Magnetostratigraphy and Clockwise Rotation of the Plio-Pleistocene Mojave River Formation, Central Mojave Desert, California.

Christopher J. Pluhar and **Joseph L. Kirschvink**, Division of Geological & Planetary Sciences, The California Institute of Technology, Pasadena, CA 91125, and **Robert W. Adams**, 7400 Tampa Ave., Reseda, CA 91335

ABSTRACT

Oriented samples collected for paleomagnetic analysis from sediments of the newly-named Mojave River Formation (Nagy & Murray, 1991, this volume) possess stable characteristic components of Natural Remanent Magnetization (NRM). Progressive demagnetization reveals characteristic components of both normal and reversed polarity which are stratigraphically distinct. The oldest sediments exposed within the field area are reversely magnetized and were probably deposited during the early portion of the Matuyama reversed Chron. Stratigraphically higher units contain what appears to be the Olduvai normal Subchron, as well as a shorter normal zone which probably is either the Cobb Mountain or Jaramillo Event. The location of the Brunhes/Matuyama boundary at one site is within an alluvial fanglomerate which grades upward conformably into the lowest unit of the overlying Manix Formation, possibly accounting for the absence of the Bishop ash in the section.

Demagnetization data from 143 samples yielding acceptable least-squares lines suggest a net clockwise rotation of 8 $\pm$ 2.7° over the past two million years, perhaps with some of the rotation during deposition. This rate of rotation could account easily for larger rotations reported elsewhere in the Mojave Desert on units of Miocene age.

INTRODUCTION

Perhaps the best sedimentary records of latest Pliocene and Pleistocene age are found in the relict lake and playa beds of the intermontane basins of the southwest United States. However, a complete tectonic and climatic history of this period remains to be unearthed. Detailed stratigraphic and paleomagnetic studies are necessary to correlate the nature and timing of depositional and deformational events; ongoing investigations in southern Death Valley and Manix Basin are designed to provide detailed information about such events in these locations.

Death Valley is the sink for internal drainage of a vast region from the east slope of the Sierra Nevada, the Transverse Ranges and the southwestern Nevada desert. Topographic basins along major drainage systems; Owens Valley, Searles Valley, Manix Basin and Tecopa Basin all contain Pleistocene lacustrine and playa sediments dated at more than 1,000,000 years B.P...These drainages are now evidenced by dry playas and by the eroded remnants of bedded deposits from wetter periods.

Beds of volcanic ash from two source areas are evident in many of these lake beds and are potentially useful in stratigraphic correlations. Sequential eruptions in the Long Valley resurgent caldera region north of Bishop, California produced white ashes containing biotite. Gray ash, lacking biotite, was airborne into California from the Yellowstone Caldera. Of these ashes, only three are consistently identified with any degree of confidence in Southern California: the 0.73 Ma Bishop ash, the 0.6 Ma Lava Creek B, and the 2.0 Ma Huckleberry Ridge ash from Yellowstone (Sarna-Wojcicki, et al., 1984). The general similarity in chemistry within each of these suites of ashes inhibits accurate correlations of individual beds; however they are helpful in determining relative positions in a stratigraphic column.

A 400 square kilometer area in the central Mojave Desert east of Barstow was once the site of a Pleistocene lake known as Lake Manix (Buwalda, 1914; Blackwelder and

Ellsworth, 1936). Primarily supplied by the Mojave River, late Pleistocene Lake Manix persisted for more than 350,000 years (Jefferson, 1985) as an intermittent freshwater body until its permanent drainage after 14,230 ± 1325 years B.P. through Afton Canyon (Meek, 1989), possibly as a result of renewed motion along the left-lateral Manix fault. The stratigraphy and paleontology of the late Pleistocene Lake Manix deposits have been studied intensively by Jefferson (1985, 1987). Subsequent work by a California Institute of Technology group (McGill, et al., 1988; Murray, Nagy and Adams, 1990) has focused on field mapping of the older deposits that underlie the Manix Formation, referred to here and in the Nagy and Murray (1991, this volume) paper as the Mojave River Formation. Nagy and Murray provide the stratigraphic background for the present magnetostratigraphic study.

Paleomagnetic work in the Manix area has been concentrated on several separate exposures of the Plio-Pleistocene beds whose stratigraphic correlations are not always clear. Previous workers have sampled ten ash beds in these exposures and have identified them as four ashes known from other regions. Of these four ash layers, the "uppermost white ash" is in the younger series of lake beds, the Manix Formation, and has been correlated with the Long Canyon tephra in the southern Sierra Nevada at 0.185 Ma (Bacon and Duffield, 1981). Sarna-Wojcicki, et al., (1984) correlated the "lowermost gray ash" with the 2.0 Ma Huckleberry Ridge tephra from the Yellowstone caldera, whereas a "middle white ash" bed was equated with Waucoba Road bed W3A (=Taylor Canyon C @ 2.3 Ma). In one Mojave River Formation section, the "middle white ash" is stratigraphically 3 meters above the gray ash and therefore younger. (This inconsistency illustrates the general problem of attempting correlation solely by means of chemical "fingerprinting".) An "upper white ash" appears in two localities, paired with a white ash at one site and in sequence above a white ash and a gray ash at another site. Magnetostratigraphic work within the field areas were directed at providing additional tests of these stratigraphic correlations.

Site localities and abbreviations used here and in Nagy and Murray (1991, this volume) are defined relative to the dry Mojave River bed shown on their Plate 1. These include the Northern Site (NS), the Southern Cliff Site (SCS), the Southern Hill Site (SHS), the Big Bend East and West (BBE and BBW) sites, and the Southern Road Site (SRS).

METHODS

The Mojave River Formation varies in composition from well indurated claystones to friable sandstones (Nagy and Murray, 1991, this volume). These beds are difficult or impossible to sample with typical paleomagnetic techniques which employ water cooled diamond-tipped drill bits. Unlithified sandstones fall apart when drilled and the claystones turn to mud. For these reasons we used a combination of soft-sediment sampling techniques with quartz-glass cups for the sandy sediments (Weldon, 1984) and simply drilled the claystones using compressed air instead of water as the coolant for the bit. In the conglomeratic facies, we found that it was occasionally possible to obtain an oriented sample of silty standstone which had washed into gaps between adjacent cobble-sized clasts. In the fine-grained sediments we were able to collect between ten and twenty samples per hour using these techniques. Samples were collected in stratigraphic succession (one sample per horizon) from a total of seven localities on both the north and south sides of the Mojave River.

Unconsolidated samples were stabilized in the laboratory using a 10% sodium silicate solution and ceramic cement where necessary. All measurements were performed on a computer-controlled cryogenic SQUID (superconducting quantum interference device) magnetometer with a backgroud noise level of $5 \times 10^{-12} Am^2$. Progressive demagnetization experiments involved an initial alternating field (AF) demagnetization in several steps up to 15 militesla (mT) to remove any magnetically soft components which may have been the result of large, multi-domain magnetites or have been induced by the drilling process. This was then followed by progressive thermal demagnetization experiments stepping from 150° to 500°C at 50° intervals; a procedure which is usually effective for removing magnetic overprints held by maghemite, goethite, or fine-grained hematite produced by Recent weathering. Characteristic components of the Natural Remanent Magnetization (NRM) vectors were then found using the least-squares method of principal component analysis (Kirschvink, 1980).

Small amounts (approximately 0.1 g) of material were removed from representative fine-grained samples and subjected to a battery of rock-magnetic analyses, in an attempt to place constraints on the mineralogy and magnetic granulometry of the material which preserves the magnetic remanence. These sub-samples were first gently disaggregated by crushing, placed in a 1 ml plastic epindorph tube, and loaded into the fully computer-controlled SQUID magnetometer system housed in the California Institute of Technology biomagnetics clean laboratory (e.g., Kirschvink, 1983). Rock-magnetic experiments include: (1) an acquisition of Anhysteretic Remanent Magnetizaiton (ARM) in a standard 100 mT alternating field, with progressively stronger background biasing fields between 0 and 2 mT as done by Cisowski (1981), (2) the progressive AF demagnetization of the ARM after the 2 mT ARM step, (3) the progressive AF demagnetization of a 100 mT Isothermal Remanent Magnetization (IRM), and (4) an IRM acquisition experiment in fields of up to 800 mT.

RESULTS

Demagnetization Analysis

Figure 1 shows demagnetization results typical of normal, reversed, and unstably magnetized samples from the Mojave River Formation. The intensity of the NRM was fairly uniform, at about $5x10^{-4}$ Am^2/kg, which is reasonably strong for sediments, and probably reflects a significant component of detrital magnetite eroded from crystalline rocks within the drainage basin of the Mojave River. Virtually all of the samples collected contain a magnetic component aligned roughly along the present magnetic field direction which usually could be removed by low-intensity alternating fields (< 15 mT) or by thermal treatment below 250°C. This is presumably held by large crystals of multi-domain magnetite, which are magnetically viscous, or by the magnetic fine-grained ferric oxide pigments (goethite, maghemite, or hematite) produced by Recent subaerial weathering. The magnitude of this component is far less pronounced at SCS, which has excellent bed-by-bed exposures produced by Recent downcutting of the Mojave River. Recognition of this normal-polarity magnetic overprint is relatively easy in the reversely magnetized samples, as it shows up as a major junction between adjacent linear segments on the orthogonal projections, such as in Figure 1A. Due to a minimal amount of tectonic deformation, these components are sometimes difficult to recognize in the normally-magnetized samples. They often stand out as slight breaks in the demagnetization paths, yielding distinct directions with principal component analyses. As it is sometimes difficult, however, to determine precisely the point at which the overprint overlaps with the characteristic (or primary) direction, overall directions from the normal polarity samples probably have a small amount of residual contamination from these overprints.

Rock Magnetic Analysis.

Figure 2 shows typical results from the rock magnetic experiments. Information on the distribution of particle coercivities is provided by the acquisition of an IRM curve labeled on Figure 2A, indicating that most of the magnetization is gained in the interval between 10 and 100 mT. This suggests that fine-grained magnetite is the principal magnetic mineral. A slight tendency to gain magnetic remanence after exposure to peak fields above 100 mT suggests the presence of ferric iron oxide pigments. Also shown on Figure 2A are results of a modified Lowrie-Fuller ARM test (e.g., Johnson et al. 1975), which compares the resistance to alternating-field demagnetization of both the IRM produced in a 100 mT peak field and the ARM gained in a 100 mT oscillating field. The fact that the ARM demagnetizes at higher peak fields than does the IRM indicates that the magnetic remanence is dominated by fine-grained (< 10 um) particles of magnetite of single-domain or pseudo-single domain size.

Figure 2B shows the results of ARM acquisition experiments from several of the fine-grained samples from the Mojave River Formation. This procedure tests mainly for

Table 1. Summary of stable paleomagnetic directions from all sites sampled within the Mojave River Formation. Directions are based on principal component analyses of the progressive demagnetization data as described in the text, and were from specimens which yielded maximum angular deviation (MAD) values for best-fit lines of 10° or less, using the method of Kirschvink (1980). Results enclosed in parentheses have been corrected for the tilt of the bedding. The parametric test of coincident mean directions (Fisher et al. 1987, p. 211) shows that, although close, the normal and reversely magnetized direction groups are not truly antiparallel (Chi^2 = 10.96 with 2 d.f., p < .005 for rejection of the hypothesis of antiparallelism). Errors for the rotation values quoted in the text are modified from the a_{95} by the method of Demarest (1983). Bingham statistics follow the methods of Onstott (1980). The sites are located in the Mojave Desert near 35°North latitude, 243.5°east longitude. Equal-area projections for the directional data corresponding to letters A thourgh F on this table are shown on Figure 3.

	Grouping	N	Decl.	Incl.	Fisher Stats.			Bingham Statistics				
					K	a_{95}	R	K1	K2	a_{min}	a_{max}	ov.
A.	Al l	50	6.9	52.8	19.1	4.7	47.43	-14.0	-9.0	4.0	5.1	22
	Normals		(5.1	48.8	20.4	4.6	47.60	-14.3	-9.5	4.0	4.9	82)
B.	All	93	193.0	-49.2	11.8	4.5	85.22	-8.6	-6.5	4.0	4.6	99
	Reversed		(189.0	-40.8	12.2	4.4	85.46	-8.8	-6.6	3.9	4.6	114)
C.	Pre-Olduvai	73	193.0	-50.9	10.9	5.3	66.38	-8.8	-5.8	4.5	5.6	98
	Reversed		(190.0	-42.3	11.4	5.1	66.67	-9.0	-5.9	4.4	5.5	114)
D.	Olduvai & younger											
	Directions	70	8.9	50.3	18.0	4.1	66.18	-13.1	-8.8	3.5	4.4	13
			(5.1	45.1	18.0	4.1	66.17	-13.7	-8.5	3.4	4.5	3)
E.	Post-Olduvai											
	Reversed	20	193.1	-43.6	18.2	7.9	18.96	-13.0	-9.2	6.6	8.0	10
			(185.0	-35.6	17.5	8.0	18.92	-12.3	-9.2	6.8	7.8	5)
F.	All directions	143	11.1	50.6	13.6	3.3	132.52	-8.8	-7.5	3.1	3.4	86
	Combined		(8.0	43.8	13.8	3.3	132.74	-9.1	-7.5	3.1	3.4	133)

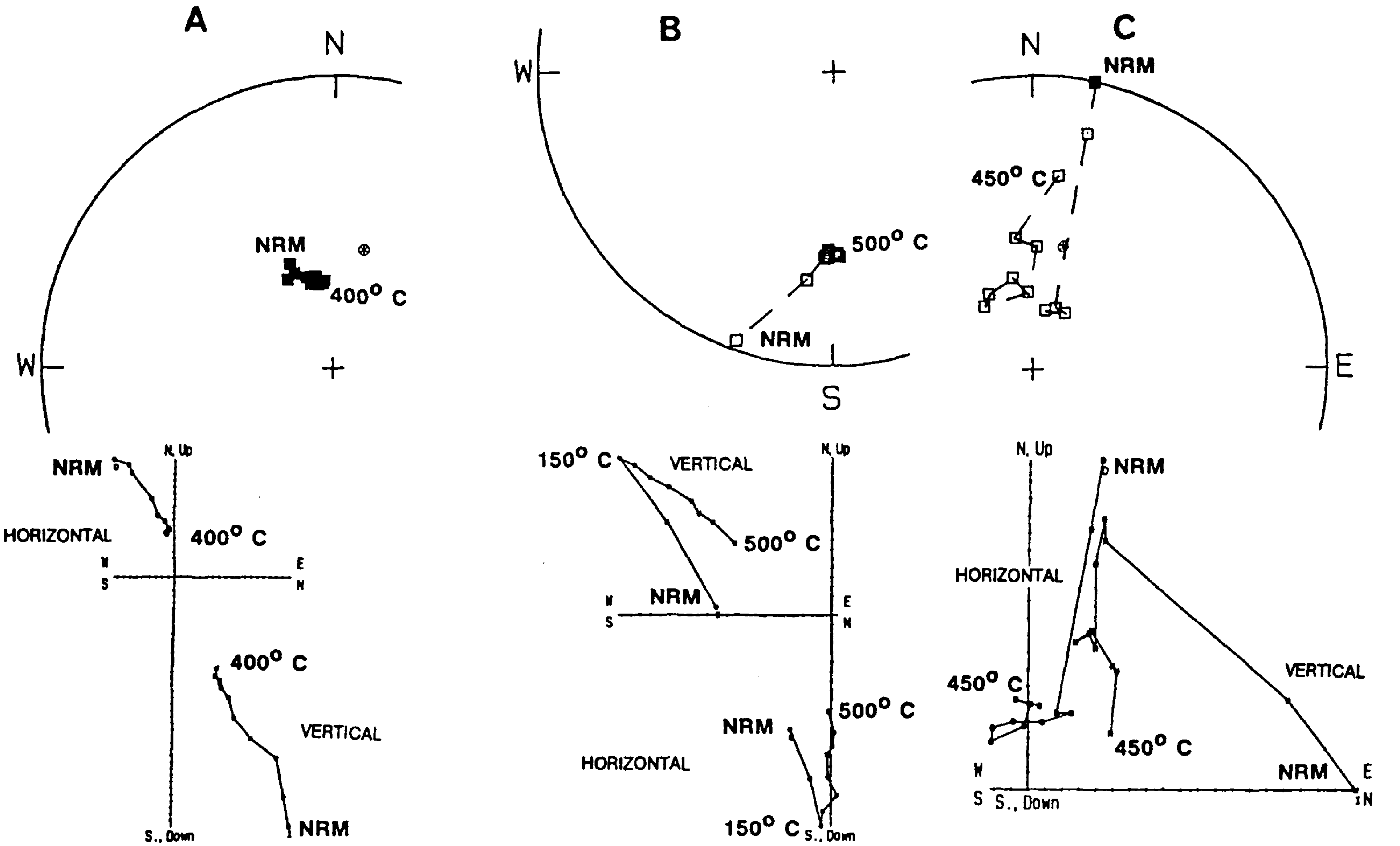

Figure 1. Progressive demagnetization of typical normal (A) and reversed (B) samples as well as an unstable sample (C). Top figures are equal area projections with open squares being the upper hemisphere and solid squares the lower. The bottom figures are orthogonal projections on the horizontal and vertical north-south planes.

the microscopic packing geometry of the fine-grained magnetite in the sediments. A sample in which the magnetic particles are separated from each other enough that they are out of range of the magnetic fields of other magnetic particles will plot above the top curve on figure 2B (labeled magnetotactic bacterium). On the other hand, samples in which the magnetic particles are clumped densely together, or which are dominated by large, multi-domain grains of magnetite, will plot on or below the lowest reference curve on figure 2B (labeled chiton tooth). Results from samples of the Mojave River Formation fall in intermediate positions, suggesting mixtures of both types of packing geometries. Hence, a considerable fraction of the magnetic particles are present as isolated grains in the clay matrix of the silty mudstones. These particles are most likely to align spontaneously with the earth's magnetic field during deposition, and therefore the natural remanent magnetization preserved by them is probably detrital or early post-depositional in origin.

Magnetic Directions

Figure 3 and Table 1 show results from the stable, characteristic magnetic components determined from the principal component analyses of the progressive demagnetization data, pooled from all sites in the field area. As the strata are mostly flat-lying, it is not possible to conduct a fold test on the sediments. When analyzed separately, the distributions for the normal and reversely magnetized samples are not quite antiparallel (Table 1), with the normal group displaying slightly less net rotation than the reversed group. This slight antiparallel offset could either be related to the presence of a small component of the recent field which is not completely removed by the demagnetation treatment, or it may be due to a progressive rotation during the deposition of the sediments, as the majority of reversed directions are from before the Olduvai normal Subchron. Grouping the data into two sets, one pre-Olduvai and the other Olduvai and younger (Table 1) shows that the older sediments ($\sim$2.4 - 1.87 Ma) have been rotated clockwise an average of 10 $\pm$ 4°, whereas the younger group ($\sim$1.87 - .7 Ma) is only rotated clockwise 5.1 $\pm$ 3.3° from the expected north-south direction (rotational-only errors have been calculated according to the analysis of Demarest, 1983). Hence, rotations were probably happening *during* deposition of the lake sediments, and this is the most probable cause for slight mis-alignment of the total normal and reversed groups.

It is intriguing to note that the youngest group of samples (post-Olduvai reversed in Table 1) have the shallowest average inclination. These samples at SCS of the Mojave River Formation, however, include the gradual transition up into the conglomeratic beds of the overlying basal Manix Formation. This decrease in dip may be due either to the effects of depositional inclination error, which ought to be more pronounced with an increase in grain size, or to a loss of proper quiet-water bedding planes necessary to correct for tectonic tilt.

Magnetostratigraphy

Figure 4 shows the Virtual Geomagnetic Pole (VGP) latitude from all samples yielding least-squares directions which were judged to be reliable enough to use for magnetic polarity interpretations (MAD values generally < 15°), plotted with respect to stratigraphic position within the sequence. Locations of the three ash units as well as the lithologic groups of Nagy and Murray (1991, this volume) are also shown for comparison.

It is clear from these data that the normally and reversely magnetized samples occur in stratigraphically concordant groups. The presence of these layer-bound, correlative units is the strongest field evidence that the primary magnetic directions were acquired at or soon after deposition of the beds. The thickest continuous stratigraphic section is the NS locality. This section is a composite of three, which overlap stratigraphically, but are offset laterally from each along the "middle and upper white ashes", respectively. The 75-meter-thick composite NS section is reversely magnetized except for a 12-meter-thick normal magnetozone which contains the "upper white ash". The lower reversed zone has the "middle white ash" within it as well as a discontinuous exposure of the "gray ash", identified as the 2.0 Ma Huckleberry Ridge by Sarna-Wojcicki, et al., (1984), an interpretation supported by Nagy and Murray (1991, this volume). Hence, the normal magnetozone overlying the "gray ash" can be identified

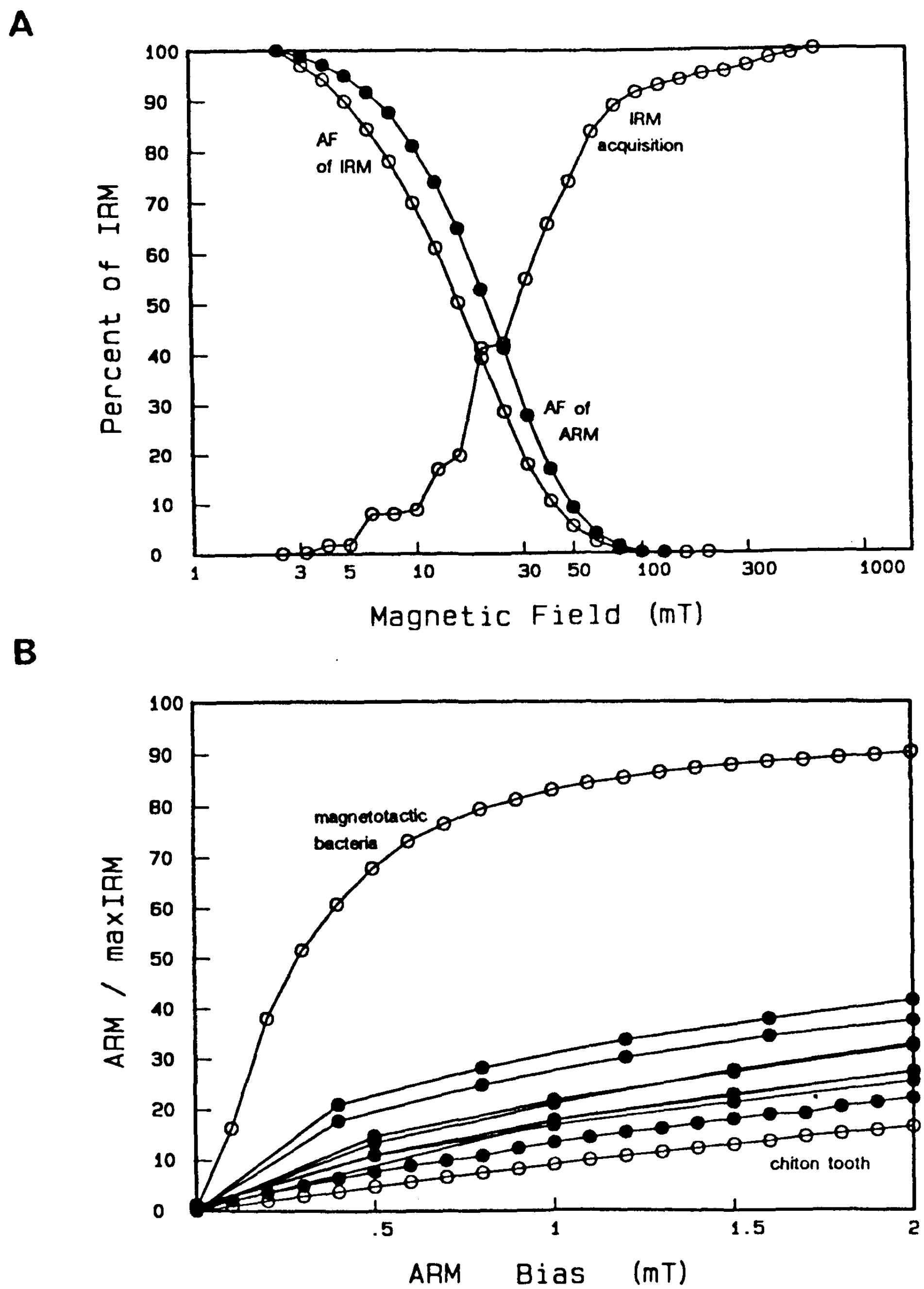

Figure 2. Rock Magnetic Properties; (A) Isothermal Remanent Magnetization (IRM) acquisition and demagnetization (open circles) and Anhysteretic Remanent Magnetization (ARM) demagnetization (solid dots) of a typical sample. These studies indicate that magnetite minerals in this rock are dominated by pseudo-single and single domain magnetite with some ferric iron minerals. (B) ARM acquisition for several samples indicating that a substantial fraction of the magnetic particles are in magnetic isolation.

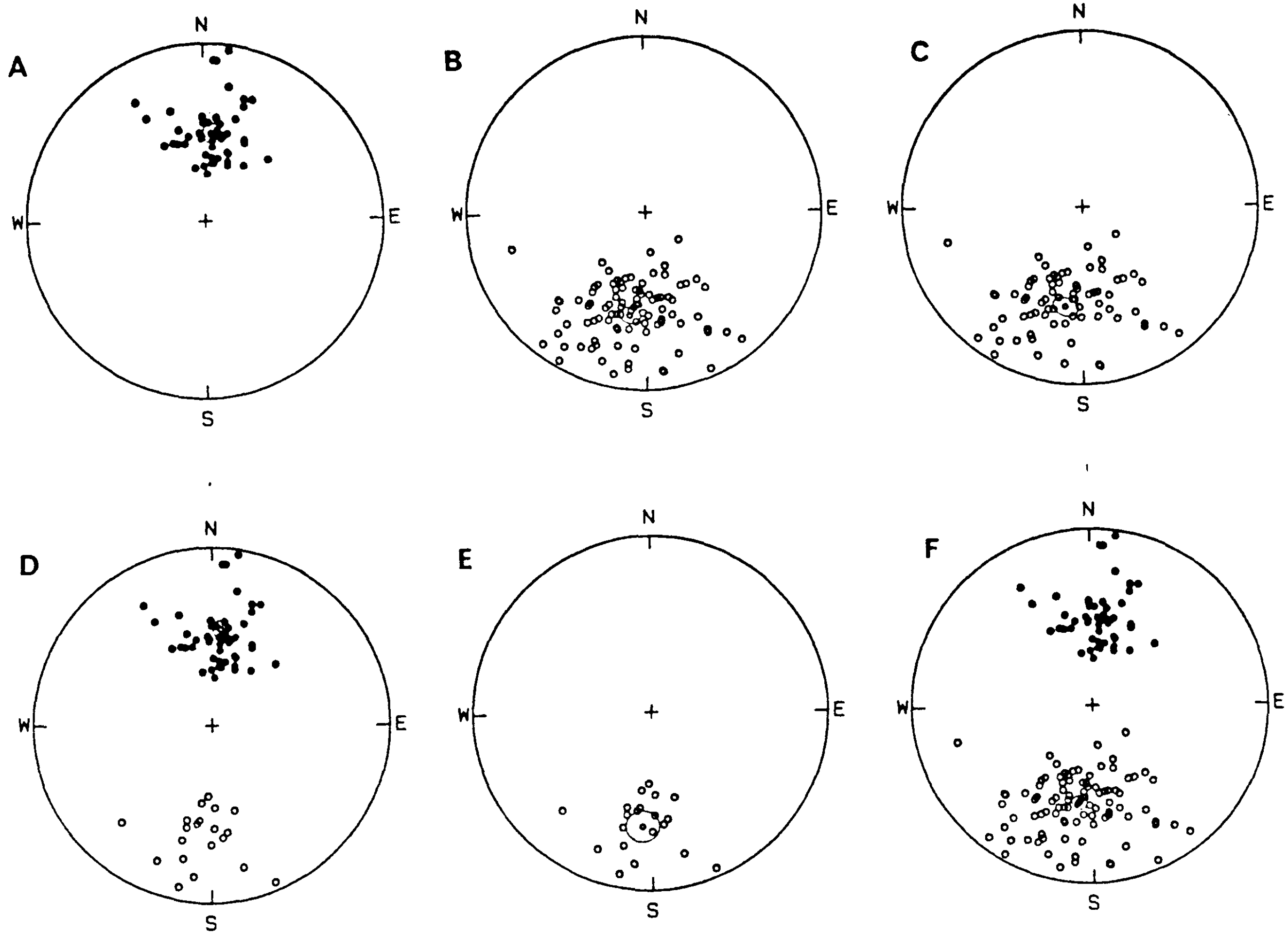

Figure 3. Equal area projections of the groupings of samples from Table 1. Mean directions are indicated by the larger open circles. (A) all normal samples, (B) all reversed samples, and (F) all samples grouped together. (C) all samples older than 1.87 Ma and (D) samples younger than 1.87 Ma. (E) all reversed samples younger than 1.67 Ma.

confidently as the Olduvai normal Subchron which ranges from 1.67-1.87 Ma (Harland et al., 1990).

No clear evidence exists in this section for the presence of the Reunion events. Two of the pre-Olduvai samples at the NS locality (one each at the 37 and 50 meter levels) may have an underlying normal component. However, these samples did not yield reliable directions during the progressive demagnetization experiments (figure 4, indicated by triangular symbols).

Both the normal zone and the two white ashes from NS correlate uniquely across to the SCS and SHS exposures on the southern side of the Mojave River, as discussed in detail by Nagy and Murray (1991, this volume). In particular, the SCS section contains both white ashes and the Olduvai normal Subcron, and extends stratigraphically higher in the sequence. The upper portion of this section includes a very thin normal zone which was initially discovered as a single sample, and then confirmed by resampling. Its stratigraphic position suggests that it is either the Jaramillo Event (0.91-0.97 Ma) or the Cobb Mountain Event (1.1 Ma), although its rather short stratigraphic thickness in comparison with that of the Olduvai suggests that it is the Cobb Mountain Event.

Southwest of the SCS site, stratigraphically higher lake sediments and interfingering conglomerates are exposed. Two of the 'Big Bend' sites (BBE and BBW) gave consistently normal directions. In addition, the section at BBW is within the basal units of the Manix Formation, which based on U/Th analyses and vertebrate faunal correlation is believed to be late Pleistocene in age (Jefferson, 1985, 1987). These sites are within the Brunhes normal Chron, and the Brunhes/Matuyama boundary presumably lies in a conglomeratic section between the SCS and BBE sections. Hence, the absence of the Bishop ash, which slightly post-dates this reversal boundary, may be due to its local deposition in an environment unfavorable for its preservation.

Two other sections corroborate data from the NS and SCS sites. SHS duplicates the stratigraphy of the "grey ash" below the "middle white ash", with an intervening reverse-to-normal transition (Figure 4). The section at SRS also contains the "lower grey ash" within a reversed polarity zone.

Stratigraphic thicknesses and age constraints of the reversals and the "lower grey ash" are used to calculate deposition rates within the Mojave River Formation. For these calculations the "lower gray ash" is taken as the Huckleberry Ridge ash (@ 2.0 Ma), the normal zone above it as the Olduvai normal Subchron (1.87-1.67 Ma) and the thin normal event above that, found only in section SCS, as the Cobb Mountain event. The reversed section under the "gray ash" must have had a deposition rate of greater than 9.7 cm per thousand years since the top of the Gauss normal Chron was not found there. The section between the "gray ash" and the bottom of the Olduvai normal Subchron had a deposition rate of 5.5 $\pm$ 0.3 cm/kyr at site NS, and 4.7 $\pm$ 0.6 cm/kyr at SHS. During the Olduvai Subchron the deposition rate was 5.3 $\pm$ 0.5 cm/kyr at NS and only 3.9 $\pm$ 0.3 cm/kyr at SCS. If the short normal zone in the upper part of the SCS section is the Cobb Mountain Event, then the deposition rate between it and the top of the Olduvai Subchron would be 2.8 $\pm$ 0.2 cm/kyr. Extrapolating this rate to strata higher in that section implies that the Jaramillo Event is not present there. If, on the other hand, the short normal is indeed the Jaramillo Event, then the deposition rate between it and the Olduvai Subchron would be 2.2 $\pm$ 0.2 cm/kyr, and less than 0.6 cm/kyr within the Jaramillo Event itself. In this scenario the overlying section the deposition rate at SCS could not be less than 1.3 cm/kyr since the Brunhes-Matuyama reversal was not found within the section.

DISCUSSION

Combined data from magnetostratigraphy and tephrochronology indicate that deposition of the Mojave River Formation began substantially earlier than the eruption of the 2.0 Ma Huckleberry Ridge ash and continued until after the Jaramillo Event at rates which fluctuated by nearly an order of magnitude. From these inferred deposition rates, the two white volcanic ashes analyzed by Nagy and Murray, the "middle white" and "upper white", (1991, this volume) may be assigned extrapolated ages of 1.8 and 1.95 Ma respectively. The distinctive "gray ash" found in the reversed magnetozone of the Mojave

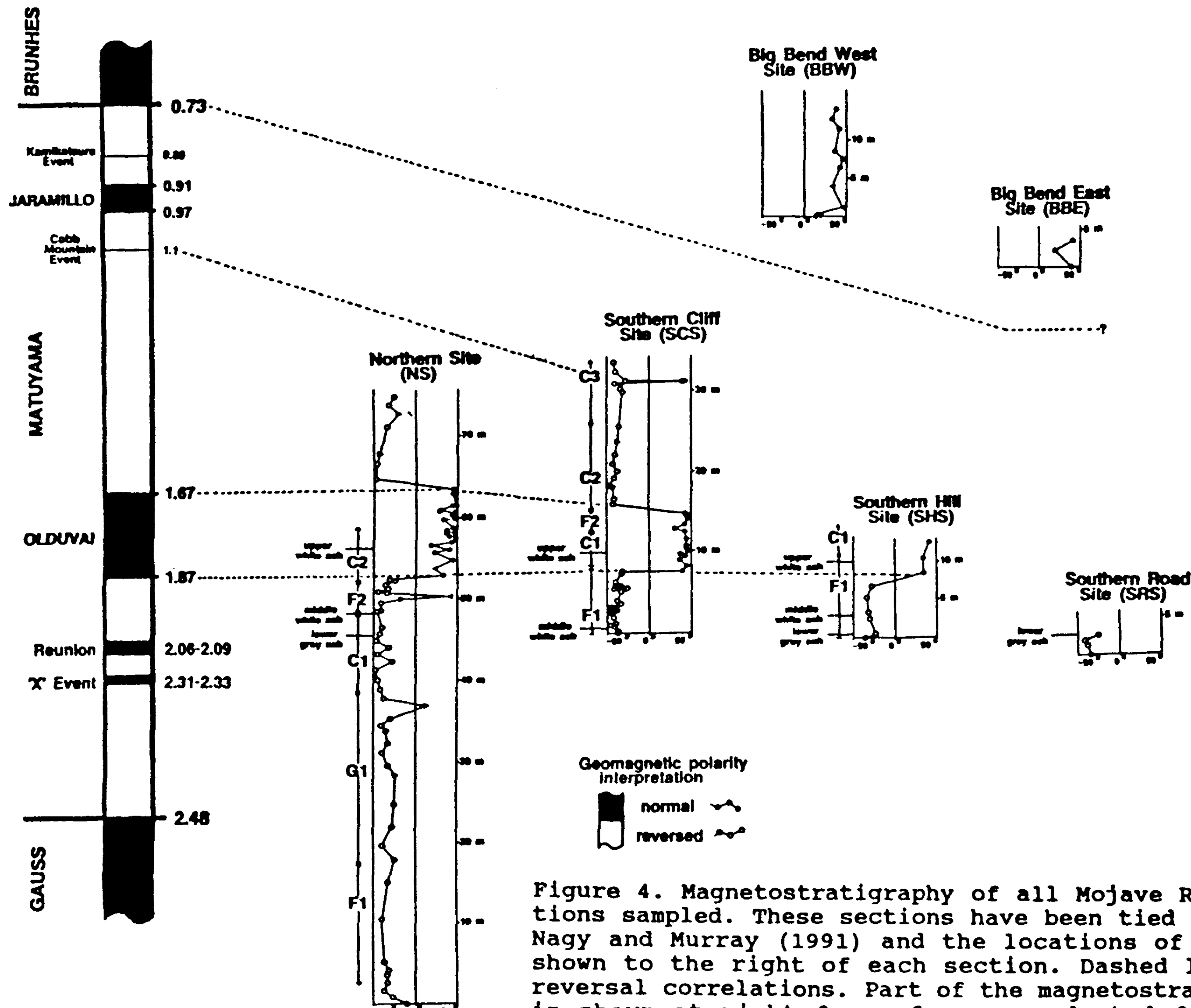

Figure 4. Magnetostratigraphy of all Mojave River formation sections sampled. These sections have been tied to the MRF units of Nagy and Murray (1991) and the locations of volcanic ashes are shown to the right of each section. Dashed lines show magnetic reversal correlations. Part of the magnetostratigraphic timescale is shown at right for reference, adapted from Harland et al. (1990).

River Formation is most probably the Huckleberry Ridge tephra since the other Yellowsone gray ashes may be eliminated from consideration: the 0.6 Ma Lava Creek tephras are within the Brunhes normal Chron and the Mesa Falls ash has not been found west of Nebraska. Additional trace element analyses reported by Nagy and Murray (1991, this volume) confirm this identification. Thus the reverse-normal transition above the gray ash can be identified with the lower boundary of the Olduvai normal sub-chron @ 1.87 Ma. This relationship is consistent with strata in the Confidence Hills of southern Death Valley where the gray Huckleberry Ridge ash beds and the entire Olduvai normal Subchron are reliably placed in a 110m section of similar sediments.

A stratigraphically higher normal magnetozone entirely within a reversed section may be either the Cobb Mountain Event (@ 1.1 Ma) or perhaps the Jaramillo Event (0.92-0.97 M). The "upper white ash" in the normal magnetozone may belong to the Glass Mountain series from the Bishop region. Stratigraphic description of the Mojave River Formation (Nagy and Murray, 1991, this volume) can aid in the interpretation of the ages and depositional sequences of this tectonically complicated area and result in a better correlation of the ash "marker" beds in the region.

Our observation that the oldest sediments are rotated tectonically more than the younger suggests that the area has been moving clockwise at an average rate of approximately 5° per million years for at least the past 2 Ma. This is the first detection of rotation in beds as young as 2 Ma in the Mojave Desert. Several authors (Ross et al., 1989; Golombeck and Brown 1988) have suggested substantial (up to 50°) clockwise rotation of Miocene volcanic rocks in the Mojave Desert from a number of localities. Wells and Hillhouse (1989), however, find no evidence for such consistent rotation of large regions in their paleomagnetic studies of the widespread Peach Springs Tuff (dated at 19 Ma); their 11.6° and 13.1° clockwise rotations in the Cady Mountains and near Barstow, respectively, may be attributed to drag effects from nearby strike-slip faults. The Manix Basin may likewise be affected by the immediately adjacent, left-lateral Manix Fault, which has been active for at least the past 1 Ma (McGill et al., 1988). Hence, it seems reasonable to suggest that the larger rotations in the Miocene volcanics are due simply to similar tectonic rotation processes acting over longer intervals of time.

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