DESIGN AND CALIBRATION OF AN ASTATIC SUSCEPTIBILITY METER

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INTRODUCTION

It was the purpose of this study to develope an instrument capable of determining the hysteresis curve produced by the magnetization by a rock specimen. From such a study it would be possible to determine not only its susceptibility for any field strength within the limits of the instrument, but also give some idea of its past geologic history as the values of coercive force and remnant magnetism is related to the dynamo-metamorphism.

In all this work I have received from Doctor Heiland invaluable help and suggestions, acknowledgement of which is hereby made. I wish also to acknowledge the kind cooperation of Doctor Adams.

THEORY OF THE INSTRUMENT.

The principle of the method is to measure by the deflection of an astatic magnetic system the magnetization produced in a specimen by the magnetic field inside a solenoid. In the final method chosen two solenoids of equal field strength are on both sides of the magnetic system at equal distances so that their influence on the magnetometer without the specimen is zero. When a sample is inserted in one solenoid and the deflection thus produced on the magnetometer is neutralized by adjusting the current in an auxiliary winding. The current required to neutralize the deflection is a measure of the induction of the specimen produced by the field of the solenoid.

Another feature of the astatic arrangement of the magnetic system is that the effect of the earth's field and its fluctuations are eliminated. Instead of determining the torque produced by the action of the magnetic fields on a single magnet a magnetic system is provided for which contains two equal magnets, seven inches apart. They are so oriented with one another that they exert no torque in a homogeneous field. As the axis of the two solenoids pass through that of the lower magnet, the torque on it is much greater than that on the upper magnet, and the torque produced will be a function of the difference of the fields produced by the coils.

This instrument is similar to a method described by Ambronn. In this method a single magnetic needle is placed on the position of the lower magnet in the present instrument. Since there is only one magnet present, the magnetic system is not astatized, and is subject to errors produced by magnetic influctuations. The position of equalibrium is determined as is done with the present instrument. However, when a specimen is inserted, the null position is obtained by the use of a third solenoid which is the same method as used there in the present method. In this method a cylindrical tube filled with the sample to be tested is used, so that the specimen occupies the whole volume of center of the solenoid. As most specimens of the size and form suitable for insertion in the coils cannot be cut from rocks, the samples are pulverized. However, by pulverizing samples we change the susceptibility of samples. This was proven by Puschin in experiments on pow-

ders of different fineness in which he showed powders composed of finer grains have a smaller susceptibility than powders of coarser grain. Because of this fact the samples were not pulverized. However, to do these the calculations as to susceptibility have to be so modified as to correct for the volume of the sample.

Another instrument used as a guide in the design of this instrument is one described by E. A. Johnson and H. P. Steiner. This instrument consists of an astatic system as is in the present instrument, but the instrument was intended to measure the susceptibility by the deflection of this system instead of the use of a null position as in the present instrument.

To choose the proper distance between the two magnets of the astatic system several factors must be considered. The farther apart the two magnets are placed the greater will be the resultant movement produced by the field of the coils as the distance from the lower magnet will remain constant while that from the upper magnet decreases. Therefore, the greater the distance between the magnets, the greater the sensitivity of the instrument as a greater restoring force is necessary to return the system to its null position.

Another factor to be considered is that the differences in stray fields may increase as the distance between the magnets increases. Since it is the purpose of this instrument to estimate these stray fields if the magnets are placed too far apart as the effectiveness of the instrument is lost.

For this reason the distance of seven inches between the magnets was chosen. The greatest sensitivity is obtained when the magnets are at right angles to the axis of the coil.

To determine the effect of the solenoids on the two magnets we must determine the fields at those points. The field of a solenoid along the axis is $H=\frac{2\pi Si}{10\ell}[\cos\theta_1-\cos\theta_2]$ where I is the current in the solenoid, ℓ is the length, S is the number of turns and θ is the angle between the axis and the extremities of the coil at the radius of the coil. The field inside the coil is then 13.32 gauss where $\frac{S}{\ell}=12.6$ turns per centimeter. The length of the coil is 15.4 centimeters and its field is calculated to be 4.17 gauss at the magnet

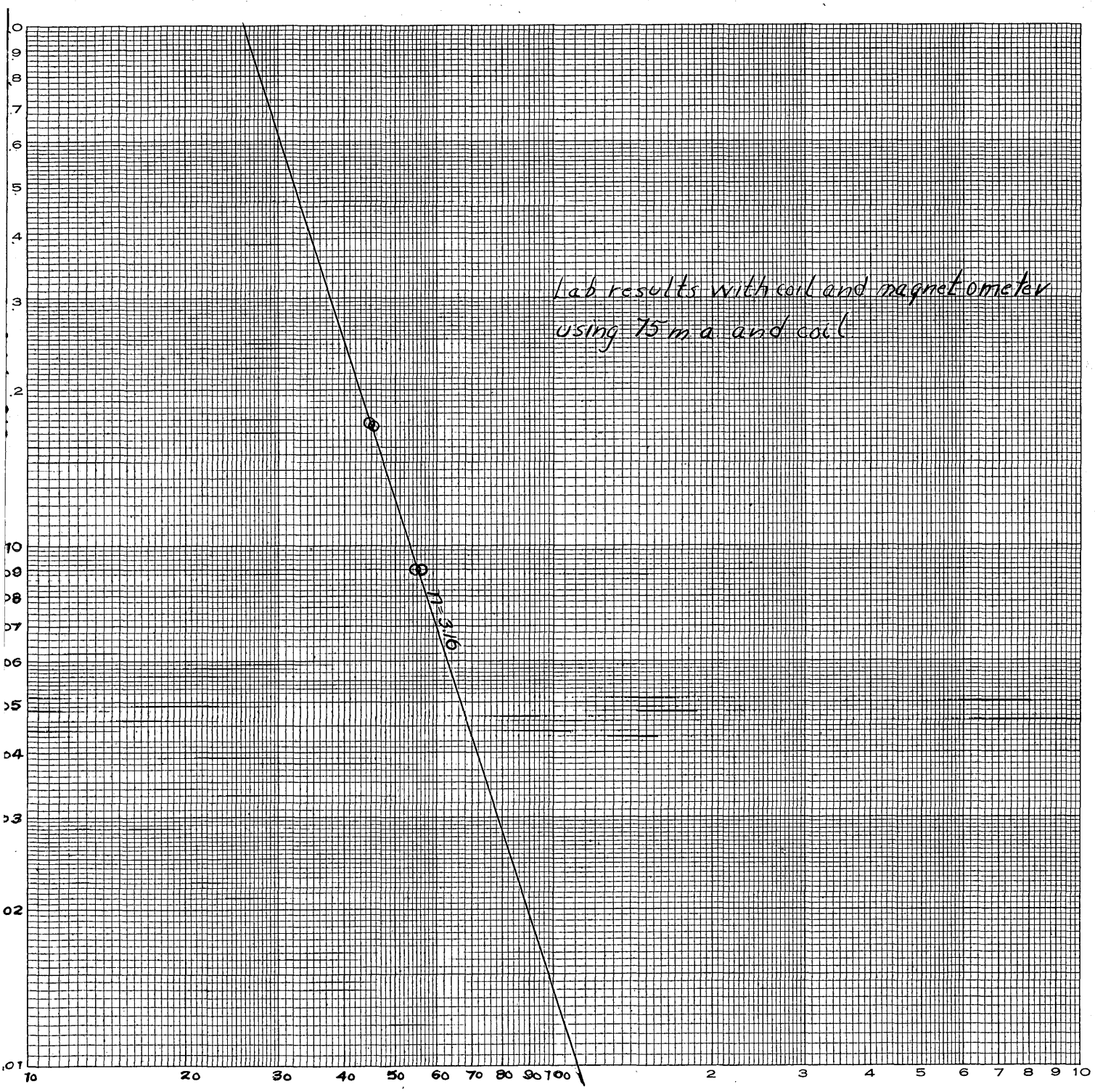
To obtain the field due to the coil at a point not on the axis of the coil we find from Jeans #5 that the potential for the field of a circular coil is $V=2\pi I\{\frac{1}{2}(\frac{a}{r})^2P_1\cos\theta+\cdots\}$ This equation is given in spherical coordinates in which the origin is placed at the center of the loop and the axis of the coil is taken as $\theta=0°$. P_n is the Legendre coefficients. a is the radius of the loop and r is the distance from the center of the loop to the point at which the potential is to be determined. As $\frac{a}{r}$ is less than $\frac{1}{4}$ for the distances used the higher terms can be ignored so $V=\frac{\pi I a^2}{(x^2+y^2)^{\frac{3}{2}}}$ where x is the distance along the axis of the loop and y is the perpendicular distance from the axis. The field along the X direction is then $H_x=\frac{\partial V}{\partial x}=\pi I a^2\{\frac{r^2-3x^2}{r^5}\}$ (1)

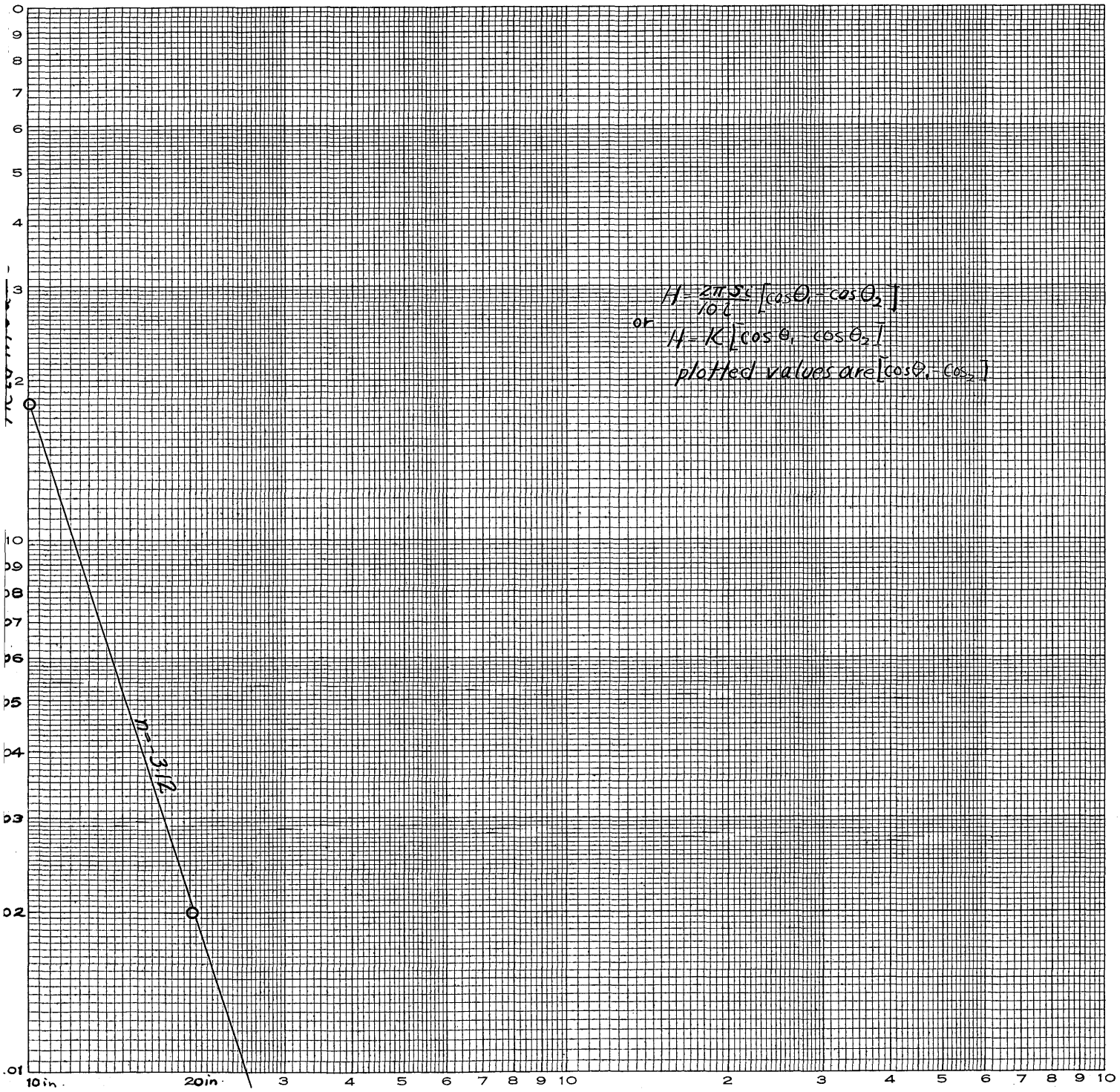
If x=r we have the condition for the field along the axis of the coil. Substituting (1) we have $H_x = \frac{2\pi a^2 I}{x^3}$

If we determine the field along the axis of a coil by the use of $H = \frac{2\pi I S}{10 l}(\cos\theta_1 - \cos\theta_2)$ for various points along the axis of the coil and then plot the results on logarithmic paper, we see fig. (1) that the field varies at the distance from the coil in which we are interested inversely as the cube of the distance from the center of the coil. This was further verified by experiments by placing a coil at various distances from a horizontal magnetometer fig. (2). Therefore, If I is the current per unit length of a solenoid, $H = \frac{2\pi a^2 i S}{10 l x^3}$;for points not on the axis of the coil from (1) $H = \frac{\pi I a^2 S}{10 l}\left\{\frac{r^2 - 3x^2}{r^5}\right\}$ the field for the magnet not on the axis of the coils is .007451 gauss.

Since the field at the magnet on the axis is 4.17 gauss, the field at the magnet not on the axis of the coil can be ignored, and the resultant turning moment of the system is $C = M\frac{2\pi S i}{10 l}[\cos\theta_1 - \cos\theta_2]$

another factor to be considered in the design of the instrument is the selection of a wire with the correct modulus of regidity. If the modules of rigidity is too low, there is great difficulty in placing the magnets in a zero position by turning the torsion head if the fields produced by the opposing solenoids do not produce equal fields.

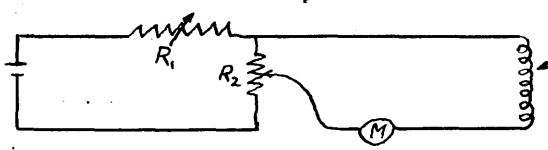

Lab results with coil and magnetometer
using 75 m a and coil
n = 3.6
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
10
20
30
40
50
60
70
80
90
100
2
3
4
5
6
7
8
9
10
Distance in cm

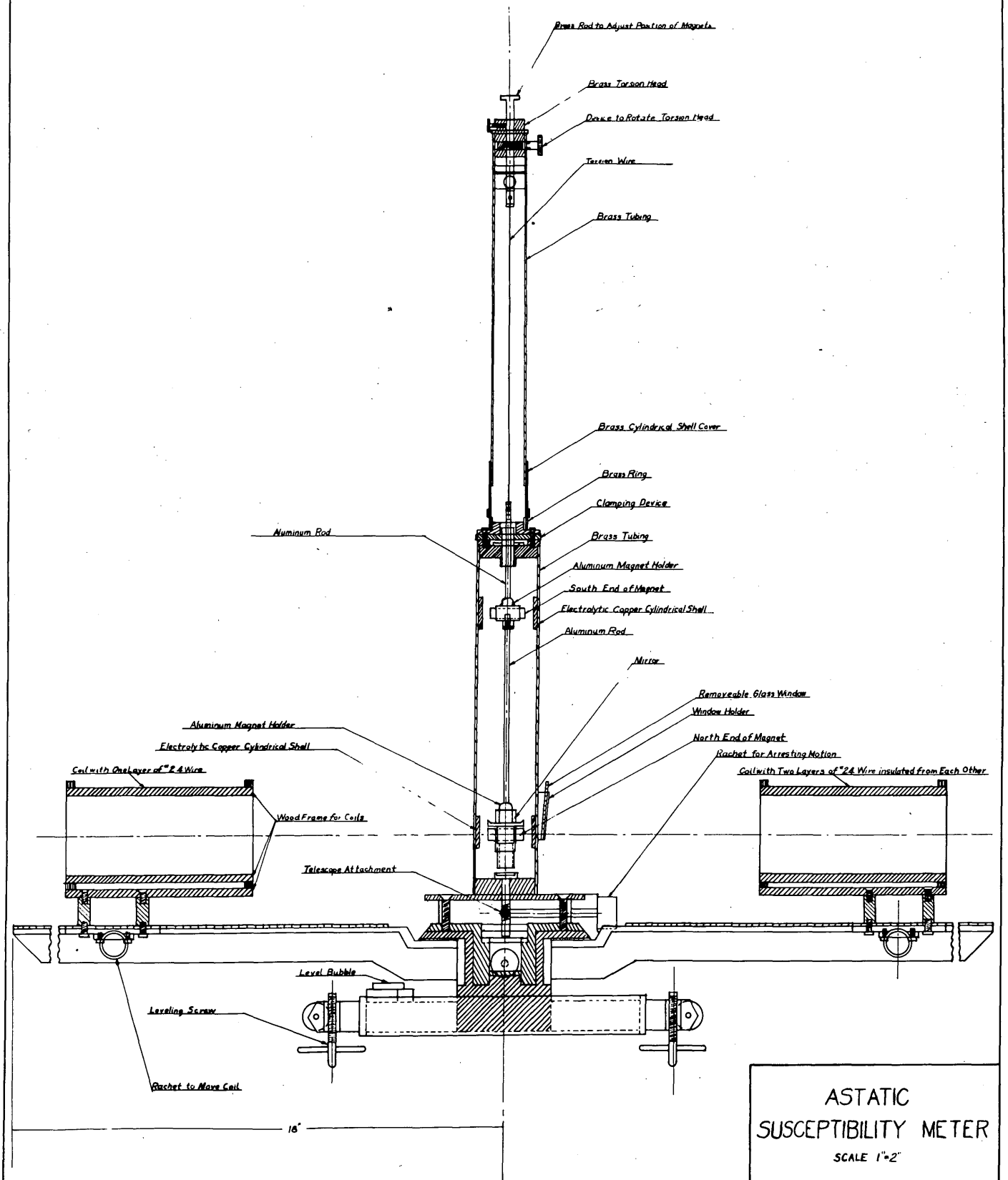

$H = \frac{2\pi\Sigma\epsilon}{10\,L}\left[\cos\theta_1 - \cos\theta_2\right]$
or
$H = K\left[\cos\theta_1 - \cos\theta_2\right]$
plotted values are $\left[\cos\theta_1 - \cos\theta_2\right]$
n = 3.12
10 in.
20 in.
Distance in cm.

DESCRIPTION OF THE INSTRUMENT.

As stated before, the instrument has an astatic magnetic system so arranged that its field is neutralized by two solenoids which lie in the same axis. The magnetic system is so arranged that it is suspended by a torsion wire so that its axis is perpendicular to the axis of the solenoids. The second magnet is placed seven inches from the magnet in the axis of the solenoid on the aluminum magnet holder such that a field would produce a counter-torque between the two magnets. The torsion wire is also attached to a torsion head which permits the rotation of the magnetic system. Attached to the magnetic system is a mirror. By means of this and a telescope arrangement, the position of the magnetic system can be determined.

Two of the opposing solenoids are connected in series so that the fields oppose each other. There is a meter provided to measure the current field passing through this circuit. This circuit is supplied by a six-volt storage battery. In the third solenoid the current has to be controlled much more delicately; the circuit is as shown in the diagram: R_1 is used for a rough adjustment, and R_2 for the fine adjustment, a one and one-half volt dry-cell being used for the supply. By the use of this circuit currents as low as .001 amps. may be passed through the solenoid





ASTATIC SUSCEPTIBILITY METER

SCALE 1"=2"

RALPH C. LORING APRIL 1939

OPERATION OF THE INSTRUMENT.

While other procedures may be used, the one to be described appears to give the best results.

Before the specimen is placed in the solenoid, the current is passed through the two opposing solenoids at its proper value. These solenoids are placed at the same distance from the magnet system and as close to the magnet system as possible. After the null point has been determined the specimen is then placed in the solenoid which contains only one coil. If this reading should be off scale, the torsion head is rotated until the null position in on the scale. Then the specimen is placed in the solenoid which contains only one coil. Then the current is varied in the third coil such that the reading on the scale is reduced to the previously mentioned null position.

DISCUSSION OF QUANTITIES MEASURED

From the results of the hysteresis curve, we see that there is a field due to the specimen at zero field which is called remnant magnetism. From the same curve coercive force is determined which is the field necessary to reduce the remnant magnetism to zero. Retentivity is the remnant magnetism of a substance in relation to the maximum magnetizing force in the solenoid, or retentivity equals $\frac{B_{rem}}{H_{max}}$

In the case of geologic specimens it is believed that these forces are related to the pressures and temperatures which have been exerted on rock specimens. Therefore, the value of remnant magnetism and coercive force may give information as to the geologic history of a rock specimen.

As the specimens which are used in this instrument do not occupy the complete volume inside the solenoid, it is necessary to determine the effect of volume on the results obtained by this instrument.

The magnetic moment of an element of volume of magnetic is $\mathcal{I} dx\,dy\,dz$ as $\mathcal{I} = \frac{M}{V}$ where $\mathcal{I}$ is the intensity of magnetization, and M is the moment of magnetic matter whose volume is V.

The field intensity at the lower needle due to another magnet in the first position of Gauss is $H' = \frac{2M'd}{(d^2 - l^2)^2}$ where M' is the moment of the magnet, d is the distance from the center of the magnet to the needle and l is one-half the length of the magnet. Since the moment of the specimen is $\mathcal{I}\,dx\,dy\,dz$ $H = \frac{2d\mathcal{I}\,dx\,dy\,dz}{(d^2 - l^2)^2}$ From this it is seen that the value of $\mathcal{I}$ can be determined

from the field necessary to compensate the field produced by the specimen and the volume of the specimen. If we plot the field to which the specimen has been subjected to against the field necessary to return the magnetic system to a null position for different values of field strength we can obtain a hysteresis curve.

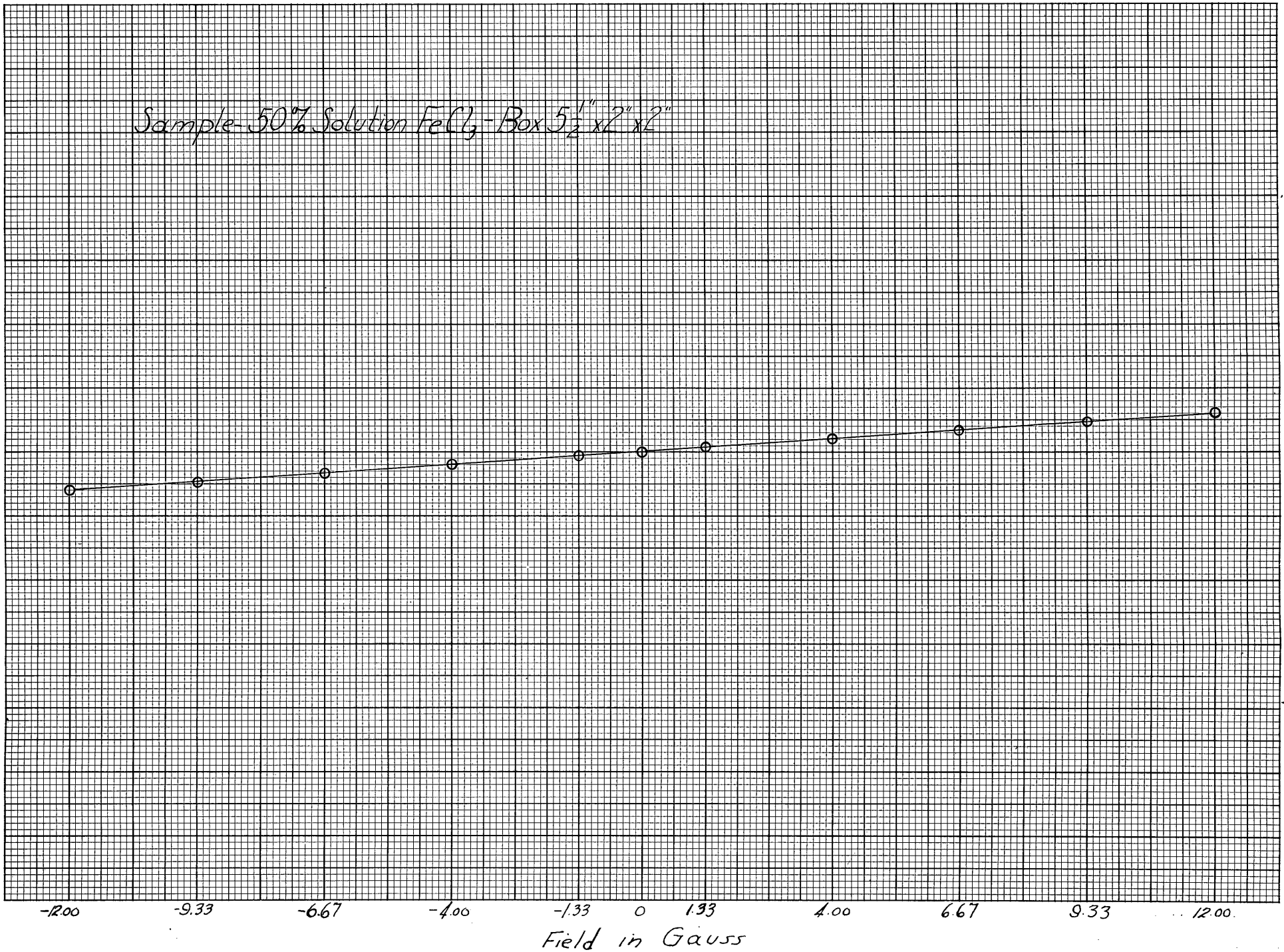
CALIBRATION OF THE INSTRUMENT

It would be possible to make calculations in order that the susceptibility of the specimen might be determined. However, from the dimensions of the instrument, if the coils of the susceptibility-meter are not perfectly matched these determinations would be in error. It was therefore determined to calibrate the instrument by the use of a fifty per-cent ferric chloride solution. The magnetic susceptibility of such a solution is $K \times 10^{-6} = \delta(88.78p - 0.78)$ where δ is the density, and p is the percentage of iron chloride; then $K \times 10^{-6} = 1.551(88.7 \times .5 - 0.78) = 67.5 \times 10^{-6}$

From the theory of the induction produced by a given field we know that the susceptibility depends on the field strength and the volume of the specimen. To obtain the susceptibility, we can compare the magnetization of the ferric chloride and the specimen at the same field strength per unit of volume of the virgin curve. As the values obtained from the curve are quite small, less error will be made in determination of the susceptibility if the highest value of field strength is used.

To get the susceptibility we have $K = \frac{CI}{HV}$ or $C = \frac{KHV}{I}$

$C = 1395$ The value is an instrument constant, and K is ~~susceptible~~ susceptibility and V the volume. As a straight line can be drawn through all the points on the hysteresis loop, the susceptibility does not appear to vary as a function of field strength for the ferric chloride solution. It is also


Sample-50% Solution $FeCl_2$-Box $5\frac{1}{2}$" x 2" x 2"
.1332
Intensity of Magnetization
-.1332
-12.00
-9.33
-6.67
-4.00
-1.33
0
1.33
4.00
6.67
9.33
12.00
Field in Gauss

seen that there is no hysteresis loop.

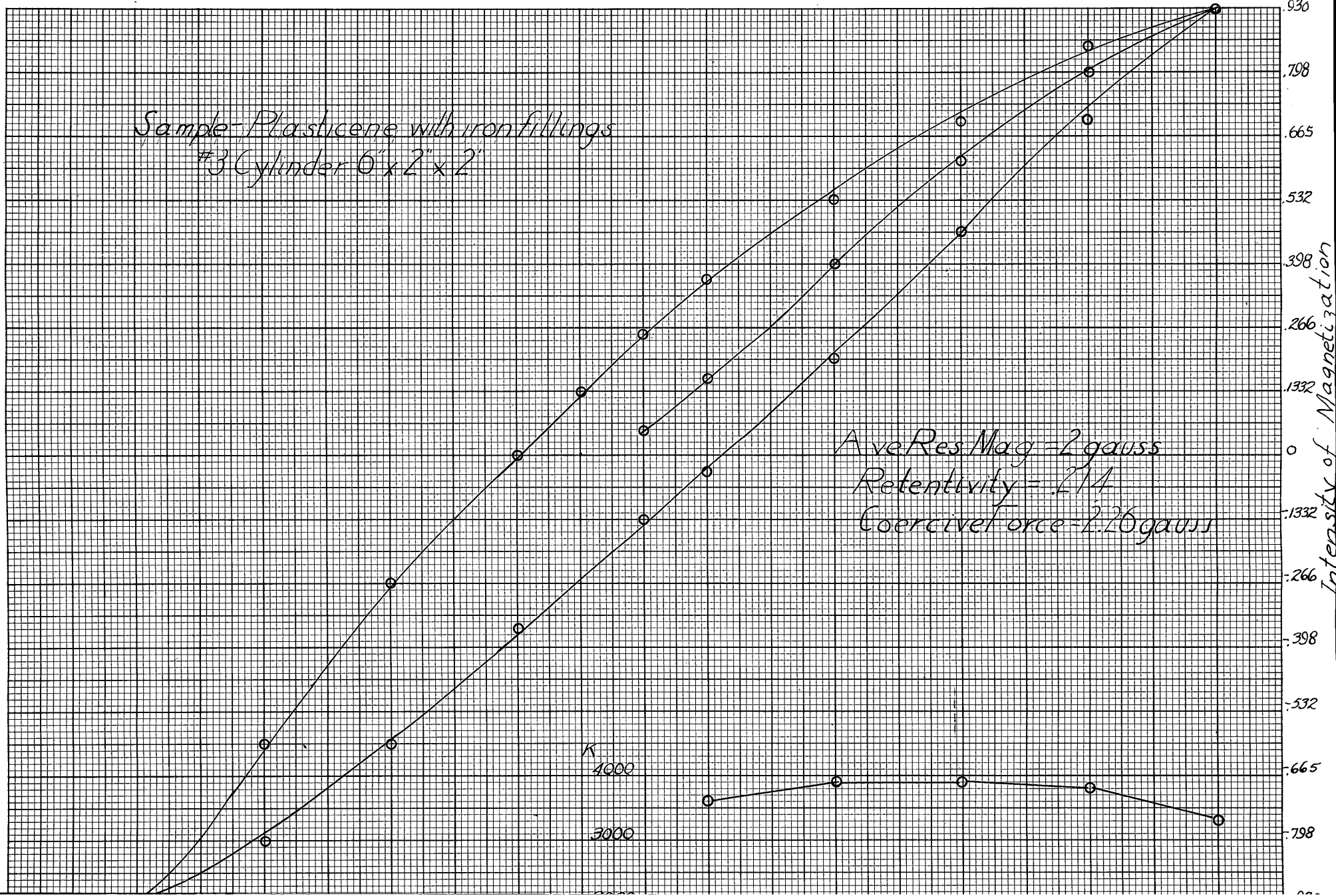
DISCUSSION OF CURVES OBTAINED BY THE INSTRUMENT

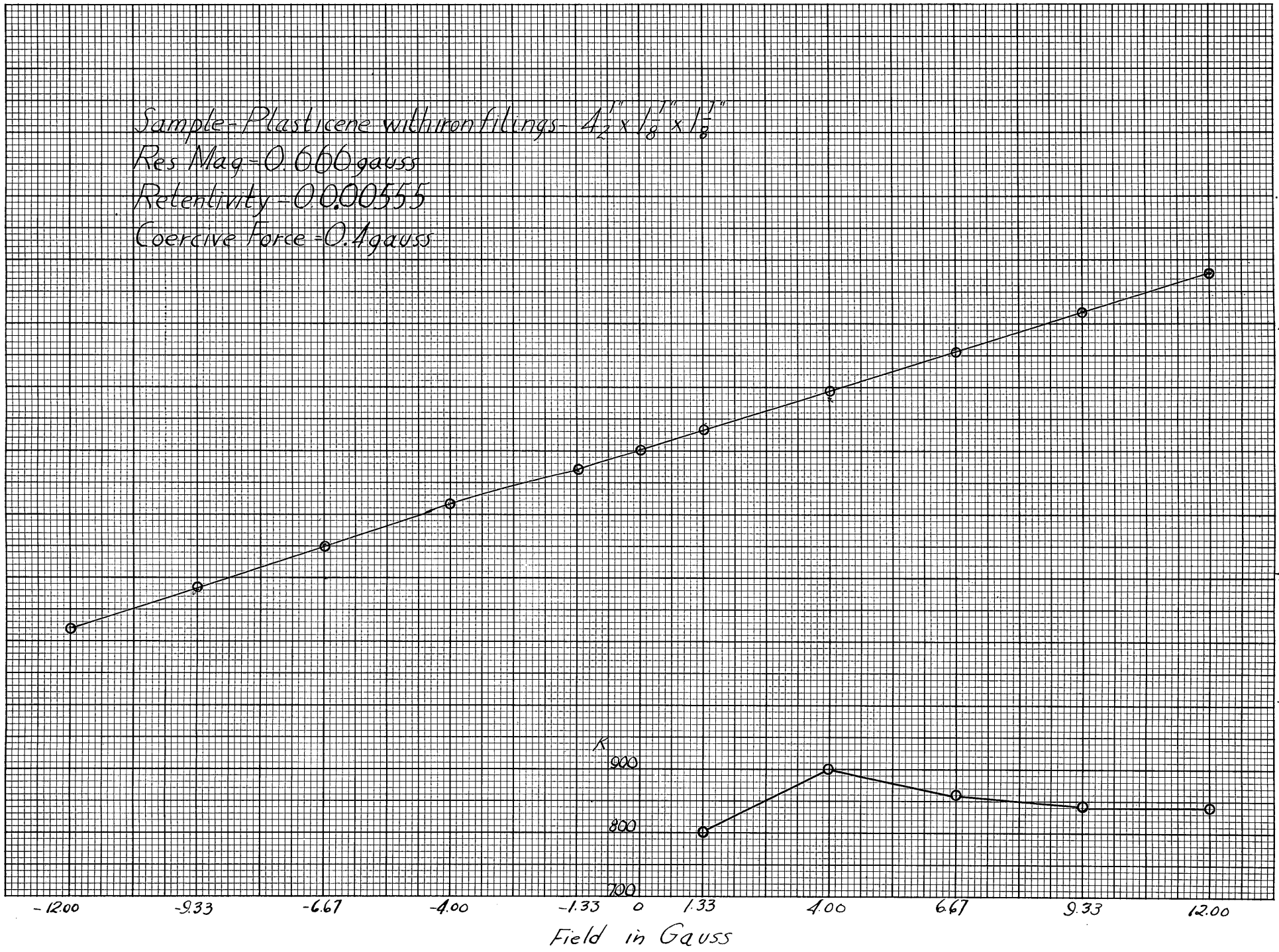
Discussion: Pliastocene Sample No. 1.

The first curve obtained by the instrument was that of a cylindrical specimen, two inches in diameter and six inches in length. The sample consisted of iron filings worked into pliastocene. As there was some remnant magnetism before the sample was run. The true remnant magnetism and coercive force was obtained by averaging the values obtained. The remnant magnetism was 2 Gauss, and the coercive force was 2.26 Gauss. To obtain the susceptibility for a field of 0.9 amps, we use the relation $K = \frac{CI}{HV} = 3520 \times 10^{-6}$ at the earth's field the susceptibility is 3500×10^{-6}

Discussion: Pliastocene Sample No. 2.

Another sample of pliastocene filled with iron fillings was run which however, had a somewhat different susceptibility than the sample previously tested. It had the form of a regular prism about four and one-half inches long, one and seven-eights inches wide and one and seven-eights inches in breadth. The remnant magnetism and coercive force was too small to be plotted on, on the diagram, but were .395 Gauss, and .4 Gauss respectively. The susceptibility as a function of the field strength is shown in the left hand corner. The susceptibility at the earth's field is 770×10^{-6}




Sample = Plasticene with iron filings - 4½" x 1⅛" x 1⅞"
Res Mag = 0.660 gauss
Retentivity = 0.00555
Coercive Force = 0.4 gauss
.266
.1332
0
.133
-.266
Intensity of Magnetization
K
900
800
700
-12.00
-9.33
-6.67
-4.00
-1.33
0
1.33
4.00
6.67
9.33
12.00
Field in Gauss

GRANITE- EMPIRE, COLORADO

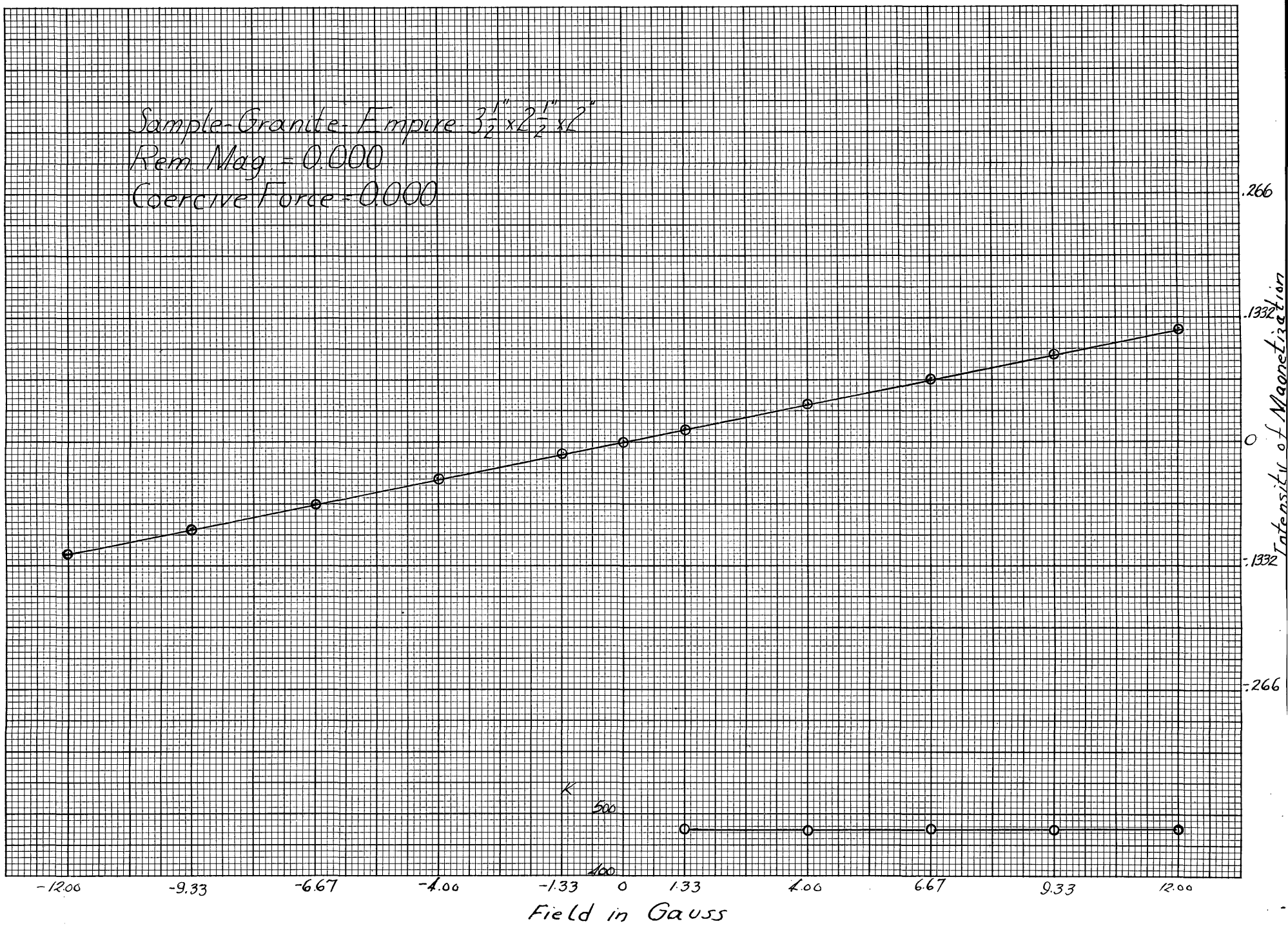
Another sample of granite was tested which was obtained at Empire, Colorado. This specimen's dimensions were $3\frac{1}{2}" \times 2\frac{1}{2}" \times 2"$. The susceptibility at the earth's field strength was $K = 474 \times 10^{-6}$. Since all the points fall on a straight line, the susceptibility does not vary as a function of the field of magnetization. The great difference of susceptibility of this specimen as compared to the previous one is due to the high percentage of magnitite content in the previous sample. There is no hysteresis loop present.

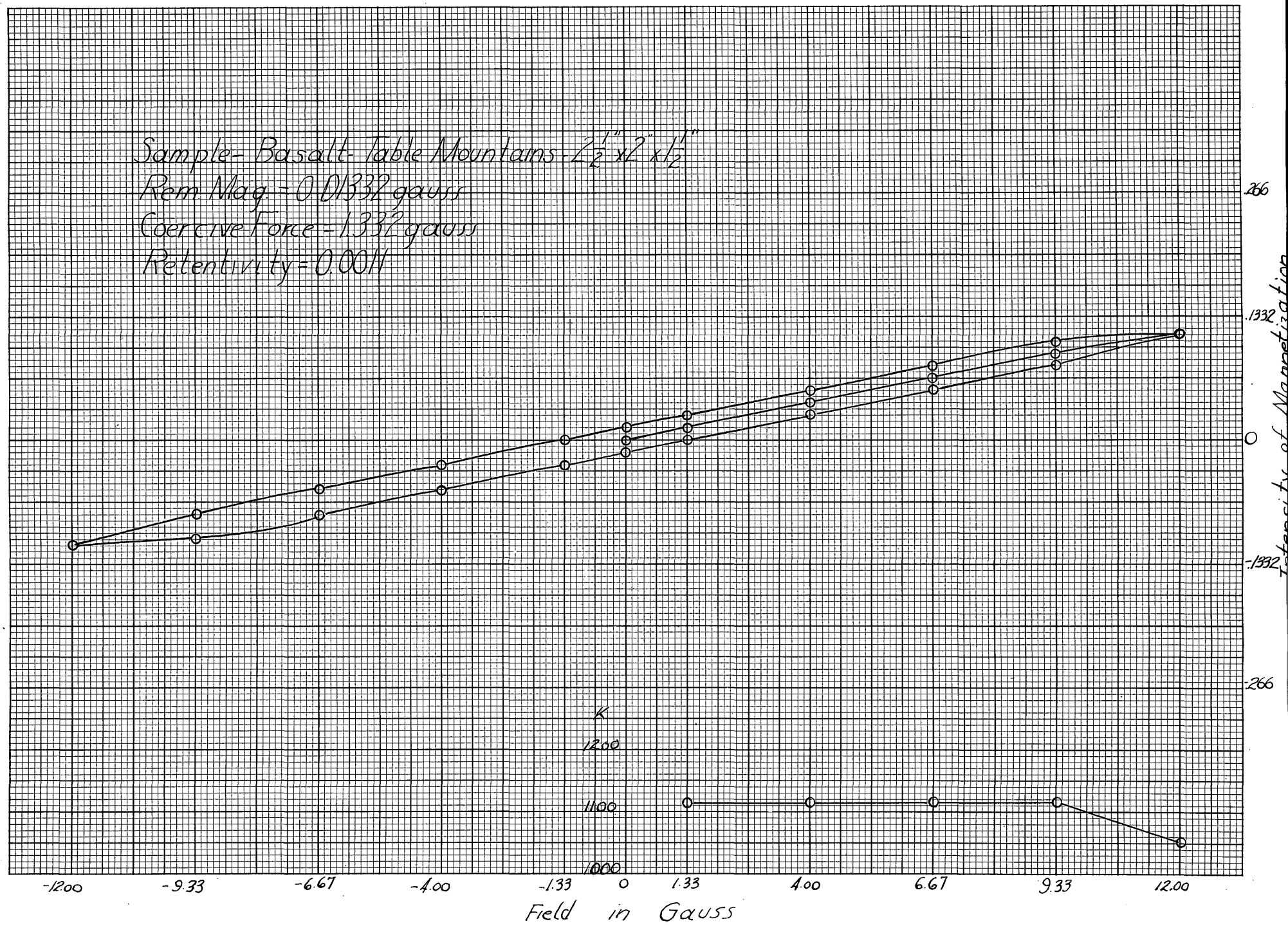
BASALT- RALSTON PIKE

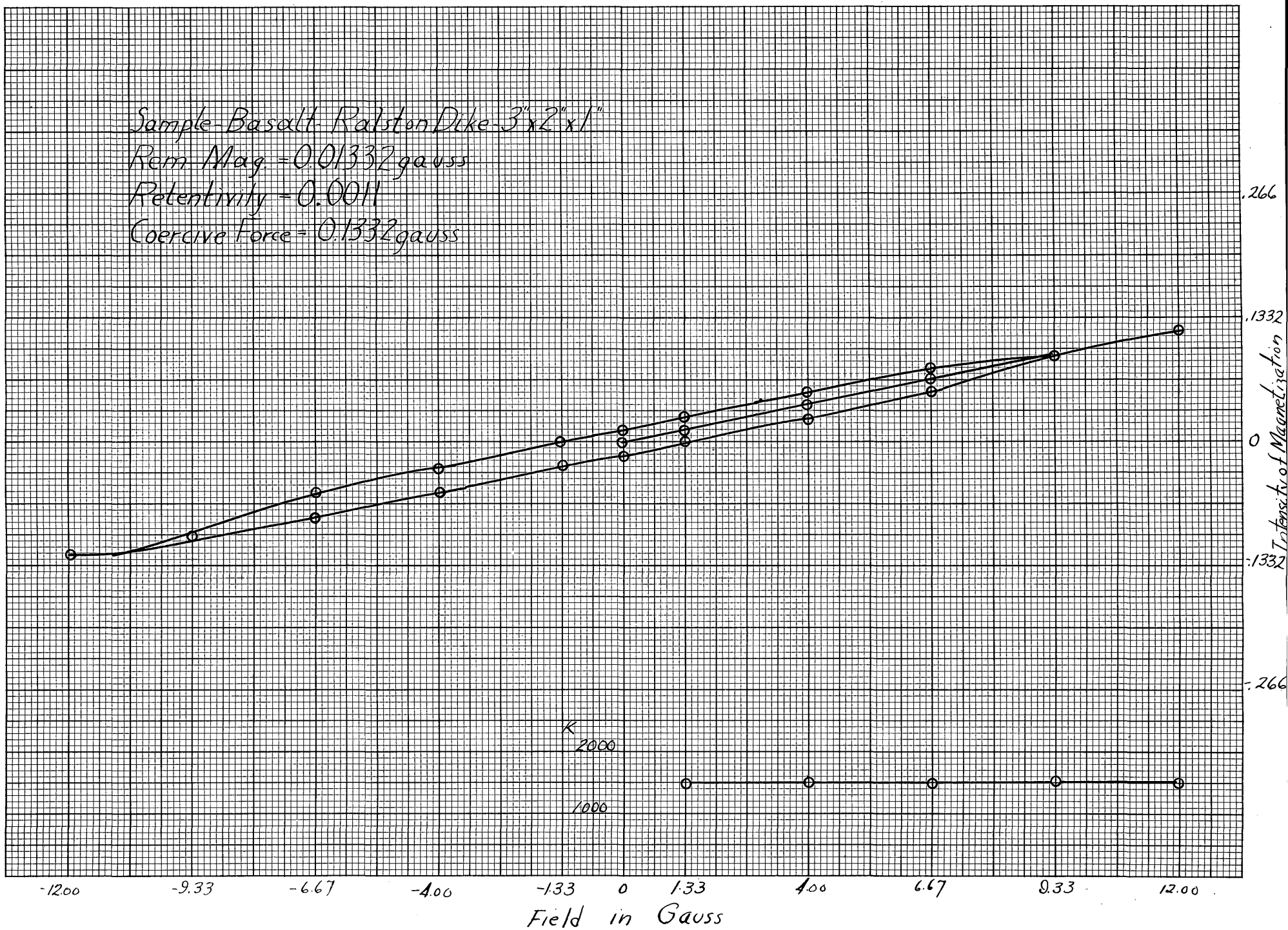
The specimen studied next is a basalt from the Ralston Pike. Its dimensions were $3" \times 2" \times 1"$. The susceptibility of the specimen at the earth's field is 1420×10^{-6} . Since a straight line will pass through all the points on the virgin curve the susceptibility will be constant for all values of the field. The coercive force is .332 Gauss, and the remnant magnetism is .01332 Gauss. The retentivity is $\frac{.001}{0.9} = .0011$

BASALT- TABLE MOUNTAINS

A basalt specimen taken from the Table Mountains near Golden, Colorado was studied next. Its dimensions were $2\frac{1}{2}" \times 2" \times 1\frac{1}{2}"$. The susceptibility at the earth's field is 1115×10^{-6} . The coercive force is .332 Gauss, while the remnant magnetism is 0.1332 gauss The retentivity is $\frac{.001}{.9} = .0011$

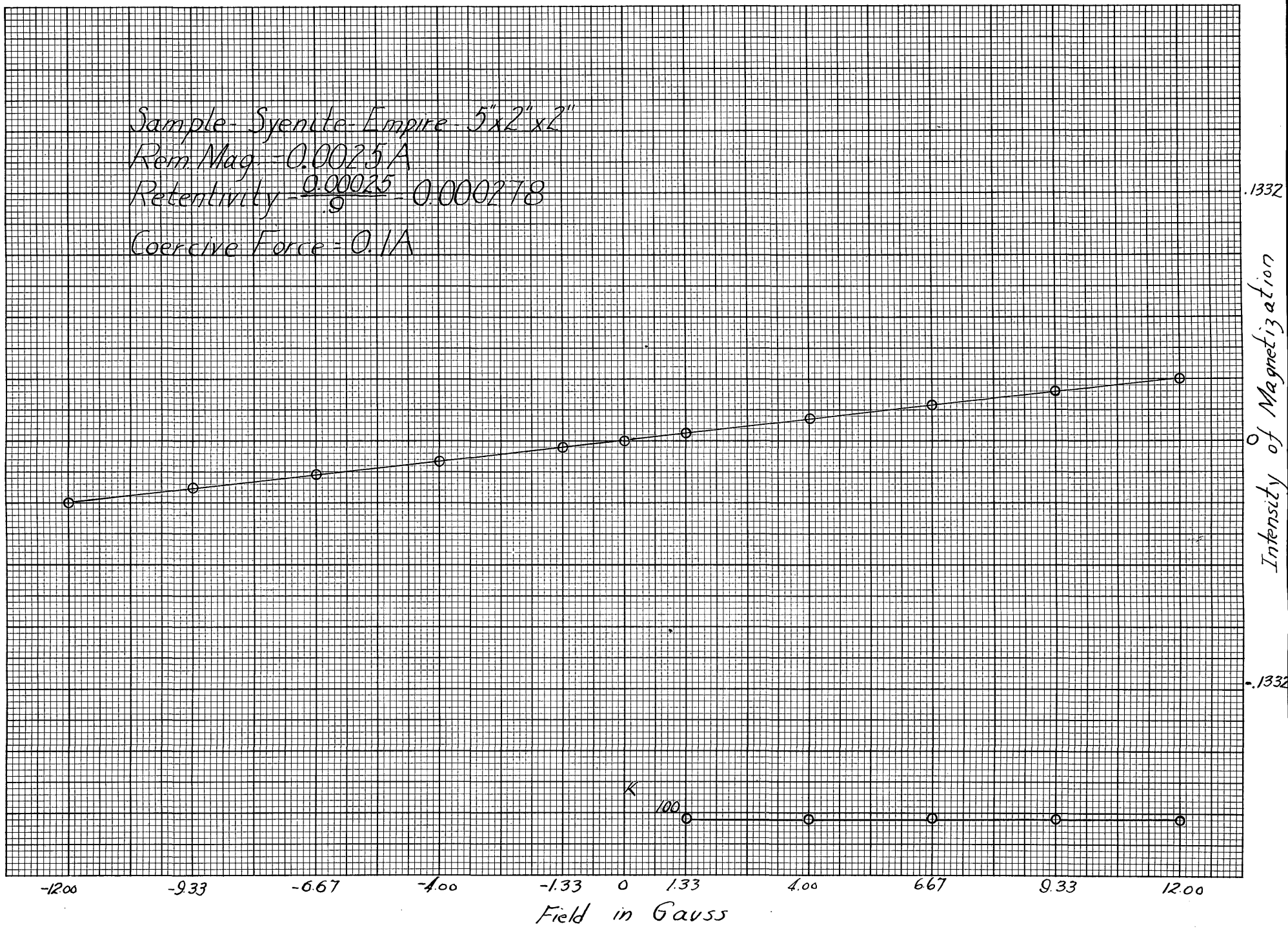

Sample-Granite-Empire 3½"x2½"x2"
Rem. Mag. = 0.000
Coercive Force = 0.000
.266
.1332
0
-.1332
-.266
Intensity of Magnetization
K
500
100
-12.00
-9.33
-6.67
-4.00
-1.33
0
1.33
4.00
6.67
9.33
12.00
Field in Gauss


Sample- Basalt- Table Mountains - 2 1/2" x 2" x 1/2"
Rem Mag. = 0.01332 gauss
Coercive Force = 1.332 gauss
Retentivity = 0.001
.266
.1332
0
-.1332
-.266
Intensity of Magnetization
K
12.00
11.00
10.00
-12.00
-9.33
-6.67
-4.00
-1.33
0
1.33
4.00
6.67
9.33
12.00
Field in Gauss


Sample-Basalt Ralston Dike-3"x2"x1"
Rem. Mag. = 0.01332 gauss
Retentivity = 0.001
Coercive Force = 0.1332 gauss
.266
.1332
0
-.1332
-.266
Intensity of Magnetization
K
2000
1000
-12.00
-9.33
-6.67
-4.00
-1.33
0
1.33
4.00
6.67
9.33
12.00
Field in Gauss

Syenite-Empire, Colorado

The next specimen to be studied was a syenite specimen from Empire, Colorado. Its demensions were 5"x2"x2". The area of the hysteresis loop was very small, but the coercive force is 1.332 gauss, and the remnant magnitism is .00334 gauss. The susceptibility at the earth's normal field is 96.8×10^{-6}. Since a straight line can be drawn through the points on the curve, we can say that the susceptibility does not vary as a function of the field.

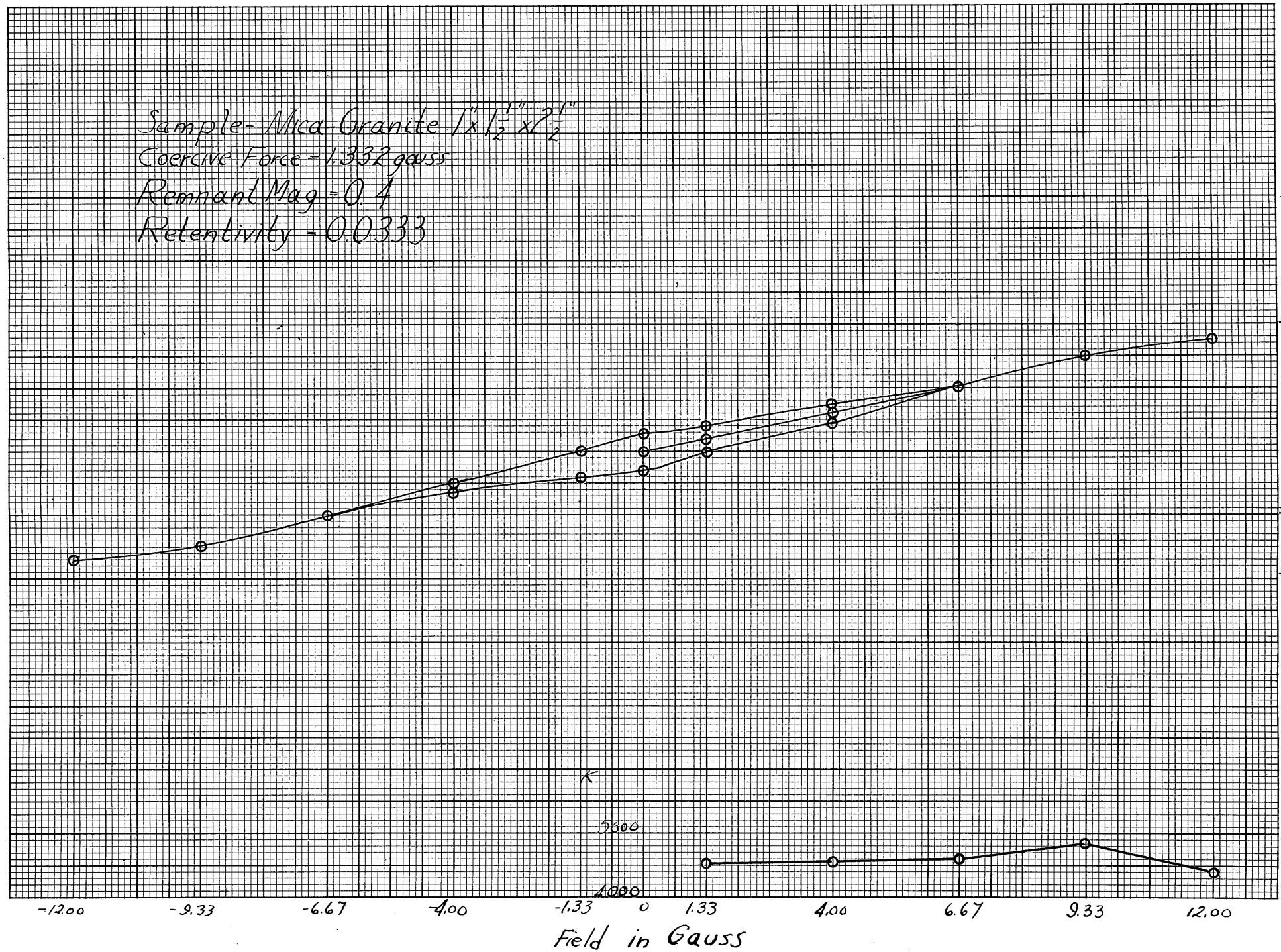

Sample - Syenite - Empire - 5"x2"x2"
Rem. Mag. = 0.00025 A
Retentivity = 0.00025 / .9 = 0.000278
Coercive Force = 0.1A
.1332
0
-.1332
Intensity of Magnetization
K
100
-12.00
-9.33
-6.67
-4.00
-1.33
0
1.33
4.00
6.67
9.33
12.00
Field in Gauss

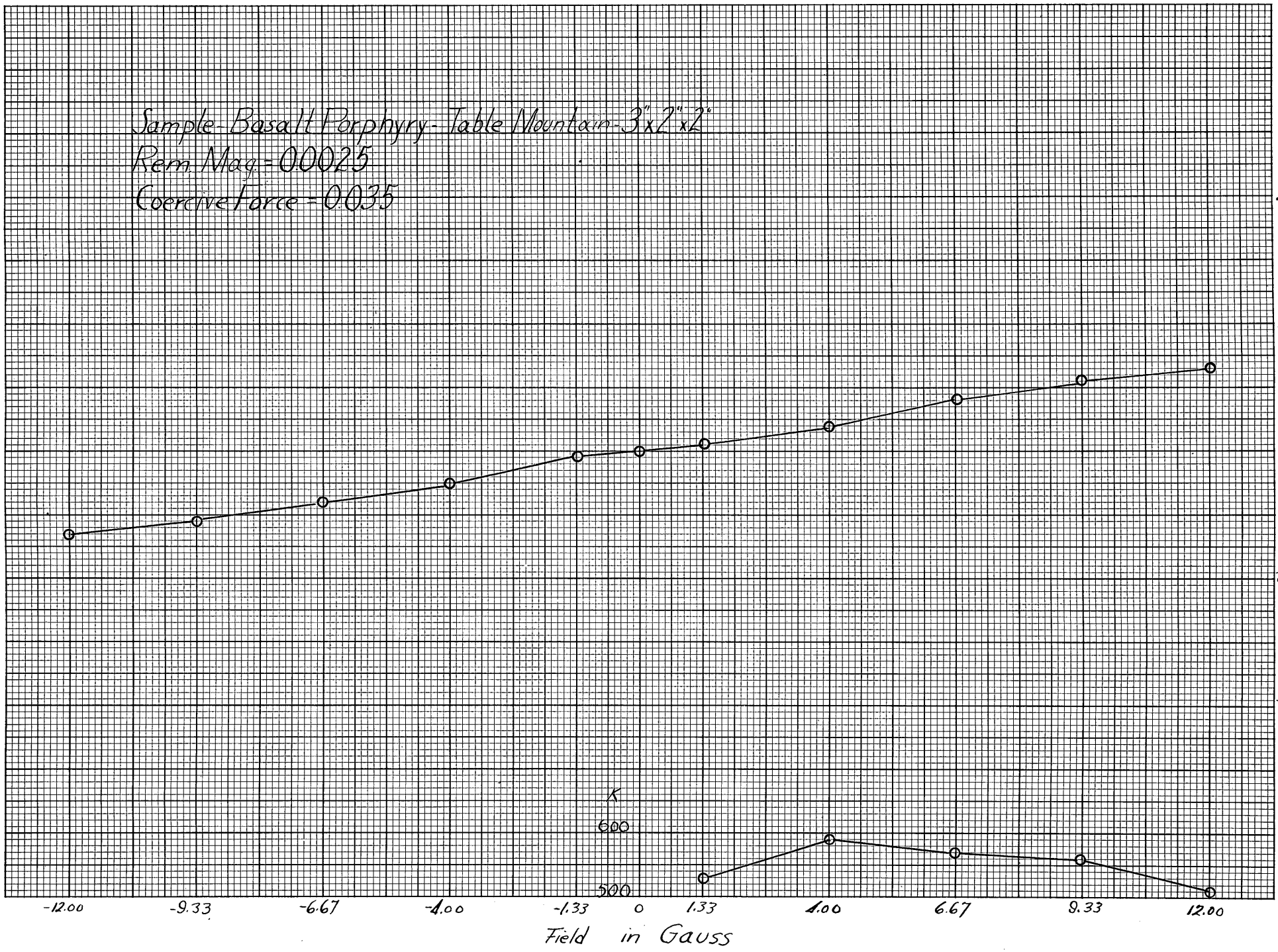
MICA-GRANITE

The first actual rock specimen tested was a sample of mica-granite. The dimensions of this sample were $1'' \times 1\frac{1}{2}'' \times \frac{1}{2}''$. The coercive force is 1.332 Gauss and the residual magnetism is .04 Gauss. The retentivity is $\frac{.03}{.9} = .0333$ The susceptibility at the earth's field was 4550×10^{-6}.

BASALT PORPHYRY TABLE MOUNTAINS

The last specimen tested with the instrument was a basalt porphyry from the table mountains near Golden, Colorado. Its dimensions are $3'' \times 2'' \times 2''$. The remnant magnetism is .0366 Gauss and the coercive force is .0467 Gauss. The retentivity is $\frac{.0025}{.9} = .00278$. The susceptibility at the earth's field is 510×10^{-6}


Sample - Mica-Granite 1"x1½"x2½"
Coercive Force = 1.332 gauss
Remnant Mag = 0.4
Retentivity = 0.0333
.266
.1332
0
.1332
.26
Intensity of Magnetization
K
5000
4000
-12.00
-9.33
-6.67
-4.00
-1.33
0
1.33
4.00
6.67
9.33
12.00
Field in Gauss


Sample - Basalt Porphyry - Table Mountain - 3" x 2" x 2"
Rem. Mag. = .0025
Coercive Force = 0035
.266
.1332
0
-.1332
-.266
Intensity of Magnetization
K
600
500
-12.00
-9.33
-6.67
-4.00
-1.33
0
1.33
4.00
6.67
9.33
12.00
Field in Gauss

CONCLUSIONS

To summarize, the purpose of this instrument is to study the magnetic properties of the specimens tested. These purposes may be sub-divided into two classes. The first class and probably the most important in the interpretation of magnetic results is the determination of the susceptibility as a function the magnetizing force to which the specimen has been subjected.

Other items of interest which are determined by this instrument are the remnant magnetics and coercive force. It appears that, since studies of the coercive forces and remnant magnetics may give valuable information as to the past geologic history of an area studied, this may lead to a more enlightened interpretation, so that this phase of information may be of positive value.

In principle two opposing solenoids are employed to bring the astatic system to a null position. Then the specimen is inserted in one of the coils and the instrument is again brought to a null position by the use of a third or compensating coil. The field of the third coil necessary to do this is then equal to the field due to the induction due to the specimen. To determine the magnetic properties of a specimen we need to take into account the volume of the sample used.

With a patient and careful laboratory ~~technique~~ technique, this instrument will give satisfactory results and give the information to be divulged. The information may not be ob-

tained as rapidly as other methods, but is is of a more complete nature.

Syenite-Empire, Colorado

The next specimen to be studied was a syenite specimen from Empire, Colorado. Its demensions were 5"x2"x2". The area of the hysteresis loop was very small, but the coercive force is 1.332 gauss, and the remnant magnitism is .00334 gauss. The susceptibility at the earth's normal field is 95.8×10^{-6}. Since a straight line can be drawn through the points on the curve, we can say that the susceptibility does not vary as a function of the field.