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PRELIMINARY REPORT
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UPDATE ON ROCK MAGNETISM -- EAST RIFT ZONE KILAUEA

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PURPOSE:

The east rift zone of Kilauea is characterized by distinctive aeromagnetic anomalies. Broad magnetic lows flanking the rift zone have been interpreted as arising from rock whose magnetization has been lowered due to hydrothermal alteration. A string of magnetic highs, which lies on or near the active rift zone, has been attributed to intrusions that are interpreted to be more highly magnetic than the surrounding flows [*Lenat*, 1987; *Malahof and Woollard*, 1966; *Flanigan and Long*, 1987; *Hildenbrand et al.*, 1993].

Little rock magnetic data have been available to constrain the magnetic models used in these studies. The purposes of this study are (1) to acquire rock magnetic data from rocks in and around the east rift zone of Kilauea, (2) to derive petrologic interpretations for observed variations in magnetic properties, and (3) to use these properties and interpretations to constrain magnetic modeling.

FACTORS INFLUENCING MAGNETIZATION:

For igneous rocks, like those in Hawaii, four factors influence the magnitude of magnetization:

1. *Quantity of titanomagnetite (Ti-Mt)*: Both remanent magnetization and magnetic susceptibility are proportional to the quantity of Ti-Mt.
2. *Composition of Ti-Mt:* For a given volume of Ti-Mt in a given domain state, thermoremanent magnetization increases as Ti-content decreases (i.e., remanent magnetization will vary as

saturation magnetization). Magnetic susceptibility varies little as a function of Ti content [*Day*, 1977].

3. *Magnetic grain size:* **This is the most important factor controlling the magnetization of Hawaiian rocks.** Magnetic grain size refers to the domain state of Ti-Mt grains. Single domain (SD) grains are "small", multidomain (MD) grains are "large", and pseudosingle domain (PSD) grains are intermediate in size. Remanent magnetization decreases as the number of domains ("magnetic grain size") increases. This is a very large effect when the number of domains is small. Magnetic susceptibility increases as the number of domains increases. In comparison to changes in remanent magnetization, changes in susceptibility tend to be small. For a given "magnetic grain size" or domain state the physical dimensions vary as a function of Ti-Mt composition. For equidimensional grains of pure magnetite the upper limit of SD grains is about 0.05 - 0.06 microns. For Ti-Mt with compositions of x=0.55 to 0.6 (like unexsolved Ti-Mt in basalt) SD grains may be as large as 0.6 microns [Dunlop, 1981].
4. *Magnitude of the field:* The magnitude of TRM is proportional to the magnitude of the field in which the rocks cool. (This will not be considered further. However, one may need to consider factor 4 in assessing variations among flows with stratigraphic position, or in comparing results from different latitudes.)

In tholeiitic basalts Ti-Mt begins to crystallize at about 1030 ^{o}C [*Wright and Clague*, 1989]. Initially the Ti content is quite high for tholeiitic basalts (x=0.64, corresponding to a Curie temperature of about 144 ^{o}C according to *Petersen* [1976]). However, in terrestrial flows much of the Ti-Mt undergoes high-temperature oxidation with concomitant exsolution of ilmenite lamellae. Ti-Mt grains that have undergone this type of high-temperature oxidation-exsolution have higher Curie temperatures (lower Ti-content) and are physically subdivided by ilmenite lamellae [*Grommé et al.*, 1969; *Larson et al.*, 1969]. **Our interest here is to examine processes that may increase or decrease magnetization relative to the typical Hawaiian flow.** Note that remanent magnetization is usually much more important than induced magnetization; therefore the total magnetization which affects the magnetic field will normally vary as the remanent magnetization. We will ignore the effects of heating in the vicinity of magma.

Advanced High-Temperature Oxidation-Exsolution: Remanent magnetization may be enhanced in rocks that have undergone a great degree of high-temperature oxidation. Magnetic susceptibility in such rocks will be lowered because the process reduces the amount of Ti-Mt. However, remanent magnetization will be increased because the process also reduces the magnetic grain size. This process may be enhanced by slow cooling which allows more time for oxidation and by a continuous supply of oxygen. In addition, portions of thick flows or large intrusions may act as semipermeable membranes which allow H_2 to escape while O_2 is retained (the gases are present due the dissociation of water at high temperature) [*Grommé et al.*, 1969]. Examples of increased magnetization due to high-temperature oxidation are provided by studies of a thick Icelandic basalt flow [*Wilson et al.*, 1968] and of the Mount St. Helens Dome [*Dzurizin et al.*, 1990]. This process could explain high magnetization in thick flows (i.e., inflated sheet flows, *Hon and Kauahikaua* [1991]) or in relatively large intrusions (currently we have no examples from Hawaii). Such rocks are characterized by high remanent magnetization, low susceptibility, and high Curie temperatures.

Rapid Cooling without oxidation: Basalts that cool very rapidly will contain fine-grained unexsolved Ti-Mt, unless cooling is so rapid that Ti-Mt did not have time to form. Small physical dimensions and high Ti content contribute to small magnetic grain size in these rocks. Examples of such rocks are pillow basalts [*Watkins et al.*, 1970] and shallow dikes [*Petersen*, 1976]. High-temperature oxidation is prevented by rapid cooling in pillow basalts. Lack of oxygen may prevent oxidation in some intrusions. Such rocks are characterized by high remanent magnetization, relatively low susceptibility, and low Curie temperature.

Slow Cooling without oxidation: Slow cooling may produce rocks with relatively coarse magnetic grain size. If oxidation occurs then the formation of ilmenite may subdivide grains so that magnetic grain size is relatively small. In the absence of oxidation, an increase in physical dimensions of grains and a progression from skeletal toward euhedral forms contribute to large magnetic grain size. If Ti remains mobile for an extended period during cooling so that it moves out of the Ti-Mt grains and forms a separate phase, then the lower Ti content of Ti-Mt will also contribute to larger magnetic grain size. Such rocks are characterized by weak "soft" remanent magnetization, high susceptibility, and high Curie temperature.

Subsequent Alteration (Olivine poor rocks): Most unaltered Hawaiian rocks contain Ti-Mt. Many alteration processes reduce the amount of Ti-Mt and thereby the magnetization. Alteration may change highly magnetic Ti-Mt to less magnetic titanomaghemite (as occurs in submarine basalts), to weakly magnetic hematite, or to nonmagnetic phases [*Watkins and Paster*, 1971]. More rarely flows may have magnetite added to them by alteration processes; *Hall and Fisher* [1988] report hydrothermal magnetite in some Icelandic basalt flows. In most cases altered rocks will be less magnetic than their unaltered equivalents.

Formation and Alteration of Olivine-Rich Cumulates: Alteration may enhance magnetizations of olivine-rich cumulates. Such cumulates may form in Hawaii anywhere magma is stored. Since olivine is non-magnetic, such rocks tend to be less magnetic than comparable olivine-poor rocks. However, alteration of olivine in such rocks may produce magnetite. This process is like that which occurs in the serpentinization of ophiolitic rocks [*Toft et al.*, 1990]. These rocks would be characterized by low remanent magnetization (?), high magnetic susceptibility, and high Curie temperature.

OBSERVATIONS FROM SOH4

1. There is a small drop in magnetization of flows that occurs at about the water table. Otherwise magnetic properties of flows are nearly constant with depth. Although

hydrothermal alteration may have destroyed magnetization in a few samples, alteration has had little effect on the magnetic properties of most rocks penetrated by SOH4.

2. Intrusions above about 3000 ft are on average more highly magnetic than flows due to high remanent magnetization. The most magnetic of these intrusions are characterized by very high and very stable remanent magnetization, low susceptibility, and low Curie temperature. Petrographic observations of a few samples from the shallow intrusions reveals cuneiform Ti-Mt grains with few ilmenite lamellae. Some profiles of Curie temperatures across a dikes exposed in the Kilauea caldera yield high Curie temperatures near the margins and low Curie temperatures toward the centers.
3. There are not enough of these highly magnetic shallow intrusions at SOH4 to provide a high enough average magnetization to account for the high amplitude aeromagnetic highs.
4. Deeper intrusions are on average less magnetic than both shallow intrusions and flows. Deeper intrusions are characterized by weak unstable remanent magnetization, high susceptibility and high Curie temperature. Estimation of the in situ magnitude of remanent magnetization is problematical because many samples possess a large very soft component of magnetization that may be an IRM imparted by drilling. Petrographic observations of a few samples reveals Ti-Mt grains that are blockier than those observed in the shallow flows. No ilmenite lamellae were observed in these grains, but TiO_2 (anatase) is widespread.
5. The average density of intrusions appears to be fairly constant below about 4000 feet and decreases upward above 4000 feet. The upward decrease in density is apparently due to an increase in vesicules.

INTERPRETATIONS:

1. The high magnetization of shallow intrusions is due to small magnetic grain size. The small magnetic grain size is attributed to (1) small physical dimensions and characteristic cuneiform shapes of Ti-Mt grains due to rapid cooling and (2) high Ti-content due to

minimal high temperature oxidation perhaps caused by a lack of O_2 in the centers of the dikes (as has been suggested for a dike on Vesuvius [*Petersen*, 1976]). Density data and petrographic observations of vesicles indicate that volatiles had been exsolved from these samples.

2. Deep dikes possess low total magnetization (the sum of a small remanent magnetization and an enhanced induced component) as a result of large magnetic grain size. Although the maximum dimensions of Ti-Mt in these rocks does not seem to be much larger than in the shallow dikes, the grains are blockier and have low Ti content. The low Ti content is not due to high-temperature oxidation; apparently elements remained mobile long enough during cooling to allow Ti to be removed from the Ti-Mt grains and to form a separate phase. These rocks have little if any vesicularity.
3. We suggest that retention of volatiles by the deep intrusions and loss of volatiles by the shallow intrusions may be an important factor controlling the different characteristics of their primary Fe-Ti oxide mineralogy. If so, we can expect depth of emplacement to control magnetic properties.
4. We suggest that high concentrations of highly magnetic dikes, with magnetic properties like those of the shallow dikes in SOH4, are the source of magnetic highs along the rift zone. Similarly, weakly magnetic intrusions, like the deeper intrusions penetrated by SOH4, may be the source of the broad magnetic lows. Although we cannot rule out the possible contributions of other lithologies (such as cumulates and hydrothermally altered rock) to the magnetic anomaly pattern, their existence in significant quantities have yet to be documented.

FURTHER WORK TO BE INCLUDED IN SOH4 PAPER AND CONSIDERATIONS FOR MODELING

1. *Laboratory TRM experiment:* It is difficult to obtain an accurate estimate of the in situ magnetization of the deep intrusions because samples of these rocks possess large soft

components of magnetization that may have been imparted by the drilling process. Ten or twelve samples of deep intrusions will be given a laboratory TRM by cooling in a field of about 0.35 Oe. TRM will be measured and subjected to AF demagnetization. These results will be compared to AF demagnetization data of NRM for the same samples. Hopefully these data will help constrain our estimates of the in situ magnetization of the deep intrusions. This procedure has a good chance of success because the deep intrusions contain Ti-poor magnetite which should change little during laboratory heating.

2. *Petrographic Observations:* As Jim K. pointed out, old intrusions should now be buried deeper than the depth at which they were emplaced. The depths of occurrence of older "shallow" intrusions should probably overlap the depths of younger "deep" intrusions. We have on hand 22 thin sections from intrusions in SOH4; to date we have examined only a few (6?). We will attempt to categorize all sections as to emplacement depth on the basis of petrographic observations (vesicularity, Ti-Mt morphology, presence of TiO_2 etc.).
3. In modeling magnetic anomalies it should be noted that "shallow" intrusions may extend to much greater depth than their depth of emplacement due to the combined effects of subsidence and upward growth of the rift zone. I have tended to think of the string of magnetic highs along the rift as arising from near surface horizontal widening and thinning of the zone. However, as Jim K. and Frank T. pointed out this pattern could just as well arise from thickening of intrusions in the vertical dimension.

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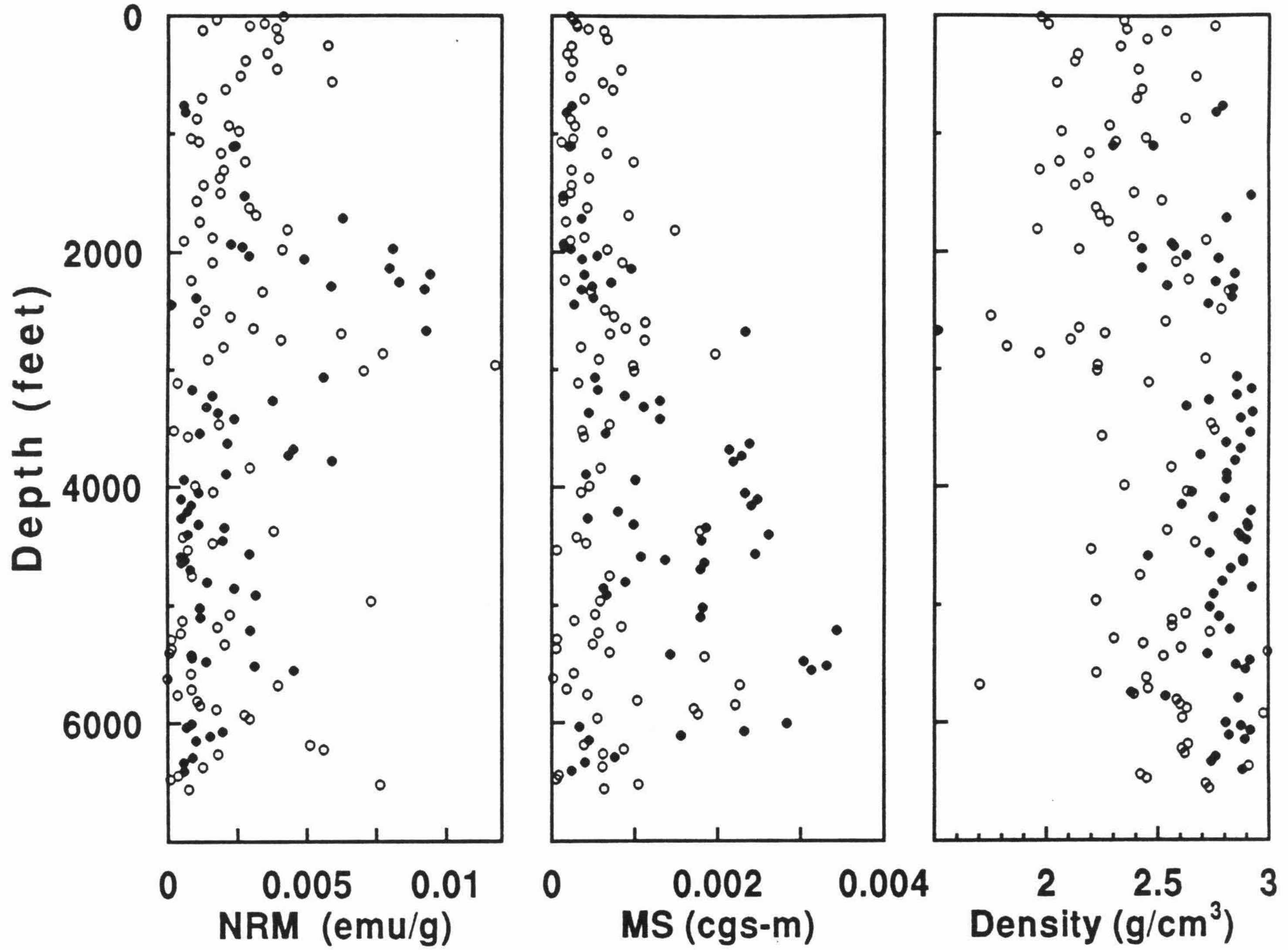
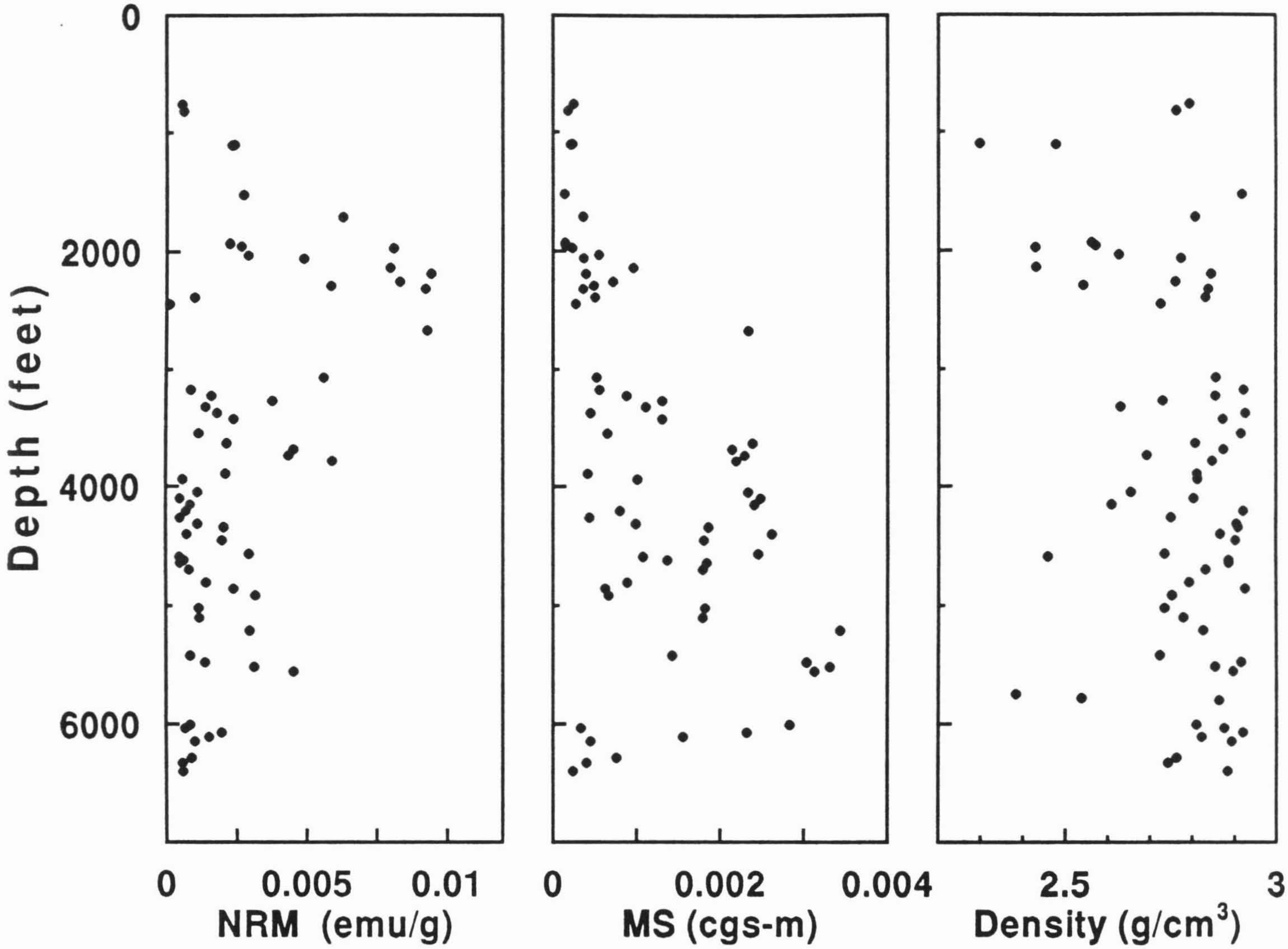
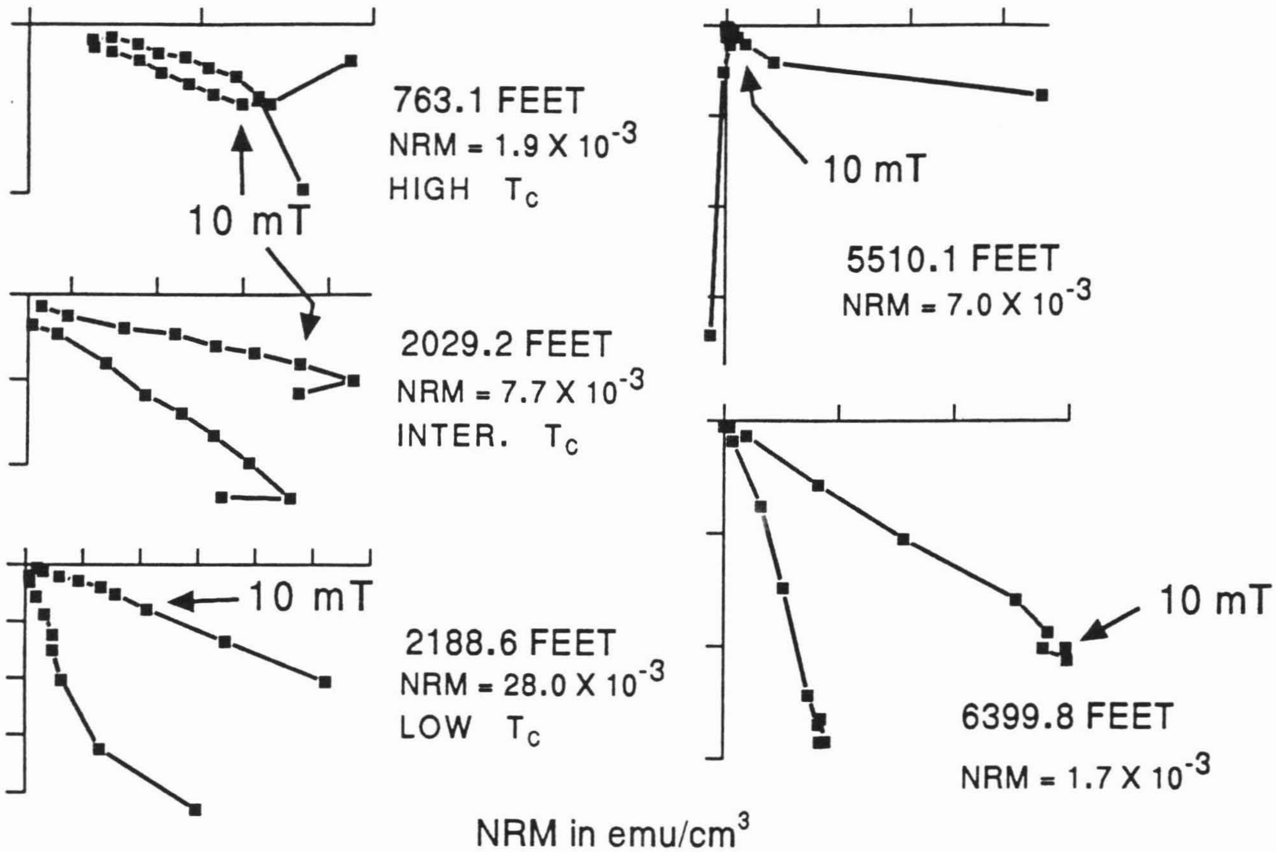


- Flow
- Intrusion

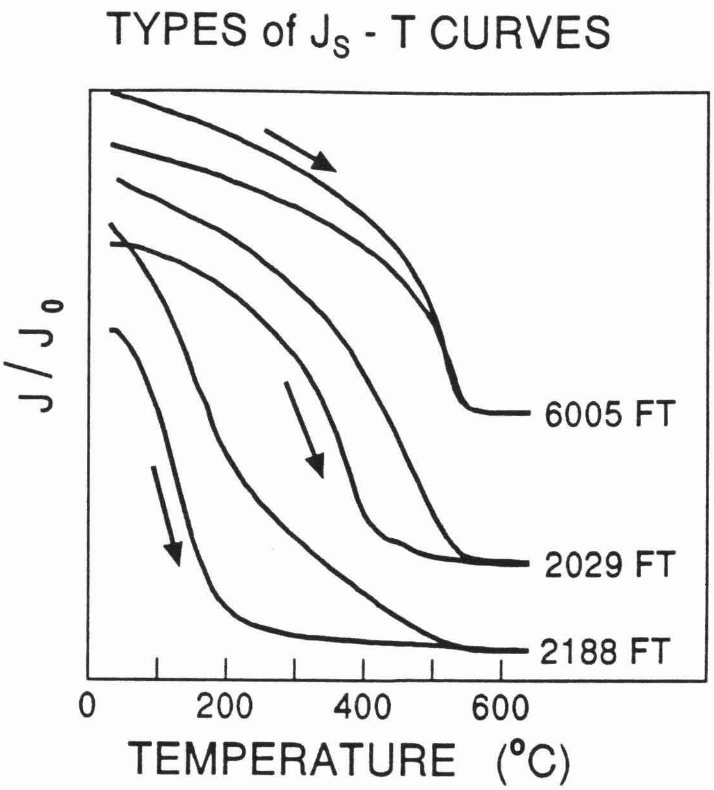
Natural remanent magnetization (NRM), magnetic susceptibility (MS), and dry bulk density for flows and intrusions from borehole SOH4. Note: Magnitudes of NRM for many samples of intrusions below about 3000 ft. are probably much larger than in situ magnetizations due to large "soft" drilling induced components.



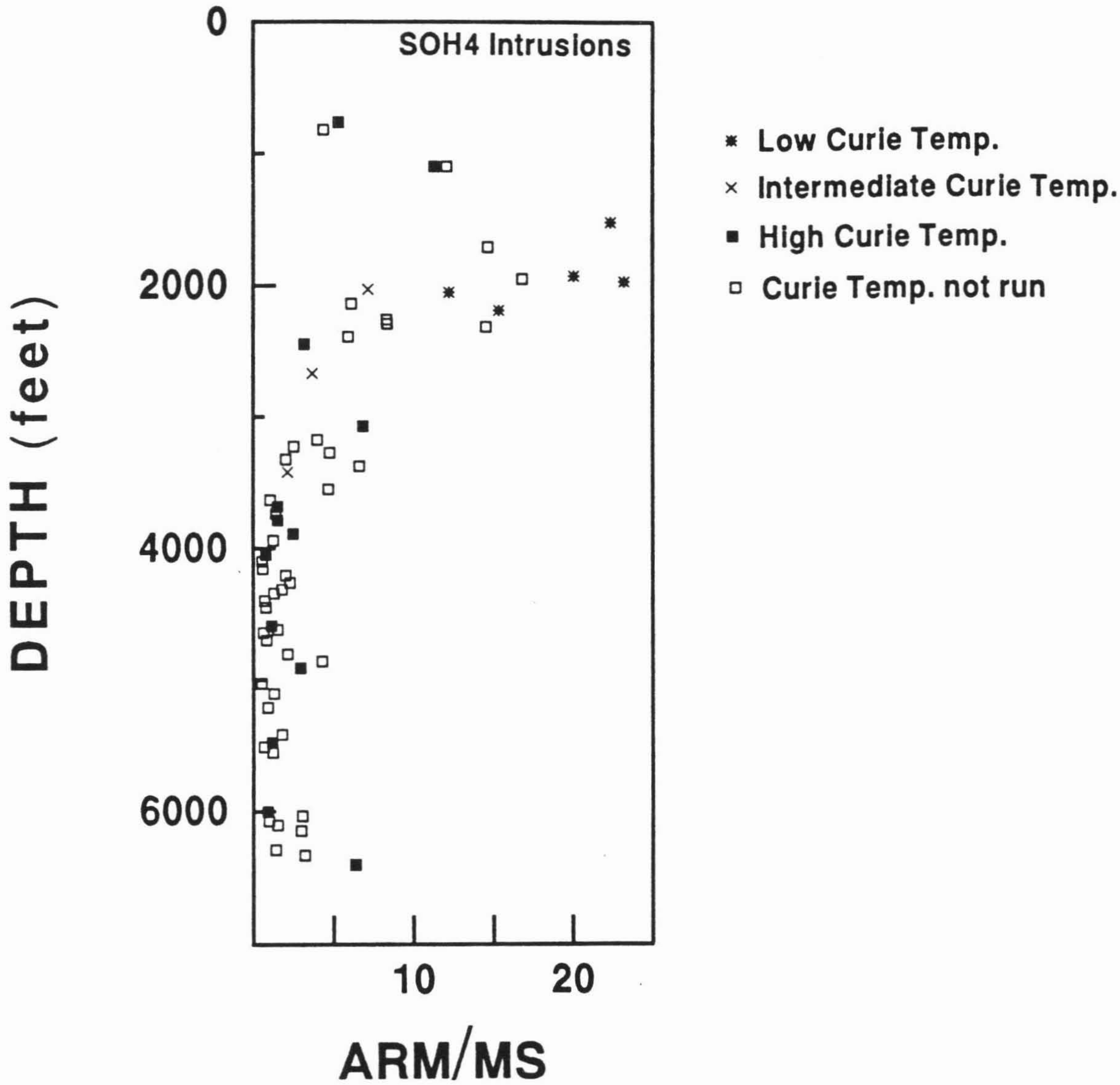
Natural remanent magnetization (NRM), magnetic susceptibility (MS), and dry bulk density for samples of intrusions from borehole SOH4. Values of NRM for many samples below about 3000 ft are probably much higher than in situ magnetizations due to large "soft" drilling induced components.



Orthogonal vector diagrams depicting alternating field demagnetization of NRM in samples from SOH4. Samples 763.1, 2029.2, 2188.6, and 6399.8 display linear decay to the origin after removal of a small "soft" component. However, a large "soft" component was removed from 5510.1. A large portion of the NRM of 5510.1 may be a VRM or an IRM induced by drilling. 5510.1 is typical of the "deep" intrusions.



Saturation magnetization vs. temperature: Samples from SOH4 show low (about 200°C for 2188 ft), intermediate (about 400°C for 2029 ft), and high (about 550°C for 6005 ft) Curie temperatures.



High values of ARM/MS indicate small magnetic grain size.

ARM is anhysteretic magnetization. MS is magnetic susceptibility.