U. S. Geological Survey.

REPORTS-OPEN FILE SERIES, no. 973: 1967.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

AEROMAGNETIC ANOMALIES RELATED TO REMANENT MAGNETISM IN VOLCANIC ROCKS, NEVADA TEST SITE

By

GORDON D. BATH, 1914

Open-file report

1967

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U. S. GEOLOGICAL SURVEY
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For release DECEMBER 28, 1967

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3 3. Aeromagnetic map of part of the Wonder quadrangle, Nevada, by the U. S. Geological Survey. 1 sheet.

4. Aeromagnetic map of the Weber Reservoir and Allen Springs quadrangles and parts of the Fallon and Carson Lake quadrangles, Nevada, by the U. S. Geological Survey. 1 sheet.

5. Aeromagnetic map of the Como and Wabuska quadrangles and parts of the Churchill Butte and Silver Springs quadrangles, Nevada, by the U. S. Geological Survey. 1 sheet.

6. Aeromagnetic map of the Carson City and Dayton quadrangles and parts of the Truckee, Mount Rose, Virginia City, and Tahoe quadrangles, Nevada-California, by the U. S. Geological Survey. 1 sheet.

7. Aeromagnetic anomalies related to remanent magnetism in volcanic rocks, Nevada Test Site, by Gordon D. Bath. 20 p., 7 figs. Denver

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8. Aeromagnetic map of the Great Falls-Brown Lake area, northwestern Montana, by the U. S. Geological Survey. 1 sheet.

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AEROMAGNETIC ANOMALIES RELATED TO REMANENT MAGNETISM IN VOLCANIC ROCKS, NEVADA TEST SITE

By

Gordon D. Bath

ABSTRACT

Studies of the magnetic properties of hundreds of surface samples and more than 500 underground samples of nonwelded and welded rhyolitic tuff, rhyolite lavas, lavas of intermediate composition, and basalt lavas show that remanent magnetization is responsible for almost all of the prominent aeromagnetic anomalies associated with Tertiary volcanic rocks in the Nevada Test Site and vicinity. Although average induced magnetization ranges from about 1.5×10^{-4} emu/cc for rhyolitic lava and tuff to 3.6×10^{-4} for trachybasalt, this effect is not sufficient to explain measured anomalies. Remanent intensities vary from about 1.5×10^{-4} emu/cc for nonwelded tuff to about 30×10^{-4} for strongly-magnetized welded tuff, to about 85×10^{-4} for a very magnetic facies of rhyolite, and to about 70×10^{-4} for trachybasalt.

Of the more than 50 volcanic units investigated to date, only 14 have the remanent intensity and thickness required to produce aeromagnetic anomalies. Of the 14 units, 7 are normally-magnetized and give positive anomalies, 6 are reversely-magnetized and give negative anomalies, and 1 has normal and reverse magnetization and gives both positive and negative anomalies. The remanent directions in rock free from near-surface lightning effects are consistent within individual stratigraphic units, and are either approximately along (normal polarity) or opposite (reverse polarity) to the present geomagnetic field. Application of rock polarity measurements assisted the geologist in making correlations of exposed volcanic units.

INTRODUCTION

During the past 15 years the airborne magnetic survey has become an important method of geophysical prospecting. It has been used with success in petroleum districts to estimate the thickness of "nonmagnetic" sediments that overlie "magnetic" rock, and in mining districts to outline intrusive rock and iron-formation features. But seldom has it been used in areas of volcanic rock.

Many surveys are terminated before the areas of near-surface volcanic rock are reached, because of the complicated anomaly pattern found over these rocks. Anomalies there are just as likely to be negative as positive, and interpretations at best are limited to outlining the lateral extent and depth of a magnetic facies that is unknown. In most instances, we do not know the anomaly-producing rocks or the anomaly amplitude and sense expected. So far, very little work has been done to identify the magnetized rocks, and to determine their magnetizations and the kinds of anomalies they can cause.

One exception is the study the U.S. Geological Survey has undertaken at the Nevada Test Site. A 5,000-square mile aeromagnetic survey of the test site and large areas to the north and northwest shows numerous anomalies that come from Tertiary volcanic rock. These data were published by the U.S. Geological Survey as Geophysical Investigations Maps (Boynton and Vargo, 1963a, b; Boynton and others, 1963a, b). Many of the anomalies are in mountainous regions where the rocks are exposed, making it possible to collect rock specimens suitable for magnetization measurements. Such rock magnetization data often enable the geophysicist to relate a specific aeromagnetic anomaly to a specific geologic feature. Anomalies are not confined to mountainous areas. An almost equal number of anomalies come from buried and unknown rock units in adjacent valley regions.

The first phase of this study is to establish the relation between an anomaly and a known volcanic unit, using as a basis the magnetic properties of rock samples collected from surface outcrops, drill core, and underground workings. The second is to use these data to predict the identity of the particular unit that produces an anomaly in areas of alluvium cover, or where the unit is buried by "nonmagnetic" volcanic rock. Before undertaking an interpretation of a magnetic anomaly in terms of lateral extent or depth, we must identify the magnetic facies that is responsible for the magnetic anomaly.

NORMAL AND REVERSE POLARITY

The explanation for the presence of prominent negative and positive aeromagnetic anomalies over a relatively flat-lying unit of volcanic rock requires a large change in direction of remanent magnetization. For post-Eocene rock, experts in paleomagnetic investigations of remanent magnetization predict that at the time of rock emplacement and cooling through the Curie temperature point, directions will either be close to the present earth's magnetic field, or in a direction almost opposite to it (Cox and Doell, 1960). The phenomenon of reversal in remanent direction is usually interpreted as the result of reversals in the earth's field at certain intervals throughout geologic time.

To determine the polarity of a rock unit, we measure the remanent directions of collected rock samples. For the latitude of the Nevada Test Site, a normal direction is close to the present earth's field which is northward, having a positive (downward) inclination of about 63°.

A reverse direction is nearly opposite the earth's field, or southward with a negative (upward) inclination of about 63°. Figure 1 shows the remanent directions of 36 cylindrical samples drilled from 12 large pieces of rock collected from the surface of the basalt of Buckboard Mesa. The directions are too scattered for reliable determination of polarity. Although four directions are very close to the earth's field, many are over 25° away, and 8 samples have negative inclinations.

After partial alternating field demagnetization of the 36 samples, the directions cluster close to the earth's magnetic field, as shown in figure 2. The upper flow of the basalt of Buckboard Mesa is therefore designated as having normal polarity. Lightning strikes provide a reasonable explanation for the very large differences in remanent direction of figures 1 and 2 (Cox, 1961). Lightning effects add a relatively strong component of remanence that is confined to the near-surface rocks, and this magnetization is, therefore, not representative of the true average magnetization of a large rock mass.

Table 1 gives the polarities of the volcanic units mentioned in this report. Potassium-argon ages (Kistler, written commun., 1966 [redacted]) range from less than 6.2 million years for the basalt of Buckboard Mesa to about 21 million years for the tuff of White Blotch Spring. Polarities of many other units have been determined to assist the geologist in making correlations of exposed volcanic units. However, these data are not included here because either the total intensities or the thicknesses were so small that the total effect of the volcanic unit was insufficient to produce a significant aeromagnetic anomaly.

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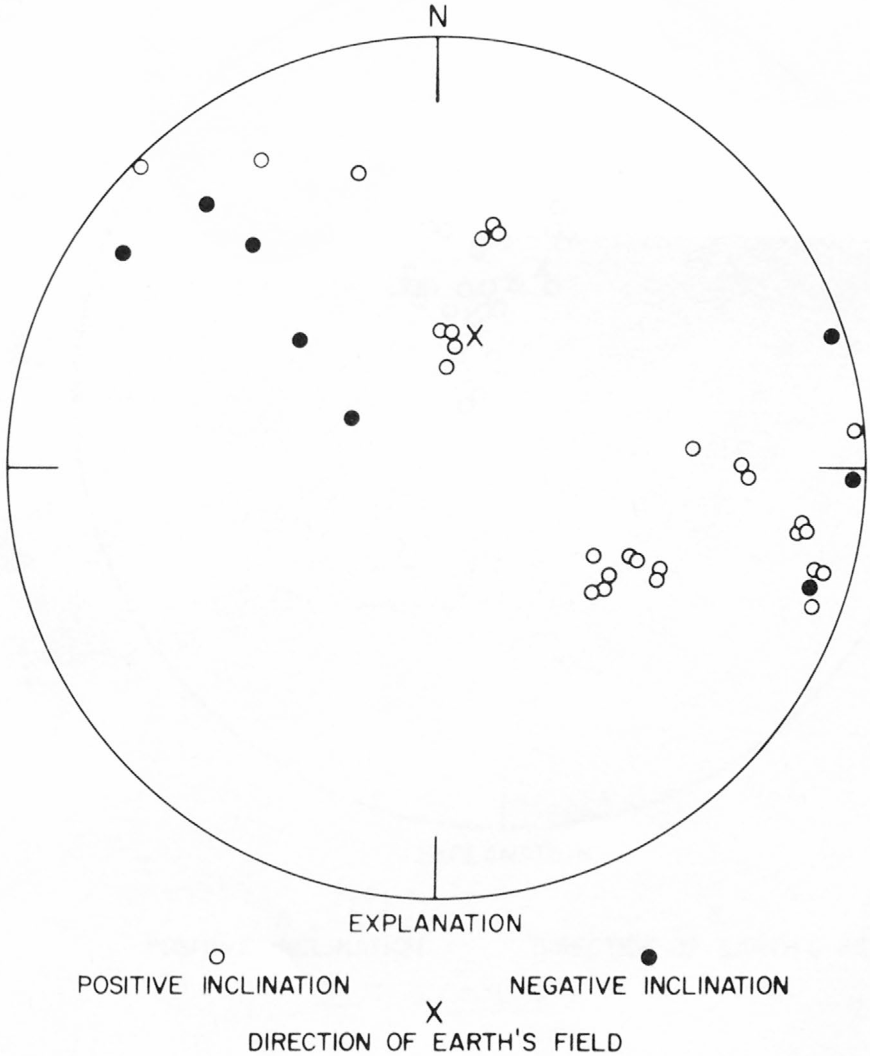

Figure 1.--Remanent directions of 36 samples from trachybasalt of Buckboard Mesa before partial alternating field demagnetization. The scatter of many directions away from earth's field leaves unanswered the question of the polarity of this basalt.

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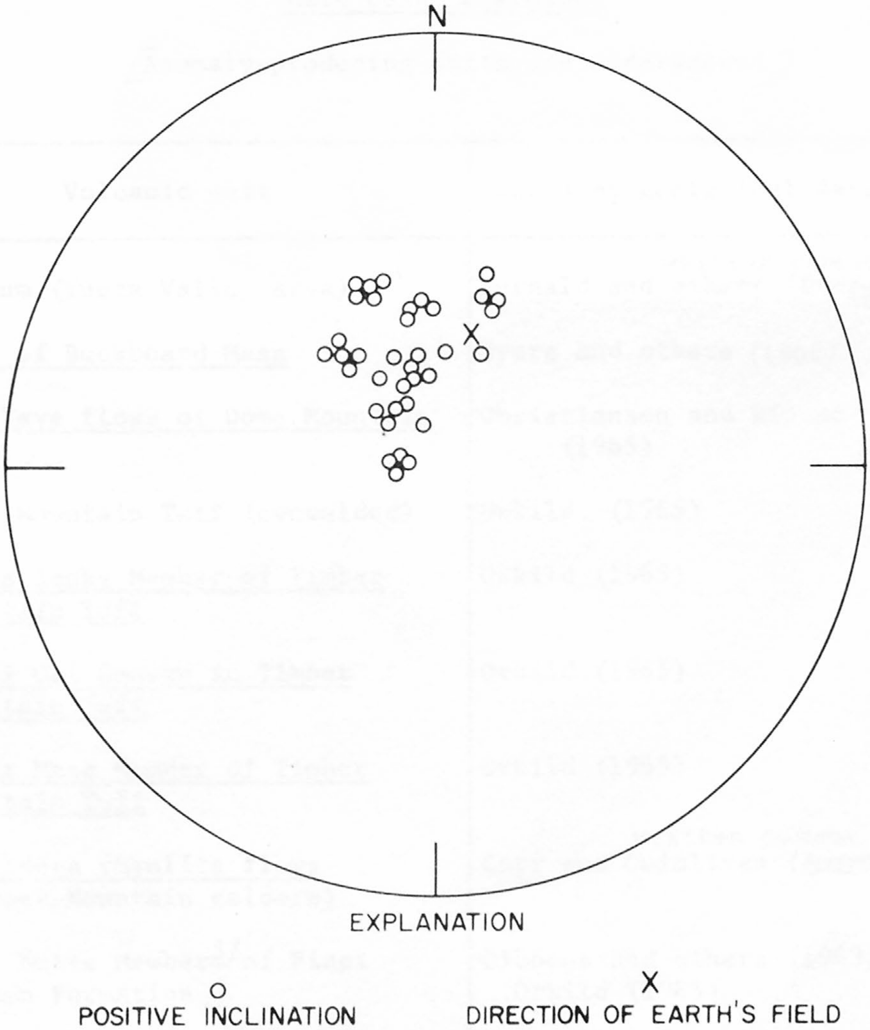

Figure 2.--Remanent directions of 36 samples from trachybasalt of Buckboard Mesa after partial alternating field demagnetization. Nearness of directions to earth's field shows that this basalt has normal polarity.

Table 1.--Polarities of volcanic units for which magnetic properties have been determined

[Anomaly-producing units are underscored]

Volcanic unit	Source of geological data	Polarity
Alluvium (Yucca Valley area)	Fernald and others ([redacted] written commun., 1966)	[1]
Basalt of Buckboard Mesa	Byers and others (1966)	Normal
Mafic lava flows of Dome Mountain	Christiansen and Lipman (1965)	Normal
Timber Mountain Tuff (nonwelded)	Orkild (1965)	[2]
Ammonia Tanks Member of Timber Mountain Tuff	Orkild (1965)	Normal
Tuff of Cat Canyon in Timber Mountain Tuff	Orkild (1965)	Normal
Rainier Mesa Member of Timber Mountain Tuff	Orkild (1965)	Reverse
Postcaldera rhyolite flows (Timber Mountain caldera)	Carr and Quinlivan ([redacted] written commun., 1966)	Reverse
Survey Butte Member[3] of Piapi Canyon Formation	Gibbons and others (1963); Orkild (1965)	Normal
Rhyodacite of the northern part of Wahmonie Formation	Poole and others (1965)	Normal
Topopah Spring Member of Paintbrush Tuff	Orkild (1965)	Normal
Rhyolite associated with Paintbrush Tuff	Orkild (1965)	Reverse

See footnotes at end of table, page 8.

Table 1.--Polarities of volcanic units for which magnetic properties have been determined--Continued

[Anomaly-producing units are underscored]

Volcanic unit	Source of geological data	Polarity
Tunnel bed no. 4, lower member of Indian Trail Formation	Gibbons and others (1963)	2/
Tunnel bed no. 2, lower member of Indian Trail Formation	Gibbons and others (1963)	2/
Rhyolite of Area 20	Orkild and others ([redacted]) written commun., 1966	Normal
Rhyolite of Silent Canyon Center	Orkild and others ([redacted]) written commun., 1966	Normal
Tuffs of Chocolate Mountain and Pinyon Pass	Christiansen and Lipman (1965)	Reverse
Fraction Tuff	Rogers and others ([redacted] 1967) [redacted]	Reverse
Lavas of intermediate composition	Anderson and Ekren ([redacted]) written commun., 1966	Reverse and normal
Tuff of White Blotch Spring	Rogers and others ([redacted] 1967) [redacted]	Reverse

1/ Polarity not measured. It is assumed that during the rapid depositional process in Yucca Valley, the rock fragments that make up the alluvium were rotated in a random manner and did not attain a preferential alinement.

2/ Geological evidence clearly shows these beds were deposited at temperatures much lower than their Curie points.

3/ Dropped from use as of Orkild (1965).

TOTAL MAGNETIZATION

Although we must find the polarities of the volcanic rocks, the most difficult and time-consuming part of our study is the evaluation of the total intensity of magnetization. Polarities can be obtained from partially demagnetized samples, but for intensity determination we must collect additional samples that are free from lightning effects. Whenever possible we use specimens collected underground, which when demagnetized show consistent remanent directions and do not have soft components of magnetization. When forced to work with surface samples, we must discard data from those samples that have directions deviating significantly from either normal or reverse polarity.

The average total magnetization of a uniformly magnetized rock mass, denoted as the vector $\vec{M}_t$, is defined as the vector sum of the induced $\vec{M}_i$ and remanent magnetization $\vec{M}_r$ of the mass,

$$\vec{M}_t = \vec{M}_i + \vec{M}_r. \tag{1}$$

The intensity of induced magnetization is a function of the magnetic susceptibility, k, and the strength, H_o, of the earth's magnetic field,

$$M_i = kH_o. \tag{2}$$

Fortunately, equation (1) can be simplified when considering magnetization of volcanic rock at the Nevada Test Site. As previously stated, measurements on a large number of rock samples show that the remanent direction is nearly collinear with $\vec{M}_i$, having either the same or opposite sense. If the directions are within about 25° of collinear, then

$$M_t \approx kH_o \pm M_r, \tag{3}$$

where the alternative sign applies to direction (+) along and (-) opposite to the direction of the earth's field.

Total magnetization is the parameter that separates the "nonmagnetic" rocks from the "magnetic" ones. "Nonmagnetic" rocks are defined as those that have a total magnetization too low to give an aeromagnetic anomaly of 20 gammas, the contour interval of the published GP aeromagnetic maps (Boynton and others, 1963a and b; Boynton and Vargo, 1963a and b). Computed anomalies for sheet-like, horizontal models of various lengths and widths show that the maximum amplitude of aeromagnetic anomaly, ΔT_{max}, produced by a lava or ash flow of thickness, ε, is

$$\Delta T_{max} = 2.6\, M_t \left(\frac{\varepsilon}{d}\right), \tag{4}$$

assuming $\frac{\varepsilon}{d} < 0.5$, where $d - \frac{\varepsilon}{2}$ is the distance from the datum plane to the top of the flow.

Taking as a typical example a flow thickness of 200 feet, a terrain clearance of 1,000 feet, and a total magnetization of 5×10^{-4} emu/cc, equation (4) gives an anomaly amplitude of about 20 gammas. The amplitude increases for increasing flow thickness and decreases for increasing terrain clearance. For studies at the Nevada Test Site 5×10^{-4} emu/cc was accepted as a reasonable upper limit for the total magnetization of "nonmagnetic" rock.

MAGNETIC SUSCEPTIBILITY

The magnetic susceptibility values for the volcanic rocks at the test site are surprisingly low. If it were not for the contribution of remanent intensity to the total magnetization of these rocks (equation 1), they would be designated as nonmagnetic, and except for very thick deposits, they would give aeromagnetic anomalies of about 20 gammas maximum.

Figure 3 shows the magnetic susceptibility of lava flows, and figure 4 shows the magnetic susceptibility of tuff and alluvium. The most magnetic rock measured, basalt of Buckboard Mesa, has a magnetic susceptibility less than 8×10^{-4} emu. Applying equation (2) and using $H_o = 0.53$ oersted at the latitude of the test site converts a susceptibility of 8×10^{-4} emu to an induced magnetization less than 5×10^{-4} emu/cc.

To investigate the relation of susceptibility to approximate percentage of mafic minerals, the susceptibility of lava flows is plotted against grain density. Grain density is the density of the mineral constituents of the rock, and an increase in mafic minerals usually means an increase of grain density. The dashed line of figure 3 shows a linear relationship for all the rock, except the rhyolite of Silent Canyon Center and the Wahmonie rhyodacite.

Smith (1960) reports that most ash flows have an initial porosity of about 50 percent, and that subsequent compaction and welding reduces porosity. Data in figure 4 shows that a porosity of about 24 percent is the dividing line between nonwelded and welded tuff. Welded tuffs are the Topopah Spring Member of Paintbrush Tuff and all units with lower porosities.

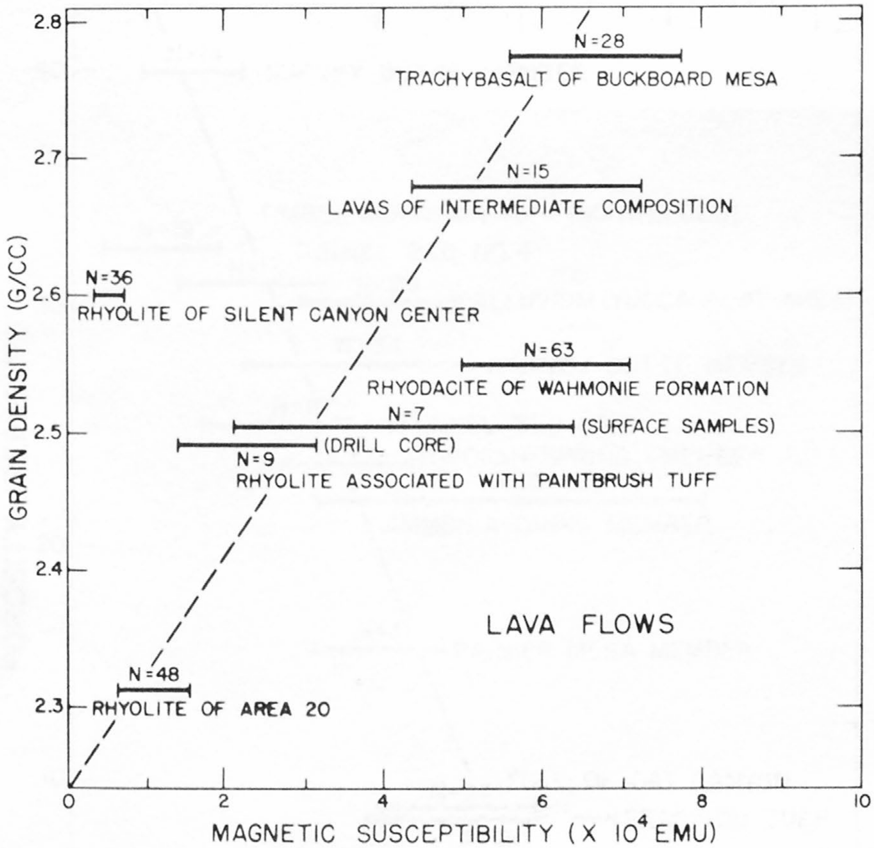

Figure 3.--Magnetic susceptibility of lava flows and its dependence on grain density. Bars show the 95 percent confidence interval of average magnetic susceptibility. N equals the number of samples measured. Heavy dashed diagonal line shows a linear relationship for all but two units.

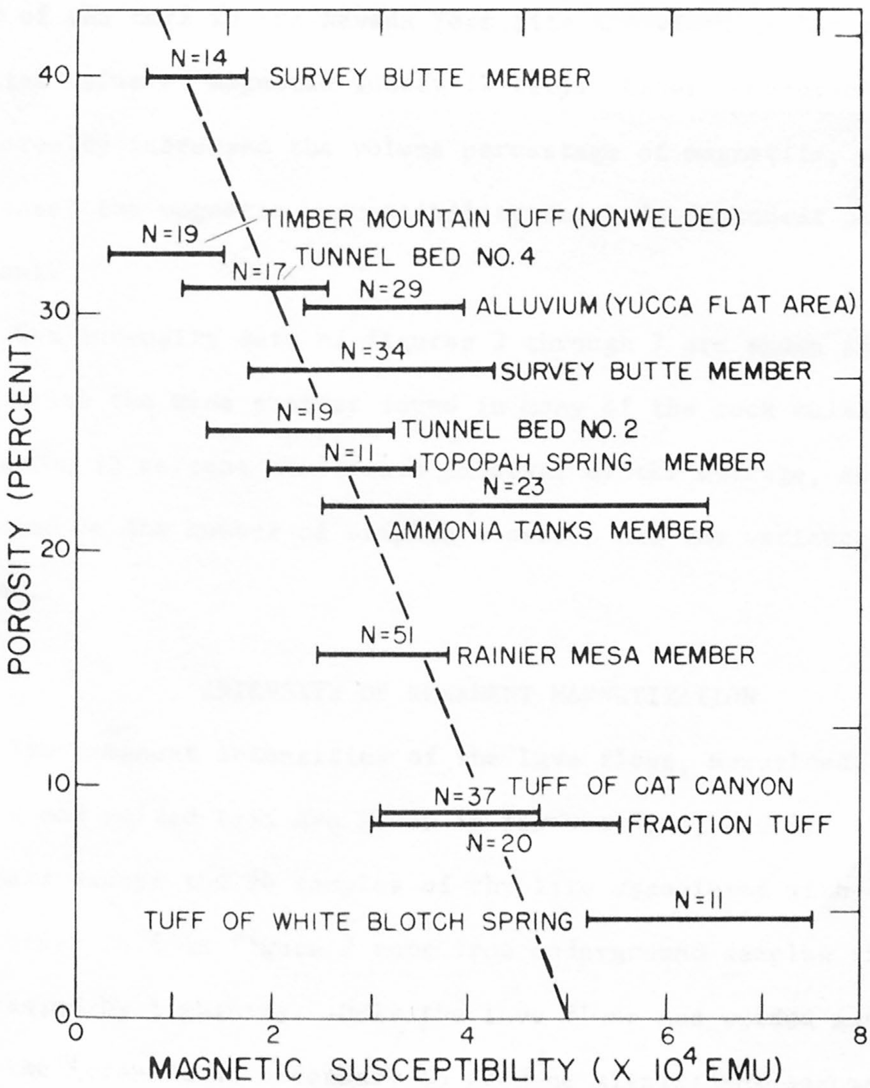

Figure 4.--Magnetic susceptibility of tuffs and alluvium, and its dependence on porosity. Bars show the 95 percent confidence interval of average magnetic susceptibility. N equals the number of samples measured. Heavy dashed diagonal line shows a linear relation for all but three units.

The dashed line of figure 4 shows a linear relation between magnetic susceptibility and porosity that is sufficiently good to predict that most of the tuff in the Nevada Test Site and vicinity had about the same initial value of magnetic susceptibility. Later compaction and loss of porosity increased the volume percentage of magnetite, and thereby increased the magnetic susceptibility which is dependent on magnetite content.

The intensity data of figures 3 through 7 are shown as bars to illustrate the wide scatter found in many of the rock units. The bar gives the 95 percent confidence interval of the average, and its length is based on the number of samples measured and the variance of the sample values.

INTENSITY OF REMANENT MAGNETIZATION

The remanent intensities of the lava flows, nonwelded, air-fall, bedded and welded tuff are given in figures 5, 6, and 7. All of the data except the 24 samples of rhyolite associated with the Paintbrush Tuff in figure 7 come from underground samples that are unaffected by lightning. Only the lava flows and welded ash-flow tuffs have the intensities necessary to produce significant aeromagnetic anomalies: Table 1 lists the 14 volcanic units we have found to date that have the necessary combination of remanent intensity and thickness. Of the 14 units, 7 are normally-magnetized and give positive anomalies, 6 are reversely-magnetized and give negative anomalies, and the thick section of lavas of intermediate composition has partly normal and partly reverse magnetization and gives both positive and negative anomalies.

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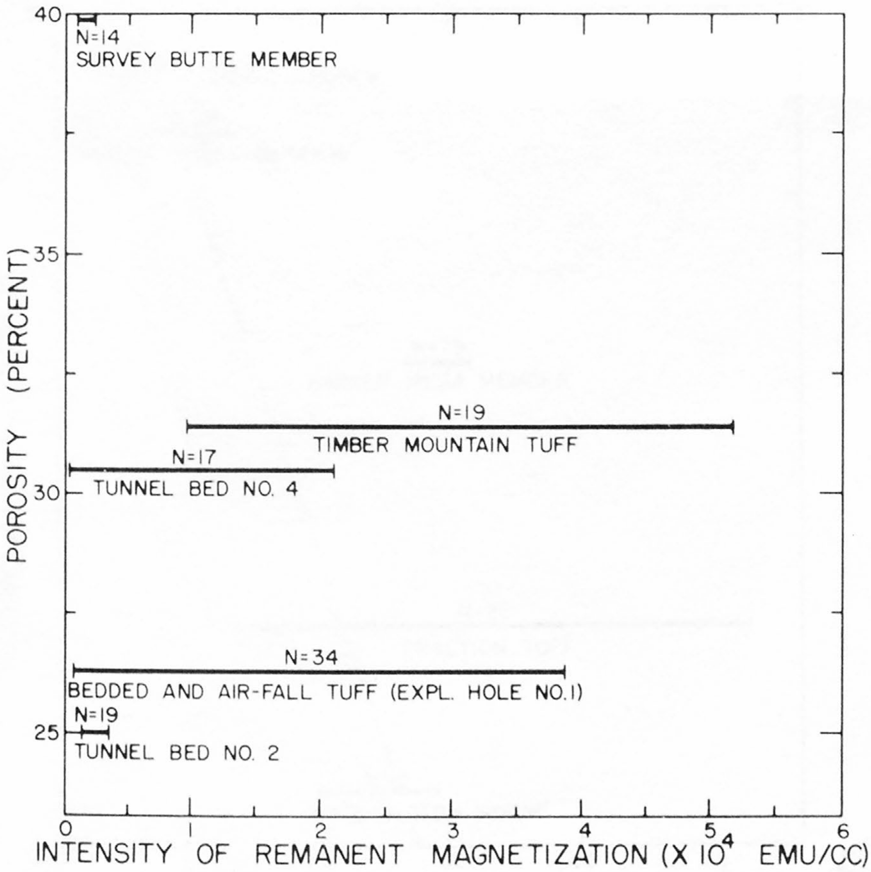

Figure 5.--Remanent intensity of nonwelded, air-fall, and bedded tuff, and its dependence on porosity. Bars show the 95 percent confidence interval of average intensity. N equals the number of samples measured.

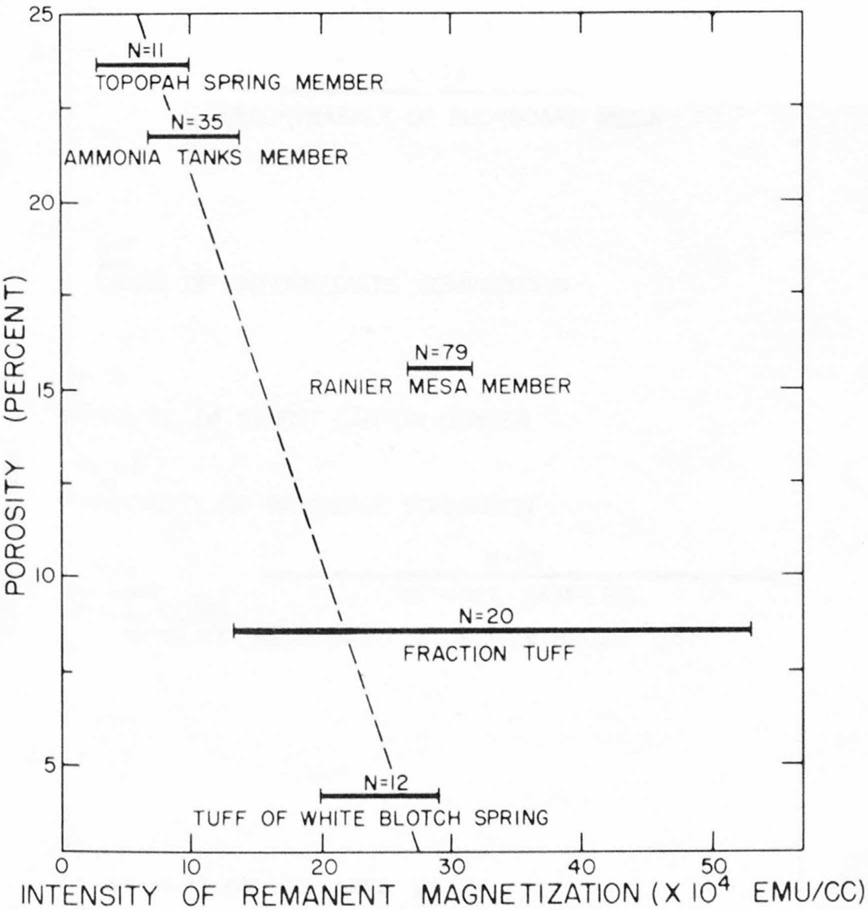

Figure 6.--Remanent intensity of welded tuff and its dependence on porosity. Bars show the 95 percent confidence interval of average intensity. N equals the number of samples measured. Heavy dashed diagonal line shows a linear relation for all except the Rainier Mesa Member.

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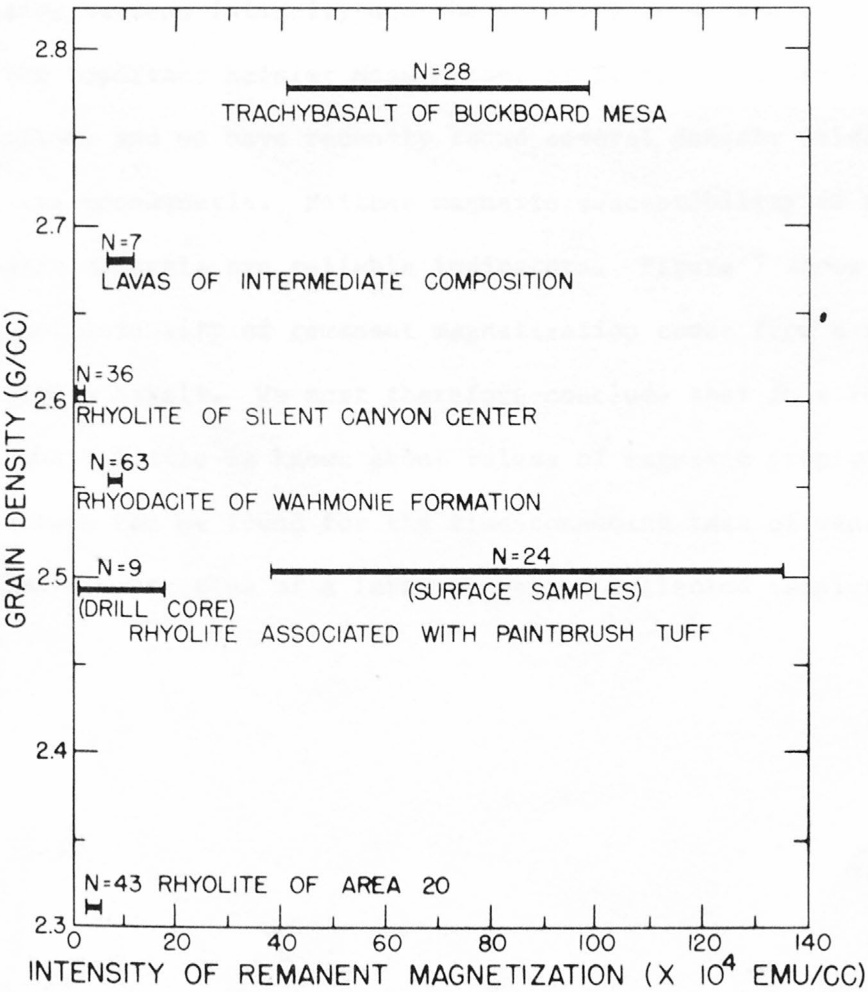

Figure 7.--Remanent intensity of lava flows and its dependence on grain density. Bars show the 95 percent confidence interval of average intensity. N equals the number of samples measured.

We have found no reliable method of predicting intensity of remanent magnetization. The dashed line of figure 6 suggests a relation between intensity and the porosity or degree of welding. But the important Rainier Mesa Member of Timber Mountain Tuff is an exception, and we have recently found several densely welded tuffs that are nonmagnetic. Neither magnetic susceptibility or percentage of mafic minerals are reliable indicators. Figure 7 shows that the greatest intensity of remanent magnetization comes from a rhyolite and not from a basalt. We must therefore conclude that in a Tertiary volcanic area where little is known about values of magnetic properties, no substitute can be found for the time-consuming task of measuring the remanent intensities of a large number of collected samples.

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