concentration. Values of total magnetization from NRM and MS data indicate that Santa Fe Group sediments are capable of producing moderate to weak magnetic anomalies that have been identified in recent high resolution aeromagnetic surveys of the Albuquerque basin. Coarse-grained rocks have the highest total magnetization and greatest potential for generation of aeromagnetic anomalies where juxtaposed with fine sediments along faults.

INTRODUCTION

The 98th Street core hole was drilled on the west side of Albuquerque, New Mexico (35°05'32" N, 106°44'52" W), to provide key stratigraphic and hydraulic-property information for upper parts of the Santa Fe Group within the Albuquerque basin of the Rio Grande rift (Stone and Allen, 1998). The core hole was drilled cooperatively by the U.S. Geological Survey and the City of Albuquerque and investigated in collaboration with the New Mexico Bureau of Mines and Mineral Resources and the New Mexico Office of the State Engineer. Detrital sediment recovered in the core provides material for detailed investigation of magnetic properties of the upper and middle Santa Fe Group strata. Remanent magnetization has been studied in the core sediments to attempt to define a magnetic polarity zonation for the stratigraphic interval. Comparison of this polarity zonation to the geomagnetic polarity time scale (GPTS) has potential to provide close chronologic control. Variations among magnetic susceptibility (MS) and natural remanent magnetization (NRM) as well as a proxy for the concentration of magnetizable magnetic material (anhysteretic remanent magnetization (ARM)) give insight into the potential sources within the Santa Fe Group of aeromagnetic anomalies that have been detected in recent high-resolution surveys in the region (e.g., Grauch, 1998, 1999, this volume). This report summarizes magnetic properties obtained for the core sediments and gives some preliminary interpretations of their importance.

A total of 232 m of sediment, or about 50%, of the 457-m total depth was recovered during drilling (core diameter of 5 cm) of the 98th Street core hole in 1997 (Fig. 1). Stone and Allen (1998) proposed a fourfold division of the core sequence consisting of: (1) Quaternary eolian sand and valley-border alluvium from 0–8-m depths, (2) coarse-grained pebbly sandstone of the upper unit of the Santa Fe from 8–30-m depths, (3)

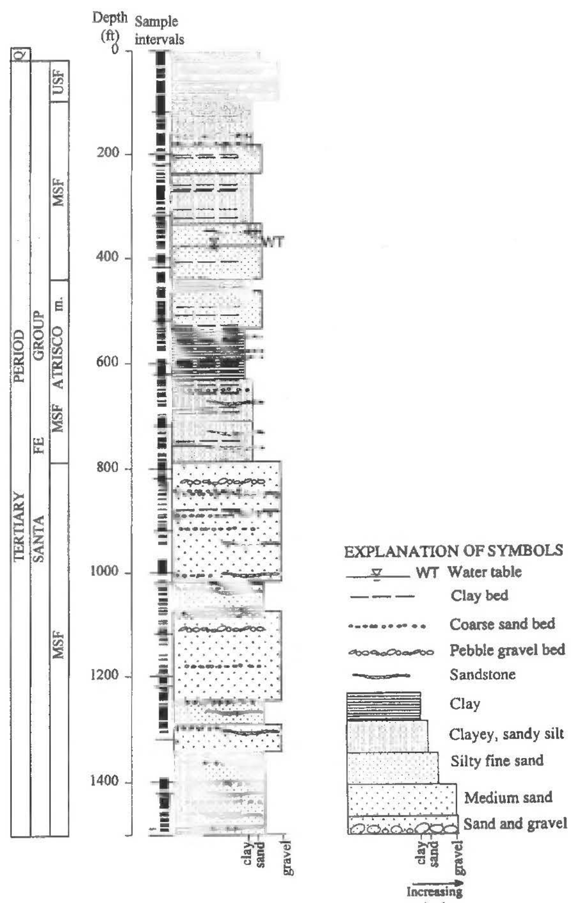

FIGURE 1. General stratigraphic column of the 98th Street core hole, adapted from Stone et al. (1998). Q, Quaternary; USF, upper unit of Santa Fe Group; MSF, middle unit of Santa Fe group; Atrisco m., Atrisco member of Connell et al. (1998).

a fine-grained interval tentatively correlated with the middle unit of Santa Fe from 30–240-m depths, and (4) a lower part of the middle Santa Fe unit from 240–457-m depths consisting of channel-fill medium sand and underlying sand, silt, and clay overbank deposits. The upper part of the middle unit of the Santa Fe Group contains thick laminated red and olive brown clay and silt deposits (148–240 m) within a laterally extensive unit named the "Atrisco member" (informal) by Connell et al. (1998).

The time period recorded by the 98th Street core interval is only broadly known. Coarse deposits of the upper Santa Fe Group unit are correlated with an integrated river system that was established within the Rio Grande rift before 4.5 Ma (Stone et al., 1998), suggesting this core unit is probably 4.5 Ma or younger. Stone et al. (1998) suggested that the middle unit of the Santa Fe in the core may correlate with middle Santa Fe sediments exposed about 22 km to the north at Loma Colorado. These strata contain vertebrate fossils that are Blancan (2.5–4.6 Ma) age (G. S. Morgan, personal comm., 1998).

METHODS

Discrete specimens for direct measurement (one specimen per stratigraphic interval) were taken from the core in the form of 7-cc nonmagnetic plastic cubes (Fig 1). Fine-grained sediments were preferentially sampled. The specimens were oriented vertically within cored segments but lack azimuthal orientation. Natural remanent magnetization (NRM) for the cube specimens (336 total) was measured with a three-axis superconducting magnetometer in a magnetically shielded room at the University of New Mexico. To assess the character and stability of the remanent magnetization, samples were subjected to progressive alternating-field (AF) demagnetization over 13 to 16 steps at peak fields ranging from 3 to 115 mT. All demagnetization results for samples were inspected on orthogonal vector diagrams to interpret their magnetic polarity and reliability. Directions of remanent magnetization components isolated by demagnetization were determined using principal component analysis (Kirschvink, 1980). Magnetic susceptibility for the cube specimens (total of 282) was measured using a commercial induction coil operating at about 750 Hz. Anhysteretic remanent magnetization was imparted using a 0.1 mT DC field in a peak alternating field of 95 mT. Magnetic susceptibility measurements were also made on whole-core segments employing a commercial pass-through induction coil operated at an 800 Hz frequency. A total of 1344 measurements were spaced through the 457-m core length. The coil sensed an approximate 5-cm core length centered about the coil midpoint. A more complete list of magnetic property data can be found in Hudson et al. (1998), although later recognition of a calibration error has led to revision of the MS values for some core samples and the interpretations derived from them.

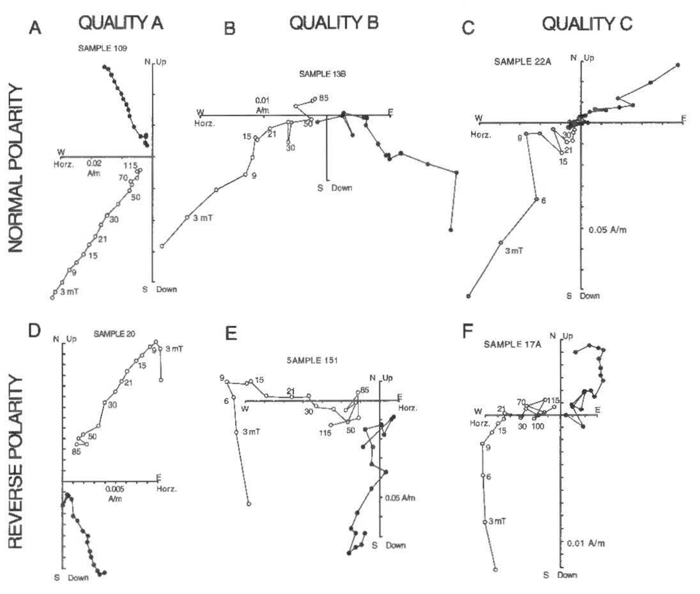

FIGURE 2. Representative orthogonal demagnetization diagrams (Zijderveld, 1967) summarizing our definition of quality of alternating field demagnetization behavior, using examples of the three different quality (**A**, **B**, and **C**) responses for specimens assigned normal and reversed polarities. Solid and open circles are projections on horizontal and vertical planes, respectively.

MAGNETIC POLARITY ZONATION

The demagnetization character of each specimen was examined on orthogonal vector diagrams (Fig. 2) to assign a magnetic polarity and an estimate of its quality (to which we assign A, B, or C). Greatest weight in assigning polarity was given to the demagnetization response over the interval between 15 and 115 mT. Strongly magnetic cubic spinel minerals such as magnetite, that would most likely carry a detrital remanence, typically are demagnetized over this interval. Many specimens also contained a low-coercivity, positive-inclination component of probable viscous origin that was removed by about 15 mT (Fig. 2C, E, F). After removal of the magnetite component by 115 mT, some specimens retained a high-coercivity component that is probably carried by hematite (Fig. 2E).

Specimen (interval) polarities were assigned a highest A quality if they had linear trajectories that trended toward the origin of vector diagrams and if most of their remanence was removed over the 15–115 mT interval (Fig. 2, A, D). Sixty-three percent of the specimens were classified as quality A (Fig. 3). Quality B specimens (24%) also had clear polarity but yielded either partly curved trajectories on vector diagrams or trajectories that did not trend toward the origin due to the presence of a high coercivity hematite component (Fig. 2E). Assigning polarities for quality C specimens (12.5%) was more subjective, either because they displayed erratic trajectories on vector diagrams (Fig. 2C) or because most of their remanence was dominated by a low-coercivity viscous component (Fig. 2F). For quality C specimens, we attempted to assign polarity on the basis of the inclination of the remanence removed

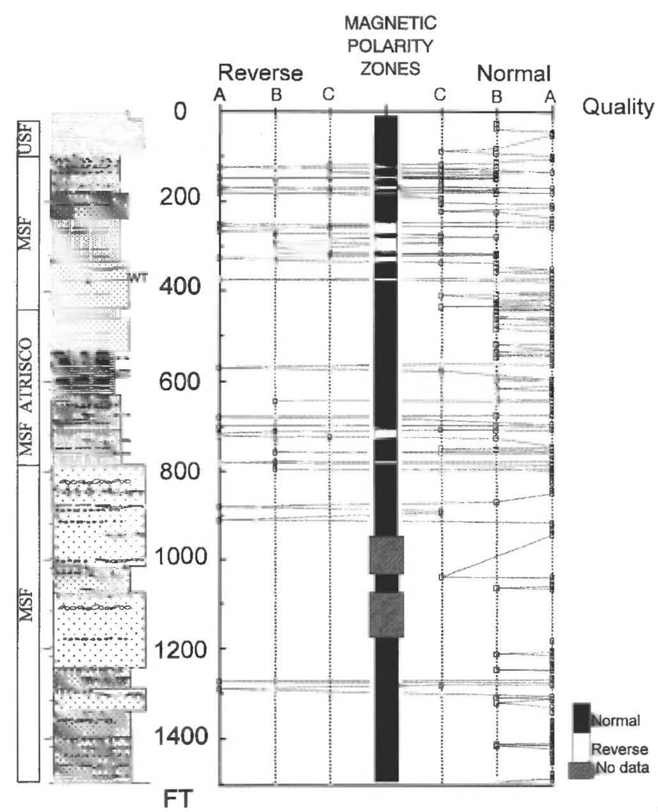

FIGURE 3. Interpretative magnetic polarity zonation for the 98th Street core. Polarity determinations of quality A, B, and C for individual specimens are identified by squares.

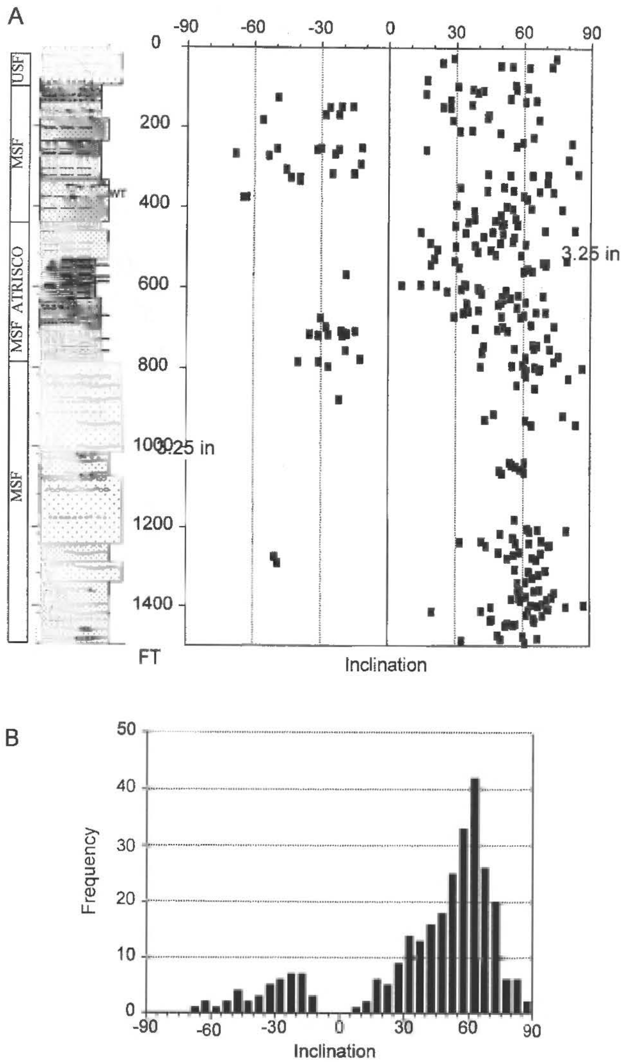

FIGURE 4. Inclinations of the moderate coercivity magnetization component, determined for specimens with A and B quality demagnetization behavior, versus **A**, depth, and **B**, frequency.

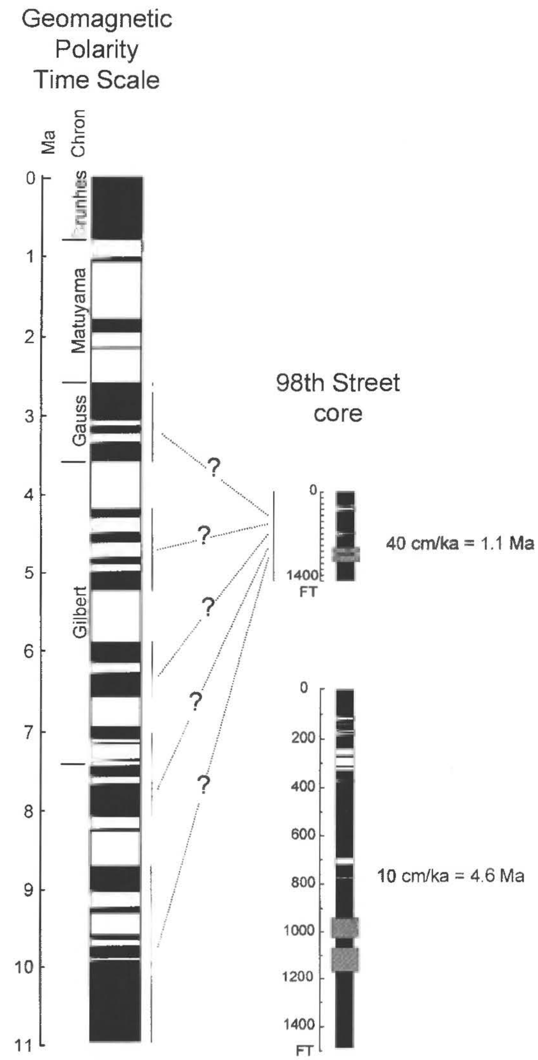

FIGURE 5. Geomagnetic polarity time scale for the last 11 Ma (Cande and Kent, 1995) compared to the polarity zonation for the 98th Street core plotted at scales of 10 cm/ka and 40 cm/ka.

over some limited demagnetization interval above about 15 mT. No polarity was assigned for two specimens yielding remanence with nearly horizontal inclination.

Inclination was determined by principal component analysis (typically using the 18–85-mT demagnetization interval) for the moderate-coercivity component in each specimen having A or B quality demagnetization behavior (Fig. 4). Positive inclinations (normal polarity) for these samples cluster most strongly between 50° and 70° (Fig. 4B), similar to time-averaged inclinations (53–55°) for normal-polarity paleofields from middle Miocene to present at the location. Negative inclinations (reverse polarity) average about –30°, and the inclination angles for many normal-polarity specimens are also <35°. Explanations for such low inclination values include shallowing of magnetization due to sediment compaction (e.g., Kodama and Sun, 1992) or, for reverse polarity, the incomplete separation of the magnetite component from a component of opposite polarity, such as a hard viscous component carried by pigment hematite (Dunlop and Stirling, 1977).

The magnetic polarity of specimens in the core (Fig. 3) is dominantly normal (83%), but specimens with reversed polarity cluster over three main depth intervals (37–46 m, 76–115 m, and 216–239 m). A total of 21 "apparent" polarity zones were defined to include intervals containing at least two adjacent specimens of the same polarity (Fig. 3). In addition to these polarity zones, several single specimens having polarity opposite to those of adjacent specimens were identified. These single-specimen polarity intervals could reflect short-lived transitional geomagnetic fields. Alternatively, sediment rotation due to core deformation, or simply a misorientation of core fragments, could readily explain these data.

The prevalence of normal-polarity magnetization, particularly in the lower part of the core, below about 122 m, prompts concern that the 98th Street core could have been remagnetized in the contemporary magnetic field during drilling. Paleomagnetic studies of other drill cores have detected low coercivity, steeply inclined, isothermal remanent magnetizations (IRM's) that were generated by fields aligned along axes of steel core barrels (e.g., Ade-Hall and Johnson, 1976). For the 98th Street core, however, the moderate inclinations (Fig. 4) and the range of coercivities typical of most magnetization components do not support a secondary IRM origin.

Comparison of the 98th Street core polarity zonation to the geomagnetic polarity time scale for the last 11 Ma (Cande and Kent, 1995) does not yield a unique, convincing correlation (Fig. 5). As defined by its polarity record, the time span recorded by the core interval should correlate with a one of several possible periods of closely spaced GPTS normal subchrons since the middle Miocene. If the correlation by Stone et al. (1998) of the middle unit of the Santa Fe in core to surface exposures at Loma Colorado (bearing Blancan fauna) is accepted, the core polarity zonation may correspond with closely spaced normal polarity subchrons of the Gauss chron between 2.6 and 3.6 Ma or within the upper Gilbert chron between 4.2 and 5.2 Ma (Fig. 5). Alternatively, the polarity zonation might correlate with older periods of closely spaced normal subchrons such as those at about 6–6.5 Ma, 7–8 Ma, or 9–11 Ma. Any hiatuses within the core sequence, such as at the base of the upper unit of the Santa Fe (Stone et al., 1988), will complicate correlation of the core polarity zonation to the GPTS. If each of the 21 apparent magnetozones were taken at face value to correspond to a different subchron in the GPTS, they would require an interval of at least 5 Ma. Such a direct correlation is not favored, however, because of the poor correspondence of relative lengths of normal and reversed polarity zones in the core and GPTS. Regardless of the correlation favored, the stratigraphic thickness of the normal polarity zones suggests an unusually rapid accumulation rate for much of the core sediment. For the 427 m thickness of the middle unit of the Santa Fe in the core, deposition over 1–2 m.y. gives accumulation rates of 427–214 m/Ma. For comparison, accumulation rates calculated from magnetostratigraphic studies of, for example, the Plio–Pleistocene Camp Rice and Palomas formations in the southern Rio Grande rift (Mack et al., 1993) are 20–30 m/Ma and from the middle Miocene Tesuque Formation of the Española basin (Barghoorn, 1981) are 120–170 m/Ma, depending on specific GPTS correlation. The high accumulation rate we infer for much of the 98th Street core interval might provide evidence for enhanced tectonism and creation of accommodation space within the basin during sedimentation. Note that when plotted at a high 400 m/Ma rate, the thin (<1 m) reversed intervals within the 98th Street core become insignificant (Fig. 5), implying that they represent short-lived paleofield events rather than magnetic subchrons of the GPTS.

ROCK MAGNETISM

Both magnetic susceptibility and natural remanent magnetization vary greatly over the 457 m depth of the core interval (Fig. 6). Magnetic susceptibility values for whole core measurements range from 8.9E-5 SI to 6.7E-2 SI. Magnetic susceptibility values obtained from the cube specimens vary from 4.8E-5 to 1.5E-02 (SI volume). Natural remanent magnetization for the cube specimens varies from a minimum of 8.37E-04 to a maximum of 2.72E-01 A/m (Fig. 6). The variation of MS and NRM with stratigraphic depth corresponds, at least partly, to variations in sediment type (Fig. 6). Clay- and silt-rich horizons, such as those within the Atrisco member, generally have lowest values of MS and NRM, and fine- to medium-grained sandstones of surrounding intervals typically have higher values. Comparing MS or NRM versus sediment grain size (estimated for discrete specimens during core logging) reveals that higher MS and NRM correspond with coarser sediment grain size (Fig. 7), supporting their lithologic dependence. Comparing MS and NRM reveals an essentially continuous distribution of values (Fig. 8A) and therefore a nearly constant NRM/MS ratio for most of the sample population. The data define a single population of magnetized sediments with variations in magnetic properties that, to a first order, probably reflect modal concentration of magnetic phases. The ARM acquisition experiments on the same specimens also identify a single population of magnetized materials (Fig. 8B) and support a lack of any large contrasts in magnetic mineral properties within the Santa Fe section sampled. Further rock magnetic studies and petrographic inspection will aid in characterizing the magnetic mineralogy within the Santa Fe sequence sampled.

SURFACE EXPOSURES

To complement studies of 98th Street core material, we have begun sampling a surface reference section at Arroyo Ojito (Cerro Conejo 7.5-minute quadrangle), Zia Pueblo (Koning et al., 1998), that may correlate with the Santa Fe interval in the core (F. Pazzaglia and D. Koning, personal comm., 1998). In reconnaissance, six to nine oriented block samples were obtained at each of six stratigraphic intervals (individual beds or a thin sequence of beds of similar character). Samples were collected from two intervals in the Cerro Conejo [Tsfm] Formation, three intervals over a 1-m thickness in the lower member of the Arroyo Ojito Formation [Tsful], and one in the Atrisco member [Tsfu2] of the Arroyo Ojito Formation (stratigraphic nomenclature from Connell et al., this guidebook). The lowermost four intervals are medium- to fine-sands; the fifth interval is silty mudstones, and the Atrisco interval is

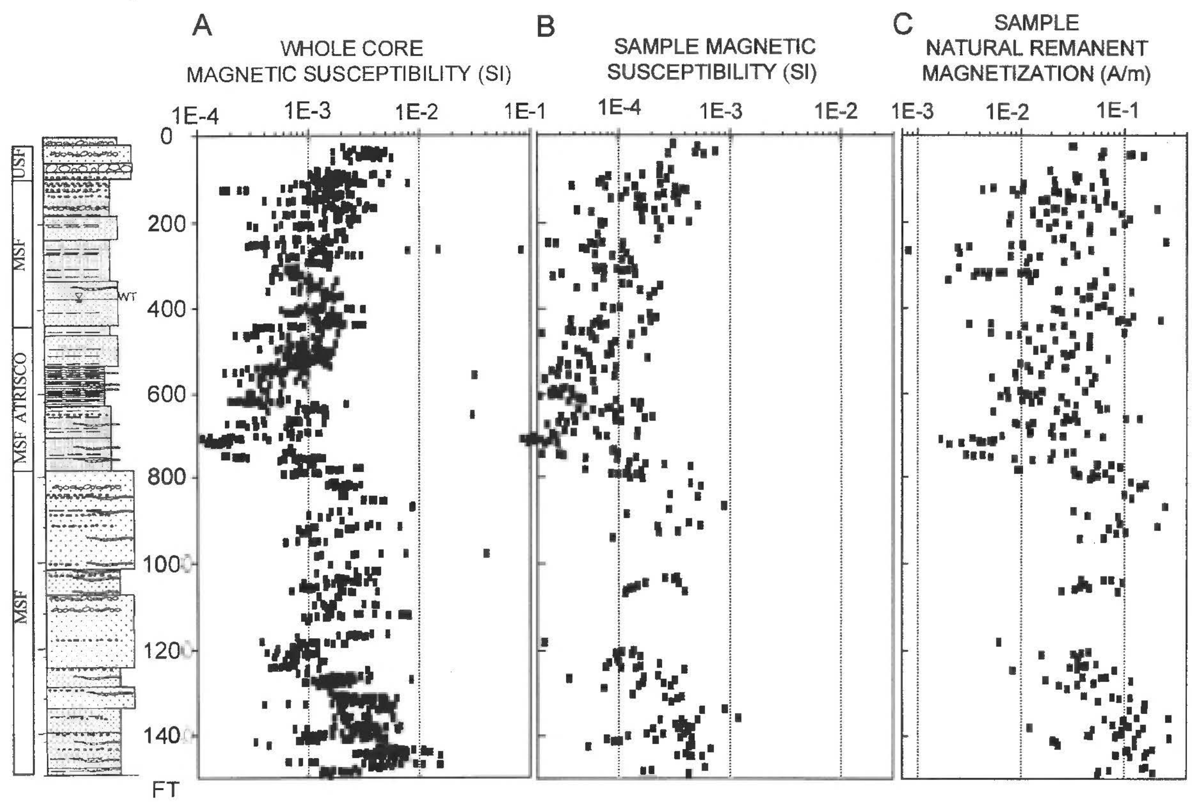

FIGURE 6. Magnetic properties versus depth for the 98th Street core. **A**, whole-core magnetic susceptibility. **B**, discrete cube specimen magnetic susceptibility (SI volume). **C**, natural remanent magnetization.

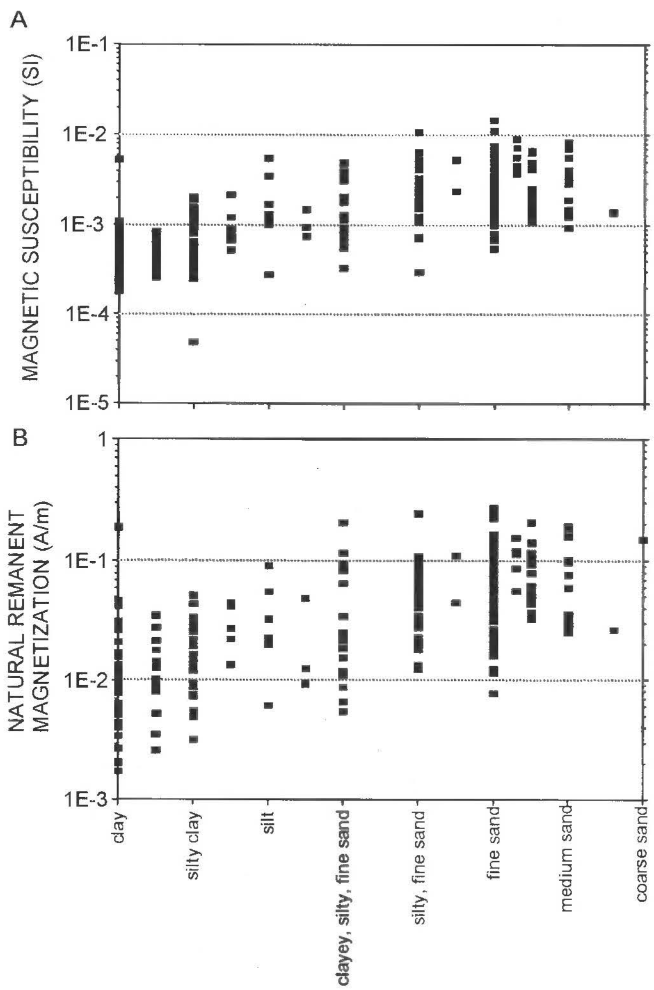

FIGURE 7. Sediment grain size versus **A**, discrete cube magnetic susceptibility, and **B**, natural remanent magnetization for specimens from the 98th Street core.

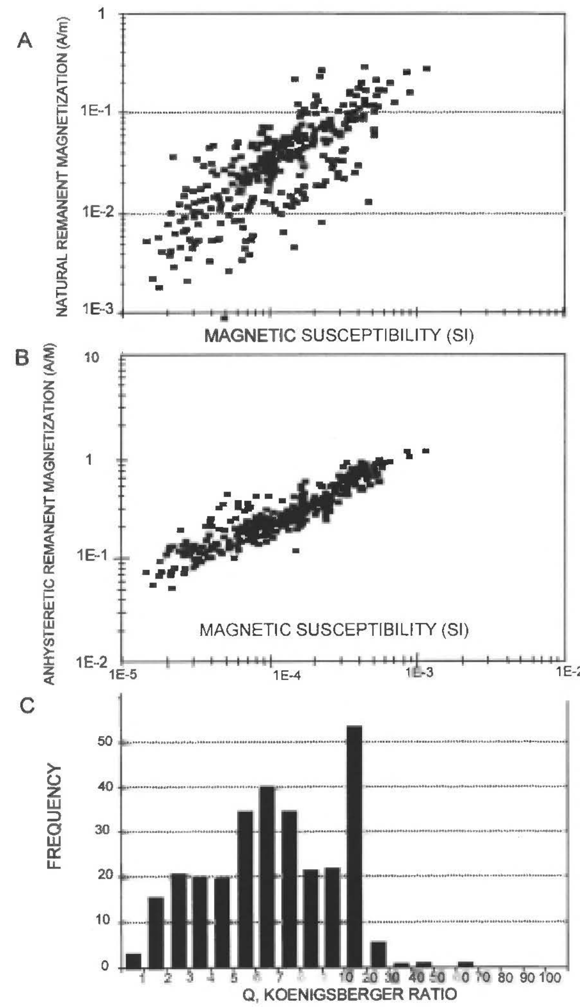

FIGURE 8. **A**, Magnetic susceptibility (discrete cube) versus NRM. **B**, magnetic susceptibility versus anhysteretic remanent magnetization. **C**, histogram of Koenigsberger ratio, Q, for samples from the 98th Street core. Note dual bin sizes for Q values.

dominated by well-indurated, buff-colored, silty mudstones. In AF demagnetization, most samples display class A behavior. The lower five intervals carry reasonably well-grouped magnetizations of normal polarity (Table 1). The Atrisco interval, however, yields a consistent reversed polarity magnetization (Table 1). Sites 3–6 yield anomalously shallow inclinations compared to an expected time-averaged latest Tertiary field, even after modest (<5°) structural correction for tilt of the Santa Fe sequence (Table 1). As discussed above, it is possible that substantial inclination shallowing has taken place in sediments with a large clay fraction. Although the reconnaissance sampling is too sparse to establish or refute correlation of the Arroyo Ojito and 98th Street sediment intervals, the surface samples do carry reproducible magnetization components whose demagnetization behavior and inclinations are similar.

SANTA FE GROUP SEDIMENTS AS MAGNETIC ANOMALY SOURCES

High-resolution aeromagnetic surveys within the middle Rio Grande rift have detected numerous low amplitude (2–10 nT), linear anomalies that have been attributed to fault offsets within Santa Fe sediments (Grauch, 1998, 1999). Magnetic anomalies arise from contrasts in total magnetization of the source materials. The total magnetization is the vector sum of remanent and induced magnetization components and can be approximated from MS and NRM values for 98th Street core materials to evaluate potential contrasts of total magnetization within Santa Fe Group sediments.

Whereas remanent magnetization is directly measured in the specimens, induced magnetization is the product of MS and the Earth's field strength (~50 μT). The quotient of NRM and induced magnetization values, the Koenigsberger ratio (Q), is a common measure of the rela-

TABLE 1. Paleomagnetic data from surface exposures of Santa Fe strata, Arroyo Ojito.

Site no.	Rock type	n/N	Decl.	Incl.	a 95	k	Sdecl.	Sincl.	Type demagnetization
1	med ss	7/7	14.0	60.8	12.8	23.3	16.8	64.5	A
2	med ss	6/7	4.5	49.0	13.9	23.9	5.4	52.9	mixed A, B
3	fine ss	7/9	13.1	24.6	11.7	27.8	13.8	28.4	A
4	fine ss	7/7	5.8	27.8	17.8	12.4	6.3	31.7	mixed A, B
5	mudst.	7/8	6.0	19.5	11.2	30.0	6.3	23.4	mixed A, B
6	mudst.	4/5	161.5	-25.1	24.2	15.4	161.0	–29.0	A

Explanation: n/N = ratio of number of samples included in site mean determination to the total number of samples demagnetized (one specimen demagnetized per sample); Decl. = declination of the estimated site mean direction, in degrees clockwise from north; Incl. = inclination of the estimated site mean direction, in degrees positive downward and negative upward; a95 = semi-angle of the cone of confidence, at a 95% confidence level, about the estimated site mean direction; k = estimate of the Fisher concentration (precision) parameter; Sdecl. = declination of estimated site mean direction, corrected for stratigraphic tilt; Sincl. = inclination of the estimated site mean direction, corrected for stratigraphic tilt.

tive importance of these two contributors to the total magnetization. The observed NRM and MS values for the Santa Fe core specimens (Fig. 8A) yield a relatively narrow range of Q populations for the core specimens (Figs. 8C, 9, 10). Most specimens have low Q values, with a mode of 0.4–0.6, indicating that the total magnetization is dominated by the induced magnetization component. For those few specimens with Q values greater than 1.0, the total magnetization is dominanted by the remanent magnetization component.

Lacking azimuthal orientation, declination of NRM for core specimens is unknown, so it is impossible to calculate a true vector sum of the remanent and induced magnetization components. Normal-polarity late Miocene through Quaternary paleofields, however, typically had directions that were nearly parallel (within 30°) to the present-day field. As an approximation, we add the remanent magnetization for normal polarity specimens as a scalar value to the induced magnetization component that is parallel to the present field. Conversely, remanent magnetization for reversed polarity specimens can be subtracted from the induced magnetization component. Total magnetizations for core specimens calculated in this manner range from –0.13 to 0.84 A/m (Fig. 9). Bath and Jahren (1984) proposed the following classification for expression of magnetic anomalies based on total magnetization: (1) strong, >1.5 A/m, (2) moderate, 1.5–0.5 A/m, (3) weak, 0.5–0.05 A/m, and (4) nonmagnetic, <0.05 A/m. Compared to these classes, maximum contrasts in the total magnetizations for the core sediments can generate moderate to weak anomalies (Fig. 9), qualitatively compatible with the 2–10-nT anomalies detected over intrabasin faults in the Albuquerque basin (Grauch, 1998).

If in error, the total magnetizations we have calculated above probably overestimate contrasts in magnetization. The error potential is greatest for high-Q, remanence-dominant specimens. For normal polarity samples, non-parallellism of induced and remanent components will reduce the resultant magnitude of the total magnetization vector from the scalar estimate. Moderate to high-Q, reversed polarity samples have greatest potential for error because the presence of an overprinting normal polarity viscous magnetization (e.g., Fig. 2E) can strongly bias the NRM direction away from the assumed antipode to the field direction. In this case, subtracting the remanent magnetization component will result in a calculated total magnetization that is less (perhaps even more negative) than the true resultant vector. Nonetheless, we think the data in Figure 9C illustrate a reasonable range of total magnetizations within the core because most of the samples have low Q ratios and thus are less prone to errors.

Within the 98th Street core, stratigraphic intervals that are dominantly sandstone have higher total magnetizations than clay- and silt-rich intervals such as the Atrisco member (Fig. 9). Predictably, total magnetization has crude positive correlation with sediment grain size (Fig.

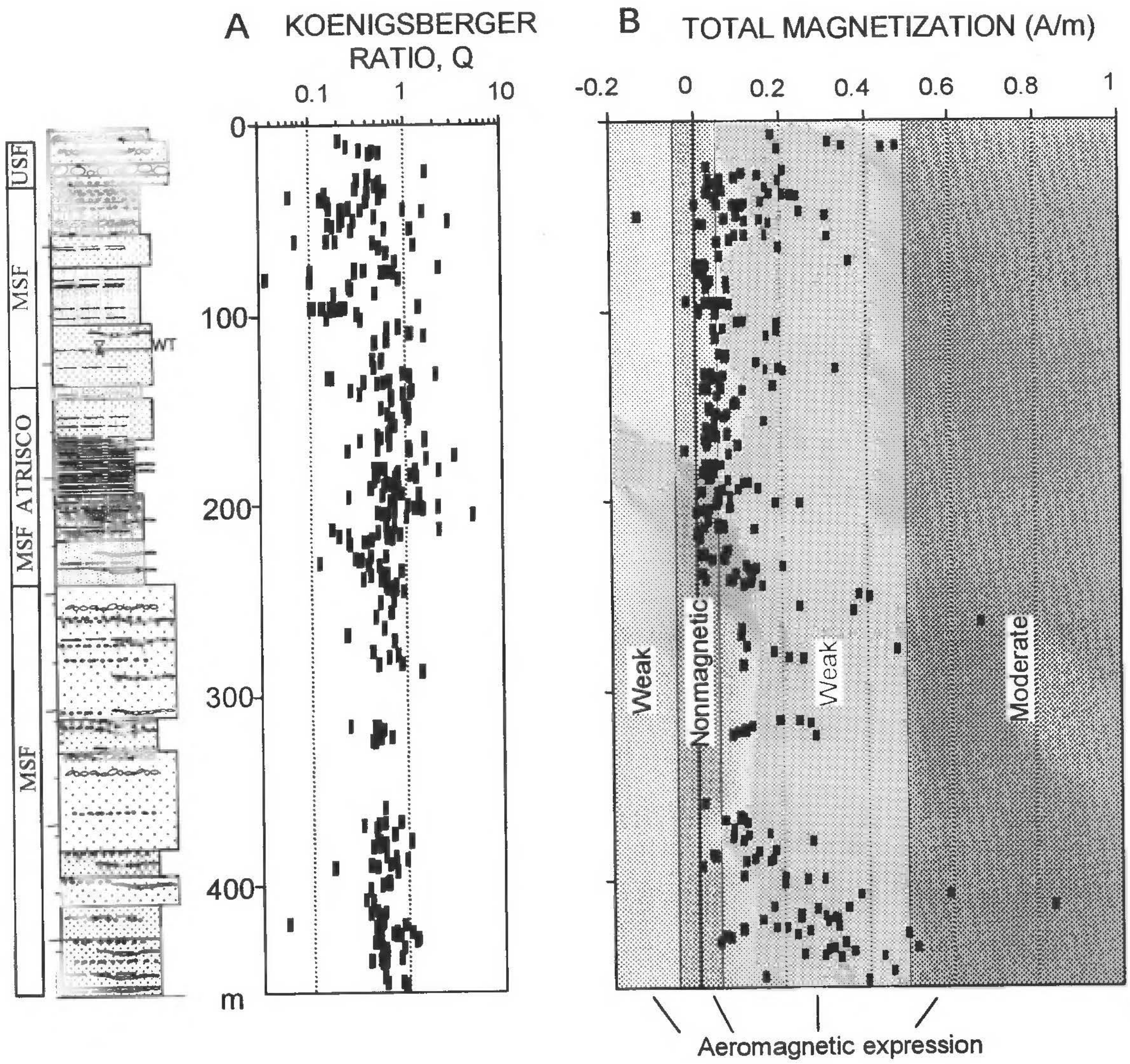

FIGURE 9. Plot of A, Koenigsberger ratio, and B, model total magnetization versus depth for samples from the 98th Street core hole. Total magnetizations are superimposed on classes of magnetic anomaly expression from Bath and Jahren (1984).

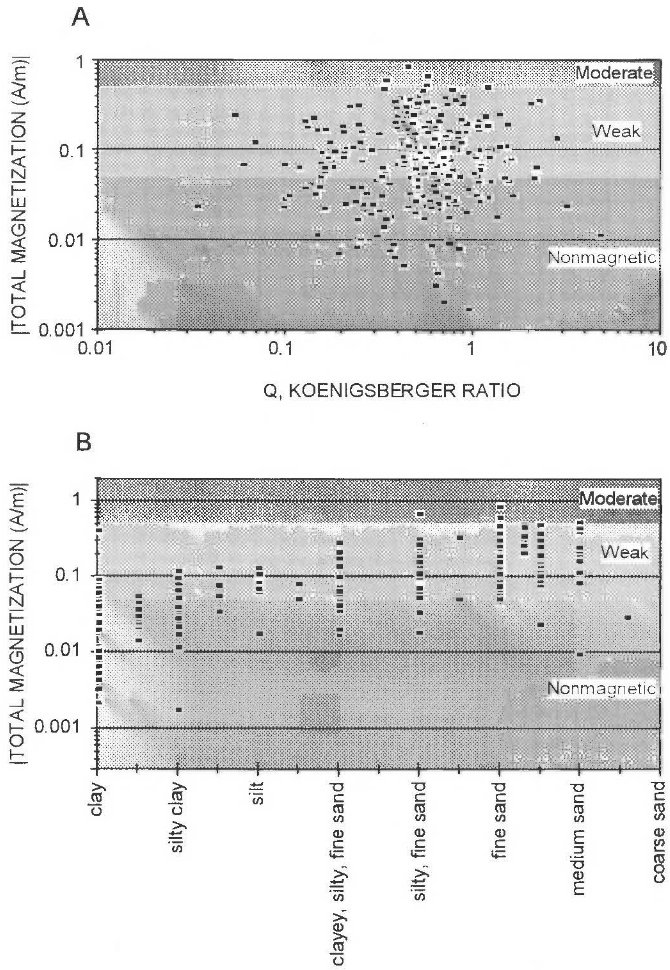

FIGURE 10. Absolute value of total magnetization versus **A**, Koenigsberger ratio, and **B**, sediment grain size superimposed on classes of magnetic anomaly expression from Bath and Jahren (1984).

10B) similar to that for NRM and MS (Fig. 7). These data suggest that coarse-grained rocks should have maximum total magnetizations and thus greatest potential for generation of aeromagnetic anomalies where juxtaposed with fine sediments along faults.

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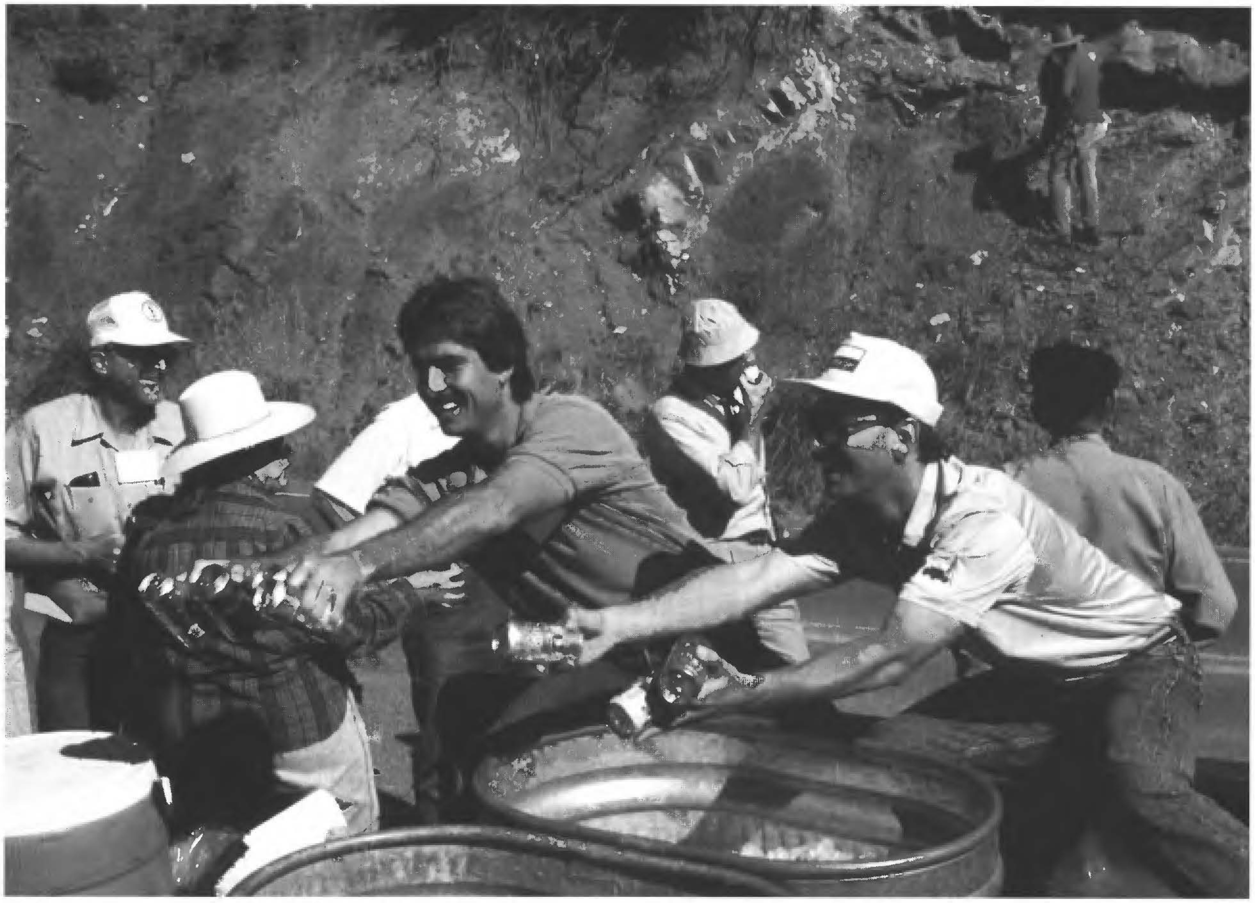

Enthusiastic volunteers helping participants to enjoy the Schlumberger-provided liquid refreshments on the 1991 NMGS trip to the the south-central New Mexico mountain ranges (photograph courtesy of Ed Smith).