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X-644-72-159
PREPRINT

NASA TM-X 65941

MAGNETIC HYSTERESIS CLASSIFICATION FOR THE LUNAR SURFACE AND THE INTERPRETATION OF PERMANENT REMANENCE IN LUNAR SAMPLES

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JUNE 1972

GSFC

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Magnetic Hysteresis Classification of the Lunar Surface and the Interpretation of Permanent Remanence in Lunar Surface Samples

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Abstract:

A magnetic hysteresis classification of the lunar surface is presented. Particular emphasis is placed on the mode of origin of the samples which determine their hysteresis properties. The hysteresis ratios R_H and R_I, where R_H is the ratio of remanent coercive force (H_R) to coercive force (H_c) and R_I is the ratio of saturation remanence (I_R) to saturation magnetization (I_S), are the basic data used for the classification.

There is a distinct correlation between natural remanence (NRM), saturation magnetization (I_S), and the hysteresis ratios for the rock samples. The hysteresis classification is able to explain some aspects of time dependent magnetization in the lunar samples and relates the initial susceptibility to NRM, viscous remanence, and to other aspects of magnetization in lunar samples.

The framework of the hysteresis classification can be utilized in evaluation of the processes active in the formation of the regolith, and specifically in the classification of microbreccia types. The stability of permanent remanence, the recognition of two modes of time dependent remanence, one associated with the superparamagnetic fraction, the other with the multidomain fraction in lunar samples, as well as other magnetization features, are compatible with the classification and indeed are predictable if the hysteresis properties are measured.

Since up to 60% of the iron in the lunar soil may be super paramagnetic at 400° K, and only 10% at 100° K, the 50% which becomes ferromagnetic over the cycle has the characteristics of thermoremanence and may provide for an enhancement in measurable field on the dark side during a subsatellite magnetometer circuit.

Introduction:

Permanent magnetism is present in all samples returned from the moon, and fields ranging up to 300 gamma have been measured by astronauts using a portable magnetometer. However, at present time there is no clear indication as to what is the magnetization mechanism or what is the source of the field which induced the permanent magnetism.

The simplest explanation is to assume a dipole field in a manner analagous with thermoremanence acquisition in the earth's crustal layer. There are difficulties involved with assuming a dipole field. A dynamo is required to generate and sustain the field, and since there is no field at present, a dipole up to about 3.4×10^9 years is necessary, active for the period of time coincident with the radiometric record. The apparent inhomogeneous distribution of magnetization in the lunar surface layer would also seem to argue for obliteration of the dipole record.

There are problems associated with remanence acquisition in iron containing samples. The remanence acquisition efficiency of iron containing samples depends on the size and shape of the iron grains. Paleointensity estimates for a normal basalt and a contemporaneous reduced sample (Wasilewski, 1972) containing the same Fe+ $FeTiO_3$+Fe_2TiO_4 assemblage found in lunar rocks differed by two orders of magnitude. The paleointensity estimate for the normal basalt was 0.33 Oersted, and for the reduced sample the estimate was 0.0031 Oersted. This disagreement was not expected even for the simple NRM-TRM comparison which was used for estimating the inducing field. The extreme case of shape was also investigated. A needle was given a TRM both parallel and perpendicular to the needle axis. For the perpendicular case no remanence could be measured, but for the parallel case a strong remanent component was measured. The only conclusion which can be reached is simply that the paleofield estimates published for lunar samples cannot be taken seriously.

Carbonaceous chondrites and other meteoritic samples contain oriented vector magnetism (Wasilewski, 1972) indicating that other sources of permanent remanence inducing fields exist aside from the geomorphic dynamo.

The body of experimental data which exists to present does not explain (a) the precise mode of remanence, (b) the type of inducing field, (c) the time of magnetization, (d) the magnitude of the inducing field. To attempt to answer the numerous questions precipitated by the measurement of permanent remanence in the lunar samples, we must first understand what kind of ferromagnetic dispersion we are dealing with and what effect thermophysical processes active in a lunar environment would have on the remanence characteristics of lunar samples.

Magnetic hysteresis characterization provides a step in the proper direction. In this paper I will demonstrate that the magnetic hysteresis characteristics are diagnostic and can be utilized as a classification tool for all lunar samples and that thermophysical processes will effect changes in the hysteresis characteristics of lunar samples which are both predictable and useful.

<u>Some Magnetic Hysteresis Aspects of Iron Dispersions Relevant to Lunar Research</u>:

The makeup of the ferromagnetic dispersion in terms of the size and shape of the ferromagnetic components and the range of saturation magnetization will determine the magnetic hysteresis of the dispersion.

If a superparamagnetic dispersion of iron has a magnetization value, M_s, at saturation, it will after time, t, have a value, $M=M_r$, defined by

$$M_r=M_s \, \mathrm{EXP}(-t/\tau) \qquad 1$$

where $1/\tau = f_o \, \mathrm{EXP}(-KV/kT)$ (Neel, 1949). A spherical iron particle of radius, 115 Å, with the crystalline anisotropy, K_1, being the only anisotropy, has a value of $\tau = 10^{-1}$ seconds, and when the radius increases to 150 Å, the value of $\tau = 10^9$ seconds, and the particle is a stable ferromagnetic grain. Superparamagnetism is defined with $H_c=0$, and though it does not contribute to H_c, it will reduce H_c, if present with single domain particles, according to the argument $H_c \cdot q/\bar{I}_R$ in the equation

$$\bar{H}_c = H_c \quad 1 + (H_c \cdot q/\bar{I}_R)\ \epsilon/(1-\epsilon) \quad ^{-1} \qquad 2$$

where $q = V\ M_x/3kT$ for superparamagnetism, where V is the volume, M_s, the magnetization, k, Boltzman's constant, and T, the absolute temperature. If large multidomain grains are present with single domain grains, the same argument holds as above, except that $q=(NM_s)^{-1}$, where N is the demagnetization factor. The above discussion is based on the work of Kneller and Luborsky (1964), summarized by Kneller (1969).

It has been experimentally verified by Wasilewski (1972) that mixing two distributions represented by discs of basaltic rock, one with H_c=50 Oersted, the other with H_c=420 Oersted, produces a reduced H_c value in accordance with the calculations of Wohlfarth (1954) for two sorts of particles with $H_{c_1} < H_{c_2}$. Exact agreement cannot be expected since each H_c disc value is the effective H_c value for a distribution itself, with the resultant distribution being bimodal.

In a fine dispersion, the initial susceptibility is more sensitive to the larger particles and the approach to saturation is largely governed by the smaller particles in the distribution.

Since a single domain particle cannot change its magnetization except by rotation of the spontaneous magnetization against anistropy forces, the particle has coercivity determined by the crystalline anisotropy characteristic of the material. For iron and dilute

FeNi alloys with high saturation magnetization the coercivity is proportional to the magnetization, and it is easily demonstrated experimentallly and theoretically (Kittel, 1949) that shape anisotropy is the usual anisotropy that figures in the evaluation of the coercivity of irregular grain dispersions.

For oriented iron particles (Luborsky and Paine, 1962) the H_c value and the R_I value depend on the measurement angle, θ, with respect to orientation. The maximum R_I occurs for $\theta=0^o$ and the minimum for $\theta=90^o$. The maximum H_c value occurs at an angle, $\theta=50^o$, for dilute assemblages, but for increased packing magnetostatic interaction becomes important and the 50^o maximum is suppressed. The minimum values of H_c occur at 90^o. The lunar soil may contain an oriented thin film surface of metallic iron, and it is clearly shown (Carter, 1971) that the surface of the soil particles contain fine (0.03 to 0.5 μm) mounds of magnetostatically interacting iron. A definite surface anisotropy which should provide a magnetic stratigraphic boundary zone in a core should be present, particularly if the metallic coating is associated with discrete cratering events.

Rotational hysteresis (W_r) measurements provide a useful check on the existence of exchange anisotropy and magnetically uniaxial components. The only rotational hysteresis work to date was performed by Runcorn _et_ _al_.

(1970). They wrongly ascribe the large W_r values at high measuring fields to iron, explaining the W_r losses to shape anisotropy. Their Figure 9 appears to be impossible as the work of Jacobs and Luborsky (1957) and Campbell et al. (1957) clearly demonstrates. High field W_r is due to anisotropy of uniaxial, induced, or exchange character (see Meikeljohn, 1962). For Ni, Fe_3O_4, and Fe in bulk or dispersed systems, no significant high field W_r is expected. That Runcorn et al. have observed high field W_r is of course significant, but their interpretation is quite wrong. They also observed high field W_r for an assemblage of polycrystalline iron spheres (5μm). There is something peculiar with their experiment since their result (a) does not agree with theoretical studies nor (b) does it agree with previously determined W_r-H curves for single and multidomain iron. Intergrowths such as Fe-FeS, where exchange anisotropy has been observed (Greiner et al., 1961), or Fe-FeO epitaxial overgrowths will give the results they observed. This proposition can be easily verified (Meikeljohn, 1962).

In iron dispersions, if size is important, then both H_c and H_R are linear functions of temperature. If shape is important, there should be different effects, since the temperature coefficient of H_c depends on shape.

There are two types of time dependent effects which can operate in the lunar samples. The first is ascribed to the superparamagnetic component which was considered earlier (equation 1), and the other is due to multi-domain iron which is described by $\Delta I = S \log t + \text{constant}$. It should be noted that S, the viscosity coefficient depends on (a) the shape of iron particles (Street et al., 1952; and Yakubaylik, 1967) and on (b) the alloy composition, since the magnetization value and structure will change.

Magnetic Hysteresis in Lunar Samples:

A tabulation of some data presented by Nagata et al. (1970, 1971, 1972) for Apollo 11, 12, and 14 samples is presented (Table 1). The samples are placed into two groups based on R_I and R_H values. Group A contains crystalline rocks and thermally metamorphosed breccia samples, (F 4 - Jackson and Wilshire, 1972). Group B contains the lunar fines and the welded breccia samples, (F 1 - Jackson and Wilshire, 1972).

The hysteresis loop and the various parameters, including the measurement paths, are illustrated in Figure 1. The hysteresis ratios R_I and R_H are demonstrated to be characteristic for each group of natural materials (Wasilewski, 1970, 1972 , 1972 , 1972). The R_I and R_H values plot as two distinct groups (Figure 2A). One group with $R_I < 0.02$ and $R_H < 10.0$ contains the igneous rocks and thermally metamorphosed breccia samples, the other group with $R_I > 0.04$ and $R_H > 10.0$ contains the fines and welded breccia samples.

The H_c values for all samples fall between 10 and 50 Oersted (Figure 2B), as shown by the dotted lines, and the lunar samples are subdivided into two groups on the basis of the R_I vs. H_c data, one group with R_I between 0.004 and 0.02 contains the crystalline rocks and thermally metamorphosed breccia samples, the other with R_I between 0.04 and 0.072 contains the lunar fines and welded breccias. The R_I vs. H_c data clearly demonstrate that H_c is a meaningless parameter when applied to lunar samples, and the reasons for this are quite obvious. Wasilewski (1972 , 1972) has discussed this aspect of natural materials in terms of the experimental and theoretical work of Meikeljohn (1953), Wohlfarth (1958), Stoner and Wohlfarth (1948), and Kneller and Luborsky (1964). Mixtures of single domain iron particles with either multidomain or superparamagnetic particles will result in a reduction in H_c. A given volume fraction of superparamagnetic material will reduce H_c more than an equivalent volume of multidomain material.

The R_I vs. H_R plot (Figure 2B) results in two distinct and characteristic groups defined on the basis of R_I and H_R values. For the first group, which includes the crystalline rocks and thermally metamorphosed breccia samples, $R_I < 0.02$, and H_R varies between 75 and 180 Oersted, while for the second group, which includes the fines and welded breccias, $R_I > 0.04$, and H_R varies between 300 and 520 Oersted. The R_I vs. H_R plot appears to be most informative.

The presence of three discrete iron modes provides for a 10^3 range in grain H_c ranging from $H_c=0$ for the superparamagnetic material to $H_c \sim 10^3$ for single domain material. All of the the hysteresis loops thus far presented for lunar samples show constriction in the region of low measuring fields. This constriction can be found in partially oxidized terrestrial basalts (Wasilewski, 1972), chondrite meteorites (Wasilewski, 1972), and in the lunar samples (Nagata _et_ _al_., 1970, 1971, 1972).

Discussion:

The data presented in Table 1 is quite systemmatic despite the limited sampling. The samples were arranged in order of increasing R_H values, and all other parameters follow a systemmatic increase or decrease accordingly. It is also of interest to note that Nagata has defined two types of viscous (VRM) behavior for the analyzed lunar samples, and type I VRM behavior is associated with group A hysteresis characteristics, and type II VRM behavior is associated with group B hysteresis behavior.

Saturation in the positive H direction will result in a finite remanence when H is returned to zero. This remanence depends on the magnetization mechanisms in the single domain and multidomain size fractions, but does not depend on the superparamagnetic or paramagnetic components. The H_c value is meaningless, as was indicated earlier, and the H_R field is that required to produce a zero remanence state in the sample after saturation. A direct sample to sample comparison of this value is informative since it indicates the magnitude of the field needed to reverse half of the irreversible remanence left in the sample after saturation. The R_I value is also a relative indication of the amount of irreversible magnetization, and, as can be seen in the R_I vs. H_R plot, this value increases as H_R increases.

In practice the R_H value is a complex number, in that it can depend on

(a) grain size
(b) grain shape
(c) packing fraction
(d) grain alignment
(e) exchange anisotropy
(f) degree of strain anisotropy
(g) degree of strain anisotropy
(h) anisotropic structures
(i) size distribution
(j) amount of superparamagnetism.

The lower the H_R value the more viscous is the size fraction larger than single domain size. There are two components which are included in time dependent changes, (a) the superparamagnetic fraction and (b) the multidomain fraction. This is reflected in the R_H values, the H_c

values, and the initial susceptibility. For a constant H_R value the R_H value will depend on the amount of superparamagnetism. A more detailed study of viscous behavior based on low temperature analysis of the blocking spectrum will allow the size spectrum of superparamagnetism to be separated from the multidomain size spectrum.

This is a critical aspect of lunar magnetization since the total magnetization of the sample depends on the handling of the sample over a temperature range equivalent to the range in which the Apollo samples were handled, and unless the blocking spectrum for this range is defined I do not believe we can eliminate the noise associated with the transfer of the samples from the moon to earth.

Based on the experimental studies of Nagata et al. (1970, 1971, 1972), Thorpe and Sentfle et al. (1970, 1971), Jedwab (1971, 1972), Carter (1971), Carter and MacGregor (1970), Chao et al. (1971), and many others we can conclude that the relative significance of supermagnetism (SP) can be specified:

$$SP(\text{Fines}) > SP(\text{Welded Breccia}) > SP(\text{Igneous Rocks}) > SP(\text{Thermally Metamorphosed Breccia}).$$

Therefore, the H_c value will be reduced relatively more significantly in the reverse order of the list above, and the R_H value will depend on the H_R value almost exclusively, particularly since the H_c values (Table 1 and Figure 2B) are limited to a narrow range.

The H_R value will depend on the shape and range of the size distribution. For igneous rocks and thermally metamorphosed breccia samples the H_R value is expected to be lowest since the majority of iron grains will be multidomain with single domain or small multidomain grains carrying any stable component. As the shape of the size distribution becomes wider, shifting to a smaller size range, or bimodal, as in the case of the fines and welded breccia, the H_R value should increase since a large fraction of the iron will be single domain or nearly so. The fines contain the broadest size distribution of ferromagnetic components, and welding the fines should not produce any significant alterations to the distribution. Thermal metamorphism will destroy some or all of the superparamagnetism, and an effective shift of the size distribution will result in a decrease in H_R, R_H, and R_I, as observed.

The data thus far accumulated provides distinct evidence that the lunar samples are quite different from terrestrial samples, mainly because there is iron in the lunar samples.

The consistent R_H and H_R values for the lunar fines suggest a common origin and common size and shape modes for the ferromagnetic fraction. Though data is sparse at present, there is a definite suggestion that the permanent remanence of each lunar sample can be understood in terms of the hysteresis properties of each sample. The path the hysteresis parameters will take depends on the mode of origin and acting thermomechanical processes. A soil can be welded, thermally metamorphosed, or shock lithified. Each of the three processes will produce different effects depending on

(a) the behavior of the SP component

(b) the change in the ferromagnetic component size distribution

(c) the magnetostatic interaction

(d) the influence of the shape of the ferromagnetic components

(e) the composition of the alloy, i.e. Ni+Co content.

Conclusions:

I. There are well defined groups of lunar materials based on their magnetic hysteresis properties.

II. Natural remanence correlates directly with saturation magnetization, the R_I value, and the initial susceptibility for crystalline rocks.

III. In lunar samples the low H_c values are due in part to the presence of superparamagnetic iron and in part to multidomain iron.

IV. The H_c value is a meaningless parameter for lunar samples.

V. The H_R value is important and diagnostic since it is due to near single domain and multidomain grains. It is independent of the superparamagnetic fraction.

VI. Microbreccia samples can be analyzed non-destructively and classified as to their mode of origin based on magnetic hysteresis. This approach will be more effective with a more systemmatic array of data.

VII. It is possible that the measured surface fields can be due to a magnetized regolith. This requires further verificati on, but it is a distinct possibility which must be considered.

VIII. A soil can be subjected to welding, thermal metamorphism, or shock lithification. Each of the three processes will produce different hysteresis characteristics and remanent states depending on

(a) the behavior of the SP component

(b) the change in the effective grain size distribution

(c) the development of eutectic intergrowths

(d) the phase composition, i.e. Ni+Co content

(e) the thermomagnetic anomalies of the ferromagnetic components.

IX. Two distinct viscous or time dependent features are characteristic of iron in the lunar samples. The first concerns the superparamagnetic fraction, and the second concerns the soft multidomain iron fraction. Both features are temperature dependent.

X. From the hysteresis data and other published results it appears that relative superparamagnetism (SP) can be specified:

$$SP(\text{Fines}) > SP(\text{Welded Breccia}) > SP(\text{Igneous Rocks}) > SP(\text{Thermally Metamorphosed Breccia}).$$

The H_c value will be relatively reduced in the opposite order.

TABLE 1

(Tabulation of data from Nagata *et al.*)

Sample	$\chi_o (10^3)$	$I_n (10^5)$	I_s	R_H	R_I	$I_R (10^2)$	H_c	H_R
Group A - Crystalline rocks and thermally metamorphosed breccia								
14053	2.24	203.0	2.2	4.0	0.019	4.0	20	80
14303	0.69	13.0	1.27	6.6	0.016	2.1	27	180
14311	0.46	0.81	0.74	8.2	0.006	0.43	17	140
Group B - Welded breccia								
10048		5.6	1.8	10.4	0.072		50	520
14047		1.23	1.4	13.4	0.044	6.1	26	350
- Lunar fines								
10084			1.17	12.78	0.072		36	460
14259			1.5	15.7	0.04	6.0	19	300
14161			0.98	16.5	0.044	4.3	26	430
12070			1.28	20.45	0.048		22	450

FIGURE CAPTIONS

Figure 1 - Schematic diagram of magnetic hysteresis loop illustrating the measurement paths and defining the loop parameters

I_R - Remanent magnetization

I_S - Saturation magnetization

H_c - Coercive force

H_R - Remanent coercive force

R_I - I_R/I_S

R_H - H_R/H_c

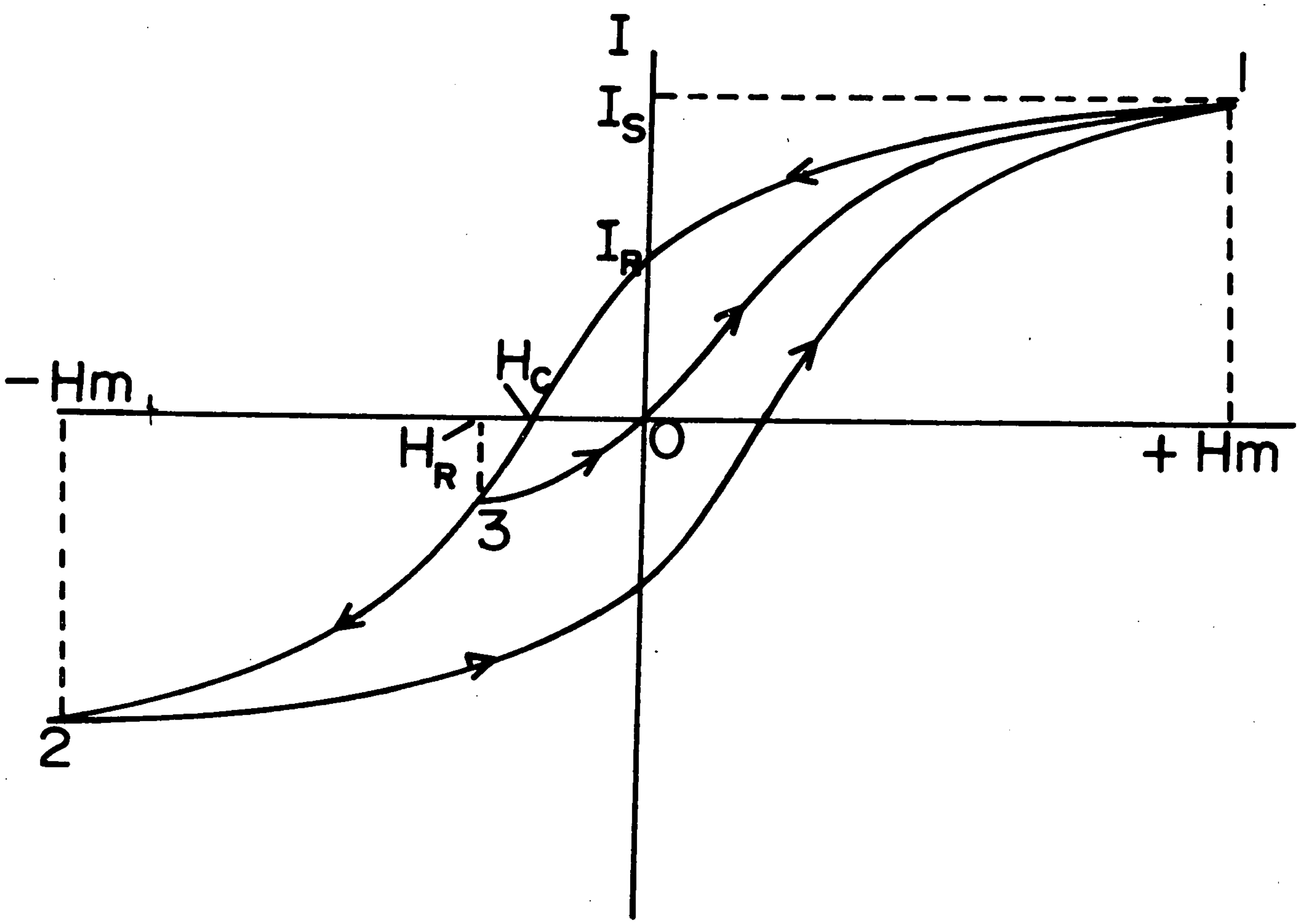
(1-2-1, measurement path for full loop; 1-3-0, measurement path which reduces I_R to zero and defines H_R)

Figure 2A- Relationship between R_I and R_H for lunar samples (Data from Nagata et al., 1970, 1971, 1972)

Figure 2B- Relationship between R_I and H_R for lunar samples (Data from Nagata et al., 1970, 1971, 1972) The R_I vs. H_c values for the lunar samples are included in the dotted areas labelled I and II.

FIGURE I

MAGNETIC HYSTERESIS LOOP



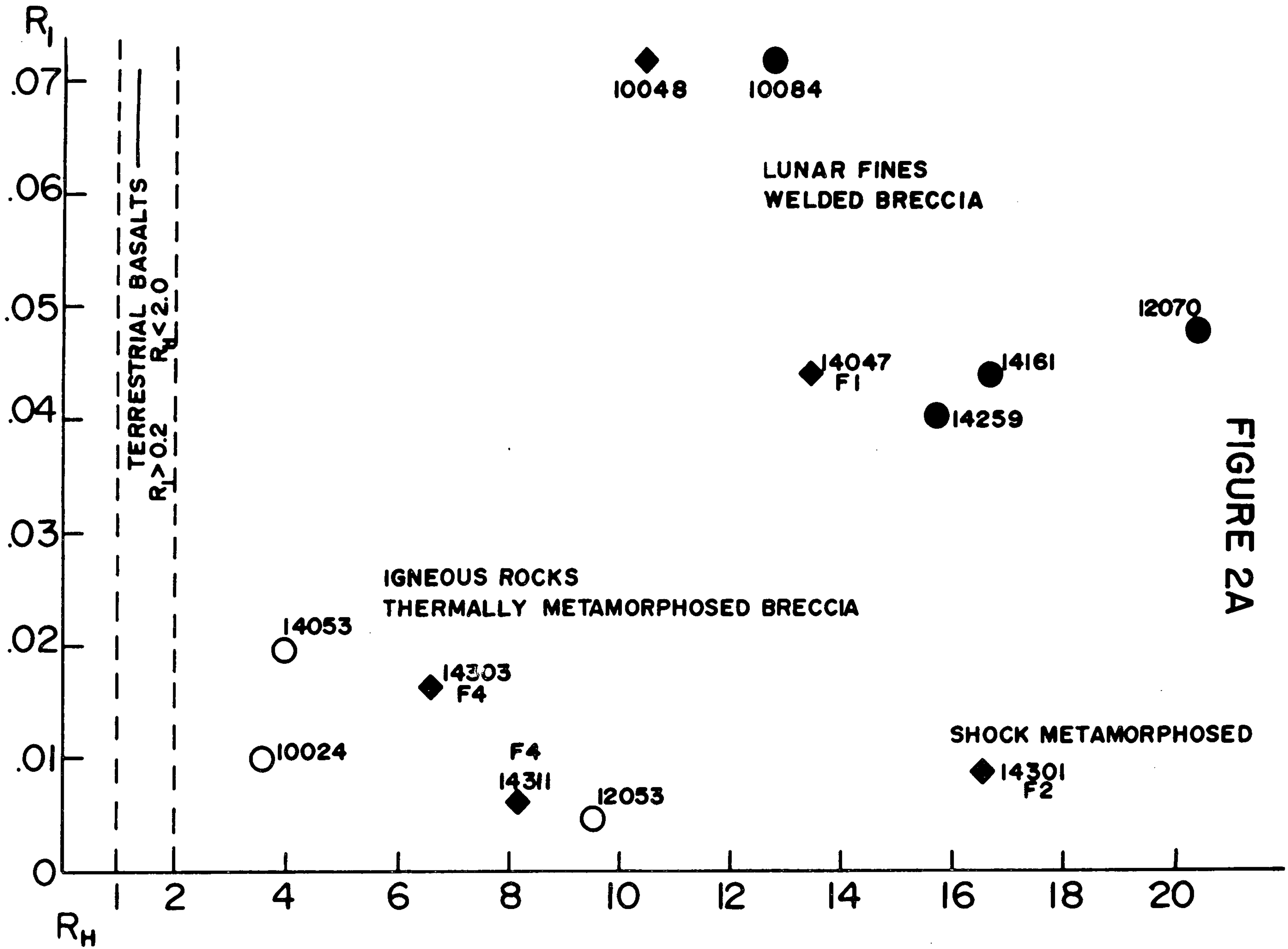
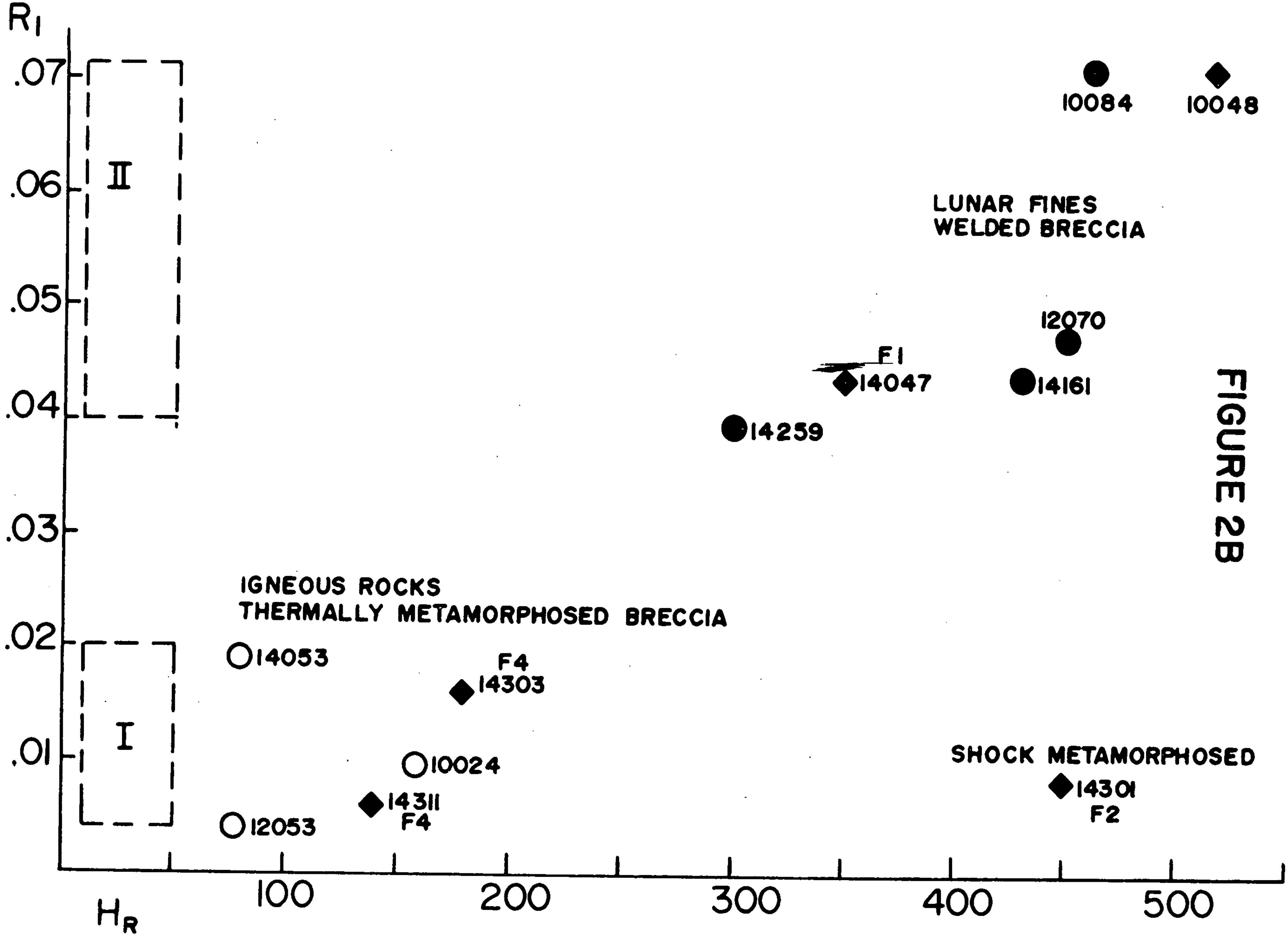

R_I
.07
.06
.05
.04
.03
.02
.01
0
R_H
2
4
6
8
10
12
14
16
18
20
TERRESTRIAL BASALTS
$R_I > 0.2$
$R_H < 2.0$
10048
10084
LUNAR FINES
WELDED BRECCIA
12070
14047
F1
14161
14259
IGNEOUS ROCKS
THERMALLY METAMORPHOSED BRECCIA
14053
14303
F4
10024
F4
14311
12053
SHOCK METAMORPHOSED
14301
F2

FIGURE 2A



R1
.07
.06
.05
.04
.03
.02
.01
II
I
HR
100
200
300
400
500
10084
10048
LUNAR FINES
WELDED BRECCIA
12070
F1
14047
14161
14259
IGNEOUS ROCKS
THERMALLY METAMORPHOSED BRECCIA
14053
F4
14303
10024
14311
F4
12053
SHOCK METAMORPHOSED
14301
F2

FIGURE 2B

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