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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

MAGNETIC PROPERTIES OF DRILL CORE AND SURFACE SAMPLES FROM THE CALICO HILLS AREA, NYE COUNTY, NEVADA

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By

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MAGNETIC PROPERTIES OF DRILL CORE AND SURFACE SAMPLES FROM THE CALICO HILLS AREA, NYE COUNTY, NEVADA

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ABSTRACT

The interpretation of the aeromagnetic survey of the Calico Hills area of the Nevada Test Site, Nye County, Nevada, required the determination of magnetic properties of rocks exposed in the region. Eighty-two samples representing a variety of units found at the surface show that most rocks in the Calico Hills, other than parts of the Eleana Formation, are relatively nonmagnetic. The magnetic vector of the Eleana Formation at the surface was found to point northward and downward. Remanence directions were scattered, but a remanence azimuth of 16° east of north was assigned on the basis of present-day declination. Measurements of 123 samples of the Eleana Formation from the exploratory drill hole UE25a-3 indicate that some facies are strongly magnetic. The average total magnetization of the argillite samples is 3.89 A/m (0.00389 emu). These samples have an average natural remanent inclination of 76°. Results of demagnetization demonstrated that this relatively high inclination is due, at least in part, to a soft vertical component of remanent magnetization. The magnitude of the component could not be determined. Further tests showed that the tendency to pick up a soft component of magnetism may be a function of rock type. Inhomogeneity of the Eleana argillite was probably the cause of some differences in remanence values between large and small samples from the same depth.

INTRODUCTION

The Calico Hills area, Nevada, has been the site of geologic and geophysical investigations in support of the U.S. Department of Energy NNWSI (Nevada Nuclear Waste Storage Investigations) program (Maldonado and others, 1979; Daniels and Scott, 1980; Snyder and Oliver, 1981). Magnetic-properties data were collected to aid in the interpretation of aeromagnetic and ground magnetic traverses of the region. In particular, laboratory determination of the total magnetization of rocks from the Calico Hills is vital for interpreting magnetic surveys and correlating magnetic anomalies with specific geologic features.

System of Magnetic Units

In this paper we use the mks or International System (SI) of units. The following table will help readers familiar with the cgs system to understand our use of the International System. See Sheriff (1973) for a more detailed list of terms.

Term	SI (mks) units	Symbol	cgs equivalent	Symbol	
Magnetization or magnetic intensity (magnetic dipole moment per unit volume)		ampere/meter	A/m	10^{-3} emu	emu
	nanotesla	nT	gamma	gamma	
Magnetic field strength (tesla)		T	(10^9 gamma) (10^4 gauss)		
Magnetic susceptibility (dimensionless)		K_{SI}	K_{SI}	$4\pi k$	k

The gauss, originally a cgs unit, is often used informally in the SI for 10^{-4} tesla.

Acknowledgments

We would like to thank G. D. Bath, USGS (U.S. Geological Survey), for providing information about aeromagnetic anomalies and for his valuable discussions on the content of this report. We gratefully acknowledge the expert advice of J. G. Rosenbaum, USGS, on rock magnetism. Ray Martinson, USGS, drilled small cores of the Eleana Formation in the field and measured their magnetic properties. D. R. Townsend, F&S (Fenix & Scisson, Inc.), gave helpful advice and support, and lent his drafting expertise to many figures in the report. D. Watson and R. Reynolds of the USGS Rock Magnetism Laboratory gave freely of their advice and allowed unlimited use of their facilities. F. Maldonado, USGS, read this report critically and made many helpful suggestions.

AREAL GEOLOGY

The Calico Hills area of the NTS (Nevada Test Site) is geologically complex (McKay and Williams, 1964; Orkild and O'Connor, 1970) (figs. 1, 2). Field data indicate that there have been episodes of regional thrust faulting and doming. The Calico Hills comprise Paleozoic carbonate and clastic rocks, surrounded by Tertiary volcanic rocks (fig. 3). Parts of several Paleozoic units have been thrust over younger volcanic rocks.

The Eleana Formation is a widespread, thick sequence of Devonian-Mississippian marine sediments. It is thought to have been laid down as a flysch deposit, in response to the Antler Orogeny (Poole, 1974). Parts of Units J and I, an argillite and a carbonate, respectively, are present at the Calico Hills. At other localities, Unit J is at least 1,067 m (3,500 ft) thick, and Unit I, at least 152 m (500 ft) thick (Poole and others, 1961).

High-angle faulting and extensive hydrothermal activity in the region may be related to doming and an inferred intrusive body (Maldonado and others, 1979). Much of the Eleana Formation in the Calico Hills area has been hydrothermally altered from the shale and limestone composing this formation elsewhere. In drill hole UE25a-3, the argillite shows a mottled hornfelslike texture, and the carbonate has been altered to marble.

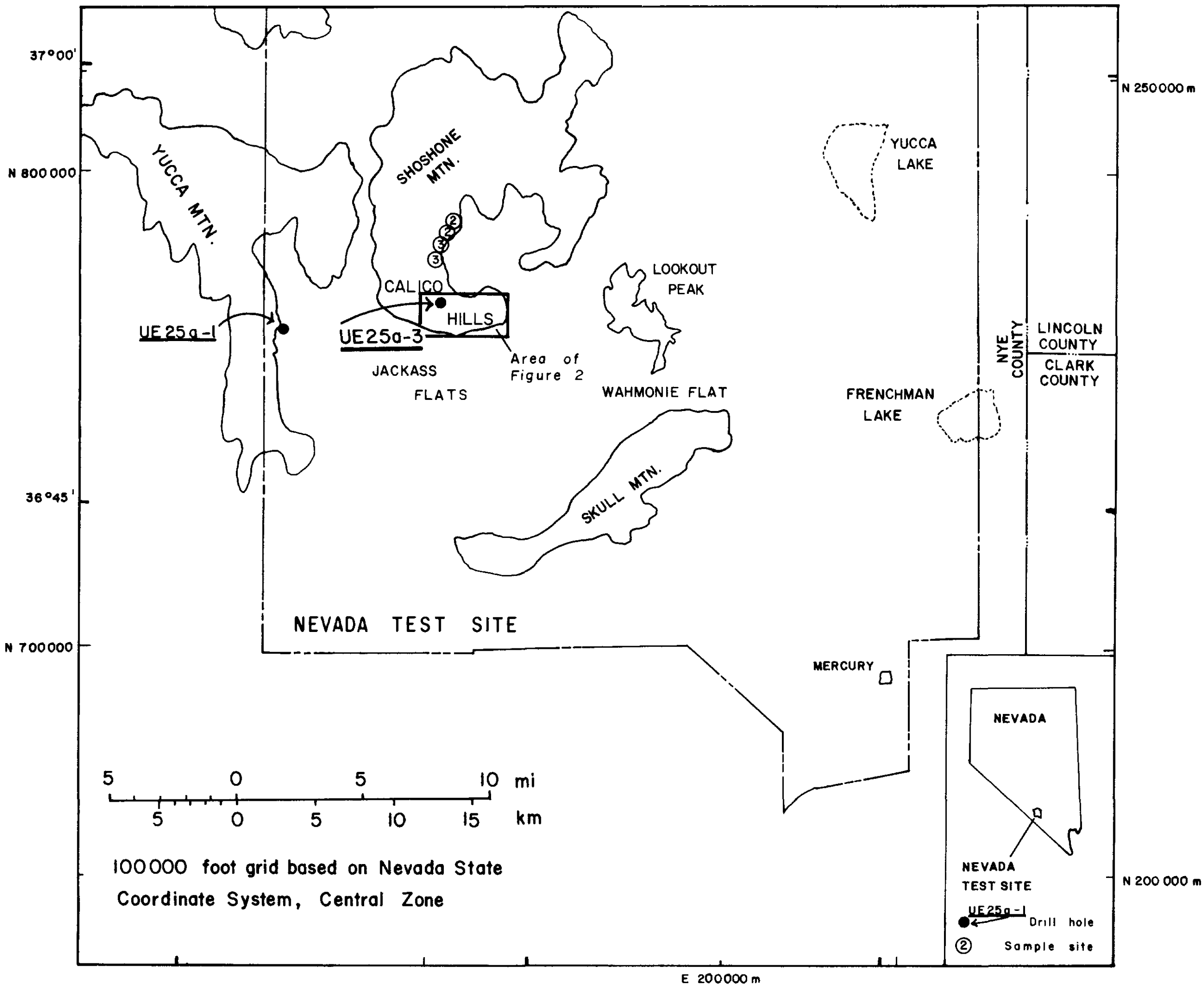

Figure 1.--Reference map showing the Calico Hills area and surface sample sites.

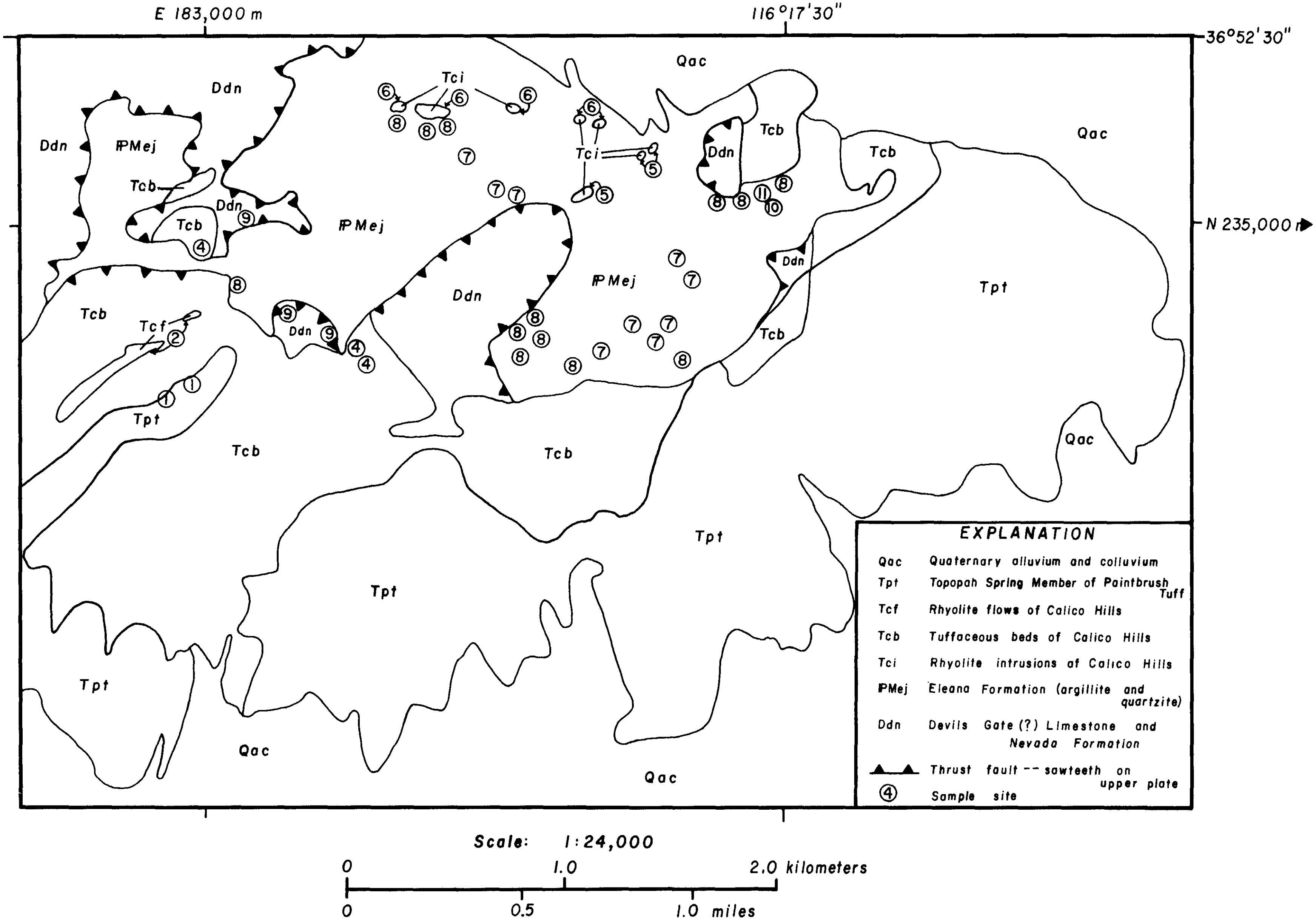

Figure 2.--Generalized geologic map of southern Calico Hills showing surface sample sites.

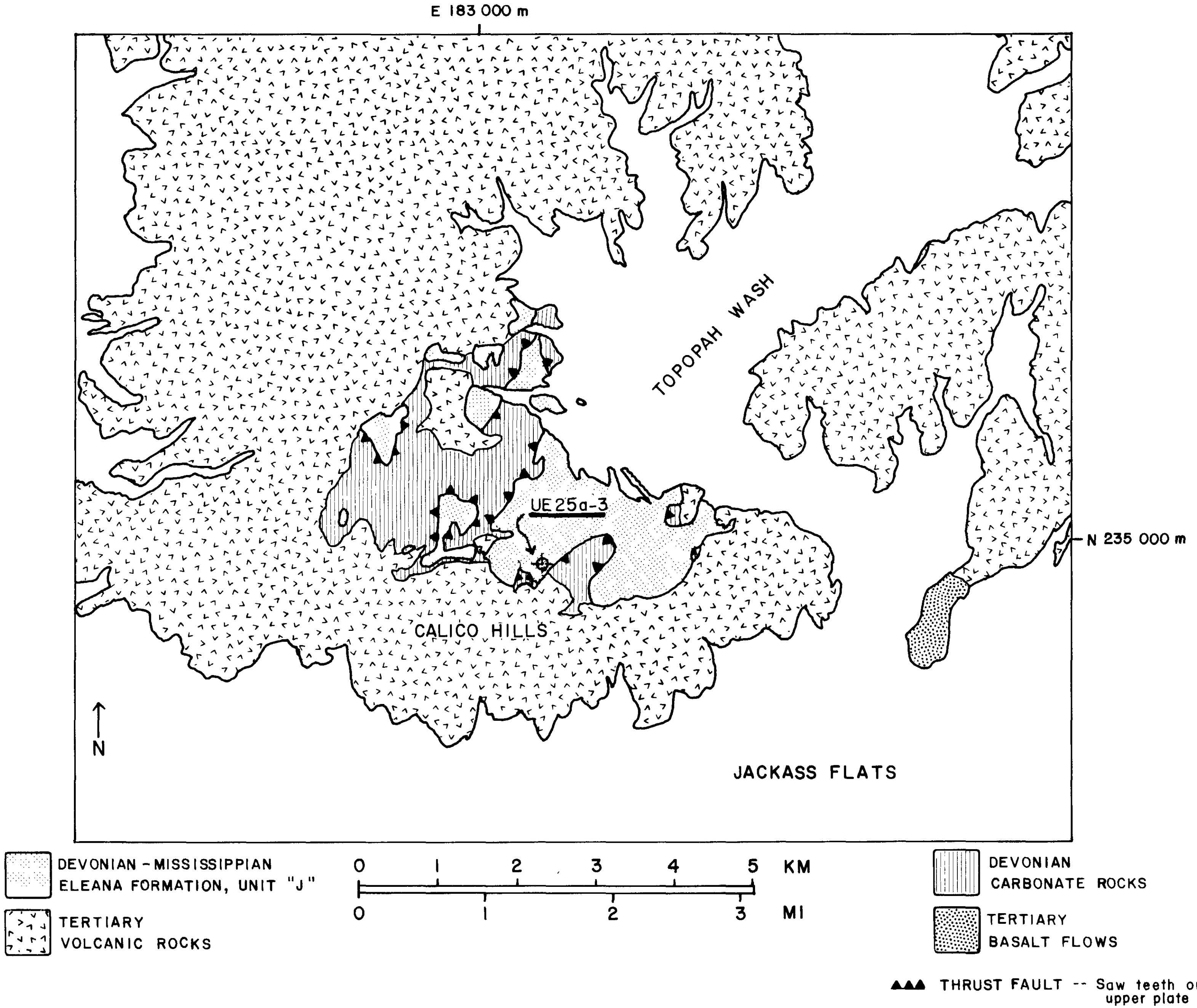

Figure 3.--Generalized geologic map of bedrock outcrop in the Calico Hills area.

An intrusive crystalline body has been hypothesized from aeromagnetic data as shown on figure 4 (G. D. Bath, oral commun., 1978; U.S. Geological Survey, 1979). Figure 4 shows the strong positive anomalies that reach a maximum of 2,343 nT over the Eleana Formation. Measurements were at about 120 m (400 ft) above ground surface along east-west flight lines about 400 m (1,312 ft) apart. Values were corrected for the International Geomagnetic Reference Field plus a 300 nT regional correction. Exploratory hole UE25a-3 was drilled in an effort to determine the depth to this body, but at 771.2 m (2,530.1 ft), the TD (total depth) of the drill hole, no crystalline rocks had been penetrated. Alteration of the rocks did, however, increase with depth (Maldonado and others, 1979).

MAGNETIC SURVEY

A magnetic survey detects geologic features that have magnetic properties causing a disturbance, or an anomaly, in the Earth's magnetic field. The anomaly arises when a feature has an intensity of total magnetization that differs by at least 0.05 A/m from intensities of adjacent features (G. D. Bath and others, written commun., 1981). Features with total magnetizations less than 0.05 A/m are designated nonmagnetic. Those features having greater intensities are designated as either weakly, moderately, or strongly magnetized, as defined by the following limits:

nonmagnetic <0.05 A/m
0.05 A/m $<$ weakly magnetized <0.50 A/m
0.50 A/m $<$ moderately magnetized <1.50 A/m
1.50 A/m $<$ strongly magnetized

Total magnetization of a sample is the vector sum of its remanent and induced components. Remanent magnetism can be measured with a variety of instruments. Induced magnetization is determined from measurements of susceptibility.

Various problems may arise in assigning a magnetization to a particular rock unit. Inhomogeneity of the rocks may make it difficult to obtain values that are representative of a given unit, as is the case with the Eleana Formation. The magnetic properties of surface samples may be altered as a result of lightning strikes or weathering. Rocks collected underground, from tunnels or drill holes, should be free of these problems. However, sampling or laboratory techniques such as drilling may sometimes disrupt in situ magnetic properties.

SURFACE SAMPLES

Rocks exposed at the surface within the Calico Hills aeromagnetic anomaly were sampled to determine their magnetic properties. The formations sampled include the Devils Gate(?) Limestone and Nevada Formation, the Eleana Formation, rhyolite lava flows and tuffaceous beds of the Calico Hills, the Topopah Spring Member of the Paintbrush Tuff, and various small rhyolite intrusions. Oriented, roughhewn samples of each unit were collected in 1978-79 (figs. 1, 2). Analysis of these samples and core from UE25a-3 showed the Eleana Formation to have some magnetized facies. Small oriented cores of Eleana rocks were drilled in 1979 to investigate this phenomenon further.

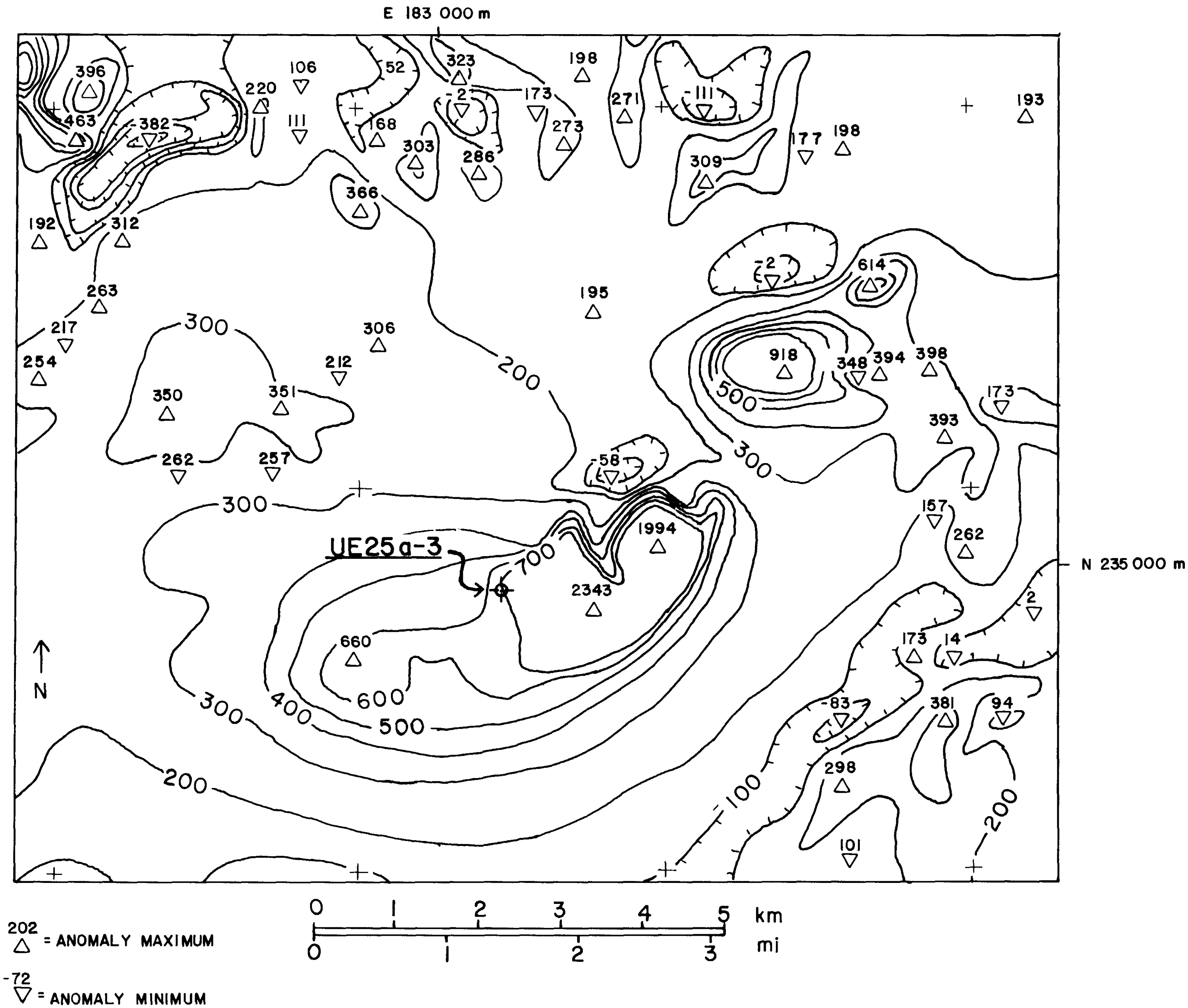

Figure 4.--Residual aeromagnetic map of the Calico Hills area.

Table 1 gives a summary of the magnetic properties of the roughhewn surface samples measured using the method of Jahren and Bath (1967). Limestones, quartzites, and some of the volcanic rocks showed no measureable magnetism. Other volcanic units were moderately magnetic, while the argillite of the Eleana Formation was strongly magnetic. The remanent magnetic vector was normal (pointing northward and downward) for all measureable samples.

A summary of the magnetic properties of field-drilled oriented cores of surface rocks is presented in table 2. All samples are from the argillite of the Eleana Formation, and all but three show moderate to strong magnetization in a normal direction. After measurement of remanent magnetization on a Schonstedt spinner magnetometer, model SSM-1A, five of these samples were subjected to alternating field demagnetization, using a Schonstedt model DSM-1. Remanences were then remeasured. Values after demagnetization are shown in table 2 in parentheses.

The results of these studies indicate that certain facies of the Eleana Formation at this locality are moderately to strongly magnetic, while most of the other units are nonmagnetic. Although remanent directions determined for samples of the Eleana are scattered, they are mostly northward. For purposes of anomaly calculations, the remanences can therefore be considered parallel to the present-day magnetic field, 16° east of north.

DRILL HOLE UE25a-3

Vertical drill hole UE25a-3 was drilled in September 1978 (fig. 1). Core taken was 63 mm (2.48 in.) in diameter to a depth of 598.5 m (1,963.5 ft), where core size was changed because of operational problems to 47 mm (1.85 in.) to a TD of 771.2 m (2,530.2 ft). A suite of logs was run in the drill hole by Birdwell, Inc., and the USGS, which included a magnetic-susceptibility log (Daniels and Scott, 1980).

Several subunits of the Eleana Formation were penetrated in the drill hole. These included argillite of Unit J, altered argillite of Unit J, an altered sequence of thin intercalated marble beds and calcareous argillite of Unit J, and marble of Unit I (Maldonado and others, 1979). No intrusive rocks were penetrated by the drill hole. See figure 5 for the stratigraphy and generalized lithology of UE25a-3.

Magnetic Properties of Core

The magnetic susceptibility log for UE25a-3 (Daniels and Scott, 1980) presented on figure 5 shows two main zones of high-susceptibility rocks, from approximately 290 to 405 m (951-1,329 ft), and from 430 to 680 m (1,411-2,231 ft). We chose samples of core from within these magnetic intervals and from the lower nonmagnetic interval of core. Samples were taken approximately every 3 m (10 ft) in the intervals 278.0 to 406 m (915-1,332 ft) and 438.9 to 771.2 m (1,440-2,530.2 ft TD), and were cut to lengths of nine-tenths the core diameter. The downhole direction was marked on each sample. After measurement, 20 of these samples were re-cored, with a new axis parallel to the original hole axis, to a diameter of 2.5 cm (1 in.), and cut to a length of 2.5 cm.

Table 1.--Magnetic properties of oriented roughhewn surface samples from the Calico Hills area

[Properties measured at the NTS; see figs. 1 and 2 for maps showing sample locations; J_T=total magnetic intensity (averaged vectorially), in amperes/meter; direction of J_T, "normal" direction indicates that vector representing magnetic intensity points northward and downward; leaders (---) indicate direction of magnetization cannot be determined for weakly magnetic samples]

Map reference number	Rock unit	Rock type	Map symbol[1]	J_T (A/m)	Direction of J_T	Number of samples
1	Topopah Spring Member of Paintbrush Tuff	Welded tuff	Tpt	<0.05	---	2
2	Calico Hills	Rhyolite lava flows	Tcf	1.1	Normal	11
3	Do.	Tuffaceous beds	Tct	1.9	Normal	4
4	Do.	Tuffaceous beds	Tcb	< .05	---	3
5	Do.	Rhyolite intrusions	Tci	2.6	Normal	3
6	Do.	Rhyolite intrusions	Tci	< .05	---	7
7	Eleana Formation	Argillite	Mej	4.6	Normal	29
8	Do.	Quartzite	Mej	< .05	---	10
9	Devils Gate(?)	Limestone	Ddn	< .05	---	4

[1]McKay and Williams, 1964; Orkild and O'Connor, 1970.

Table 2.--Magnetic-properties data from Eleana Formation argillite surface samples drilled in the field

[J_I, intensity of induced magnetization, which equals 0.53 X ($k_{SI}/4\pi$)X 10^3 where k_{SI} is susceptibility; J_R, intensity of natural remanent magnetization; A_R, azimuth of natural remanent magnetization; IR, inclination of natural remanent magnetization; J_T, intensity of total magnetization; AZT, total magnetic azimuth; I_T, total magnetic inclination. Values in parentheses were measured after alternating-field demagnetization at a peak of 200 gauss]

Samples[1]	J_I (A/m)	J_R (A/m)	A_R (degrees)	I_R (degrees)	J_T (A/m)	AZT (degrees)	I_T (degrees)
2a	0.66	0.82	23 (30)	59 (54)	1.48	20	61
2b	.51	.28	3 (44)	70 (59)	.79	12	66
2c	.30	.21	15	47	.51	15	56
6a	.04	.37	313 (320)	59 (45)	.40	318	60
6b	.04	2.84	324 (334)	39 (30)	1.87	325	39
6d	.80	1.31	20	53	2.14	18	57
6e	.10	.11	28	44	.20	24	53
6f	.02	.02	11	-12	.03	13	29
6g	.70	2.95	321 (7)	- 5 (15)	3.16	326	7

[1]Map reference numbers (see fig. 2)--samples 2a-c denoted on map by 10; samples 6a-g denoted on map by 11.

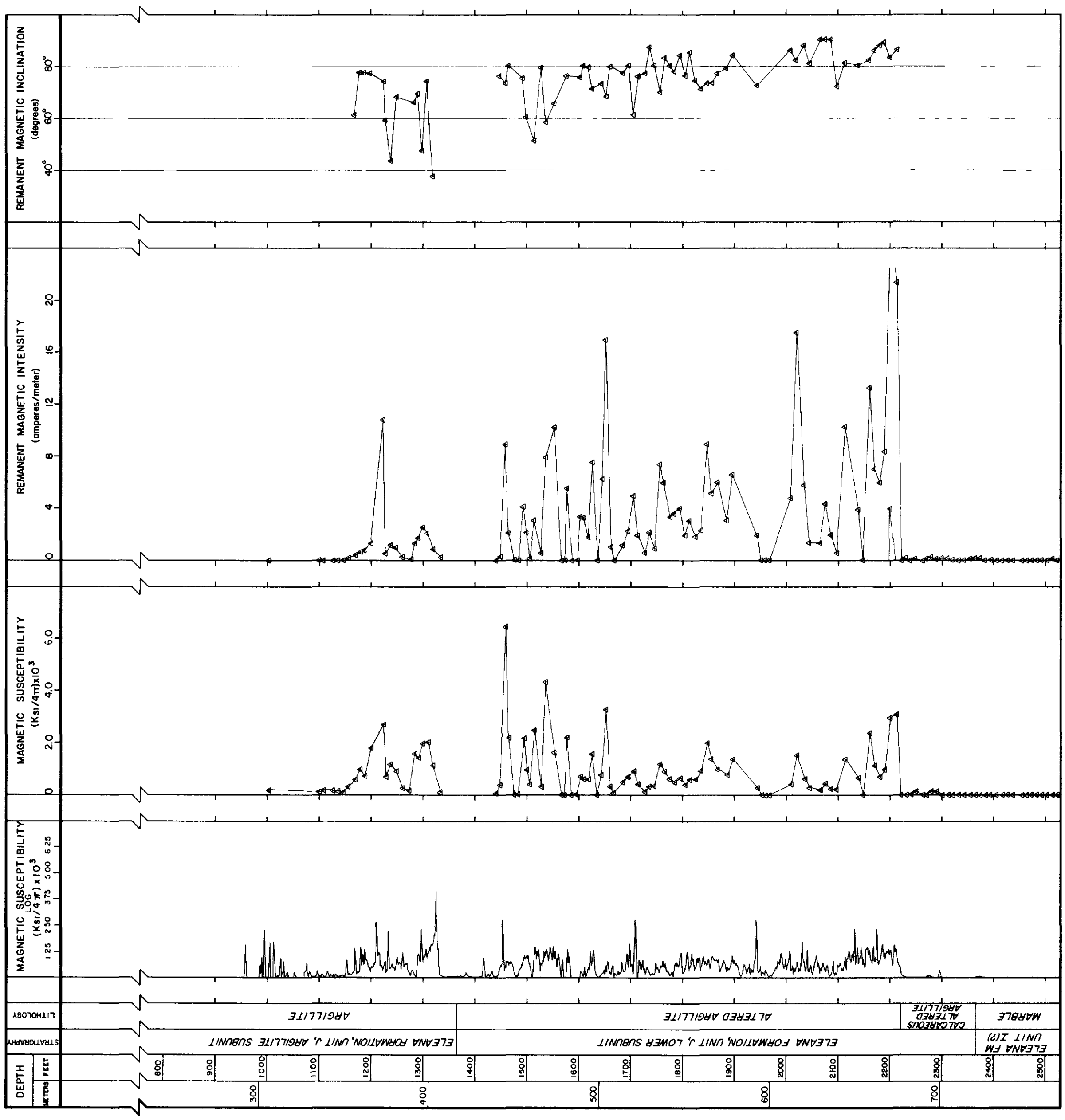

Figure 5.--Magnetic properties of rock from drill hole UE25a-3, before demagnetization, showing lithology, in-hole susceptibility log, sample susceptibility, natural magnetic remanent intensity, and remanent inclination.

Measurements of susceptibility and remanent magnetization were made using the method of Jahren and Bath (1967). The smaller size core samples were taken to Denver for demagnetization and measurement with the spinner magnetometer. The remanent magnetization of each sample was remeasured on the spinner magnetometer, and then 10 samples were progressively demagnetized in an alternating field at peak fields of 50, 100, 150, and 200 gauss. Four samples were demagnetized in 25-gauss steps, and six others were demagnetized in 100-gauss intervals. Data for both large and small core samples are given in tables 3 and 4.

Large Core Samples

Susceptibility values for large core samples are quite variable within magnetized zones penetrated by the drill hole. This is probably due to the stratified nature of the rock and the large number of filled fractures. Layers of argillite alternate with thin quartz-rich, carbonate-rich, or magnetite(?)-rich layers. Fractures and veinlets may be filled with calcite, chlorite, pyrite, or magnetite(?).

Remanent magnetic intensity varies from sample to sample, also reflecting the layered aspect of the argillite. Values as high as 26.6 A/m and as low as 0.0001 A/m were measured in "magnetic" facies of core. The remanent inclination of the core samples is normal in every case. The inclinations, however, are quite high in most cases, averaging 74° for the argillite units and 81° for the carbonate unit.

The arithmetic average of the total intensities of 93 large samples from the depth intervals 278.9 to 406 m (915-1,332 ft) and 438.9 to 677.3 m (1,440-2,222 ft) is 3.89 A/m. The average for 30 samples from the interval 677.3 to 771.2 m (2,222-2,530.1 ft) is 0.0587 A/m.

Small Core Samples

The results of demagnetization on 20 small cores drilled from UE25a-3 core are presented on figure 6 and in table 3. Stereo plots of the remanence vectors of four samples are presented on figure 7, and show the original direction and direction after demagnetization at 50, 100, 150, and 200 gauss. Because these samples are from unoriented core, azimuths shown are arbitrary. "Up" was known on the core, however, so the inclinations shown are real. Plots for 1440 and 1886 (lower diagram on fig. 7) show no directional change. The plots for 2009 and 2160 indicate a high-angle soft component of remanent magnetization removed by the demagnetization process. All samples are normally magnetized. Demagnetization removed a steep component from 13 samples, so that their average remanent inclinations were reduced from $74.6° \pm 8.6°$ to $54.8° \pm 7.4°$ (fig. 5).

Seven large-core samples whose remanent inclination angles were high seemed to lose the component responsible for the high inclination sometime before remeasurement on the spinner magnetometer (see sample nos. 1489, 1626, 1660, 1694, 1795, 1886, and 2064 in table 4. Two other samples showed an increase in remanent inclination (samples 2096 and 2160).

Table 3.--Magnetic properties of drill core samples from UE25a-3, measured at the Nevada Test Site on large-sample magnetometer

[k, susceptibility; J_I, intensity of induced magnetization; J_R, intensity of remanent magnetization; I_R, inclination of remanent magnetization; J_T, intensity of total magnetization (calculated with assumed remanent azimuth direction of N. 16° E.); I_T, inclination of total magnetization; nc, indicates that magnetic intensity of sample was too low to be able to calculate inclination angles. All magnetizations given in amperes/meter]

Sample depth (feet)	k $(K_{SI}/4\pi)10^3$	J_I (A/m)	J_R (A/m)	I_R (degrees)	J_T (A/m)	I_T (degrees)
915	0.00	0.00	0.00	nc	0.00	nc
1001	.12	.06	.00	nc	.07	nc
1099	.08	.04	.00	nc	.04	nc
1107	.10	.05	.00	nc	.05	nc
1127	.11	.06	.00	nc	.06	nc
1136	.10	.05	.00	nc	.06	nc
1146	.08	.04	.00	nc	.05	nc
1156	.25	.13	.21	90	.34	79
1169	.52	.28	.41	61	.69	62
1178	.98	.52	.67	77	1.19	71
1186	.67	.36	.70	77	1.05	72
1198	1.75	.93	1.33	77	2.27	71
1222	2.68	1.42	10.76	74	12.20	73
1227	.67	.36	.48	59	.84	61
1237	1.14	.60	1.13	43	1.73	50
1248	.85	.45	.82	68	1.28	66
1260	.24	.13	.26	90	.38	81
1272	.09	.05	.10	45	.15	51
1282	1.53	.81	1.29	66	2.12	65
1290	1.35	.72	1.67	69	2.40	67
1298	1.93	1.02	2.55	47	3.57	52
1309	2.00	1.06	2.11	74	3.19	70
1318	1.08	.57	.85	37	1.40	48
1332	.09	.05	.28	90	.32	86
1440	.00	.00	.00	nc	.00	nc
1448	.32	.17	.36	76	.53	72
1459	6.47	3.43	8.90	73	12.37	70
1462	2.16	1.14	2.06	80	3.20	74
1476	.00	.00	.00	nc	.00	nc

Table 3.--Magnetic properties of drill core samples from UE25a-3, measured at the Nevada Test Site on large-sample magnetometer--Continued

Sample depth (feet)	k $(K_{SI}/4\pi)10^3$	J_I (A/m)	J_R (A/m)	I_R (degrees)	J_T (A/m)	I_T (degrees)
1481	.00	.00	.00	nc	.00	nc
1492	2.18	1.16	4.09	75	5.26	72
1498	.95	.50	2.15	60	2.67	61
1504	.35	.19	.16	90	.34	76
1513	2.44	1.29	3.05	51	4.36	55
1527	.27	.14	.53	79	.68	75
1537	4.34	2.30	7.96	58	10.31	59
1552	1.60	.85	10.31	65	11.18	65
1567	.00	.00	.00	nc	.00	nc
1571	.00	.00	.00	nc	.00	nc
1577	2.15	1.14	5.34	76	6.48	74
1586	.00	.00	.00	nc	.00	nc
1594	.00	.00	.00	nc	.00	nc
1602	.67	.36	3.30	75	3.66	74
1609	.56	.30	3.10	80	3.39	78
1618	.57	.30	1.75	79	2.05	76
1626	1.59	.84	7.55	71	8.41	70
1634	.00	.00	.00	nc	.00	nc
1644	.71	.38	6.23	73	6.61	72
1651	3.31	1.75	16.96	68	18.76	67
1660	.28	.15	1.01	80	1.15	78
1667	.00	.00	.00	nc	.00	nc
1684	.43	.23	1.18	77	1.41	75
1694	.64	.34	2.28	80	2.62	78
1704	.87	.46	4.83	61	5.30	62
1713	.39	.21	1.85	76	2.05	75
1727	.11	.06	.56	77	.62	75
1736	.29	.15	2.02	87	2.17	85
1745	.30	.16	.93	80	1.09	77
1756	1.15	.61	7.36	70	7.98	69
1764	.81	.43	5.91	83	6.32	82
1774	.55	.29	3.34	80	3.63	78
1784	.45	.24	3.60	78	3.83	77
1795	.62	.33	4.00	84	4.32	82
1804	.35	.19	1.93	76	2.12	74
1812	.57	.30	3.05	85	3.34	83
1824	.57	.30	1.84	74	2.15	73
1834	.87	.46	2.32	71	2.78	69
1846	2.00	1.06	8.88	73	9.96	72
1856	1.35	.72	5.18	73	5.90	72
1868	.97	.51	5.98	77	6.50	76

Table 3.--Magnetic properties of drill core samples from UE25a-3, measured at the Nevada Test Site on large-sample magnetometer--Continued

Sample depth (feet)	k $(K_{SI}/4\pi)10^3$	J_I (A/m)	J_R (A/m)	I_R (degrees)	J_T (A/m)	I_T (degrees)
1886	.79	.42	3.01	79	3.42	77
1896	1.36	.72	6.55	84	7.25	82
1943	.27	.14	1.87	72	2.02	72
1951	.00	.00	.00	nc	.00	nc
1958	.00	.00	.00	nc	.00	nc
1967	.00	.00	.00	nc	.00	nc
2009	.40	.21	4.70	86	4.90	85
2020	1.52	.81	17.58	82	18.37	81
2033	.60	.32	5.64	88	5.94	86
2044	.26	.14	1.29	81	1.43	79
2064	.19	.10	1.26	90	1.36	88
2074	.40	.21	4.37	90	4.56	89
2085	.20	.11	1.99	90	2.09	89
2096	.19	.10	.50	72	.60	70
2112	1.35	.72	10.25	81	10.95	80
2139	.61	.32	3.87	80	4.19	79
2149	.00	.00	.00	nc	.00	nc
2160	2.35	1.25	13.23	82	14.45	80
2170	1.07	.57	7.00	86	7.54	84
2180	.64	.34	5.94	88	6.26	86
2188	.93	.49	8.34	89	8.80	87
2200	2.97	1.57	26.55	83	28.08	82
2212	3.08	1.63	21.47	86	23.02	85
2221	.00	.00	.00	nc	.00	nc
2229	.00	.00	.16	nc	.16	nc
2239	.00	.00	.00	nc	.00	nc
2248	.09	.05	.15	nc	.18	nc
2261	.00	.00	.00	nc	.00	nc
2268	.00	.00	.16	nc	.16	nc
2279	.10	.05	.23	nc	.28	48
2289	.10	.05	.16	nc	.19	14
2299	.00	.00	.17	nc	.17	nc
2310	.00	.00	.17	nc	.17	nc
2320	.00	.00	.00	nc	.00	nc
2331	.00	.00	.00	nc	.00	nc
2342	.00	.00	.00	nc	.00	nc
2353	.00	.00	.17	nc	.17	nc
2363	.00	.00	.17	nc	.17	nc
2372	.00	.00	.16	nc	.16	nc
2384	.00	.00	.00	nc	.00	nc
2393	.00	.00	.00	nc	.00	nc
2405	.00	.00	.00	nc	.00	nc

Table 3.--Magnetic properties of drill core samples from UE25a-3, measured at the Nevada Test Site on large-sample magnetometer--Continued

Sample depth (feet)	k $(K_{SI}/4\pi)10^3$	J_I (A/m)	J_R (A/m)	I_R (degrees)	J_T (A/m)	I_T (degrees)
2416	.00	.00	.00	nc	.00	nc
2425	.00	.00	.00	nc	.00	nc
2435	.00	.00	.00	nc	.00	nc
2455	.00	.00	.00	nc	.00	nc
2462	.00	.00	.00	nc	.00	nc
2472	.00	.00	.00	nc	.00	nc
2482	.00	.00	.00	nc	.00	nc
2492	.00	.00	.00	nc	.00	nc
2502	.00	.00	.00	nc	.00	nc
2513	.00	.00	.16	nc	.16	nc
2522	.00	.00	.00	nc	.00	nc

Table 4.--Demagnetization data (with comparisons of large and small samples) including remanent intensities, remanent azimuths, and remanent inclinations

[Susceptibilities (K_{SI}); remanent intensities (J_R), in Ampers/meter; remanent azimuths (A_R); and remanent inclinations (I_R). Samples were measured at the Nevada Test Site (large) and with a spinner magnetometer (small) in Denver. * indicates values of samples with high remanent inclination; nc, indicates samples for which values of measurements on large samples were too low to calculate inclination.

Sample	Susceptibility ($K_{SI}/4\pi$)X10^3		J_R (A/m)		A_R (degrees)	I_R (degrees)		Peak demagnetizing field (gauss)
	Large	Small	Large	Small		Large	Small	
1440	0	0	0.00	0.0133	327	nc	56	---
				.0131	325		58	25
				.0127	325		57	50
				.0121	323		57	75
				.0114	324		58	100
				.0093	329		54	150
				.0077	329		54	200
1498	.95	.97	2.15	1.74	352	60	31	---
				1.58	350		31	50
				1.08	349		30	100
				.659	351		31	150
				.404	351		32	200
1626	1.59	2.91	7.55	4.32	246	71	53	---
				1.92	249		42	100
				.567	248		40	200
				.202	248		39	300
1660	.28	.50	1.01	.564	35	80*	55	---
				.379	31		56	50
				.219	31		54	100
				.133	34		57	150
				.0823	32		54	200
1694	.64	.57	2.28	.835	88	80*	64	---
				.619	97		59	50
				.359	100		56	100
				.219	105		56	150
				.137	110		56	200
1736	.29	.11	2.02	1.82	9	87*	80	---
				.364	292		86	100
				.111	225		67	200
				.0424	223		62	300

Table 4.--Demagnetization data (with comparisons of large and small samples) including remanent intensities, remanent azimuths, and remanent inclinations--Continued

Sample	Susceptibility $(K_{SI}/4\pi)X10^3$		J_R (A/m)		A_R (degrees)	I_R (degrees)		Peak demagnetizing field (gauss)
	Large	Small	Large	Small		Large	Small	
1795	.62	.48	4.00	1.11	357	84*	65	---
				.962	333		68	25
				.670	318		65	50
				.455	312		61	75
				.304	310		59	100
				.164	308		58	150
				.0946	313		54	200
				.0397	313		53	300
1824	.57	.89	1.84	1.87	279	74	71	---
				1.31	265		62	50
				.556	260		61	100
				.280	260		58	150
				.154	260		55	200
1868	.97	1.48	5.98	1.20	217	77*	79	---
				.25	327		72	100
				.0648	330		48	200
				.0278	331		46	300
1886	.79	1.07	3.01	.974	32	79*	61	---
				.662	28		60	50
				.391	27		58	100
				.227	26		57	150
				.139	30		59	200
1967	.00	.05	.00	.0033	325	nc	59	---
				.0031	326		55	50
				.0028	324		55	100
2009	.40	.65	4.70	2.19	54	86*	80	---
				1.62	44		85	25
				.609	24		81	50
				.295	11		77	75
				.186	0		73	100
				.126	355		70	125
				.0915	357		66	150
				.0608	355		63	200
				.0266	351		62	300
2064	.19	.32	1.26	.923	94	90*	82	---
				.231	74		72	50
				.106	72		63	100
				.0596	68		58	150
				.0423	68		56	200
				.0212	68		57	300

Table 4.--Demagnetization data (with comparisons of large and small samples) including remanent intensities, remanent azimuths, and remanent inclinations--Continued

Sample	Susceptibility $(K_{SI}/4\pi)X10^3$		J_R (A/m)		A_R (degrees)	I_R (degrees)		Peak demagnetizing field (gauss)
	Large	Small	Large	Small		Large	Small	
2096	.19	.10	.50	.207	339	72*	79	---
				.106	359		75	50
				.0787	316		63	100
				.0639	316		60	150
				.0519	315		59	200
2160	2.35	X	13.2	5.35	175	82*	83	---
				2.32	98		72	50
				.939	83		58	100
				.556	79		57	150
				.354	78		57	200
2212	3.08	5.29	21.47	10.8	14	86*	80	---
				6.52	354		77	25
				2.93	327		68	50
				1.79	317		60	75
				1.16	318		55	100
				.837	315		53	125
				.625	314		51	150
				.481	313		50	175
				.376	311		47	200
				.245	308		45	250
				.159	308		45	300
2221	0	0	.00	.0097	246	nc	58	---
				.0075	245		57	100
				.0061	247		55	200
2320	0	0	.00	.0315	120	nc*	74	---
				.0229	129		73	50
				.0136	135		64	100
				.0092	135		61	150
				.0062	129		60	200
2455	0	0	.00	.0012	139	nc	72	---
				.0001	199		35	100
2522	0	0	.00	.0005	259	nc	58	---
				.0003	285		54	100

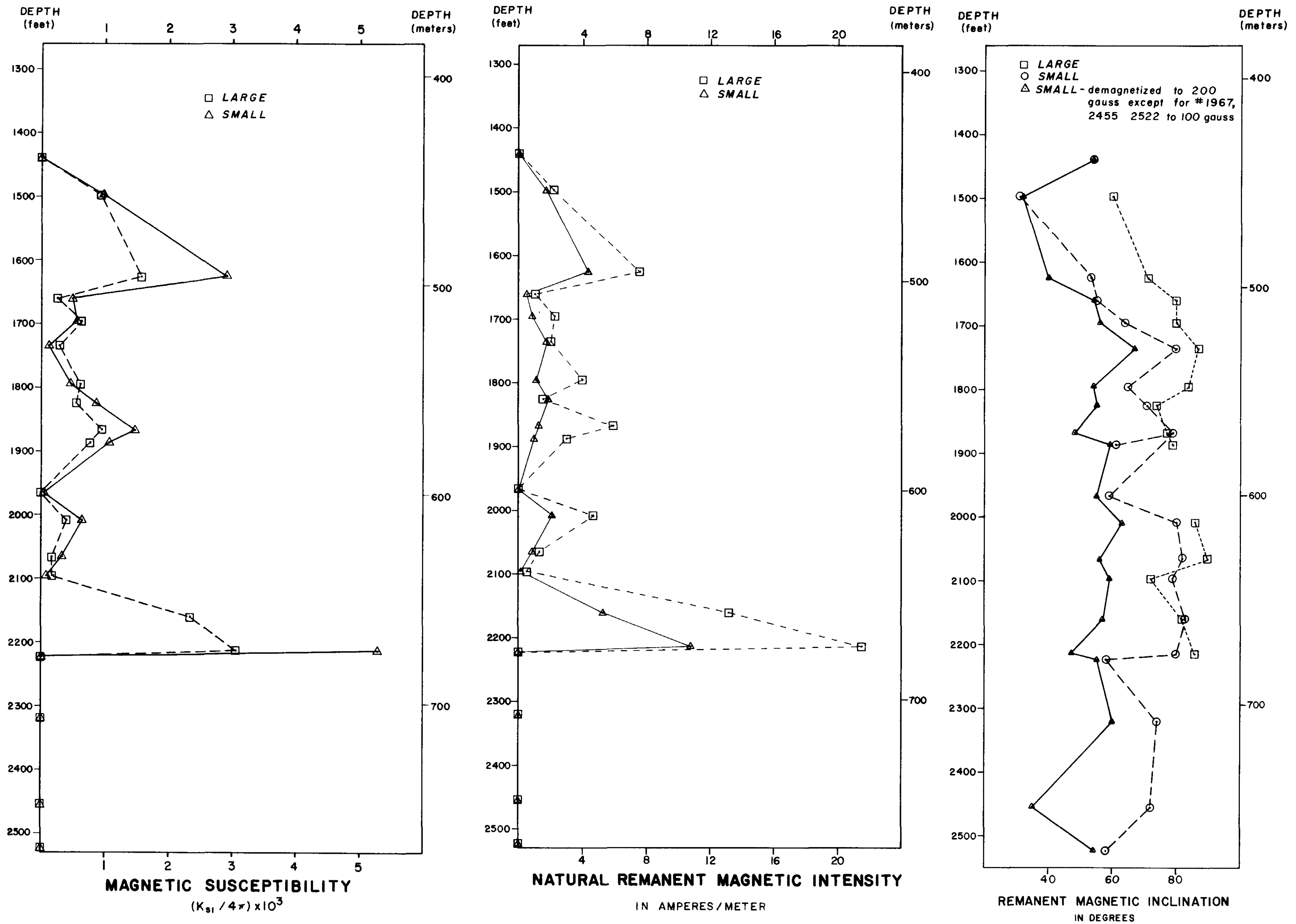

Figure 6.--Magnetic properties of small cores drilled from UE25a-3 core showing results of demagnetization or remanent inclination and comparing values of susceptibility, remanent intensity, and remanent inclination for large and small cores.

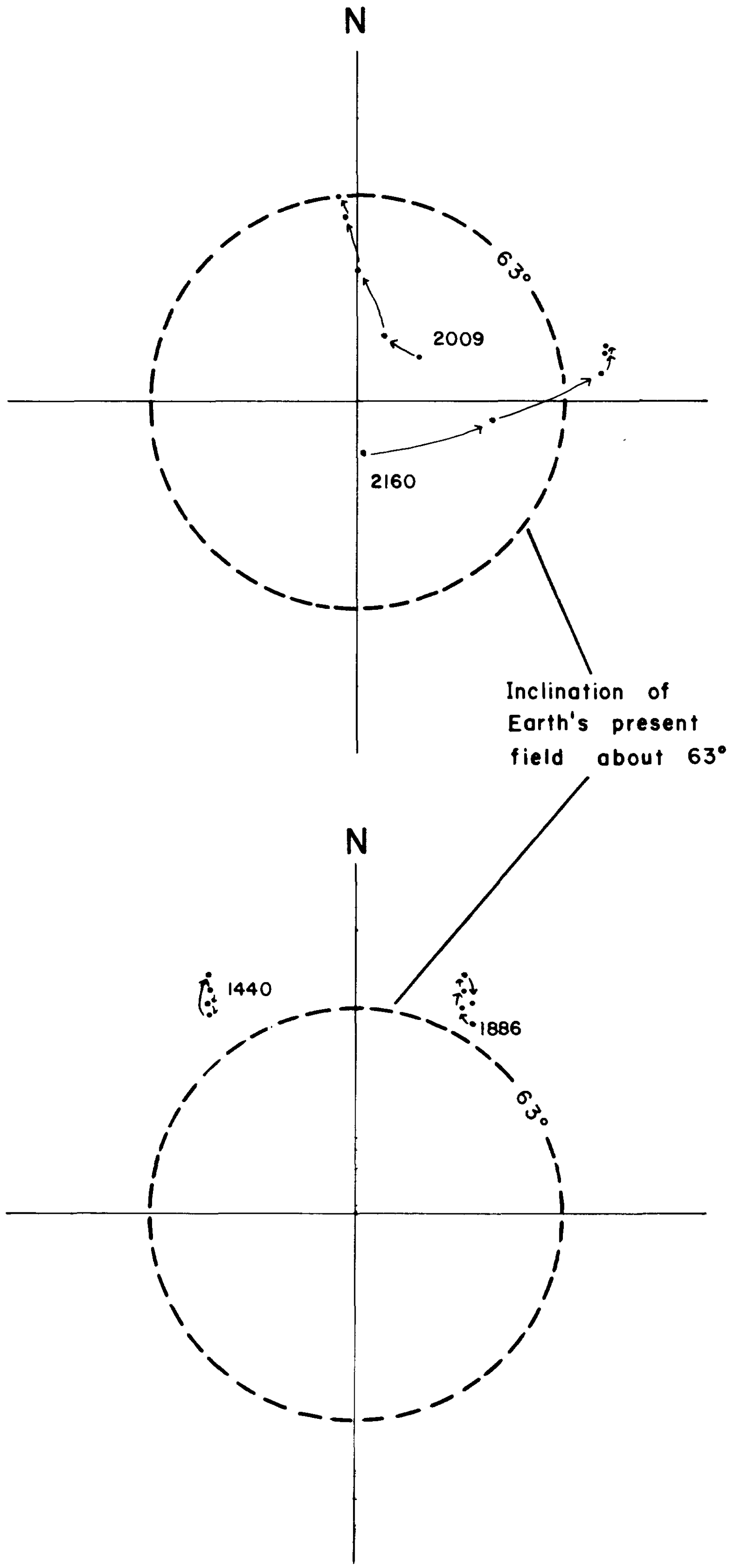

Figure 7.--Stereoplots of remanent magnetic directions before and during progressive alternating-field demagnetization of samples from four depths in drill hole UE25a-3.

Large-sample versus Small-sample Measurements

Work on two sizes of samples from the same depth gave two different values for magnitudes of magnetization, as well as for inclination angle (fig. 6 and table 4. Twenty samples that had previously been measured with the large-sample equipment at the NTS (average remanent intensity 3.55±1.88 A/m), tended to show lower values after recoring and cutting for measurement on the spinner magnetometer (average remanent intensity 1.7±1.30 A/m). There is a greater difference between two measurements of a strongly magnetized sample than for a weakly magnetized sample.

The difference in values between the large core samples and the small samples drilled from them may indicate instrumental or procedural errors, inhomogeneous distribution of magnetic minerals, or unstable magnetization. As a test of the effect of sample homogeneity on magnetic properties, and to assure ourselves that there was not some procedural error in measurements, we chose five core samples of a fairly homogeneous volcanic rock from the nearby vertical drill hole UE25a-1 (fig. 1) and two more argillite samples from drill hole UE25a-3, to compare large and small sample measurements on the same equipment. The magnetization of a small core drilled from a large sample may or may not be representative of the large sample. This problem is particularly acute if the magnetic minerals are concentrated in some manner other than being evenly disseminated through the rock. The differences probably should not always be in the same direction. If most of the magnetic mineral is concentrated (perhaps along fractures), a disproportionate number of small samples will show a relatively low magnetic moment.

We subjected the rocks to as little handling and transport as possible. We measured the remanence of the cores on the NTS large-sample magnetometer by the method described above, using the same methods of cutting and measuring core as we did for the main body of data. We then cut 2.5-cm cores out of the large cores and measured them at the NTS using a small sample-holder with the magnetometer. After these measurements, the samples were sent to Denver and measured on the spinner magnetometer. Table 5 shows that remanence values of the volcanic rock from drill hole UE25a-1 remained about the same between measurements.

The remanent magnetizations of the argillite from drill hole UE25a-3 were quite different in the first two sets of measurements, as they were in the main body of data presented above. However, they did not change further when remeasured in Denver on the spinner magnetometer (table 5). Also, inclination angle was relatively stable in demagnetizing fields up to 400 gauss in peak value. Sample 1651 changed inclination from 69° to 67°, and sample 2074 changed from 84° to 77°.

To check for the presence of unstable magnetism, we measured the susceptibility of each pair of large and small argillite samples. Susceptibility mainly reflects the abundance of magnetic material in a sample, and should not be affected by drilling or transport of samples. Thus, if the difference in remanent magnetizations between large and small samples is due to differences in concentrations of the magnetic mineral, and not due to instability of remanence, this should be reflected in susceptibility measurements. Figure 6 and table 4 give susceptibility and remanence values for large and small samples. It can be seen that differences in

Table 5.--Comparison of magnetic properties of drill core showing differences between large and small sample sizes for different rock types

[All intensities of magnetization are given in amperes/meter; k, susceptibility; J_I, intensity of induced magnetization; J_R, intensity of remanent magnetization; I_R, inclination of remanent magnetization]

Sample depth (feet)	Rock type	k $(K_{SI}/4\pi)10^3$	J_I (A/m)	J_R (A/m)		Denver spinner J_R	I_R (degrees)		Denver spinner I_R (degrees)
				Large	Small	Small (A/m)	Large	Small	Small
UE25a-1 136	tuff	0.59	0.31	1.48	1.35	1.53	-36	-33	-42.9
UE25a-1 153	tuff	.38	.20	2.30	2.13	2.34	-37	-41	-40.4
UE25a-1 166	tuff	.10	.05	1.30	1.29	1.38	-37	-43	-42.3
UE25a-1 183	tuff	.05	.03	.52	.44	([1])	-32	-42	([1])
UE25a-1 1016	tuff	.33	.18	2.29	3.26	3.49	49	47	48.1
UE25a-3 1651	argillite	3.31	1.75	14.27	9.95	10.53	68	69	69.2
UE25a-3 2074	argillite	.40	.21	4.06	1.08	.948	90	90	84.4

[1]Sample too large to fit in holder for Denver spinner.

susceptibility and remanent magnetization between large and small samples do not reflect each other. This indicates that inhomogeneity of the rock, and not unstable remanence is probably responsible for the differences between large and small samples.

The results of the comparison of large and small core samples indicate that there was no calibration problem with our equipment. Though some of the differences may be due to instability of remanent magnetism, inhomogeneity of the Eleana argillite is their probable cause.

A more elaborate study of the effects of sample handling and magnetic stability involved experimental drilling of samples. First, we simulated a sample by casting a 2.5-cm by 2.5-cm cylinder using a mixture of water-putty and powdered magnetite. After demagnetizing this sample, we drew it through a drill bit similar to the ones we had used for sample preparation. We had found by measurement that such bits have an induced magnetization of about 1,350 A/m while they are upright in the Earth's magnetic field. The bit we used had been further magnetized in a coil, however, and retained an additional intensity of 27,000 A/m. This latter magnetization was in the same direction that the bit would be magnetized in the Earth's field during the drilling process. The sample picked up a soft vertical component of magnetization in the same direction that the bit was magnetized. The vertical component of magnetization was increased from 2.6 to 9.9 A/m. It decreased spontaneously to 6.9 A/m while sitting overnight opposite to the Earth's magnetic field, and the additional magnetization was eliminated when the sample was gradually withdrawn from a decreasing 60-Hz alternating magnetic field of 138 gauss.

Our synthetic sample was about two and a half times more susceptible to magnetization than the most susceptible sample listed in table 3. Moreover, the magnetite was concentrated from Minnesota taconite and might behave differently from the magnetic component of the Eleana Formation. For these reasons we designed an experiment to test the effect of drilling Eleana Formation rocks with a magnetized bit. We continued to use the stronger bit magnetization value of 27,000 A/m, in the hope of magnifying any effect.

Next, we selected sample pairs of Eleana Formation argillite from seven different depths in hole UE25a-3. The samples are indicated by depth in table 6. Samples designated A and B in table 6 indicate the pieces of original core sawed off into cylinders with length approximately nine-tenths of their diameter. We obtained only one sample from 1858. The A samples were drilled with an unmagnetized bit and the small 2.5-cm by 2.5-cm cylindrical samples cored from them are designated A (A' for second sample). Samples designated B (B' for second sample) were cored from the B pieces in a similar way, except that a bit magnetized to 27,000 A/m was used. Sample 1858 was cored with the magnetized bit. The drilling was done vertically downward on a press, and the bit was magnetized in that direction. The bit was checked for magnetization after each drilling, and remagnetized to 27,000 A/m. Typically, less than 10 percent of the magnetization was lost during the drilling unless the sample shattered and the bit heated up. The original samples from which the small cores were drilled were then remeasured. The designation D has been used in the table to indicate these pieces.

Table 6 shows the variability from sample to sample that is often encountered in magnetic-properties measurements when replication is

Table 6.--Comparison of samples drilled with unmagnetized and magnetized drills

Sample depth		$k_{SI}/4\pi$ X10^3	J_I (A/m)	J_R (A/m)	I_R (degrees)
1647	A	7.2	3.8	38.1	79
	a	10.6	5.6	27.7	58
	B	10.4	5.5	53.0	82
	b	15.4	8.1	47.5	59
	b'	8.4	4.5	23.6	62
1677	A	8.0	4.3	35.3	82
	a	5.7	3.0	13.1	75
	B	4.2	2.2	15.1	82
	b	2.3	1.2	8.1	82
	b'	3.3	1.7	10.6	84
	BD	4.0	2.1	18.2	83
1766	A	2.4	1.3	13.3	85
	a	1.3	.7	4.8	76
	a'	2.7	1.5	9.7	79
	AD	3.0	1.6	14.0	77
	B	4.8	2.6	27.8	86
	b	3.5	1.8	11.4	68
	b'	.8	.4	2.4	76
	BD	5.0	2.7	34.9	86
1772	A	13.6	7.2	41.9	83
	a	28.9	15.3	62.0	67
	a'	1.8	.9	4.1	62
	AD	13.2	7.0	46.8	86
	B	32.9	17.4	117.3	79
	b	20.8	11.0	37.6	81
	b'	51.7	27.4	132.7	75
	BD	29.4	15.6	128.0	84
1836	A	10.4	5.5	28.2	74
	a	10.4	5.5	15.0	66
	a'	5.5	2.9	8.6	61
	AD	10.9	5.8	33.2	75
	B	10.6	5.6	29.7	72
	b	7.4	3.9	20.2	66
	b'	8.7	4.6	17.0	46
	BD	11.1	5.9	34.6	76
1858		15.2	8.1	50.3	84
	small	16.8	8.9	40.7	78
1867	A	23.3	12.3	112.3	77
	a	9.0	4.8	11.9	71
	AD	22.9	12.2	121.4	79
	B	12.2	6.5	56.7	77
	b	7.4	3.9	29.5	72
	b'	12.1	6.4	33.7	74

attempted. There is no clearly apparent systematic difference between samples drilled with the unmagnetized and magnetized bits. Neither do the small samples show remanent magnetization that is systematically different from that of the large samples out of which they were drilled.

DISCUSSION AND CONCLUSIONS

Our measurements on samples from the magnetic portion of Unit J of the Eleana Formation in the Calico Hills area penetrated by drill hole UE25a-3 indicate an average total magnetization of 3.89 A/m (3.89×10^{-3} emu) with a declination assumed to be 16° east of north, and directed downward 74° (thus, the unit is considered to be normally magnetized). This magnetic layer is approximately 366 m (1,200 ft) thick.

These Eleana rocks have a much higher susceptibility and total magnetization than Eleana rocks elsewhere. This is probably because alteration of the argillite unit has produced a magnetic phase (magnetite?) which fills fractures and is inhomogeneously disseminated throughout the rock. The bedding dips of the rocks of drill hole UE25a-3 were quite variable, ranging from nearly horizontal to as much as 38° in the sampled interval (Maldonado and others, 1979). The angles of our measured magnetic inclinations were so consistent, however, that we assume the rocks were magnetized after their structural deformation.

The measured average total magnetization of 3.89 A/m may be too high a value for the in situ magnetic interval of the Eleana Formation. Many of the samples possessed a large, soft, steeply inclined component of remanence which may have been imparted during the drilling process or some other phase of sample preparation. A limited study involving drilling this rock with a magnetized bit did not confirm such a soft component or its origin. It did demonstrate the variability of the magnetic properties of the rock.

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