Paleomagnetic and rock magnetic evidence for a secondary yet early magnetization in large sandstone pipes and host Late Middle Jurassic (Callovian) Summerville Formation and Bluff Sandstone near Mesita, west central New Mexico

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[1] Processes responsible for the acquisition of ancient yet secondary magnetizations are important facets of the geologic history of rocks and, when the age of such magnetizations can be estimated with confidence, provide useful information on the ancient geomagnetic field. In west central New Mexico near Mesita, on the Colorado Plateau, hematitic sandstone and siltstone beds of the Middle Jurassic (Callovian) Summerville Formation and overlying Bluff Sandstone are host to numerous large (up to 100 m^2 in map area) pipe-like sandstone bodies. The pipes are as strongly cemented by hematite (colors range from 10R 6/6 to 10R 3/4) as the host strata; paleomagnetic data from them and their host strata are interpreted to indicate that these rocks have been remagnetized, probably in association with sandstone pipe formation. Reverse polarity magnetizations isolated in both alternating field and thermal demagnetization from pipes are well grouped and are similar to, and not statistically distinct from, those in adjacent host strata. The grand-mean direction for 16 sites (7 sites in sandstone pipes and 9 in host strata), corrected for slight (5°) west-northwest tilt of the strata, is $D = 163.0°$, $I = -44.3°$ ($\alpha_{95} = 2.7°$, $k = 169$). This direction yields a pole position of 72.8°N, 135.7°E ($dp = 2.1°$, $dm = 3.4°$). Assuming a modest (i.e., ~5°) clockwise rotation of the Colorado Plateau, the pole lies at 68.7°N, 143.8°E. Median destructive fields for the remanence in pipes and host strata are typically 40–50 mT; over 90% of the remanence is "unblocked" or removed during changes in the magnetic mineralogy by temperatures of ~400–450°C. Isothermal remanent magnetization (IRM) acquisition data, and thermal demagnetization of "saturation" IRM, however, demonstrate that the dominant magnetic phase is of high coercivity and relatively high (above 600°C) laboratory unblocking temperatures in both sandstone pipes and host strata, yet it does not appear to contribute significantly to the characteristic remanent magnetization. The similarity in demagnetization properties between pipes and adjacent host strata, the absence of a well-defined high unblocking temperature remanence that is more typical of hematite-cemented detrital strata, and the essentially uniform reverse polarity of the remanence are all interpreted to indicate that pipes and host strata contain secondary, yet early acquired magnetizations and that magnetization acquisition continued after pipe injection. We propose that acquisition of the secondary magnetization took place in the presence of alkaline, high pH brines formed by the dissolution of the underlying gypsum-dominated Lower Jurassic Todilto Formation strata and therefore the remanence is early in age. On the basis of a comparison with Summerville and Morrison (Middle and Late Jurassic) paleomagnetic poles from rocks on the Colorado Plateau, we interpret the secondary remanence in Summerville strata and sandstone pipes near Laguna to be latest Middle to Late Jurassic in age. If realistic, this interpretation further emphasizes the importance of fluid-rock interaction in the acquisition of secondary magnetizations. *INDEX TERMS:* 1519 Geomagnetism and Paleomagnetism: Magnetic mineralogy and petrology; 1525 Geomagnetism and

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Paleomagnetism: Paleomagnetism applied to tectonics (regional, global); 1533 Geomagnetism and Paleomagnetism: Remagnetization; 1540 Geomagnetism and Paleomagnetism: Rock and mineral magnetism; *KEYWORDS:* paleomagnetism, Jurassic, remagnetization

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1. Introduction

[2] Paleomagnetic research over the past two decades has provided insight into problems associated with relatively early interpretations [e.g., *Irving*, 1979; *Irving and Irving*, 1982] of the Mesozoic apparent polar wander (APW) path for North America. The need for additional well-dated, well-determined paleomagnetic poles for parts of the Mesozoic for North America, in particular for the Middle and Late Jurassic, has become critical [*Hagstrum*, 1993], as obviously conflicting data sets have been used to argue for fundamentally different apparent polar wander paths and hence paleolatitudes for much of the Jurassic [*Butler et al.*, 1992; *Van Fossen and Kent*, 1992a, 1992b, 1993; *Courtillot et al.*, 1994]. The most abundant exposures of rocks of Jurassic age for the North American craton, sensu strictu, are of sedimentary rocks, and establishing ages of magnetization acquisition in such rocks, unfortunately, is not always possible. For sedimentary strata, field-based tests, ideally of several types, together with reliable biostratigraphic information, are as important as the documentation of adequate paleomagnetic sampling of the geomagnetic field (e.g., paleosecular variation, multiple reversals).

[3] To attempt to provide additional useful paleomagnetic information for the late Middle Jurassic, we studied a series of very gently tilted, well-exposed hematitic siltstone and sandstone strata near Mesita, west central New Mexico (Figure 1a). These strata, of the Callovian Summerville Formation and overlying Bluff Sandstone (Figure 2), are host to numerous unusually large sandstone pipes [*Schlee and Moench*, 1963; *Hunter et al.*, 1992] exposed along the southern and southeastern margin of the San Juan Basin. In the Mesita area, contacts between the sandstone pipes and host strata are sharp and readily identified (Figure 3). Macroscopically, the pipes appear as hematitic as the host strata and therefore provide an opportunity for a modified form of the classic paleomagnetic ''contact test'' to assess the age of any magnetization(s) identified in progressive demagnetization in the pipes and host rocks. The principle behind this test, and thus our working hypothesis, is as follows. If the host strata acquired and retained an early, or penecontemporaneous magnetization contained in early formed fine-grained pigment hematite and/or detrital hematite (specularite), then the sandstone pipes, clearly younger than the host strata, must have a younger magnetization. A younger magnetization, acquired via a different mechanism, could possibly have a statistically distinguishable direction, with perhaps distinct demagnetization behavior, and thus rock magnetic properties, because of a different magnetic mineralogy related to its origin. Considerable paleomagnetic information exists for the Summerville Formation elsewhere on the Colorado Plateau [*Steiner*, 1978; *Bazard and Butler*, 1992], affording, in principle, a robust test of the age of the magnetization in the sandstone pipes relative to host rocks.

2. Geology

[4] Along the southeastern margin of the San Juan Basin part of the Colorado Plateau, Middle Triassic through Upper Jurassic strata are well exposed and gently tilted [e.g., *Hunt et al.*, 1989; *Anderson and Lucas*, 1994] (Figure 1a). Middle Jurassic and some Upper Jurassic strata are considered part of the San Rafael Group [*Anderson and Lucas*, 1992, 1994] (Figure 2). In the southeast San Juan Basin and eastward to the southern High Plains, the group consists of the largely eolian Entrada Sandstone, the carbonate-evaporite sequence of the Todilto Formation, the marginal marine to fluvial Summerville Formation, and the Bluff Sandstone, also mostly eolian. The Todilto Formation contains a basal, medium to dark gray, carbonaceous, thinly laminated to thin-bedded limestone and gypsum. At Mesita, $\sim$33 m of white, crudely bedded gypsum exhibiting chicken-wire texture overlies the limestone. The Todilto strata are interpreted to have been deposited in a restricted marine embayment [*Ridgley*, 1984] or in a landlocked salina [*Lucas et al.*, 1985]. The Summerville Formation is composed of reddish-brown to white, silty sandstone, sandy siltstone, and clay stone. Bedding is thin (few centimeters) to very thick (over 1 m) and individual beds, which are typically laterally extensive, have ripple cross laminations, small-scale cross bedding, and irregular, subhorizontal, wavy laminations or flat bedding. The Summerville Formation is interpreted by *Condon* [1989] as mainly marginal marine, with sabka deposits that grade southward into fluvial deposits. The Bluff Formation consists of light colored to reddish fine- to medium-grained sandstones interpreted to be of both fluvial and eolian origin.

[5] In the Mesita area, the Summerville Formation and Bluff Sandstone are cut by numerous subvertical clastic sandstone pipes (Figures 1b, 1c, and 3) ranging from 0.1 to $\sim$40 m in diameter [*Schlee*, 1963]. *Schlee and Moench* [1963] mapped more than 90 pipes in the southern half of the 7.5' Mesita Quadrangle. The pipes are generally more resistant to weathering than host strata and stand out in relief on cliff faces and locally as isolated pillars on slopes or valley floors. The pipes are associated with large collapse structures in Todilto, Summerville, and Bluff strata and typically show no indication of primary bedding structures. Most of the pipes are homogeneous, but a few exhibit sheaths of differentiation in grain size or cementation that appear in outcrop as vertical ''layering'' or as concentric rings of differential weathering. *Moench and Schlee* [1967, p. 44] suggested

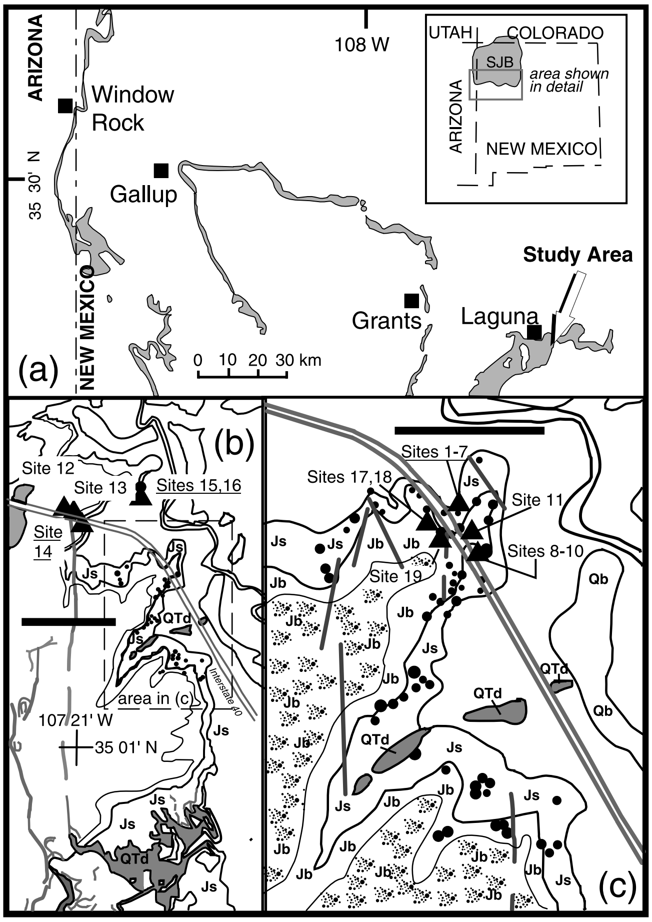

Figure 1. (a) Simplified regional geologic map of west central New Mexico, showing outcrops of the San Rafael Group (in gray) along the southern margin of the San Juan Basin and the study location (modified from *Hunter et al.* [1992]). (b) Simplified geologic map of the study area near Mesita, New Mexico (modified from *Schlee and Moench* [1963]), showing some of the paleomagnetic sampling sites. Location of Figure 1c is shown by dashed rectangle. (c) Enlarged geologic map of the study area, showing location of additional sampling sites and the distribution of sandstone pipes in the study area (modified from *Schlee and Moench* [1963]). In Figures 1b and 1c, solid circles represent sandstone pipes; triangles are specific sampling sites or localities, where several sites were sampled. Geologic map units are Js, Jurassic Summerville Formation; Jb, Jurassic Bluff Sandstone; QTd, late Tertiary to Quaternary shallow mafic intrusion; Qb, Quaternary basalt flow. Heavy dark gray lines in Figures 1b and 1c are fault traces. Scale bars in Figures 1b and 1c are 1.0 km.

that the pipes originated by downward migration of water-charged sand:

> We suggest that the pipes formed by foundering of sand into spring vents during compaction and dewatering of the sediment. At some stage in the accumulation of sand on top of water-saturated mud, the area was deformed. This deformation produced north- and east-trending synclines. The structurally low-areas received more sediments than the higher area; and the resulting greater weight of sediment in the synclines, coupled with spring activity aligned along the folds, permitted foundering of sand into spring vents. As the process continued, the sand moved downward and mixed with materials derived from the sides of the vents. The total amount of room required to accommodate the sand was probably considerably less than the volume of the pipe, because the pipes are composed of materials derived from the sides as well as the top. Room for the sand was probably created by compaction and dewatering of the finer sediment. Where spring activity extended in depth to the Todilto, solution of gypsum unquestionably enhanced formation of the pipes.

Although we do not disagree with the general interpretation offered by *Moench and Schlee* [1967], field evidence reveals that many of the pipes are injected into and/or are capped by relatively undisturbed Summerville and Bluff strata (Figure 3) and thus clearly demonstrate the local, upward migration of sand in several pipes.

[6] *Hunter et al.* [1992] investigated somewhat similar clastic sandstone pipes in identical age strata exposed between Grants and Gallup (Figure 1a). These differ from pipes in the Mesita area in that they commonly contain angular blocks of internally intact strata identical to the host rock. To explain the origin of the pipes, these workers called for gradual collapse following, and perhaps concurrent with, localized dissolution of underlying gypsum of the Todilto Member.

[7] In the Mesita area, strata of the San Raphael Group are cut by mafic dikes and sills of latest Tertiary(?) to Quaternary(?) age (Figure 1c). In the immediate sampling area, one mafic dike (0.5 m in width) is exposed in a road cut along Interstate 40 (Figure 1b). In addition, several isolated exposures are found 0.3 to 0.5 km south of the promontory intersected by Interstate 40 where our sampling concentrated. Southwest of Mesita, a mafic laccolith, up to ~45 m in thickness, was emplaced along the contact between the Entrada Sandstone and the Todilto Formation (Figure 1b). The subsurface lateral extent of the intrusion is unknown.

3. Sampling and Laboratory Methods

[8] Our sampling of Middle Jurassic strata west of Mesita was largely confined to exposures along Interstate 40 (Figures 1b and 1c) because of restricted access to Laguna Pueblo land. We report results from seven sandstone pipes, immediately adjacent host strata (nine sites) and one site

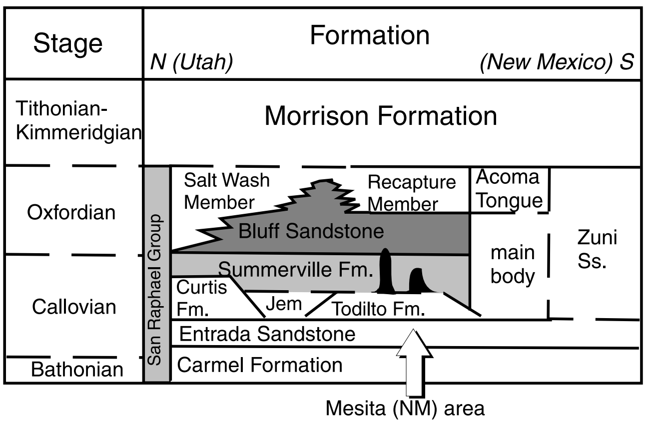

Figure 2. Generalized stratigraphy of Jurassic strata in west central New Mexico (modified from *Anderson and Lucas* [1994]). Black shows schematic positions of sandstone pipes.

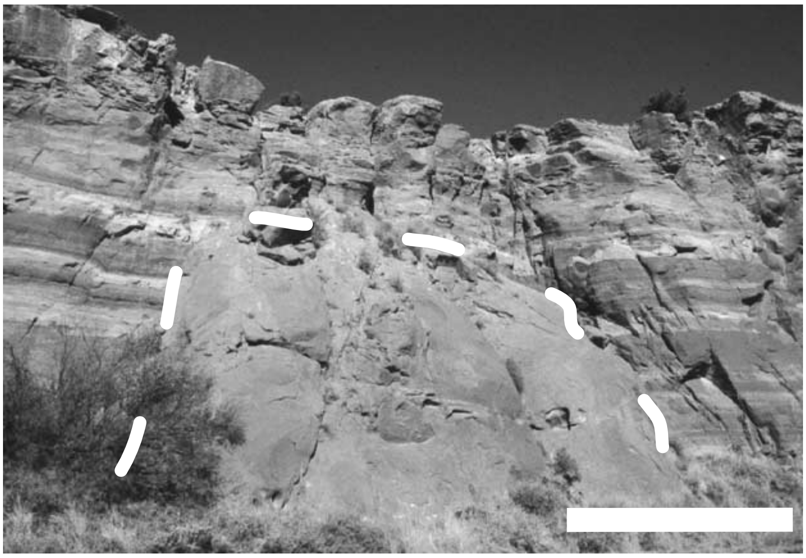

Figure 3. Photo of a typical sandstone pipe and geometric relations with surrounding strata, looking west-northwest. White bar is ~3 m length on outcrop. White dotted line shows the outline of the sandstone pipe. Paleomagnetic sampling sites 15 and 16 were collected from the pipe and immediately adjacent strata, respectively, along the northeast contact of the pipe.

(site 14) ~100 m from any exposed sandstone pipes (Table 1). Each sampling site in host strata is confined to a single bed, or at most a few beds, spanning a stratigraphic thickness of less than a meter. For sites in sandstone pipes, our samples are more randomly distributed and encompass a larger area. One altered mafic dike (site 12), ~0.5 m wide, of late Miocene/early Pliocene(?) age and contact rocks within a few cm of the dike (site 13) were also sampled. All samples were collected as cores drilled using a portable drill with nonmagnetic drill bits and oriented with magnetic and solar compasses.

[9] All remanence measurements were performed on a superconducting rock magnetometer. Progressive demagnetization employed conventional alternating field, thermal, chemical, and low-temperature (liquid nitrogen) methods. Demagnetization data were inspected using orthogonal demagnetization diagrams [*Zijderveld*, 1967] and individual magnetizations were identified as linear segments in both horizontal and vertical projections defined by three or more demagnetization steps. Characteristic directions were determined using principal components analysis [*Kirschvink*, 1980]. All accepted linear segments have maximum angular deviation (MAD) values of less than 10°. The methods of *Fisher* [1953], assuming circular distribution of individual magnetization directions about a true mean direction, were employed to estimate site- and grand-mean directions and associated statistics. We also report Bingham statistics [e.g., *Onstott*, 1980] for individual site-mean determinations.

[10] Rock magnetic investigations involved acquisition of isothermal remanent magnetization (IRM) and backfield direct field demagnetization of IRM obtained in a peak field of either 1.25 or 3.0 T, thermal demagnetization of IRM acquired at 1.25 T, thermal demagnetization of a composite IRM acquired in two different fashions, and AF demagnetization of ARM, acquired in a DC field of 0.1 mT and a peak alternating field of 95 mT. In addition, we monitored low-field susceptibility during progressive thermal demagnetization for a representative collection of samples and also conducted continuous low-frequency susceptibility versus temperature thermomagnetic measurements in air using a bridge and furnace device similar to that described by *Hrouda* [1995]. We conducted hysteresis experiments at the Institute for Rock Magnetism, University of Minnesota, using an alternating gradient force magnetometer.

4. Paleomagnetism

[11] Progressive demagnetization experiments reveal that the results from most of the sites are consistent and are atypical of demagnetization response of fine-grained, hematite-cemented sedimentary rocks. NRM intensities of the sandstone pipes and host strata are low, and typically less than 30 mA/m. Average intensities of the sandstone pipes are slightly higher than those of the host strata (e.g., 15.2 ± 7.5 mA/m for 12 pipe samples versus 5.8 ± 4.7 mA/m for n = 11 samples from a single host bed). Low-field bulk susceptibilities are similar for both pipes and host beds ($6.6 \times 10^{-6} \pm 1.1 \times 10^{-6}$ SI volume for pipe sandstones versus $6.9 \times 10^{-6} \pm 4.7 \times 10^{-6}$ SI volume for host strata). Examples of response to alternating field (AF) and thermal demagnetization (Figure 4) show that samples of the sandstone pipes and sandstone beds adjacent to the pipes respond exceptionally well to both demagnetization methods. In these materials, the principal magnetization isolated is of south declination and moderate negative inclination. In thermal demagnetization, usually some 70–90% of the natural remanent magnetization (NRM) "unblocks" or is removed over a relatively narrow (~50°C) laboratory unblocking temperature range. Notably, the total range of unblocking temperatures is between ~200 and 475°C (Figure 5). At higher temperatures, no coherent magnetization is identified at the site level for any of the sites carrying the well-grouped reverse polarity magnetization.

Table 1. Paleomagnetic Data From the Summerville Formation, Bluff Sandstone, and Sandstone Pipes, Laguna-Mesita Area, New Mexico[a]

		Stratigraphic						
Site	N/No	*D*, deg	*I*, deg	α_{95}	*k*	$\alpha_{951\text{-}3}$, $\alpha_{951\text{-}2}$	Azimuth	Rock Type, Comments, Color[c]
1A	11/12	161.3	−40.7	4.1	120.7	3.1,4.2	87	sandstone pipe
1	16/16	161.3	−48.8	1.7	480.4	0.8,2.0	49	sandstone pipe, 10R 4/6
2, af	8/9	159.2	−43.2	8.3	45.8	3.1,9.1	79	Summerville host rock, contact with site 1
2, th	13/13	160.1	−48.0	6.9	37.2	2.3,8.1	135	Summerville host rock, contact with site 1, 10R 6/6
3	5/5	166.3	−45.2	7.5	105.5	2.9,7.1	40	upper ss pipe, same as site 1, 10R 6/6
4, af	8/10	172.4	−36.8	2.5	474.5	1.2,2.7	6	Summerville, bed above pipe 1
4, th	11/11	168.5	−48.5	2.8	257.7	1.8,3.0	52	Summerville, bed above pipe 1, 10R 5/6
5	17/17	174.8	−39.2	4.5	62.8	4.1,4.3	33	Summerville host rock, contact with site 6, 10R 6/6
6[b]								sandstone pipe, bleached interior, white
7	8/9	171.4	−46.1	5.8	90.9	1.7,6.7	27	Summerville host rock, above pipe 6, 10R 5/6
8	10/10	152.4	−40.3	8.0	37.0	4.1,8.8	4	sandstone pipe, 10R 6/6
9	12/12	154.1	−45.2	5.1	72.6	2.5,5.9	41	Summerville host rock, pipe at site 8, 10R 3/4
10	10/10	158.5	−47.9	6.6	53.4	2.1,7.9	15	sandstone pipe, 10R 6/4
11	11/11	158.6	−46.7	5.1	80.1	2.8,5.7	35	Summ. host, pipe at site 10, 10R 4/6
12	6/6	39.9	71.4	6.2	116.5	3.2, 6.1	88	mafic dike, 0.5 m wide
13	3/3	161.3	−57.3	5.5	503.4	1.1,4.0	11	Bluff sandstone, contact with dike at site 12
14	6/8	16.1	68.4	5.0	179.6	2.5,4.9	170	lower Bluff sandstone, east of dike, 10R 5/6
15	7/7	168.5	−41.7	6.0	101.0	1.3,6.8	31	sandstone pipe
16	12/13	156.6	−39.1	7.2	37.1	5.9, 6.7	13	Summerville host rock, pipe at site 15, 10R 4/6
17	14/15	165.9	−45.6	3.9	101.8	2.1, 4.6	134	Summerville host rock, pipe at site 18, 10R 4/6
18	7/8	155.5	−50.3	6.4	88.7	1.4,7.3	46	sandstone pipe, 10R 4/6
19	11/11	166.7	−41.2	4.2	118.7	2.9,4.4	119.0	Bluff host, above site 18, 10R 5/3
Total	16	163.0	−44.3	2.7	168.7			stratigraphic correction (185/5) (2.0, 2.9, VGP ASD = 7.4°)

[a]N/No, number (N) of independent samples accepted for the estimate of the site-mean direction to the total number (No) of independent samples measured. *D*, *I*, declination and inclination of the estimate of the site-mean direction, in degrees east of north and positive (negative) downward (upward). Semiangle α_{95} of the 95% cone of confidence about the estimated mean direction, within which the true mean lies at a 95% probability, assuming a circular distribution of directions about the estimate of the true mean direction. *K*, best estimate of *Fisher*'s [1953] precision (concentration) parameter. Bingham estimates $\alpha_{951\text{-}3}$, $\alpha_{951\text{-}2}$ of the semiminor and semimajor axes of the 95% confidence ellipse about the estimated mean direction [*Onstott*, 1980]. Azimuth, orientation of the semimajor axis of the 95% confidence ellipse. Paleomagnetic pole, assuming no rotation of CP, 72.8°N, 135.7°E (*dp*, *dm* = 2.1, 3.4); assuming 5.4° clockwise (CW) rotation of CP, 68.7°N, 143.8°E (*dp*, *dm* = 2.1, 3.4); and assuming 11° CW rotation of CP, 64.0°N, 150.0°E (*dp*, *dm* = 2.1, 3.4).

[b]No coherent magnetization.

[c]Color estimates from Munsell soil color chart.

In AF treatment, typically over 90% of the NRM is randomized at peak fields of 120 mT, yet many samples have a considerable fraction (e.g., 20–30%) of their NRM remaining above 120 mT (Figure 4). Pilot chemical demagnetization experiments were relatively ineffective in isolating a well-defined remanence; short-term (e.g., 2–4 hours) treatment failed to decrease NRM intensity and immersion for over 24 hours destroyed the specimens. Repetitive low-temperature (liquid nitrogen) demagnetization of specimens from ten randomly selected samples failed to remove more than a few percent of the NRM.

[12] The characteristic magnetization (ChRM) of both the sandstone pipes and host strata adjacent to the pipes is of southeast to south declination and moderate negative inclination (i.e., reverse polarity) and is readily isolated in both AF and thermal demagnetization experiments (Figure 6 and Table 1). For over 90% of the samples demagnetized, this is essentially the only remanence identifiable. In a few cases, a minor low-intensity, north declination and moderate positive inclination magnetization is superimposed on this reverse polarity ChRM (Figure 4). At high peak alternating fields and/or laboratory unblocking temperatures, some samples give evidence for an additional, north directed and positive inclination magnetization, but this behavior is inconsistent at the site level and therefore the importance of such magnetizations is difficult to interpret.

[13] On the basis of a limited data set, we observe that site-mean directions in stratified rocks remote from sandstone pipes are distinct from those of the sandstone pipes and their immediately adjacent strata. Site 14, in lower Bluff strata removed from any sandstone pipes, yields a well-grouped normal polarity magnetization of inclination that is considerably steeper than those from the sandstone pipes and adjacent strata. Samples from this site exhibit a considerably lower laboratory unblocking temperature range (most of the remanence unblocked below 200°C) (Figure 5) than those from sites with the well-defined reverse polarity magnetization. Site 12, in an altered, thin mafic dike, is characterized by low-median destructive fields and yields a well-grouped normal polarity magnetization (Figure 6 and Table 1). Site 13 is represented by a small number of samples collected immediately adjacent to the mafic dike and yields a well-grouped south seeking magnetization of relatively steep negative inclination.

[14] Results for all demagnetized samples, with the exception of those from site 12 (mafic dike cutting Bluff Formation strata, Figure 1b and Table 1), site 13 (immediately adjacent host rock to mafic dike, Figure 1b and Table 1) and site 14 (Bluff strata, Figure 1b and Table 1), give an overall in situ grand-mean direction of D = 166.1°, I = −47.7° (k = 169, α_{95} = 2.7°, N = 16 sites). Corrected for the 5° west-northwest tilt of the strata about a N20°E horizontal strike axis, this direction becomes D = 163.0°, I = −44.3° and yields a pole of 135.7°E, 72.8°N (dp = 2.1°, dm = 3.4°). For reasons discussed below, we argue that this pole represents considerable geologic time,

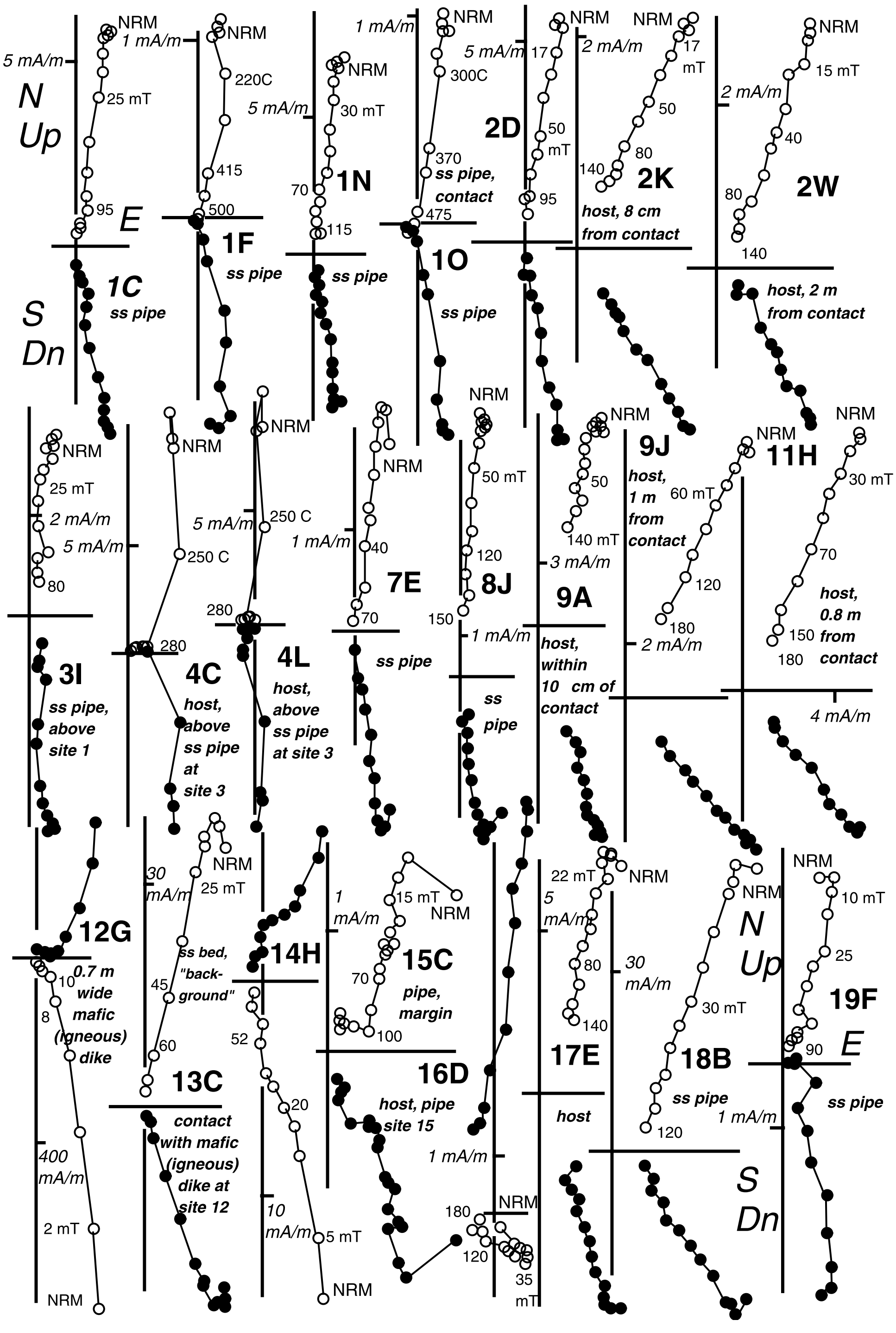

Figure 4. Orthogonal demagnetization diagrams [*Zijderveld*, 1967] showing representative alternating field and thermal demagnetization results from San Raphael Group strata from the Mesita area and one mafic dike and its contact rocks. Each diagram shows the projection of the endpoint of the magnetization vector onto the horizontal (solid symbols) and E–W/vertical (open symbols) planes. Demagnetization steps (in mT or °C) are labeled beside the vertical projections. Data are projected in geographic coordinates.

albeit possibly during only a single reversed polarity chron.

5. Rock Magnetism

[15] Several rock magnetization experiments were conducted to more fully characterize the remanence carriers in the pipes and host strata. As shown above, the general demagnetization behavior (MDFs between 40 and 50 mT, maximum laboratory unblocking temperatures or removal of the characteristic remanence below 450°C) of the pipes and adjacent host Summerville and Bluff strata is atypical for fine-grained, hematite-cemented strata where hematite is the principal remanence carrier [e.g., *Larson and Walker*,

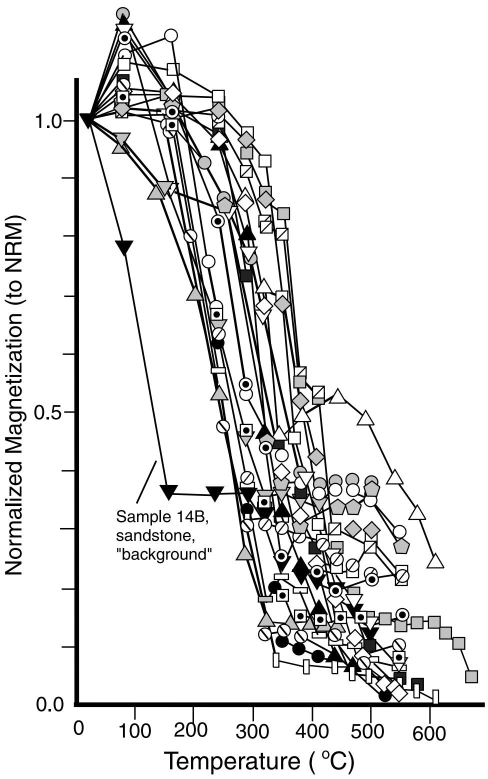

Figure 5. Normalized magnetization intensity versus laboratory unblocking temperature for specimens from 13 randomly selected samples (each specimen with a different symbol) from sandstone pipes and host Summerville strata. The specimen with over 60% of its remanence unblocked below 200°C is from site 14.

1982; *Bazard and Butler*, 1994]. Anhysteretic remanent magnetization intensities are higher than NRM values (31.7 ± 10.8 mA/m versus 14.2 ± 10.3 of the respective samples, $N = 13$ samples). The modified *Lowrie and Fuller* [1971] test [*Johnson et al.*, 1975] reveals that ARM coercivity spectra are typically lower than those of both NRM and IRM acquired in a peak DC field of 1.25 T (Figure 7). The only case is which the demagnetization response of all three magnetizations is similar is for sample 14E (Figure 7), from the site in Summerville strata well removed from any sandstone pipe (Table 1).

[16] Acquisition of isothermal remanent magnetization (IRM) curves to 3.3 T are concave downward and show nearly complete saturation by ~0.3 T and then a slight yet consistent increase to the maximum field applied (Figure 8). Backfield direct field demagnetization of near-saturation IRM shows a subtle, yet nonlinear behavior, suggesting a mixture of low- and higher-coercivity phases. Coercivity of remanence values range from ~0.3 to 0.4 T.

[17] Thermal demagnetization of IRM imparted at 1.25 Tesla (below full saturation) reveals a relatively uniform behavior with distributed unblocking temperatures up to ~680°C (Figure 9). We followed the method of *Lowrie* [1990] to give representative specimens three orthogonal IRMs, the first acquired at 3.0 T, the second at 0.3 T, and the third at 0.03 T. The specimens from most samples of the sandstone pipes and immediately adjacent strata display essentially identical behavior. The magnetizations imparted at both 3.0 T and 0.3 T are similar in magnitude and both are not completely unblocked until well above 600°C (Figure 9). IRM acquired at 0.3 T typically has 10 to 20% remaining above 600°C. The specimen from sample 5V is an exception (Figure 9) in that the magnetization acquired at 0.3 T is fully unblocked at 450°C. Notably, in all of these specimens, the magnetization acquired in 0.03 T is very low-relative to the other two and is completely unblocked by ~400–500°C. The specimen from sample 14D, from the site in Summerville strata far removed from any pipe, displays very different behavior, in that all three magnetizations are nearly completely unblocked by ~550°C.

[18] We also modified the method of *Lowrie* [1992] using specimens from samples from three sites to impart an IRM in a field of 1.2 T and then impart an oppositely directed IRM in a field of 0.2 T. In thermal demagnetization, all specimens exhibit a progressive increase in magnetization, up to about ninefold, to between 300 and 400°C (Figure 10), as the IRM imparted at 0.2 T is removed between ~400 and ~650°C, there is a uniform but minor decrease in intensity. Subsequently, most of the remaining magnetization is unblocked above 650°C. This behavior is consistent with our interpretation that the main magnetic phase in these rocks is relatively coarse hematite of high laboratory unblocking temperatures.

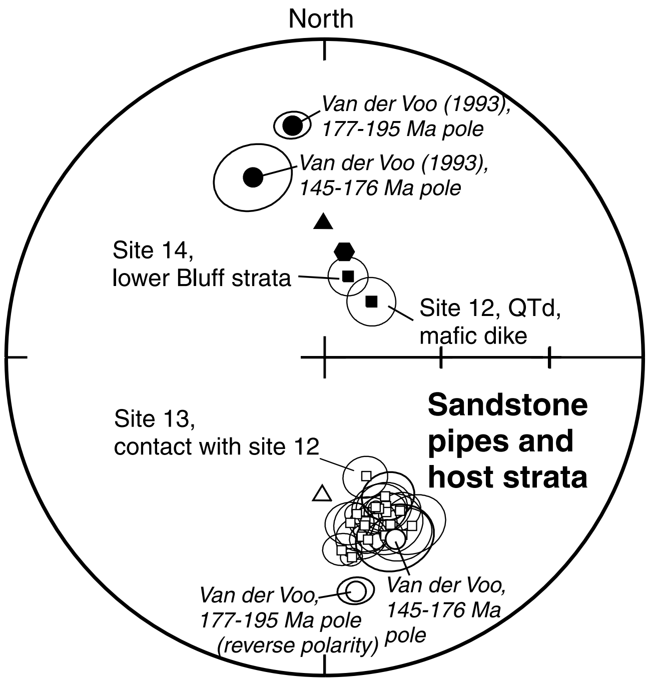

Figure 6. Equal-area projection of site-mean directions (squares) and their associated cones (α_{95}) of 95% confidence. Specific sites discussed in the text are labeled. Normal and reverse polarity axial geocentric dipole field directions are shown by triangles. The present-day field direction is shown by the hexagon. Expected field directions for selected time periods in the Jurassic, from paleomagnetic poles of *Van der Voo* [1993], are shown as circles, with approximate cones (α_{95}) of 95% confidence. Solid (open) symbols refer to lower (upper) hemisphere projections.

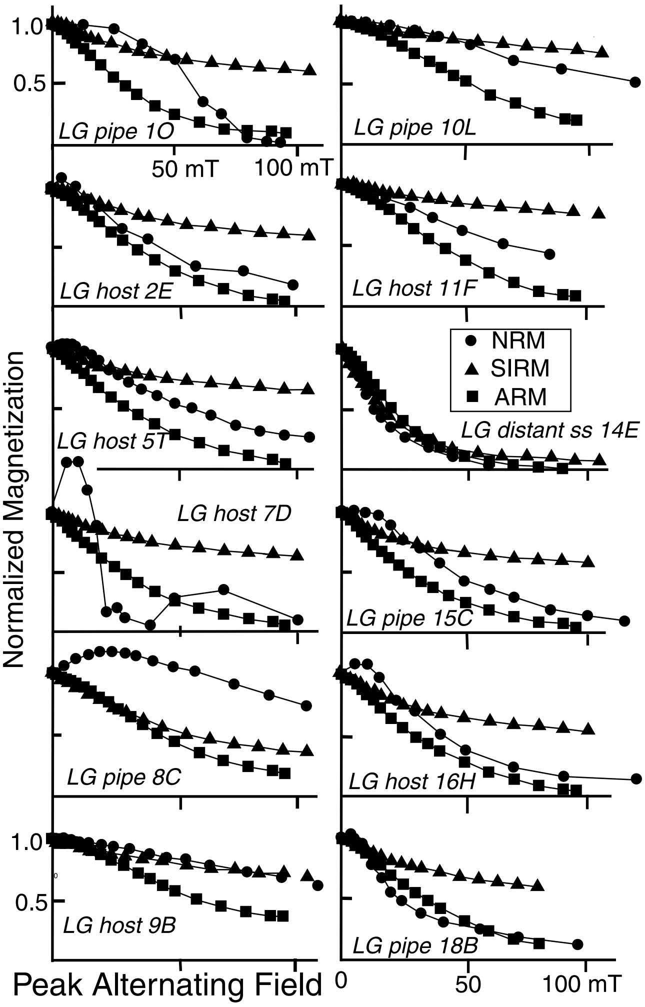

Figure 7. Alternating field (AF) demagnetization of normalized NRM, ARM, and SIRM for specimens from 11 randomly chosen samples from sandstone pipes and immediately adjacent host strata and one sample from site 14, in strata far removed from sandstone pipes (peak inducing field of 3.3 T).

[19] Bulk magnetic susceptibility measured between progressive thermal demagnetization of NRM steps shows relatively slight but smooth variation (Figure 11). Many specimens show a small increase in susceptibility between ~100 and 300°C, and then a progressive decrease, in particular over the temperature between ~300 and 450°C. For the 12 representative specimens monitored to temperatures by which over 95% of the NRM had been unblocked or removed as a result of changes in the magnetic mineralogy in thermal treatment, the maximum decrease in susceptibility was ~50% of the NRM value. Continuous susceptibility versus temperature experiments (Figure 12) reveal a broad range of responses. In all samples, there is a decrease in susceptibility between ~530 and 580°C, sometimes preceded by a major increase (Hopkinson effect). Notably, in these experiments there is no obvious decrease in susceptibility between ~300°C and ~450°C. For many samples (1D, 11J, 2NN, 9H, with normalized susceptibility curves), there is an enhanced Hopkinson effect upon cooling, indicating the generation of a single-domain (SD) cubic phase during the heating experiment, with an overall, and commonly considerable, increase in bulk susceptibility upon complete cooling. Samples showing little Hopkinson effect display, relative to the initial susceptibility, a clear decrease in susceptibility between ~530 and 580°C, and an overall decrease in susceptibility upon complete cooling. Hysteresis parameters, typically determined using an alternating gradient force magnetometer with maximum field of ±2.0 T for most samples, reveal considerable variation in the nature of the magnetic phases present. Coercivities for the sandstone pipes and adjacent strata, with a well-defined reverse polarity characteristic magnetization, range from 30 to 192 mT. The high-coercivity materials from both sandstone pipes and host strata typically show modest to well-defined "wasp-waisted" [*Tauxe et al.*, 1996] hysteresis response (Figures 13a, 13b, 13d, 13e, and 13g). Ratios of coercivity of remanence to coercivity range from above 2 to ~7. For the sandstone pipes and immediately adjacent strata, ratios of saturation remanence to saturation magnetization range from ~0.2 to ~0.5. Subsequent investigation of additional material

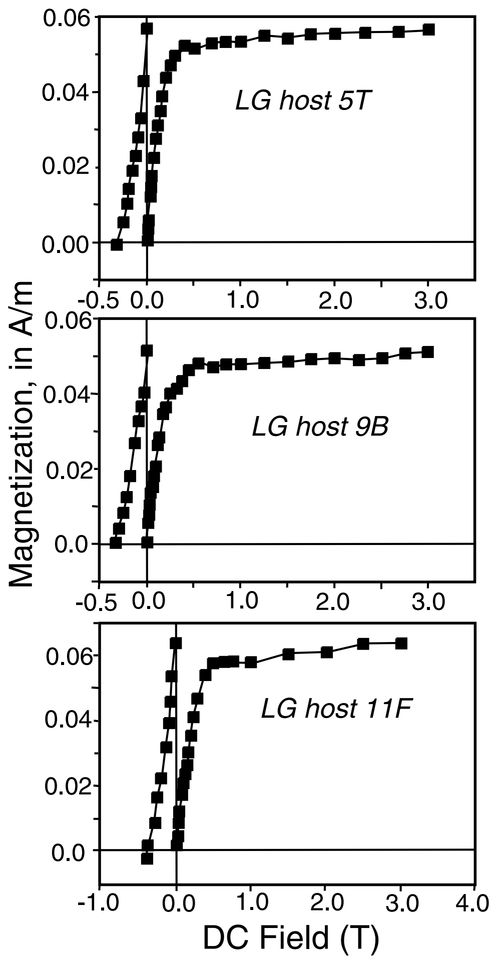

Figure 8. Curves showing the acquisition of isothermal remanent magnetization (IRM) for three specimens from three sites in host sandstone strata immediately adjacent to different sandstone pipes, up to a peak field of ~3.0 T.

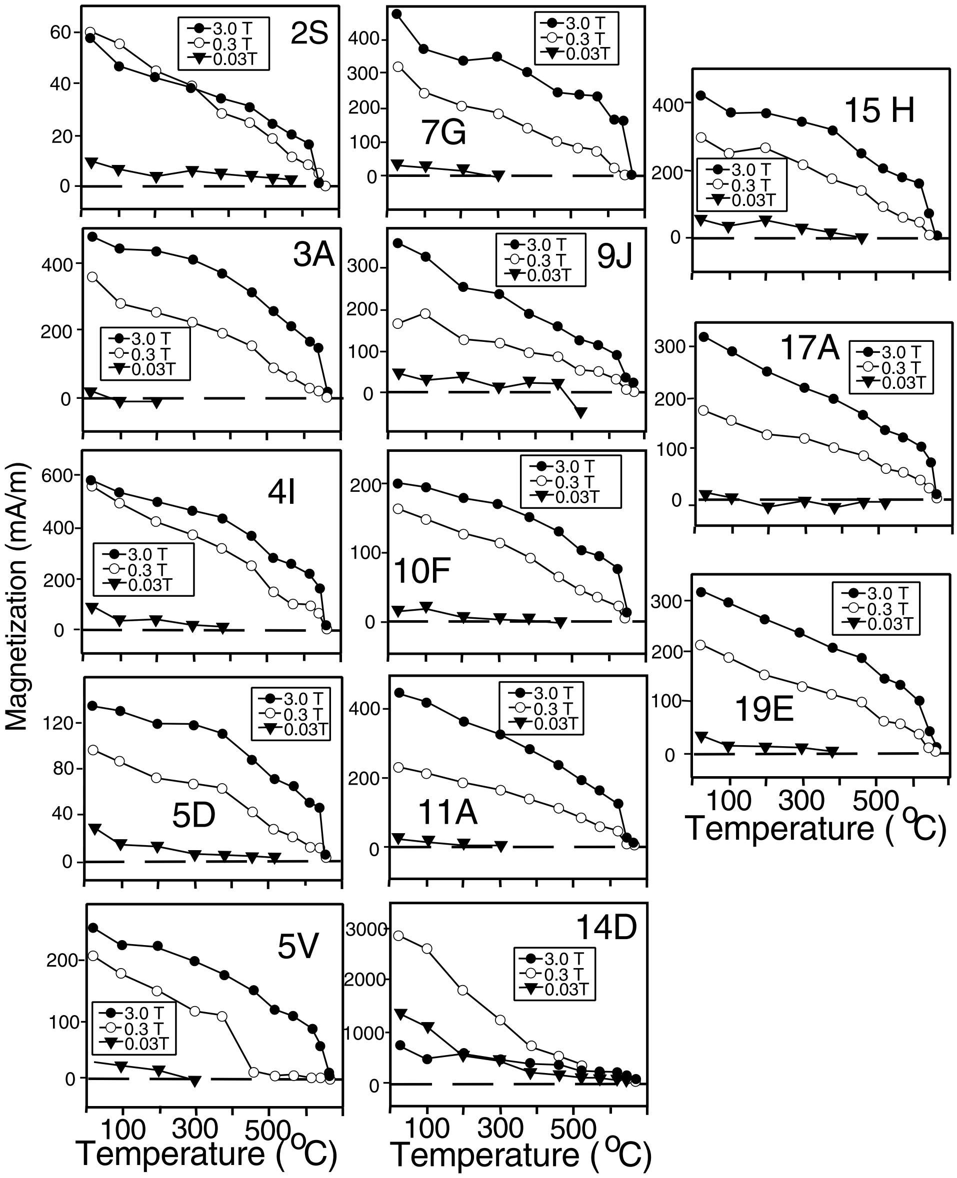

Figure 9. Three-component thermal demagnetization of IRM curves [*Lowrie*, 1990] for specimens from 12 samples of sandstone pipes or adjacent host rock and one sample from site 14, in strata far removed from sandstone pipes. Peak field values of 3.0, 0.3, and 0.03 T were used. Magnetization intensities (*Y* axis) are in mA/m.

using the Magnetic Properties Measurement System allowed a ±5 T field to be used and shows complete saturation between ~3 and 4 T and predictably different values of M_s and M_r, although only a slight different in the estimate of coercivity (Figure 13g). The material from site 14, in lower Bluff strata distant from exposed sandstone pipes, reveals lower M_r/M_s ratios, ~0.1, and coercivities less than 15 mT.

[20] Inspection of polished thin sections using reflected and transmitted light microscopy reveals that the sandstone pipes and immediately adjacent host rocks contain very few opaque detrital grains (e.g., specular hematite or magnetite). What few opaque detrital grains that we have recognized are typically in the 30 to 50+ μm grain-size range. If these are magnetite grains, they are clearly multidomain in character. Fine, translucent hematite as grain coatings is readily observable. Scanning electron microscope (SEM) examination (Figure 14) reveals the occasional presence of an iron-bearing phase, often of euhedral to subhedral crystal form, as a coating on detrital silicate mineral grains. On the basis of their morphology and cation chemistry, we interpret these grains to be a cubic iron oxide (e.g., magnetite). SEM observations further document that the rocks contain very few detrital opaque grains.

6. Discussion: Interpretation of the Origin and Age of Remanence

[21] In the context of determining a principal carrier of the magnetization in the sandstone pipes and immediately adjacent strata, demagnetization data and rock magnetic tests are somewhat equivocal, if not confusing. The

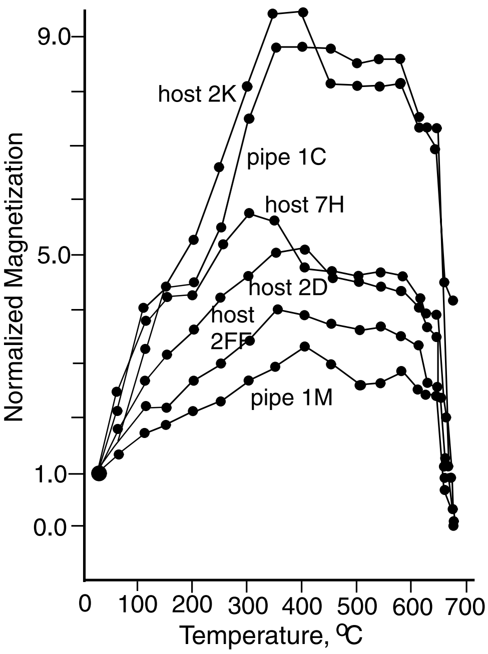

Figure 10. Normalized intensity curves of thermal demagnetization of an IRM, acquired in +Z direction in an induction of 1.2 T and in the $-Z$ direction in an induction of 0.2 T from selected samples of sandstone pipes and host Summerville strata. The application of a second, opposite directed low-field activates only cubic magnetic phases, having coercivities less than ~0.2 T.

response to progressive AF demagnetization of NRM and ARM (Figures 4 and 7) is consistent with a moderate coercivity cubic iron oxide phase (such as magnetite or maghemite), as the principal carrier of the characteristic remanence of pipes and host strata. This could account for the relatively low-and narrow ranges of laboratory unblocking temperatures, if this phase was dominated by a narrow range of fine, single-domain grain sizes [e.g., *Dunlop*, 1973; *Dunlop and Ozdemir*, 1997]. The lack of appreciable (i.e., order of magnitude or more) change in low-field susceptibility with thermal demagnetization through and above the range of laboratory unblocking temperatures suggests to us that the carrier of the remanence is at least in part thermally "stable" and that thermal demagnetization does not lead to the destruction of all existing or the creation of substantial quantities of new magnetic phases during demagnetization. However, the temperature interval over which most of the decrease in low-field susceptibility takes place (Figure 11) closely corresponds to that over which most of the remanence is thermally removed. It is likely that at least part of the remanence is being "unblocked" because the remanence carrier is being partially destroyed over this temperature interval. We note that continuous heating experiments ultimately produce what we interpret to be additional, fine, SD cubic magnetic particles with Curie temperature below 580°C in some samples, as there is a strong Hopkinson effect. Notably, the behavior of the sandstone pipes and host Summerville and Bluff strata is distinct from that described in the vast majority of studies of hematite-cemented fine-grained detrital rocks, where the principal remanence carrier is high-coercivity hematite, possibly as both pigment and detrital grains, with magnetization unblocking temperatures usually confined to temperatures above 600°C [e.g., *Roy and Park*, 1972; *Dunlop and Ozdemir*, 1997].

[22] IRM acquisition data, thermal demagnetization of IRM acquired at 1.25 T and thermal demagnetization of three component and dual-component IRM are all consistent with the colors of these rocks (Table 1) and suggest that an additional, high coercivity and high (greater than about 640°C) laboratory unblocking temperature phase is present. This phase, which is probably fine-grained, translucent hematite, does not contribute significantly to the characteristic magnetization. However, the phase is present in considerable abundance relative to the lower-coercivity phase, on the basis of several observations. First, IRM acquisition curves always show a slight, yet consistent increase in IRM above ~0.3 T, the approximate field strength for full saturation of a cubic magnetic phase. Second, thermal demagnetization of three-component and dual-component IRM reveals that phases with coercivities above 0.3 T carry a considerable IRM. Third, the constricted hysteresis curves are consistent with the presence of two phases of contrasting coercivities; the behavior requires that hematite is abundant relative to the lower-coercivity phase.

[23] It is difficult to assess the overall time duration of the magnetization acquisition process in the sandstone pipes and adjacent strata. Acknowledging that the ChRM is of uniform, reverse polarity and that the dispersion of site-mean directions is low (site-mean VGP angular standard deviation of 7.4°), magnetization acquisition was possibly of somewhat short duration. Alternatively, the field was characterized by limited paleosecular variation or the acquisition process smoothed the field record over the time of remanence acquisition. *Cairanne et al.* [2003] show that CRM acquisition is not necessarily capable of faithfully recording a dual polarity remanence. Their experiments on assemblages of hydrothermal magnetite, produced by the

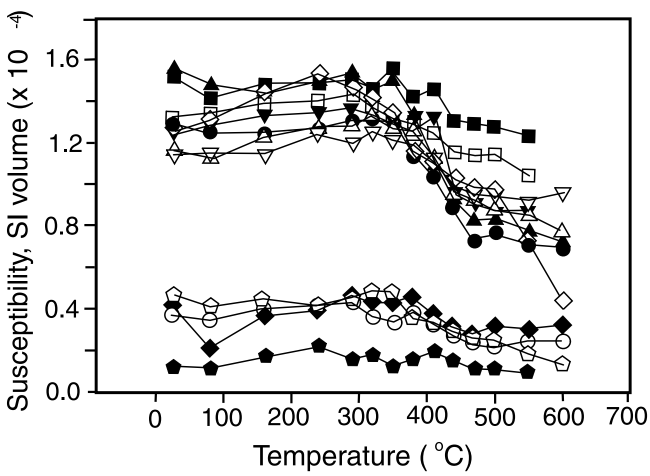

Figure 11. Curves showing bulk low-field susceptibility measured as a function of temperature after each step of progressive thermal demagnetization for 12 randomly selected specimens from sites in sandstone pipes and immediately adjacent host strata.

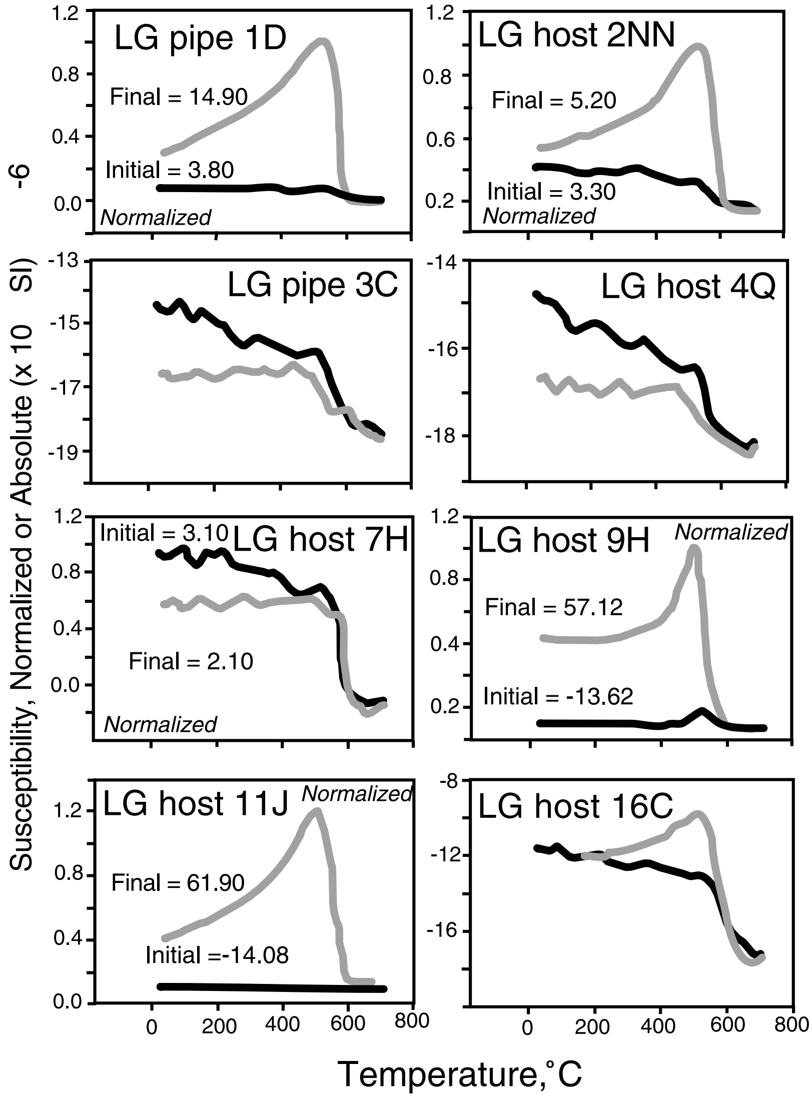

Figure 12. Curves showing continuous susceptibility versus temperature measurements for eight randomly selected specimens from sites in sandstone pipes and adjacent host strata. In those cases where a substantial increase in susceptibility occurred upon cooling (samples 1D, 2NN, 9H, 11J), and for sample 7H, the curves have been normalized to the maximum intensity, and initial and final intensities are reported. In the other examples, we report the bulk susceptibility as a function of temperature. Dark lines (gray lines) indicate heating (cooling) curves.

reduction of hematite, under conditions where the polarity of the applied field was switched, showed that the CRM acquired was only of a single polarity, as revealed by AF demagnetization, despite the fact that the ambient field was reversed during the course of the experiments. The actual amount of time required for magnetization acquisition, and hence geomagnetic field time sampled, may be in large part dependent on the process responsible for acquisition of the ChRM, of rather unique magnetic properties, in these rocks. We present two alternative hypotheses: the first is our preferred interpretation.

[24] Given the overall association between the presence of a well-defined, well-grouped reverse polarity magnetization in sandstone pipes and both the Summerville and Bluff strata adjacent to these crosscutting features, a viable hypothesis is that acquisition of this magnetization was intimately associated with injection of the sandstone pipes. This interpretation implies that the remanence is secondary, but still relatively early in age. *Hunter et al.* [1992] and *Moench and Schlee* [1967] provided considerable field evidence (e.g., drag folding of beds adjacent to the ring faults bounding the pipes, and convolute folding of beds within some pipes) for an early, prelitihification origin for the sandstone pipes. Although the details of the origin of sandstone pipes have been debated in the literature, most models involve enhanced fluid flow within and around the injected sandstone bodies [e.g., *Anderson and Kirkland*, 1960; *Netoff and Shroba*, 2001], regardless of their geometry. The formation of sandstone pipes in the southern and southeast San Juan Basin is interpreted to have involved partial to nearly complete evaporite dissolution in the underlying gypsum dominated member of the Todilto

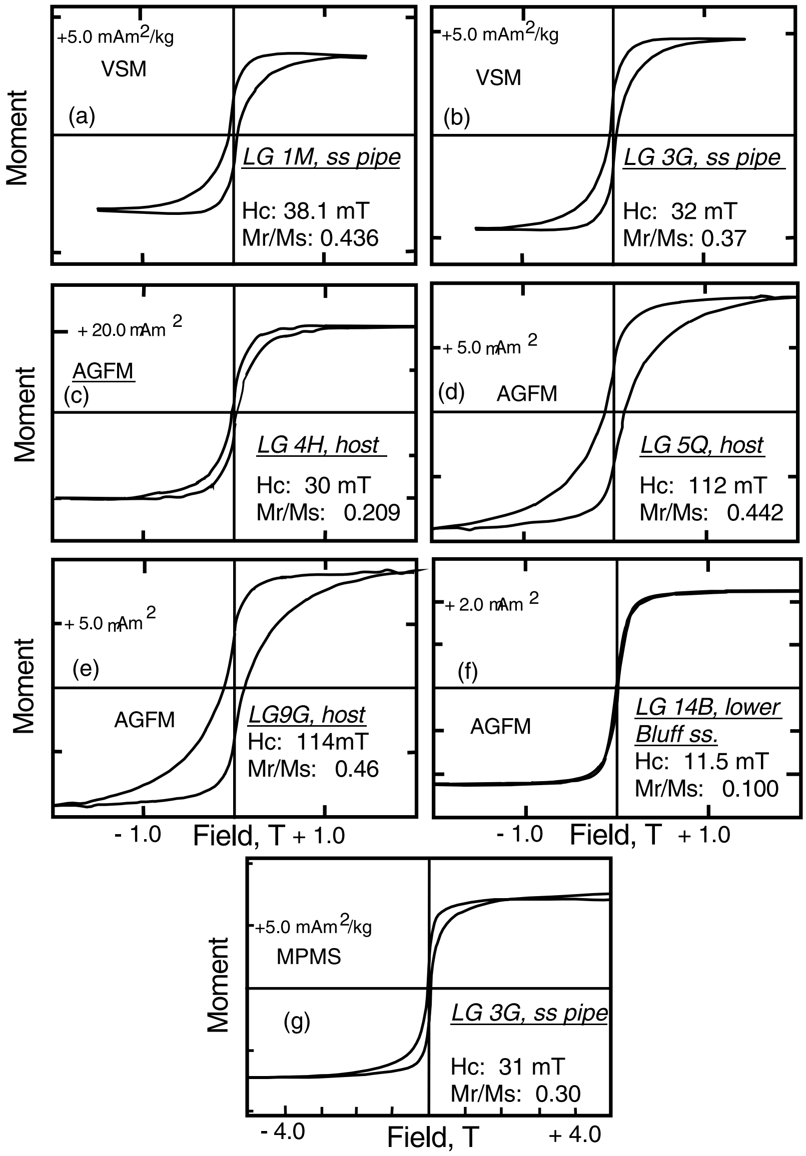

Figure 13. (a, b) Hysteresis curves, slope corrected, for two specimens from sites in sandstone pipes, measured using a vibrating sample magnetometer (VSM). (c, d, e) Curves for three specimens from sites in host strata immediately adjacent to sandstone pipes, measured using an alternating gradient force magnetometer (AGFM). (f) Curve for a specimen from site 14, in strata far removed from sandstone pipes, measured using an AGFM. (g) Replicate analysis of sample 3G (b, sandstone pipe) using a Magnetic Properties Measurement System (MPMS).

Formation [*Moench and Schlee*, 1967; *Tanner*, 1972]. We hypothesize that the sandstone pipes and adjacent strata were saturated, or nearly saturated with fluid at the time of sandstone pipe injection and suggest that the fluid associated with the pipes and that infiltrated immediately adjacent strata was capable of modifying the magnetic mineralogy of the rocks.

[25] Many studies have demonstrated changes in rock magnetic properties of sediments or sedimentary rocks subjected to geochemically reducing or oxidizing conditions [e.g., *Henshaw and Merrill*, 1980; *Canfield and Berner*, 1987; *Reynolds et al.*, 1985, 1994]. On the basis of the rock magnetic data and petrographic observations of the sandstone pipes and adjacent host rocks, we argue that geochemical conditions were appropriate to facilitate the growth of small quantities of a fine-grained cubic magnetic phase. On the basis of our petrographic and SEM inspections, we do not find evidence of appreciable detrital oxide grains in these rocks and thus argue that such grains are not the likely carrier of the reverse polarity characteristic remanence. If low-temperature, SO_4^{-2} bearing fluids formed during evaporite (gypsum) dissolution are highly alkaline (e.g., pH greater than $\sim$8.0) and reducing (Eh values less than -0.3), magnetite, which we infer to carry the secondary, chemical remanent magnetization in the Summerville and Bluff strata and crosscutting sandstone pipes, could grow at the expense of and be in equilibrium with hematite in the host rocks (Figure 15). The fact that we have not

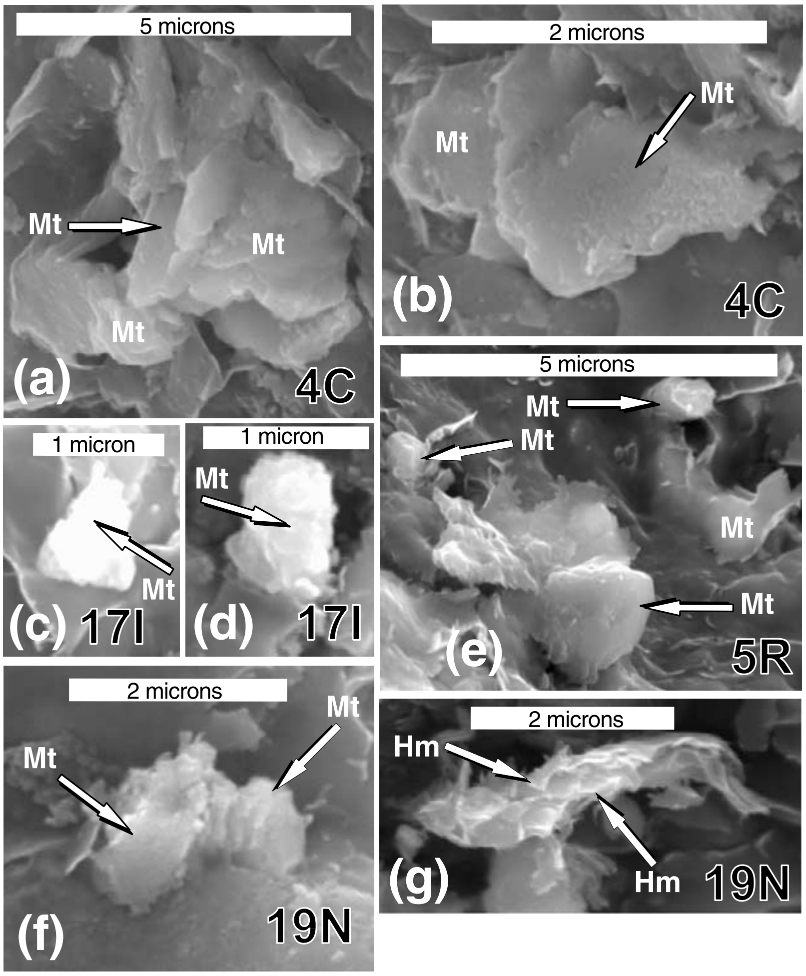

Figure 14. Scanning electron microscope photomicrographs showing examples of high-iron content mineral phases (high atomic number) present in the sandstone pipes and adjacent host strata. In Figures 14a–14f, arrows point to what we interpret to be cubic (magnetite?) (Mt) iron oxide grains, based on their morphology and approximate composition, inferred from energy dispersive X-ray analysis. In Figure 14g, arrows point to what we interpret to be a cluster of hematite (Hm) crystals, again based on morphology.

detected any iron sulfide phase in these rocks is interpreted to indicate that the conditions are moderately to strongly alkaline. Such a geochemical setting is plausible in an environment of active gypsum dissolution. For example, *Capaccioni et al.* [2001] studied the chemistry of groundwaters in the northern Apennines, Italy. The nearly isolated hydrogeologic system in that region is locally dominated by gypsum-saturated waters formed by interaction with Triassic evaporates. Maximum pH values reach 8.1, maximum SO_4^{-2} concentrations exceed 200 mg/L, and maximum water temperatures are ~16°C. The process we envision to explain the formation of modest amounts of a secondary, cubic phase carrying a well-defined remanence is similar in efficiency yet very dissimilar in chemical conditions to that described by *Reynolds et al.* [1985] for the remagnetization of Permian Cutler Formation red beds in the Late Cretaceous to middle Tertiary in response to local uranium mineralization. In the remagnetized Cutler Formation rocks, the geologically stable secondary magnetization is carried by authigenic hematite, and *Reynolds et al.* [1985] showed that partial to complete dissolution of preexisting hematite (as detrital grains or grain coatings) in a weakly acidic environment erased the record of a late Paleozoic magnetization in the mineralized zones. Our explanation, notably, does not address the interesting question of the lack of a well-defined, geologically stable magnetization in hematite in these hematite-cemented rocks. First, we note that the NRM intensities for the sandstone pipes and immediately adjacent strata are comparable to if not less than those of many hematite-cemented detrital rocks (*Butler* [1992] quotes a typical value of 10 mA/m for red siltstones; *Dunlop and Ozdemir* [1997] quote a range of 1 to 100 mA/m). We speculate that any early acquired hematite pigment in the host rocks may have been reconstituted during and subsequent to fluid infiltration attending sandstone pipe emplacement and never efficiently acquired a stable magnetization. Additionally, any preexisting pigment hematite, and the grains to which pigment may have been attached, in sandstone that was fluidized to eventually form the pipes was probably physically randomized in the process of pipe emplacement.

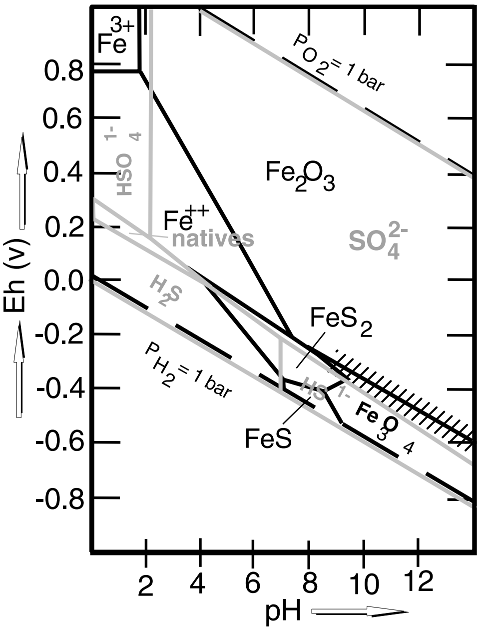

Figure 15. Superimposed Eh-pH diagrams for the S-O-H system (gray lines) at 25°C, 1 bar, and $S = 10^{-3}$ and the Fe-S-O system (black lines) at 25°C, 1 bar, and molality of solutes of 10^{-6}). Hachured area highlights Eh-Ph line where magnetite and hematite are in equilibrium. From *Brookins* [1988].

[26] Despite the fact that the paleomagnetic data from the sandstone pipes and host strata are uniformly of reverse polarity and are associated with very low-dispersion, the results are consistent with the mechanism of remagnetization we propose above. The paleomagnetic pole provided by this reversed polarity secondary magnetization (Figure 16), after correcting for a modest (e.g., ~5° (preferred) to ~11° (less preferred)) amount of clockwise rotation of the Colorado Plateau since the Late Jurassic [*Bryan and Gordon*, 1990; *Kent and Witte*, 1993; *Molina-Garza et al.*, 1998; *Steiner and Lucas*, 2000; *Steiner*, 2003] ranges from 68.7°N, 143.8°E (small rotation) to 64.0°N, 150.0°E (larger rotation). Our correction is simply based on a vertical axis rotation at the site, rather than some Euler pole rotation of paleomagnetic poles because of the uncertainty in actual location of the pole of rotation for the Colorado Plateau [e.g., *Molina-Garza et al.*, 1998]. Considering only paleomagnetic data from the Colorado Plateau for comparison, to minimize concern over the actual magnitude of Colorado Plateau rotation, the pole location is similar to previously reported poles for the Lower Morrison Formation [*Steiner and Helsley*, 1975], the Brushy Basin Member of the Morrison Formation [*Bazard and Butler*, 1994], and the Summerville Formation [*Bazard and Butler*, 1992]. The general similarity of the pole derived from remagnetized Summerville Formation strata and the sandstone pipes is, arguably, consistent with a latest Middle to Late Jurassic age of magnetization acquisition. This argument, of course, assumes that the extant Summerville results as well as other previously reported data that define a moderate latitude APW path for the Jurassic for North America are reliable. If the magnetization in the sandstone pipes and adjacent strata was acquired early, then the data provide additional support for a moderate, rather than high-latitude APW path for North America during the Late Jurassic. Clearly, the reverse polarity magnetization characteristic of the rocks in the Mesita/Laguna area was acquired after injection of the sandstone pipes. Any attempt to more accurately as well as more precisely define the age of the characteristic magnetization reported here, based on a comparison with extant Jurassic paleomagnetic data for North America, is probably unrealistic.

[27] An alternative explanation for the origin of the characteristic remanence in sandstone pipes and host Summerville strata in the sampling area is acquisition via

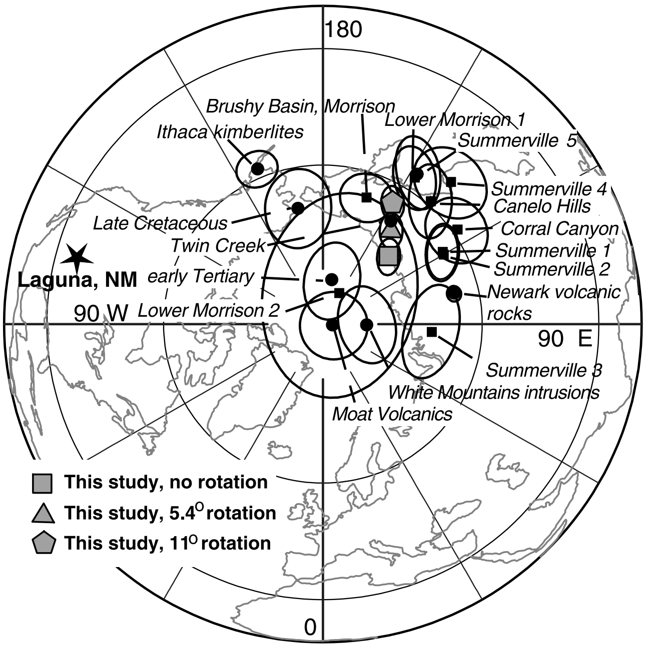

Figure 16. North polar orthographic projection of selected North American paleomagnetic poles for rocks of Jurassic age, compared with results from the Summerville/Bluff strata and sandstone pipes. Paleomagnetic poles from specific studies of rocks on the Colorado Plateau are shown as solid squares; those from rocks off the plateau are shown as solid circles. Those paleomagnetic poles from rocks on the Colorado Plateau have been rotated according to *Bryan and Gordon* [1990], restoring an inferred 5.4° rotation of the plateau, consistent with the analysis by *Molina-Garza et al.* [1998]. Sources of the paleomagnetic poles are as follows: Moat Volcanics [*Van Fossen and Kent*, 1990], White Mountains intrusions [*Van Fossen and Kent*, 1990], Summerville 1 [*Steiner*, 1978], Summerville 2 [*Steiner*, 1978], Summerville 3 [*Steiner and Helsley*, 1972], Summerville 4 [*Bazard and Butler*, 1992], Summerville 5 [*Steiner*, 2003], Newark volcanic rocks [*Smith and Noltimier*, 1979], Corral Canyon [*May et al.*, 1986], Canelo Hills [*Kluth et al.*, 1982], Lower Morrison 1 [*Steiner and Helsley*, 1975], Lower Morrison 2 [*Van Fossen and Kent*, 1992a], Twin Creek [*McCabe et al.*, 1982], Brushy Basin, Morrison [*Bazard and Butler*, 1994], Ithaca kimberlites [*Van Fossen and Kent*, 1993], Late Cretaceous [*Van der Voo*, 1993], early Tertiary [*Van der Voo*, 1993]. Star indicates study location.

thermochemical remagnetization of the sandstones in association with late Tertiary to Quaternary(?) mafic magmatism in the area. As noted above, the area has been intruded by mafic bodies (Figures 1b and 1c). This explanation seems unlikely given the distance from sampled pipes and host strata to the nearest exposures of mafic intrusions. This possibility cannot be ruled out, however, as the subsurface lateral extent of these intrusions is unknown. Data from a single thin mafic dike are exclusively of normal polarity (Site 12, Figure 1b and Table 1), yet notably of low-median destructive fields (Figure 4). Data from host rocks immediately adjacent to the dike (Site 13, Figure 1b and Table 1) are of reverse polarity, thus yielding an apparent failed baked contact test. Notably, the inclination of the magnetization in the host contact rocks adjacent to the mafic dike is considerably steeper than that of the characteristic magnetization in the sandstone pipes and immediately adjacent strata. The low-coercivity remanence in the dike, combined with the contact results, allow the possibility that the observed remanence in the dike is secondary in origin. Data from the late Quaternary basalt flow nearby (Figure 1c) are exclusively of normal polarity [*Cascadden et al.*, 1997]. Finally, site 14 (Figures 4 and 5), in Summerville strata distant from any exposed sandstone pipes yet at an identical stratigraphic level to sites adjacent to sandstone pipes and also <100 m from a large intrusion exposed along I-40 (Figure 1b) yields a very poorly defined normal polarity magnetization (Table 1). The demagnetization and rock magnetic properties of Summerville samples at this site are very different from those of Summerville strata adjacent to pipes that contain the well-defined yet secondary reverse polarity remanence. A better definition of the polarity and direction of the magnetization in the mafic intrusions in the area requires additional sampling of larger and mineralogically fresher intrusions.

7. Summary and Conclusions

[28] The magnetization characteristic of large sandstone pipes and their host upper Middle Jurassic strata, exposed in the Mesita area, New Mexico, is of reverse polarity and is carried principally in a moderate coercivity cubic magnetic phase, with unblocking temperatures in the 300–450°C interval, which we have partially identified in SEM investigation. A higher-coercivity phase, presumably fine to ultrafine hematite as a pigment in these rocks, is present, but our observations demonstrate that it does not contribute substantially to the characteristic remanence. The carrier of the characteristic magnetization is probably at least partially destroyed during progressive demagnetization. The similarity of paleomagnetic directions and overall demagnetization behavior between the sandstone pipes and adjacent Summerville strata argues for an age of magnetization that clearly postdates formation of sandstone pipes, which were formed by upward fluid injection. We propose that the most logical explanation of the magnetization is that it is a CRM whose acquisition was associated with the fluid circulation directly associated with the formation of the pipes. The paleomagnetic pole for these rocks, corrected for slight tilt of the strata and for 5° of clockwise rotation of the Colorado Plateau, is comparable with paleomagnetic poles obtained from Lower Morrison Formation strata and from the Brushy Basin Member of the Morrison Formation. Despite the fact that this magnetization, with its unusual set of rock magnetic properties, is exclusively of reverse polarity, we argue that the magnetization is probably not a simple short-lived record of the geomagnetic field, possibly acquired in response to young (latest Tertiary/early Quaternary) magmatism. Rather, we argue that the direction of the characteristic magnetization is not fortuitous but that it adequately represents a latest Middle to Late Jurassic field.

[29] **Acknowledgments.** Mike Bell, Thomas Geissman, Hope Jacunski, Rick Livaccari, and Sean Mullally aided in field sampling. We thank Chris Hunt, Jim Marvin, and Mike Jackson of the Institute for Rock Magnetism for their assistance with hysteresis measurements. Jim Karner assisted with the SEM observations. Partial support for this work was provided by the New Mexico Bureau of Mines and Mineral Resources, Socorro. The Paleomagnetism Laboratory at UNM has been maintained through several NSF grants. NSF award EAR0087556 supported the George Mason University Paleomagnetism Laboratory. Reviews by Bob Butler, Mike Jackson, and Doug Elmore are greatly appreciated.

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