FINAL MEMORANDUM REPORT

A STUDY OF THE PHYSICAL AND ELECTRICAL
PROPERTIES OF CHONDRITE METEORITES

by

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"--- Such as it is, it promises the prize
  Of the one world complete in any size
  That I am like to compass, fool or wise."
                 Robert Frost, "A Star in a Stoneboat"

I

INTRODUCTION

The non-linear electrical properties of chondrite meteorites were discovered during previous work by the University of Michigan Radiation Laboratory under NASA Research Grant NsG-4-59. The purpose of the work reported here has been to investigate these properties more thoroughly in bulk samples and to identify those materials, in the complex structure of the meteorites, which are responsible for their electrical properties.

1.1 Description of Chondrite Meteorites

The chondrites are stone meteorties which contain spheroidal grains (chondrules) of crystalline or glassy sillicates ranging in size from a small fraction of a millimeter to several millimeters. These grains may comprise practically the entire volume of the meteorite, but more commonly they are dispersed in a groundmass consisting of fragments of silicate crystals and broken chondrules. The chondrules often exhibit a "rayed" or "fan" crystal structure with the rays originating from a point on the surface.

Some chondrites are so friable that the chondrules can be easily removed from the groundmass. Others are quite hard with a compact structure, probably as a result of a metamorphic process which has caused partial recrystallization; under the microscope the chondrules are then seen only as ghost structures with indistinct boundaries.

The silicate minerals in the chondrules and groundmass are most commonly olivine, $(Mg, Fe, Mn)_2 SiO_4$, and the orthohombic pyroxenes enstatite, bronzite, and hypersthene. Enstatite has the composition $MgSiO_3$; in bronzite and hypersthene the magnesium is replaced in part by iron with small amounts of aluminum and calcium.

Grains of nickel-iron and troilite (FeS) are common constituents of most chondrites and may make up nearly a quarter of the volume. The grains occur both in the chondrules and in the matrix and have irregular outlines, their shapes being determined mainly by the shapes of the surrounding silicates. The largest grains may be several millimeters across and all sizes can be seen down to the limit of microscope resolution.

Chromite, $(Fe, Mg)(Cr, Al, Fe)_2 O_4$, is another conspicuous mineral, although it is typically only about a tenth as abundant as nickel-iron and troilite. It most commonly occurs as irregular grains similar in size and shape to the medium-sized nickel-iron and troilite grains, and may in some cases be magnetite, Fe_3O_4, rather than chomite. Some chromite grains may have a rather high nickel content.

Some chondritic meteorites are interlaced with dark veins, which may be several millimeters wide. These consist of glassy or microcrystalline silicates, usually containing globules and veinlets of metal and sulphide.

The fusion crusts which form on the surface of these meteorites during their passage through the atmosphere are typically about one millimeter thick. The crusts have a thin outer zone of glass with many minute inclusions of an opaque mineral which is probably magnetite, and an inner zone wherein the silicates have been partially melted to form glass. Metal and sulphide grains in this zone have also melted and supplied material for the fine network of veins which pervade the inner zone, filling cracks in silicate and chromite grains.

Most chondrites contain hydrated oxides of iron and nickel as replacements of metal and sulphide grains and as veins. These are more numerous in "finds" than in observed falls, and it seems likely that they are entirely of terrestrial origin. The oxide veins have formed either as crack fillings or as replacements of metal or sulphide veins which had formed previously as crack fillings, and they range in width from sub-microscopic up to several tenths of a millimeter. The larger ones may be several centimeters in length, with much complicated branching.

1.2 Classification of Chondrites

Meteorites have been classified according to several systems, most of these divide the stone meteorites into two large sub-groups: the chondrites and the

achondrites. Further classification is made difficult by the smallness of the sampling, both in numbers and in size of individuals, and by the lack of knowledge concerning the genesis of meteorites, since any workable classification system contains implicitly certain assumptions as to the origin of and relationships between the objects being classified. The most commonly-used system is Prior's modification [1] of the Tschermak-Brezina system, which divides the chondrites into three groups according to the iron content of the magnesian silicate minerals, a as enstatite-chondrites, bronzite-chondrites, and hypersthene-chondrites. Each of these groups may be further subdivided according to color, as white, intermediate, gray, or black; and structure, as crystalline (compact mass, chondrules break with matrix), spherical (friable mass, chondrules do not break with matrix), brecciated (containing conspicuous large angular fragments) and veined (containing conspicuous dark veins). A special, rare class is that of the carbonaceous chondrites.

1.3 Sources of Samples

Most of the meteorites studied during the work reported here were purchased from the American Meteorite Laboratory, Denver, Colorado, or from the American Meteorite Museum, Sedona, Arizona. Several samples were obtained on loan from the Perry Collection through the generous permission of the University of Michigan Geology Department, and several others were kindly loaned by Professor H. C. Urey

of the University of California at LaJolla. A complete list of the meteorites studied

is given in Appendix I.

1.4 Summary of Investigation

The electrical investigation began as a continuation of the studies of the

properties of large slabs with dimensions on the order of centimeters. Variations

of potential were mapped with current passing through the slabs, and conductivity

of the slabs was determined as a function field intensity and temperature. A few

measurements were made on a microscopic scale using small probes. For one

sample, the Hall Effect was measured.

Samples of many of the meteorites were studied under the microscope and

by other means in order to identify their constituents and to obtain an understanding

of their structure, both as a means of elucidating their electrical behavior and as

a first step in answering some of the many questions concerning their histories.

The samples were examined microscopically in the form of polished sections and

also as thin sections. A few areas of some samples were studied with an electron

beam microanalyzer. X-ray diffraction analyses were obtained for some of the

constituent minerals.

II

ELECTRICAL INVESTIGATIONS

2.1 Conductivity Versus Field Intensity and Temperature in Bulk Samples

General Discussion

For relatively large meteorite samples the conductivity has been found to be a power function of field intensity and absolute temperature. This has been observed in every sample whose conductivity was high enough to enable measurements to be made with the available instrumentation. The scale of the inhomogeneities in these samples is of the order of tens or hundreds of microns or less, and the "large" samples studied have dimensions on the order of tens of millimeters.

Since both field intensity and temperature are involved it is obviously important that both these variables be accurately known, if not controlled. This presented the greatest experimental problem due to the fact that the temperature of a sample depended not only on the ambient conditions but also on the amount of power dissipated in the sample during the experiment. Two different approaches were followed: one technique limited the amount of power dissipation by using a capacitor discharge circuit with a small time constant and fairly small amounts of charge; the other technique used the opposite approach and expanded the time scale of the measurement while attempting to control the sample temperature by controlling the ambient temperature. Each of these approaches had certain advantages and disadvantages.

2.2 Sample Preparation

Samples for all the "bulk" electrical measurements were prepared in the same way, and many of the samples were used in more than one type of experiment. Rectangular slabs were sawed from the meteorites, with dimensions which depended on the size of the specimen. The lengths ranged approximately from half a centimeter to five centimeters, widths from half a centimeter to four centimeters, and thicknesses were approximately half a centimeter. The faces were ground flat, and opposite faces were made parallel within 0.001 inch. The slabs were dried by heating them at 200°C. for twenty hours, and were stored between experiments in dessicant jars.

For some of the experiments silver paint was applied to two opposite faces on each slab to act as an electrical contact, but for the measurements in controlled temperature environments the slabs were simply clamped between parallel plates in a sample holder fabricated from Invar. The surfaces in contact with the sample were gold-plated.

2.3 Capacitor-Discharge Measurements

The first series of measurements was made under a previous contract [2]. The results will be reviewed here because they have in general been substantiated by later work and because they provide a good view of the relative behavior of a number of samples under similar experimental conditions. Values of capacitance

were chosen to give a time constant of 10 milli-seconds or less. Results were recorded by means of an oscilloscope and Polaroid camera.

Eleven samples were used, all from the group purchased from the American Meteorite Laboratory. (See Appendix I.) Two of the samples, Hugoton 280.335 and Norcatur 525.18, had such low conductivities that their characteristics could not be measured.

The results are given in Figures 1 and 2. (Note the difference in scale between the two figures.) The curves are identified by the American Meteorite Laboratory numbers of the specimens, which are listed in Table I.

TABLE I

AML No.	Meteorite Name
92.1277	Plainview
92.1280	"
92.1281	"
92.1290	"
176.34	Harrisonville
234K	Roy
405.60	Ladder Creek
464.181	La Lande
670.14	Calliham

Note: Measurements were made for current passing in the direction of the c-axis, except where noted.

Curves for samples 92.1290(b) and 234 K are practically coincident.

Field Intensity, thousands of volts per meter
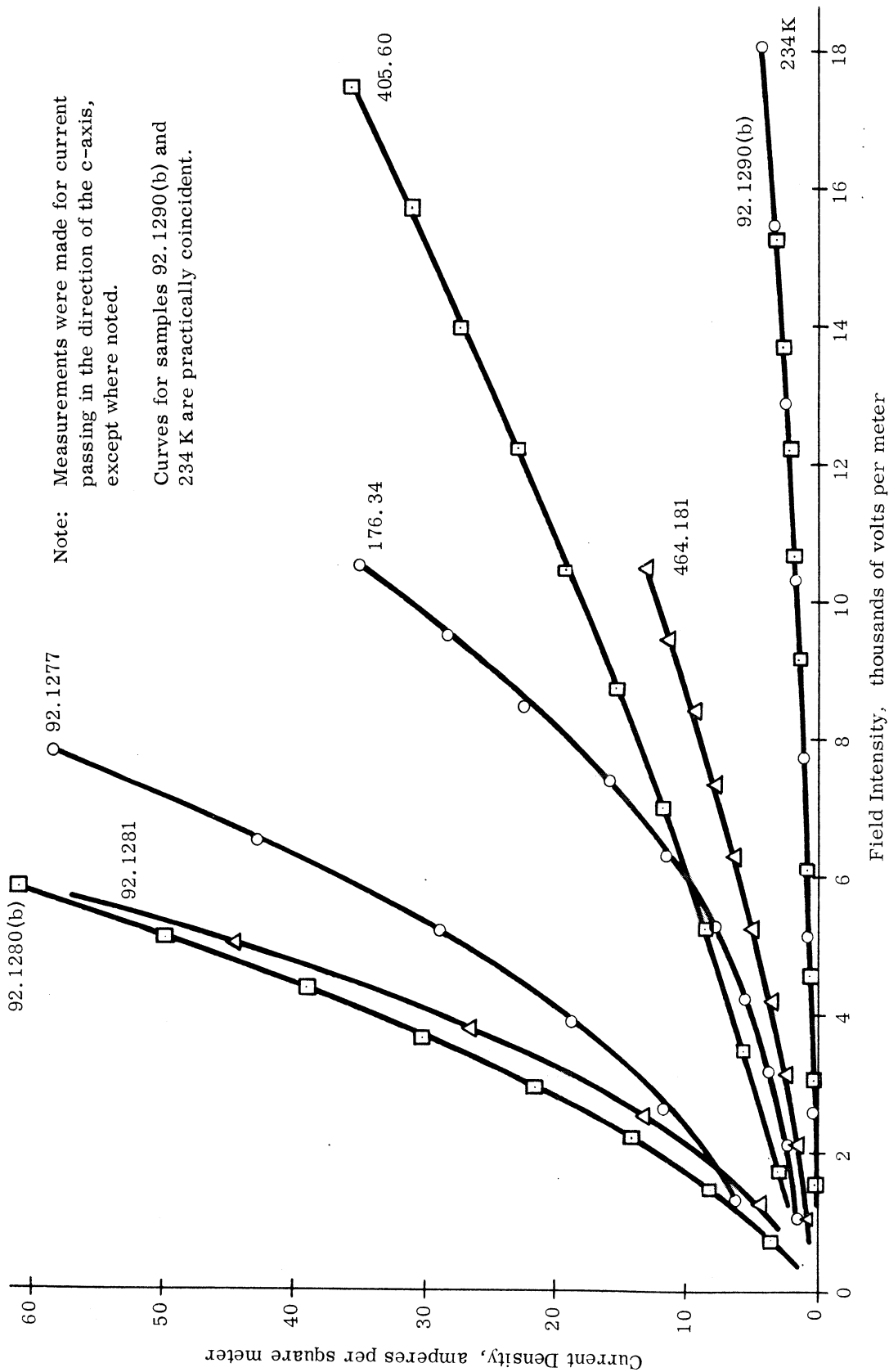
FIGURE 1. TYPICAL CHONDRITE CHARACTERISTICS

Current Density, amperes per square meter

405.60

176.34

464.181

92.1277

92.1281

92.1280(b)

92.1290(b)

234 K

9
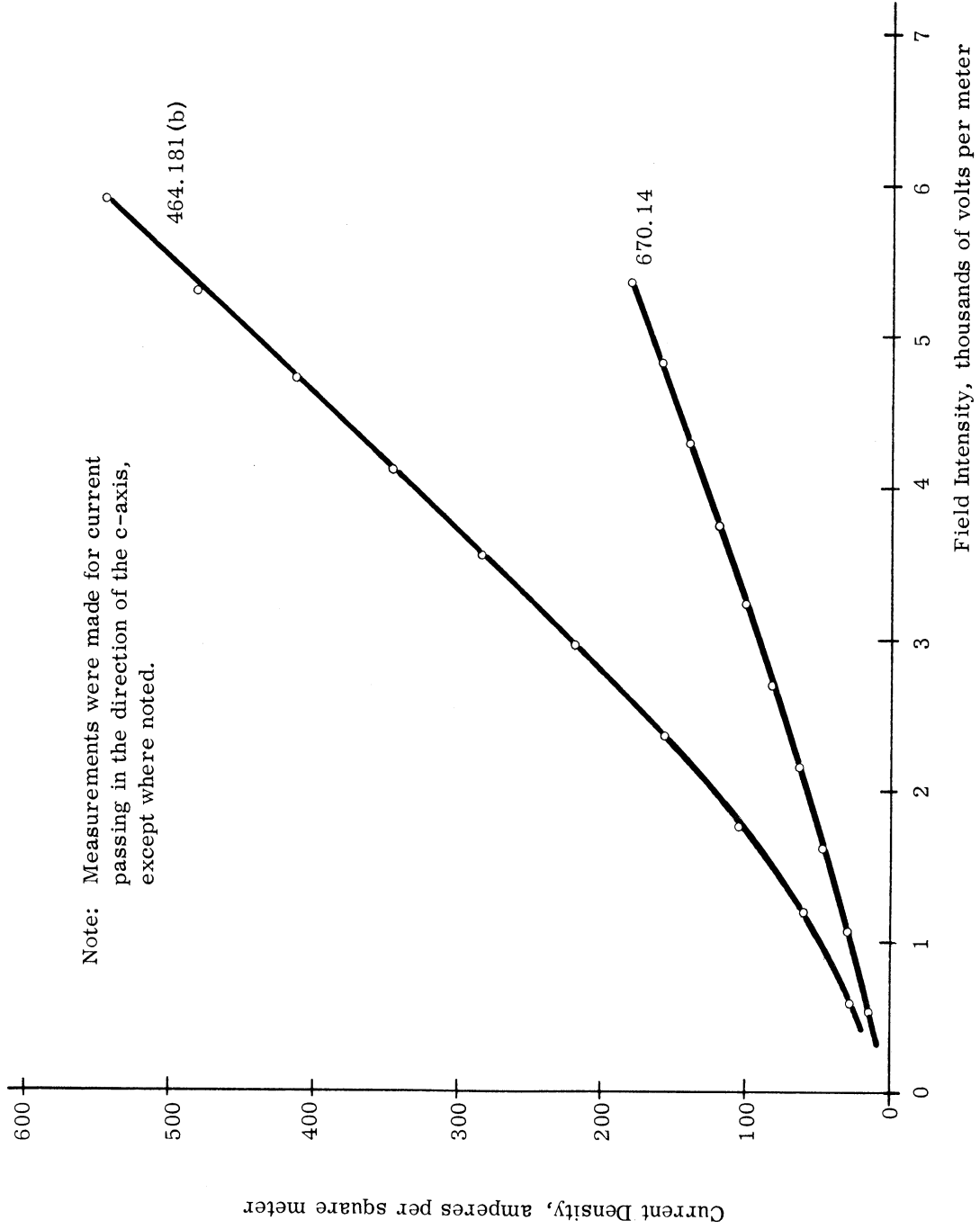
FIGURE 2. CHARACTERISTICS OF THE LALANDE AND CALLIHAM CHONDRITE

Note: Measurements were made for current passing in the direction of the c-axis, except where noted.

Most of this data was obtained with the current flow parallel to the longest dimension of the slabs, except that in three cases the current flow was made parallel to the intermediate dimension, as indicated by a (b) after the identification number. One sample was measured in both directions with quite different results. The slab of Plainview 92.1281 contained a transverse crack, and after measurements were made on the whole slab it was sawed in half perpendicular to the long dimension and the measurements were repeated. The conductivities of the two halves and of the uncut sample were all of the same order of magnitude, but the non-linearity of the half containing the crack was greater than that of the whole slab. Since the cracked half actually showed the highest current density of the three pieces, for the higher values of field intensity (and higher values than the whole slab for all field intensities) it would seem that the influence of the crack is at least obscure.

The conclusions from this series of experiments were as follows: All samples which could be measured exhibited the non-linear behavior, some more than others. The degree of non-linearity was felt to be related to the number of cracks and veins in the sample.

There was some concern that some or all of the apparent non-linearity might be due to temperature rise in the samples, even though the power input was very small. Under the present contract, therefore, a series of measurements was made on two samples (Plainview 92.1281 and Potter 476.75) using progressively

smaller values of capacitance. The smallest time constants for which data could be obtained were, for Plainview, about 100 microseconds and for Potter, about 36 microseconds; the upper and lower extreme values of time constant differed by a factor of at least 100.

2.4 Measurements with Controlled Temperature

The sample temperature was controlled by two means. For one series of experiments an oil bath was used; for another series an oven was used, first with an air atmosphere and later with a nitrogen atmosphere.

2.4.1 Oven with Air Atmosphere

Experimental Set-up

The first series of measurements was made in an oven with no attempt to control the atmosphere. The Temco oven was capable of providing temperatures up to 1100° C., and the temperature was sensed by a chromel-alumel thermocouple junction placed in contact with one of the gold-plated electrodes of the sample holder. The thermocouple leads were brought out to the "X" input of a Mosely X-Y recorder.

The majority of the measurements were made using a constant-current source consisting of a regulated power supply with a high resistance in series with the sample. The voltage across the sample was impressed on the "Y" input of the recorder.

Procedure and Results

It was found that thermal gradients in the oven during the warming-up period made the data unreliable. Therefore, each run was made by first bringing the oven rapidly up to the maximum desired temperature and then allowing it to cool slowly with the heater turned off. Data was recorded during the cooling period, which lasted about eight hours.

Measurements were made on several different slabs of Leedy and Plainview. One of the preliminary runs on a Plainview sample showed that after heating to 500°C. the conductivity suffered a permanent change. Two fresh slabs of Plainview were then each taken to successively higher temperatures in two series of runs, the last run in each case going to about 360°C. After the temperature went above approximately 130°C., there was a progressive and irreversible increase in conductivities; the curve for each run was smooth except for an inflection at about 130°C. which persisted until the final run to 360°. The reason for this was not apparent. The possibility of errors in temperature measurement or of changes in the characteristics of the contacts between the sample and the electrodes and of oxidation effects in the sample and the electrodes could not be discounted. (The gold-plated electrodes became tarnished during these runs.) It was therefore decided to proceed with experiments which would eliminate these possible sources of error.

2.4.2 Oil Bath

Experimental Set-Up

A Pyrex vessel 30 inches in diameter and 30 inches high was filled with five gallons of transformer oil; heating elements and a cooling coil were mounted near the bottom and an electrically-driven stirrer provided continuous oil circulation. Temperature was measured by a mercury-in-glass thermometer, the bulb of which was about 10 cm from the sample. The sample holder was of the same type used in the oven experiments.

Voltage from a regulated power supply was impressed on the sample and also on the "X" input of the X-Y recorder; a voltage proportional to the current through the sample was impressed on the "Y" input.

With this arrangement it was felt that the sample and the oil were isothermal within $1^{o}C.$, provided that power dissipation in the sample was less than four or five watts (depending on the size of the sample). Temperatures were limited by the characteristics of the oil to a maximum of about $150^{o}C$.

Procedure and Results

Runs were made at ten-degree intervals of temperature, the voltage being increased smoothly and rapidly from zero to the maximum permissible value by manually rotating the power supply control knob. (The upper limit of voltage was determined by the allowable power dissipation in the sample, see above.) For every

sample, this gave a family of smooth curves of voltage versus current with

temperature as a parameter. The record of the runs on Plainview 92.1281 is

reproduced as an example in Figure 3. Figure 4 is a replot of this data in terms of

current versus temperature with voltage as a parameter. By plotting this data on

log-log paper it becomes apparent that the current is a simple power function of

absolute temperature for constant voltage, and a single equation in T and V was

found to provide a good fit to the entire family of curves:

$$I = (0.453 \times 10^{-17}) \, T^{3.70} \left[(V + 90)^{2.41} - 50800 \right]$$

where

I = current, amperes
V = volts
T = temperature, $^\circ K$

Taking into account the overall dimensions of the sample, it is possible to

express the behavior in terms of average current density and voltage gradient.

$$|\vec{j}| = (2.89 \times 10^{-17}) \, T^{3.70} \left[(|\vec{E}| + 46.9)^{2.41} - 10500 \right] \qquad (2)$$

where

j = amperes/cm^2
E = volts/cm

Similar results were obtained for a slab of Calliham, yielding data for which
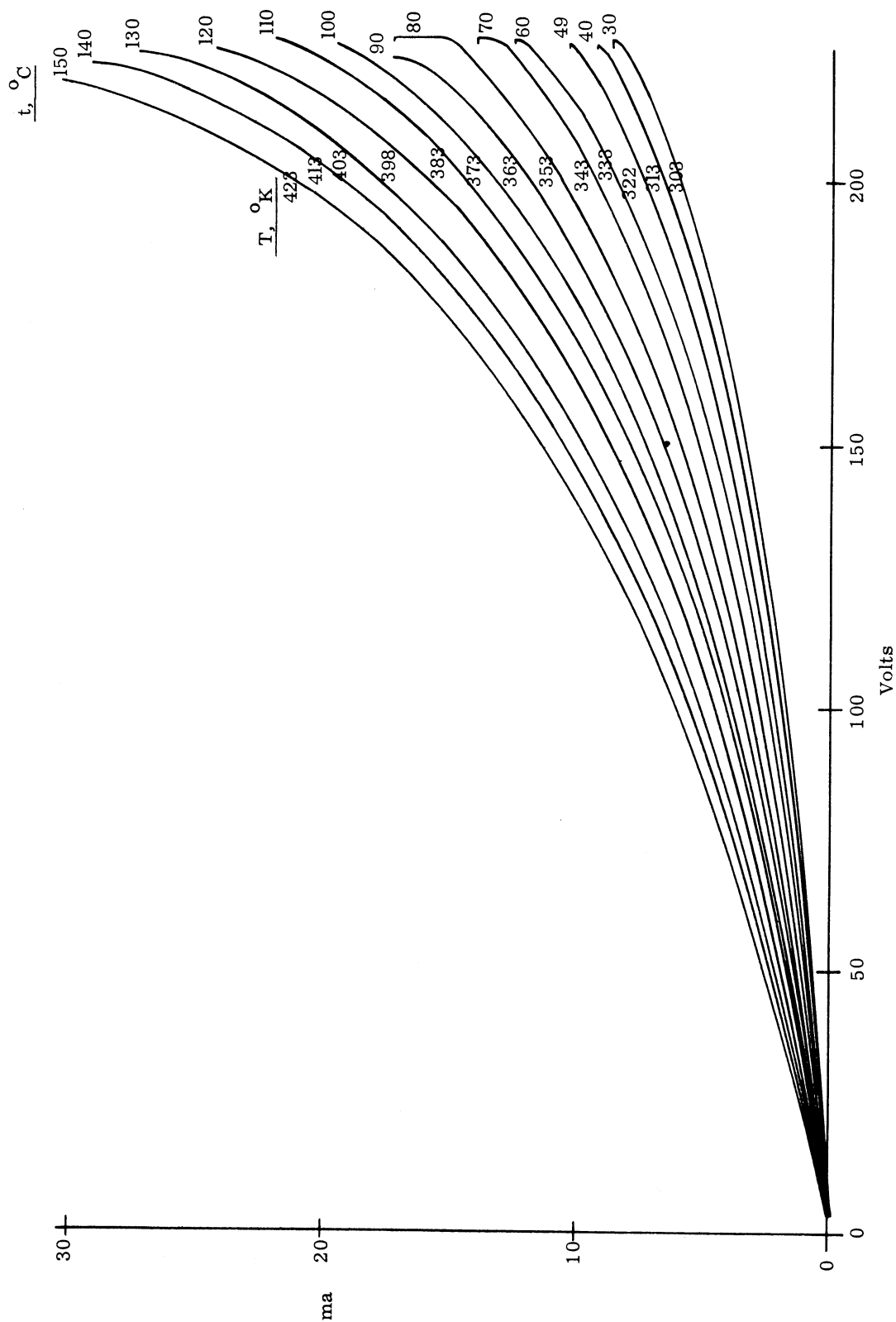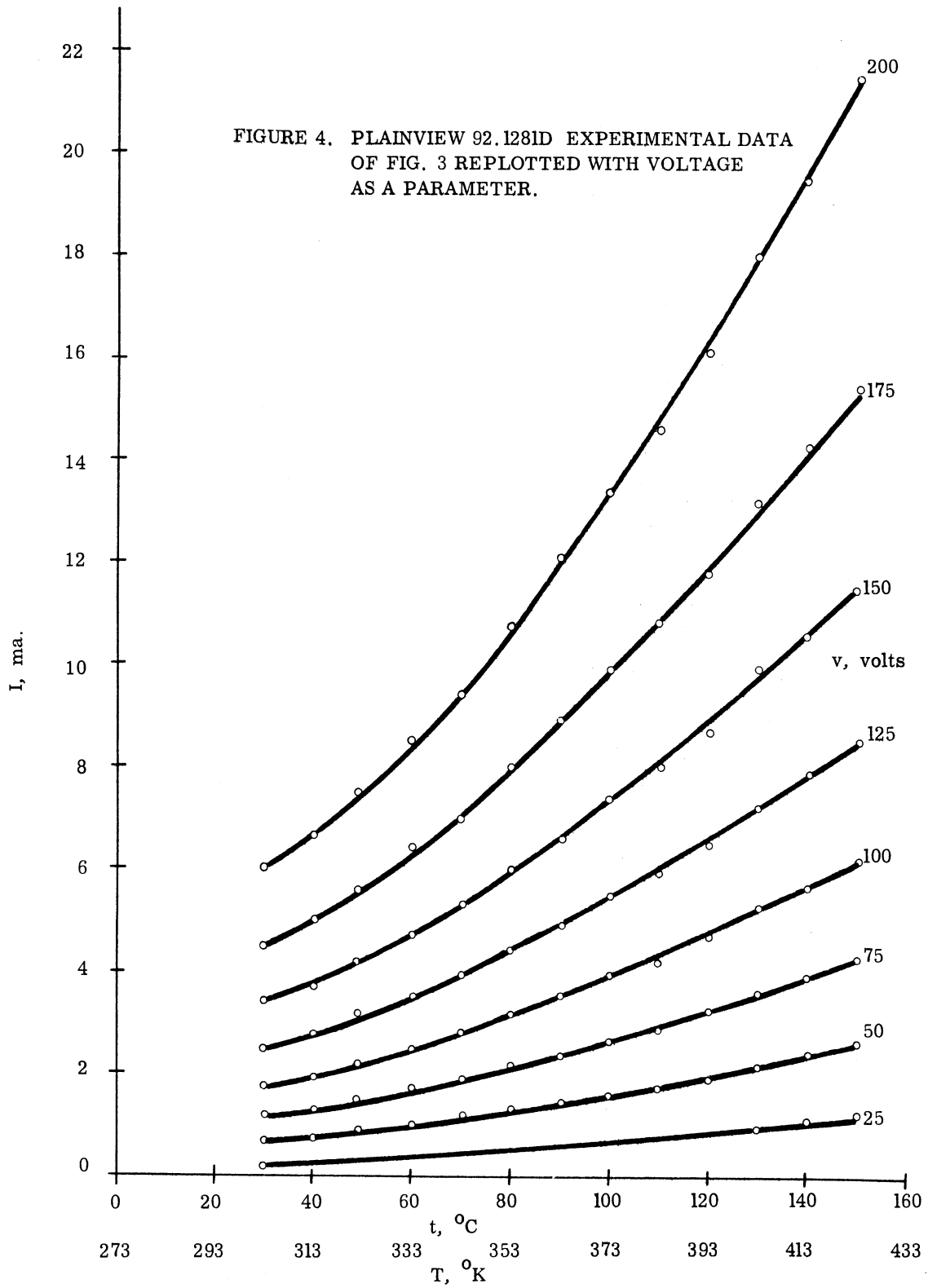
the following provided a good fit:

FIGURE 3.   PLAINVIEW 92.1281D CURRENT VS VOLTAGE WITH TEMPERATURE AS A PARAMETER:
SAMPLE IN OIL BATH

FIGURE 4. PLAINVIEW 92.1281D EXPERIMENTAL DATA OF FIG. 3 REPLOTTED WITH VOLTAGE AS A PARAMETER.

$$I = 10^{-13} \, T^{4.0} \left[2.88 \, (V + 127)^{1.67} - 9020 \right]$$

Not all the samples tested gave similar results, however, and for some it was not possible to separate the voltage and temperature dependencies.

For all these meteorites there was no apparent change in characteristics within this temperature range, and curves obtained for ascending and decending temperatures were very nearly identical. However, a sample of Potter 476.75 underwent a permanent change at about $370^{\circ}K$. The effect of this is shown in Figure 5. After the change the current apparently became a linear function of temperature.

2.4.3 Oven with Nitrogen Atmosphere

Experimental Set-up

The oil bath experiments provided a good environment for the samples, but were subject to an upper temperature limit of $150^{\circ}C$. Therefore, an enclosure was constructed for the oven so that a non-corrosive atmosphere could be provided for experiments at higher temperatures. This enclosure was made from a pneumatic water tank 16 inches in diameter and 24 inches long which was cut apart and provided with flanges, inlet and exhaust ports, and pressurized insulated connectors for the oven power and test leads. The thermocouple junction was placed in contact with the sample and temperature was monitored with a potentiometer, the X-Y

FIGURE 5. POTTER 476.75B CURRENT VS TEMPERATURE
(IN OIL BATH) SHOWING PERMANENT
CHANGE IN CHARACTERISTICS AT
APPROXIMATELY 370°K
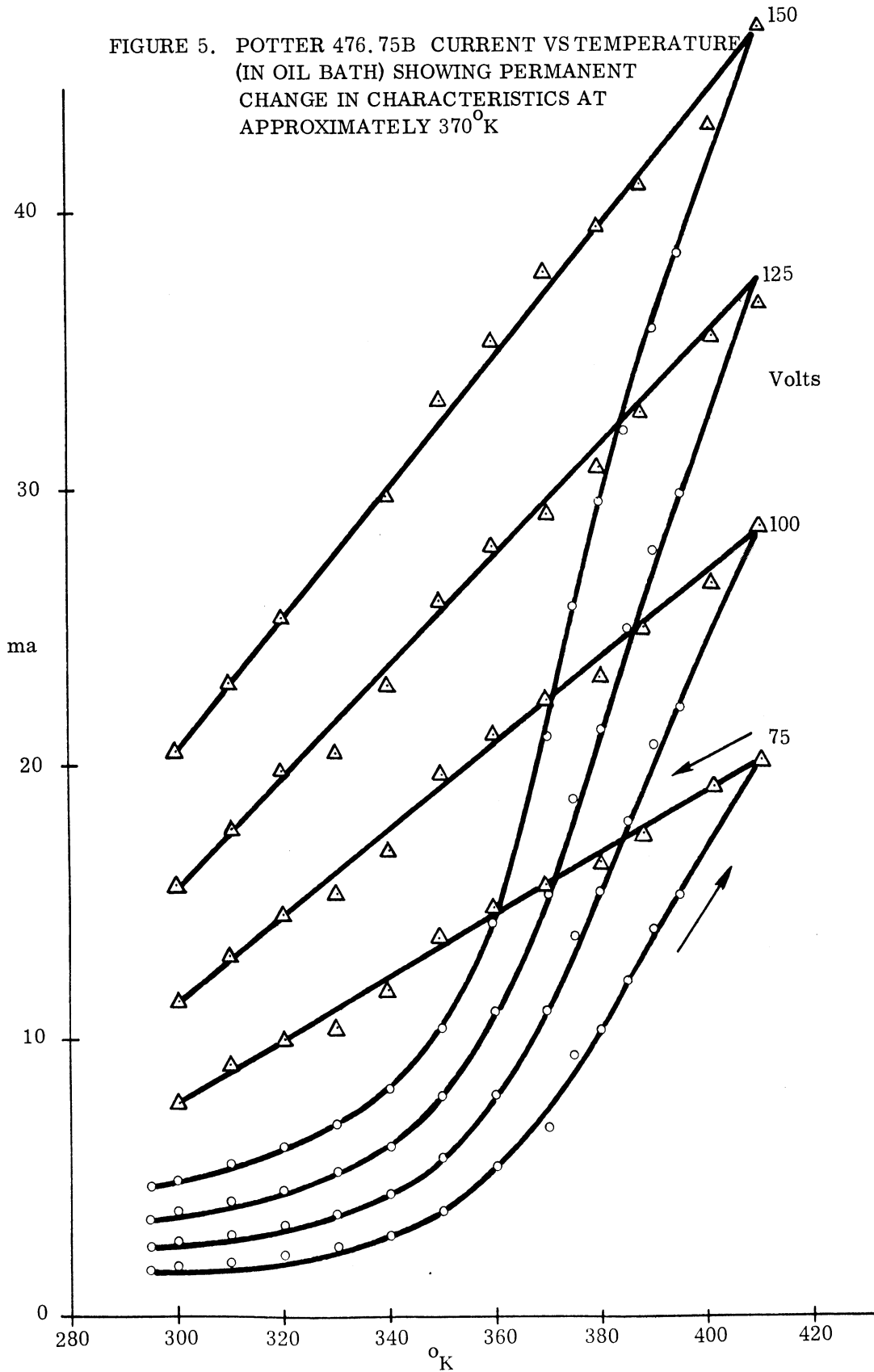
recorder being used for voltage and current measurement as in the oil bath experiments.

Procedure and Results

The enclosure was evacuated after installation of a sample, and then filled with dry nitrogen at a pressure slightly above atmospheric. Data was taken during the times of increasing temperature as well as the times of decreasing temperature. However, there was still some uncertainty as to the accuracy of the temperature measurement, or rather, as to how representative of the actual sample temperature the measured value was.

No apparent oxidation effects were observed on either the samples or the electrodes even for the highest temperatures obtained, approximately $650^{\circ}K$.

For the lower-temperature portions of the runs on samples which had been used for the oil bath experiments, the results agreed quite closely with those obtained in the oil bath. As the temperature was increased the samples generally underwent a permanent change, each in a different manner, although one, Holly, did not.

A sample of Potter 476.75 (not the same sample used in the oil bath) underwent a permanent change at about $340^{\circ}K$, (see Figure 6a.) Succeeding runs to higher temperatures caused no further changes; (See Figure 6b and c). The sample of which was used for the oil bath experiment underwent a change at approximately
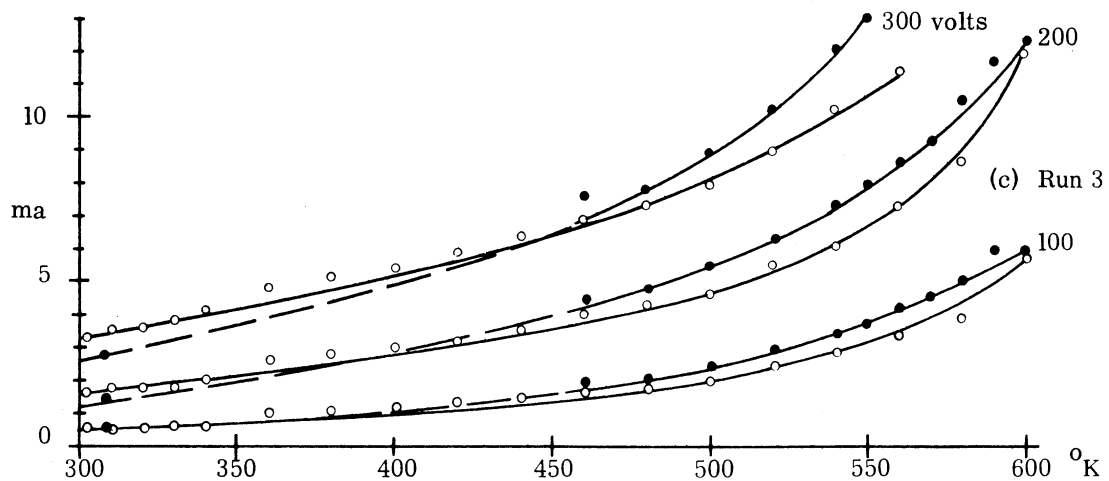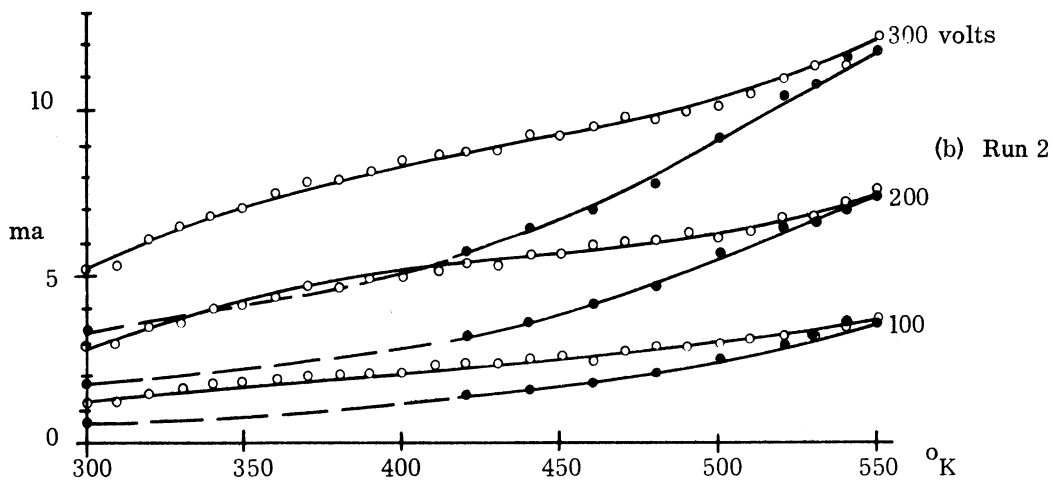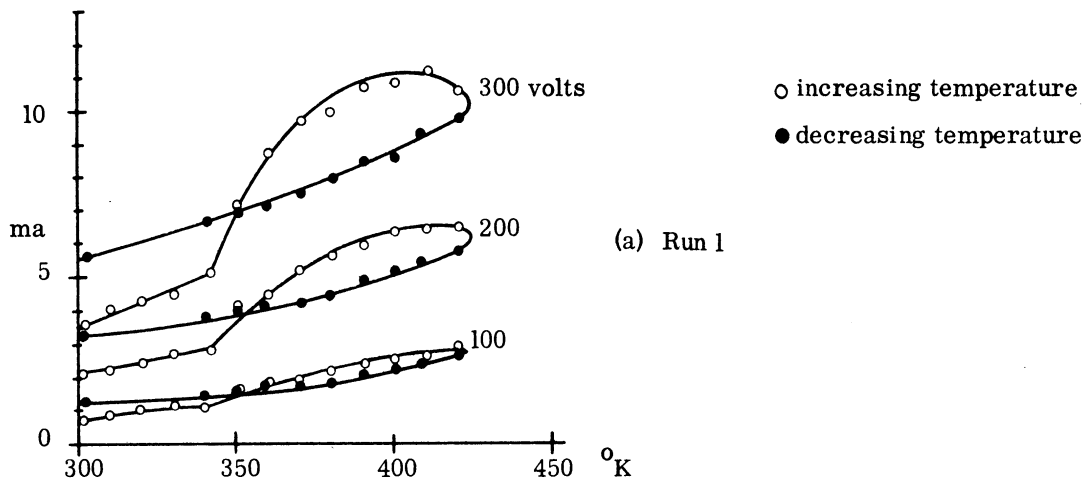
FIGURE 6. POTTER 476.75, CURRENT VS TEMPERATURE WITH THE
MAXIMUM TEMPERATURE INCREASING WITH EACH RUN.
(IN NITROGEN ATMOSPHERE)

370°K although the form of the curves during the initial heating was different. (See Figure 5.)

2.5 Measurement of Hall Effect

Experimental Set-up

The Hall Effect was measured on a slab of Plainview, 7.193 x 3.401 x 0.252 cm in size. Current and Hall voltage leads of No. 28 copper wire were attached with silver print joints approximately 1 cm long, and the magnetic field was provided by a 2000-gauss permanent magnet with pole pieces about 4 cm in diameter. A 90 volt battery was used to provide a potential of 39.5 volts through the use of a dropping resistor. The Hall voltage was recorded on the Moseley X-Y recorder driven by a General Radio DC Amplifier/Electrometer. Shielding was provided by a metal box enclosing both the sample and the magnet.

Procedure and Results

Three sets of measurements were made using three different combinations of current and field directions, each set consisting of at least three repeated measurements. In each case the value was determined by taking the average value graphically from a 100-second recording of the Hall voltage. Due to the inhomogeneity of the sample a voltage was measured in the absence of a magnetic field, and

therefore, the true Hall voltage was taken as the difference between the average values with and without the field.

Repeatability of the results was not good, but the polarity at least was consistent and indicated that if the material was homogeneous the dominant carriers are positive. The inhomogeneity of the sample, however, makes it impossible to make any definite statement as to the sign of the carriers. The average value of the Hall voltage was found to be approximately 0.19 volt, giving a Hall coefficient of 0.5 cm^3/coulomb. This compares to values for germanium ranging from 1000 to 150,000 cm^3/coulomb. The difference may be explained by the fact that the conducting portion of the meteorite occupies a very small portion of the sample volume, probably less than one percent.

2.6 Potential Maps

These measurements provided a look at the electrical properties of meteorites on a scale midway between that of the bulk measurements described in the preceding section and that of the microscopic probe experiments to be described in a later section.

Experimental Set-up and Procedure

Slabs of several meteorites were used for these studies. The slabs were cut in the same manner as were those for the bulk conductivity measurements, but

their size was somewhat greater. Silver paint was applied to opposite ends and the sample was held flat on a board between spring-loaded contact strips. The surface was explored with a steel probe which formed one of the points of a pantograph; thus the positions at which readings were taken were automatically plotted.

The applied voltage was adjusted to give a current flow of a few milliamperes through the sample, except that for samples with low bulk conductivity a maximum of 100 volts was applied. Both current and voltage were read in the measuring circuit between the probe and one end of the sample, using a Hewlett-Packard 410B voltmeter (100 megohms/volt) and a Leeds and Northrup microammeter.

The circuit is shown in Figure 7, where the dashed line represents the boundary of the sample. In this greatly simplified schematic the total end-to-end resistance of the sample is represented by two resistances in series, R_1 and R_2. Their junction, assumed to be physically close to the surface, is coupled to the point at which the probe makes contact by a third resistance, R_c. The potential, E, at the junction is desired. Rg is the resistance of the meter, and R_s is a shunting resistance approximately equal to Rg. Each measurement was made with and without the shunting resistance, thus enabling the value of both E and R_c to be calculated.

Results

The potential map for a sample of Ladder Creek is presented in Figure 8 as a typical example; some samples gave simpler, others, more complicated, patterns.
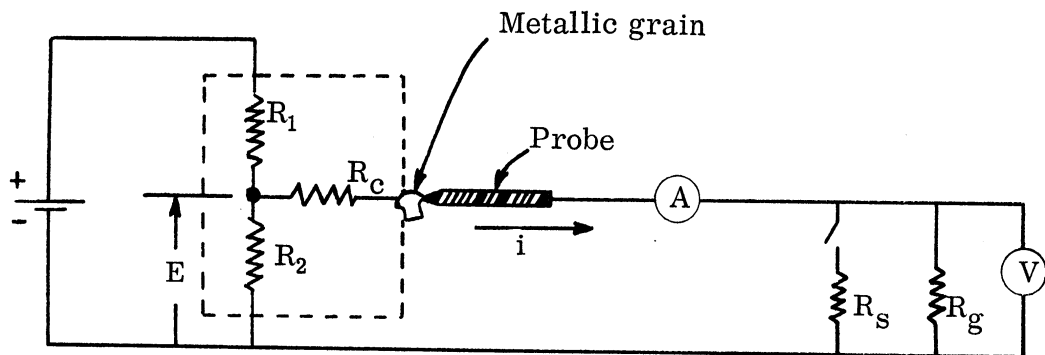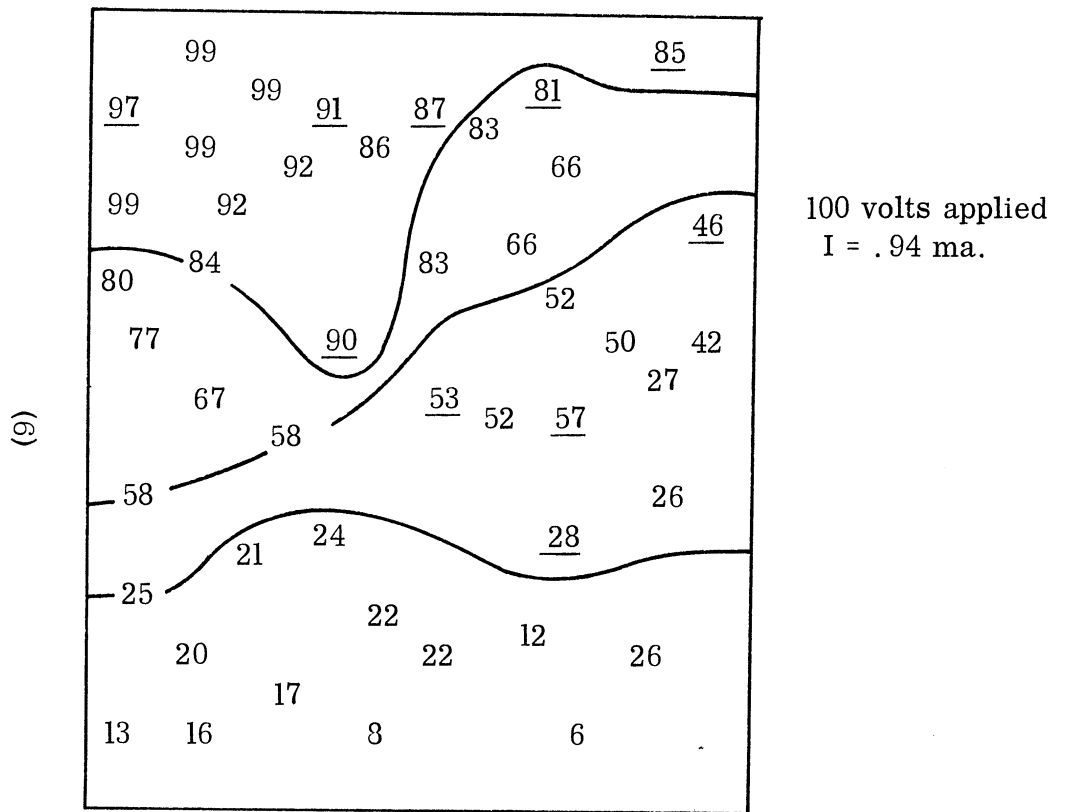
FIGURE 7. MEASUREMENT CIRCUIT FOR OBTAINING POTENTIAL MAPS.

Potential Map (volts)
Under scored values were obtained
indirectly.

FIGURE 8.   POTENTIAL MAP OF SAMPLE 405.60, LADDER CREEK,
KANSAS

Applied voltage was 100 volts, with a current of 0.94 ma. The figures represent potentials measured with the probe in contact with metal or sulphide grains at the respective locations. No potential could be measured on the silicate matrix, and some metal or sulphide grains showed zero potential. For samples with visible cracks the equipotential lines tended to be oriented parallel to the cracks.

2.7 Electric Probe Studies

The work on bulk conductivity and potential mapping had led to the hypothesis that the "grap" oxide veins in the meteorites were responsible for their behavior as non-linear conductors. It was therefore important to determine if possible the electrical characteristics of individual veins, and a series of attempts was made to design experiments using small probes and micromanipulators under the microscope. These experiments did not get beyond the exploratory stage, but a few interesting facts were discovered.

At first two probes were used, but it was determined that erroneous results were being obtained and the last experiments were carried out with four probes.

2.8 Two Probe Studies

Experimental Set-up

Probes were made from steel divider points sharpened on fine abrasive paper to a radius of approximately 0.05 mm. They were held by a pair of

micromanipulators and could thus be easily positioned within the field of view of a binocular microscope having a maximum magnification of 60x.

Three types of electrical instrumentation were employed. Preliminary explorations of the sample surface were made using a VTVM ohmeter. A few measurements were made with the capacitor discharge and oscilloscope circuit used for the bulk conductivity experiments, and other measurements employed a regulated power supply and the Moseley X-Y recorder.

Most of the measurements were made on thin slices, with a thickness of about 0, 015 inch, in order to insure that the segments of oxide vein material to be studied were as nearly two-dimensional as possible and not connected electrically with the other veins in the sample.

Procedure and Results

The binocular microscope with oblique illumination was ideal for observing the probes, but was not very good for identifying the constituents of the meteorites. A homemade vertical illuminator improved matters somewhat, but it was still quite difficult to see the smaller veins and grains, and to distinguish between metal and sulphide grains. However, this was not a major handicap in the preliminary work.

After visually locating an area of interest, the probes were lowered into contact with the surface. The pressure was not measured, but it could be estimated

and made reasonably uniform by observing the amount of movement as the probes were lowered further after their first contact, thus causing the tip to slide a short distance along the surface. (The probes were mounted in their holders at an angle of about 45° to the horizontal.) Probe spacings from a few millimeters to a few centimeters were used, with potentials of from zero to 150 volts. When the X-Y recorder was used the voltage was varied manually with the power supply control.

With this instrumentation it was necessary that the resistance of the path between the probes be approximately one megohm or less. One of the most important discoveries made during these first probe experiments was that the oxide vein material varied widely in conductivity; many large veins had resistances too high to be measured even with the probes spaced less than a millimeter apart. It was therefore necessary to explore with the probes and ohmeter to find measurable regions.

Overheating in the probe contact zones was sometimes a problem, and a few areas of metal and oxide were vaporized in the course of the experiments.

Measurements were made on oxide veins, on individual oxide replacement grains, on individual metal and sulphide grains, and between pairs of metal and/or sulphide grains. Two chunks of terrestrial hydrated iron oxide (limonite, replacement of FeS_2) and a piece of Fe_2O_3 were also probed, but their conductivities were so low that measurements could not be made.

The meteorites studied were Calliham, Harrisonville, Hugoton, Plainview, and Potter. All oxide vein material which could be measured showed non-linear characteristics. There seemed to be some correlation between conductivity and the appearance of the vein in oblique or dark-field illumination; the conducting material was dark and the non-conducting material was lighter reddish. Sometimes conducting and non-conducting material occurred side-by-side in the same vein. The silicate matrix was non-conducting. Some pairs of grains were connected electrically and others were not, confirming the results of the potential mapping work. Those that were connected showed non-linear characteristics.

The validity of the two-probe measurements was questioned on the grounds that spurious effects might be introduced at the contacts. Measurements on a carbon resistor confirmed these suspicions. Two-probe measurements on a flat ground surface of the resistor gave resistances which were too high and which showed an apparent negative temperature coefficient and a very slight spurious non-linearity in the potential-versus-current curve. When the current was carried by the resistor leads rather than by the probes, valid results were obtained. It was therefore decided to abandon the two-probe measurements and to develop a four-probe technique.

2.7 Four-Probe Studies

Experimental Set-up

The outer, current-carrying probes were the same as the ones used for the two-probe experiments; that is, they were steel divider points ground to a radius of approximately 0.05 mm. Divider points were also used for the inner probes, but the tips of these were etched to a radius of approximately 0.02 mm; this was the finest tip size for this material which could be easily manipulated without danger of frequent breakage.

A metallographic microscope was used with a magnification of 40 x. A combination of vertical and oblique illumination gave excellent visibility for both the probes and the sample surface. All work was done on well-polished samples of approximately 0.015-in. thickness.

Both inner probes, and one of the outer probes, were held by micromanipulators. The second outer probe was attached to the frame of the microscope by means of an insulating support; the microscope's mechanical stage permitted the sample to be positioned under this probe.

Power for the outer probes was supplied by a $22\frac{1}{2}$ / 45-volt heavy-duty "B" battery across a 20 K-ohm potentiometer. The maximum potential used was about 25 volts. Various combinations of meters were used to measure inner probe voltage and outer probe voltage and/or current, including a Hewlett-Packard Model 425 A

micro-voltmeter/micro-microammeter, a Hewlett-Packard Model 410B VTVM, a Knight VTVM, and several panel-type microammeters and milliammeters. The measurements were never carried beyond the exploratory stage and no great degree of accuracy is claimed for the results.

Most of the time spent on these experiments was employed in trying to discover the source of the very low-frequency noise which was picked up by the inner probes. This noise had peak values of the order of several millivolts and was present even when the outer probes were entirely removed from the sample. It was very erratic in its occurrence, but its immediate cause appeared to be mechanical vibration. Finally it was discovered that if the sample was repolished immediately before being placed on the microscope stage the noise was eliminated.

Results

After the noise probelm had been solved, three sets of measurements were made. The results of these will now be presented briefly.

The measurements were made on two different slices of Calliham, designated as Slides No. 24 and 25. These slides each contained a section of the same large oxide vein; the slices had been sawed from opposite edges of a slab about 2 cm. wide and 0.5 cm. thick which was traversed by the vein. (Figure 9 shows a portion of this vein in Slide 25.)

FIGURE 9: OXIDE VEIN IN CALLIHAM SLIDE NO. 25, SHOWING TWO OUTER PROBES. ONLY ONE INNER PROBE IS BEING USED, AND IT IS NEAR ONE OF THE OUTER PROBES. (X 40).

On Slide 24, the measurements were made on a small vein branching from the large vein, with one outer probe on the large vein near the junction. Three different runs were made, with the probe positions unchanged between the first two and changed slightly for the third. The outer probes were about 3 mm. apart and the inner probes about 0.5 mm. apart and halfway between the outer probes. During the first run the outer probe and inner probe voltages were measured yielding a non-linear relationship with a uniform drift of values during four scans of the range. For the second run the outer probe current and inner probe voltage were measured, yielding a linear relationship. For the last run, outer probe current, outer probe voltage, and inner probe voltage were measured, yielding non-linear relationships between each pair of parameters.

On Slide 25, all four probes were first placed on the large vein, spaced uniformly about 1 mm. apart. One run was made, measuring outer probe current, outer probe voltage, and inner probe voltage. Results are shown in Figure 10. Here the relationship between outer probe and inner probe voltage was linear. Measurements were repeatable within less than one percent over a period of several minutes, and reversing the polarity at the battery caused no change in values.

Finally the two outer probes were positioned about 3 mm apart on the large vein in Slide 25 and one of the inner probes was used to explore the intervening area of the vein, the voltage on the outer probes remaining at a constant 10.0 volts. The
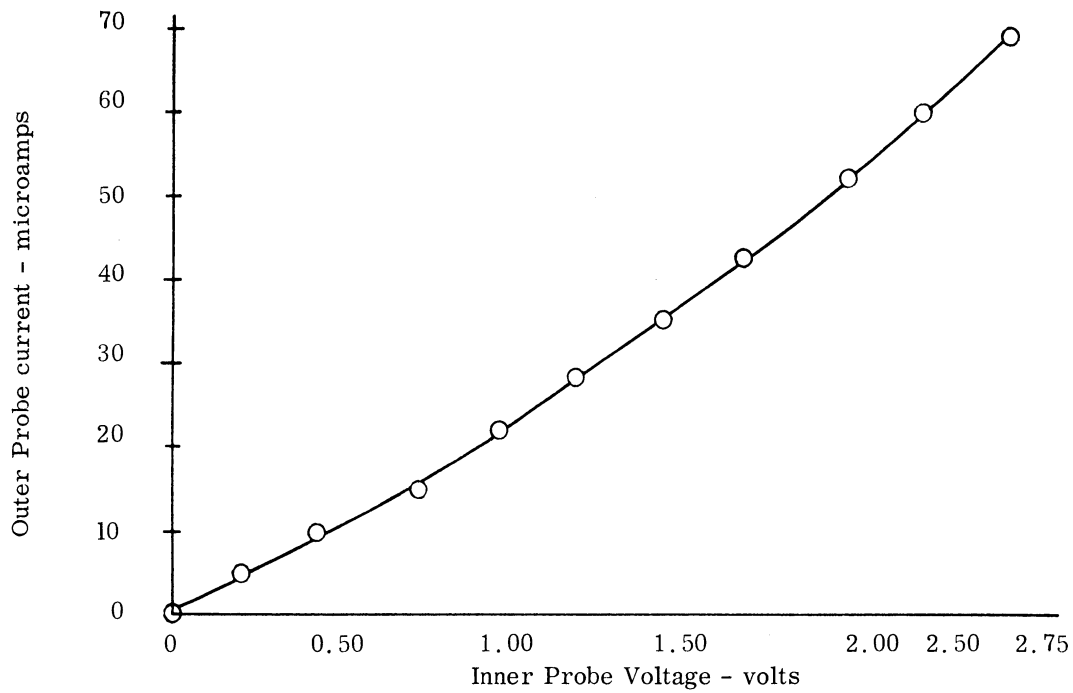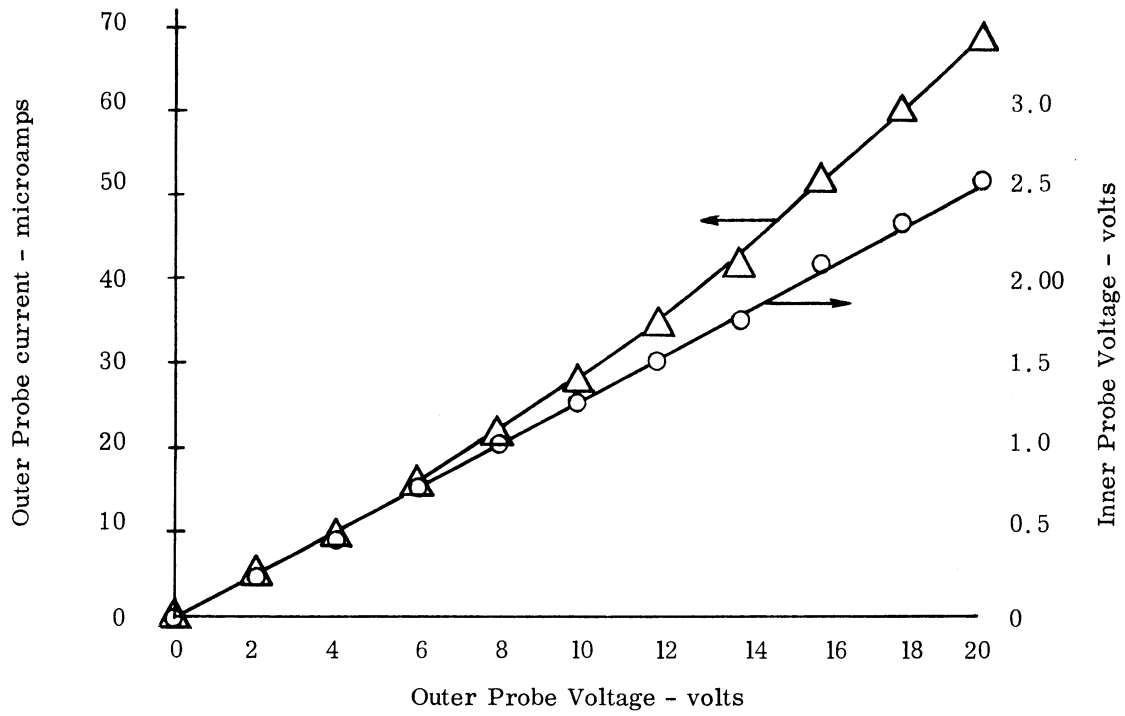
FIGURE 10. RESULTS OF FOUR-PROBE ELECTRICAL MEASUREMENTS
ON CALLIHAM SLIDE NO. 24.

outer probe current increased slowly over a period of two hours from 36 to 50

microamps, the power being on about 20 percent of the time. Reversing the

battery polarity had no effect on the values. The voltage between the inner probe and

one of the outer probes was measured, and the results were, to say the least, diffi-

cult to interpret; the vein apparently being as inhomogeneous electrically as it was

visually. A large part of the area of the vein, especially the central zone, gave

voltage readings near zero in relation to either probe. In general, the pattern of

potentials in the vein was extremely complex, and since the size of the probe was

large compared to the scale of visible inhomogeneity it was not possible to correlate

the voltage readings with, for instance, the different shades of gray within the vein.

Figure 9 is a typical example showing the inner probe near the positive probe in a

spot which gave a reading of -9.2 volts relative to the positive probe.

III

MICROSCOPIC AND ANALYTICAL INVESTIGATIONS

3.1 Techniques of Sample Preparation and Study

Since much of the time spent on this phase of the work was devoted to the

development of techniques, a brief description of these techniques will be given here.

3.1.1 Slices and Thin Sections

Some of the samples were polished and studied in the form of sawed slabs or

in the form of chunks with one side or corner sawed off to give a flat surface. For

most of the samples, however, slices 0.020 in. thick were cut from the edges of

slabs. This was done partly to conserve material, partly to provide more or less

two-dimensional sections of veins, and partly to provide a good starting point for

the preparation of true thin sections for study in transmitted light. The slices were

prepared by the Electrical Engineering Shop, using a diamond-impregnated disc on

a magnetic chuck grinder. Some of these slices were mounted in cylindrical mounts

of polyester resin or bakelite and many of them were mounted on microscope slides

using "Lake-side 70" cement.

Special techniques had to be developed for polishing the more friable

samples, although for the compact meteorites standard metallographic polishing

methods could be used. Even for compact specimens these standard methods, using cloth-covered metal laps with diamond paste abrasive, had the disadvantage of producing some relief on the surface due to the greater toughness of the metal and sulphide grains, but the method is quick and easy and the results are good enough for most purposes.

When the standard polishing methods are used for friable samples the small silicate crystals are plucked from the surface. For some of the less friable samples good results were obtained simply by using glass plates instead of cloth-covered laps and polishing by hand with two or three successively finer grades of abrasive powder in water suspension, but for the most friable specimens even this technique resulted in severe plucking.

Urey and Mayeda (Ref. 3) used a technique of plastic vacuum impregnation for their studies of the metal particles in chondrites. We have studied some of the samples prepared by them and it appears that this method prevents wholesale large-scale plucking but does not succeed in holding the smallest silicate and metal grains in place. We developed a method of surface impregnation using either "Lake-side 70" cement dissolved in alcohol or polyester resin. This method holds almost all the surface grains in place but does not result in very deep penetration, so that care is required during the preliminary polishing with 600-grit abrasive to avoid wearing away the impregnated layer. With proper care and the use of glass

plates and hand polishing it is possible to achieve very good results, but the process is rather tedious and time-consuming and was used on only a few samples. The final polish was always obtained by the very brief use of a cloth-covered metal lap with alumina abrasive, the lap having been specially prepared with a hard-textured cloth of the type generally used for diamond abrasive and without the use of a soft backing layer.

In the preparation of thin sections for observation in transmitted light, the slices were first polished on one side and then flipped over, being sure that the polished surface was parallel with the slide. (The cement is softened by heating to 140° F.) Rough grinding to a thickness of about 150 microns and polishing was done on a glass plate. Extreme care is required to maintain a uniform thickness over the whole sample.

Most of the microscopic examination of the samples was done on polished opaque sections under vertical illumination. In this type of light the silicates appear as various shades of dark gray with grain boundaries mostly invisible. Nickel-iron grains are a brilliant white, but since the samples were not etched, it is not possible to differentiate between the two metallic phases kamacite and taenite. The sulphide grains are a brilliant yellowish white. Under polarized light FeS_2 appears black at all orientations while FeS grains vary from gray to black as the stage is rotated, making it possible to determine the size of individual crystals. The

hydrated iron oxides appear as various shades of light gray and the chromite and/or magnetite grains are a uniform light gray.

When dark field illumination is used on polished sections the metal and silicate areas and the chromite/magnetite grains appear black, while the hydrated oxides vary from light orange-red to dark red. The silicate crystals are white to light orange, and areas of glass or recrystallized glass can be distinguished by their finer compact texture and sometimes by their color since they usually appear nearly black (probably due to their content of very small sulphide or metal particles).

Thin sections examined with transmitted polarized light show the structure of the silicate minerals and glass areas, and the minerals may be identified by petrographic techniques. The metals, sulphides, and magnetite of course are black, and the chromite is also black except that very thin edges may show a reddish transluscence when the analyzing prism is not used. The hydrated oxides are transluscent to opaque with reddish-orange hues.

Our thin sections were made with a highly-polished surface and without cover glasses; they appeared the same as ordinary thick polished sections in vertical illumination providing there was no reflecting surface below them. This was a valuable feature with the Leitz "Panphot" microscope, which could be used with either reflected or transmitted light by flipping a mirror in the illuminating system. Observation of thin sections in vertical polarized light gave a particularly revealing view of their structures.

3.1.2 Sulphur Prints

This technique provides a simple method of identifying and locating sulphides on polished surfaces. Ordinary photographic paper is soaked in dilute sulphuric acid and the sample is pressed against the wet paper for a few seconds. Where-ever a sulphide is present a dark spot appears on the paper.

This technique was used occasionally during the early part of the program. It has the disadvantage of being destructive, and its use was discontinued in our work, since the sulphides could be identified visually.

3.1.3 Electron Beam Microanalyzer

We had two sessions of two days each with an electron beam microanalyzer (EBM) belonging to the Advanced Metals Research Corporation of Somerville, Massachusetts.

This instrument operates by bombarding the sample surface with a beam of electrons approximately one micron in diameter. The x-rays emitted by the bombarded area are diffracted by a mica crystal and the diffracted beam is sensed by a scintillation counter. Elements with atomic weights below that of sodium cannot be detected, but for the other elements concentration can be obtained to within a few weight percent using approximate corrections and to within a few tenths of a percent using refined correction calculations.

The EBM can be used in two basic modes. Either the beam can be left on

one spot and the diffracted x-ray beam scanned for all the elements or the detection equipment can be peaked on one wavelength and the sample moved around under the electron beam to determine the concentration of a given element in any area relative to a standard for that element which is mounted beside the sample. Most of our time with the instrument was spent using the latter mode of operation.

3.1.4 X-Ray Diffraction Analysis

X-ray diffraction analysis of powder camera records was used to identify some of the minerals. Samples were obtained at first by sawing small segments of material from the edges of 0.015-inch slices mounted on glass slides. The saw was a special instrument fabricated primarily for use in isolating sections of oxide vein for electrical work. The sawing technique proved to be very laborious and was used only once. However it proved possible to obtain good samples from areas the size of the larger metallic grains by using a fine-tipped dental burr.

3.1.5 Photography

Many photographs of the samples were taken with a standard metallographic camera, at magnifications of from 70 x to 250x. Special camera equipment was set up to make macrophotographs of entire samples at approximately 5x from which enlarged prints were made with a scale of 10:1. The primary purpose of the photographs was to help in the work with the EBM, but they were also useful for all other phases of the study.

3.2 Results of Investigations

3.2.1 Hydrated Oxides

When examined under vertical illumination practically all the meteorites we have studied are seen to contain a network of gray veins. These are the surface expressions of thin interlacing sheets of oxide which fill cracks in the silicates and to a lesser extent in the metal and sulphide grains. (See Figure 11.) These veins range in size from several tens of microns down to the limit of vision. There are also gray grains which represent replacement of metal or sulphide grains by oxide; examples of all stages in the replacement process can often be found in one sample. (Figure 14) These oxides are present in all our samples of "finds"; they occur also in most of the "falls", but always less well developed both in extent and in size.

The vein walls are typically sharp and fresh-looking with no apparent reaction between the vein material and the walls; opposite walls would fit together if the vein were removed, although there are some exceptions to this. In meteorites with large and numerous oxide veins there is usually some void space in both the veins and the grains, as if the process of filling had not been completed.

The vein material appears inhomogeneous in all types of light. This is best observed in vertical illumination where one can see a complex banding of various shades of gray in all but the smallest veins. The banding is more or less parallel to the vein or grain boundaries and represents a cross section of colloform
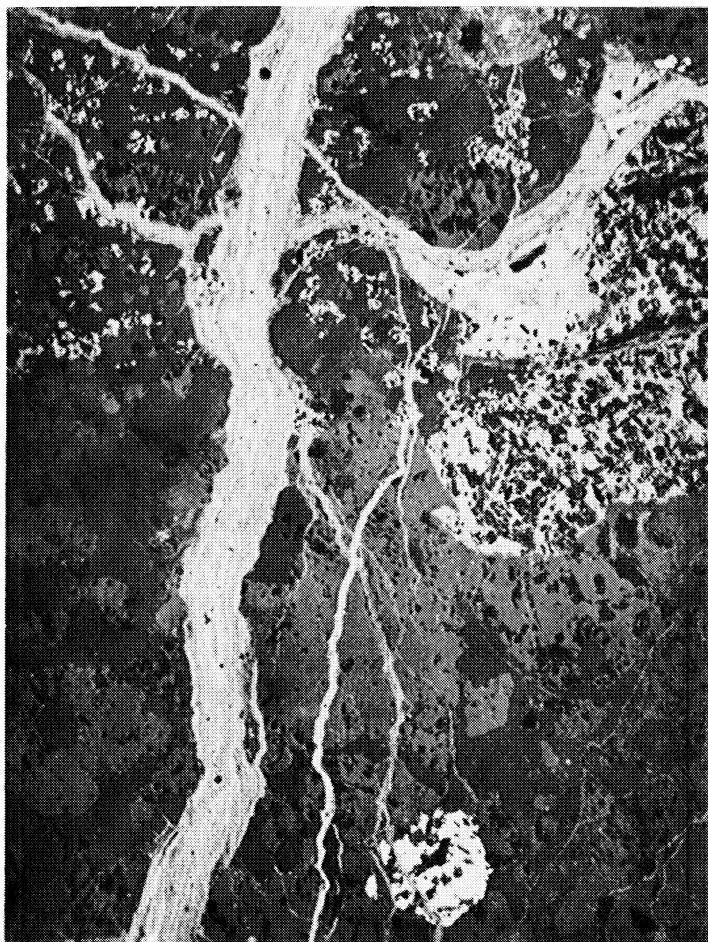
FIGURE 11: TYPICAL HYDRATED OXIDE VEINS IN CALLIHAM. LIGHT GRAIN NEAR BOTTOM OF PHOTO IS TROILITE. A LARGE TROILITE GRAIN OCCUPIES MOST OF UPPER RIGHT PORTION OF PHOTO BUT APPEARS SOMEWHAT DARKER DUE TO LIGHTING. (X 250).

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structure which results from layer-by-layer deposition of material on the walls. Exceptions to this are found in Calliham and will be discussed below.

The appearance of the oxide veins and grains is closely similar to what is observed on polished sections of samples taken from near-surface oxidized zones of terrestrial sulphide ore bodies, and the material in the meteorite veins has been shown by our x-ray diffraction analysis and by our EBM work to be essentially the same as the material in these terrestrial occurrences. The hydrated iron oxides are loosely termed limonite and were formerly thought to be amorphous. They actually occur as sub-microscopic crystals of several different minerals, the most common of which are goethite and lepidocrocite (gamma and alpha $Fe_2O_3 \cdot H_2O$ respectively); lines for both these minerals have been identified in the x-ray films. The EBM analysis of the oxides showed that in most cases they contain about five percent nickel, and rarely up to ten percent or more. Some spots contained up to about five percent of silicon and sulphur. The nickel content seemed to correlate with the color of the oxide, tne darker areas being richer in nickel. Where the electron beam remained for a considerable length of time on one spot, there developed on the oxide a network of the fine cracks suggestive of dehydration.

It was mentioned above that our samples of Calliham contain unusual structures in the oxide veins. These are rhythmic transverse bands of lighter and darker oxide material which occur in some areas of the smaller veins. (Figure 12)

FIGURE 12: HYDRATED OXIDE VEIN IN CALLIHAM WITH
TRANSVERSE BANDING. SMALLER UNBANDED
GRAINS CUT THE SILICATES AND THE LARGE
TROILITE GRAIN. DARK MARKINGS ON THE
TROILITE ARE PITS CAUSED BY POLISHING
(X 250).

The bands are always very nearly perpendicular to the vein walls. Spacing of the bands is roughly equal to the vein width. (Of course the apparent width of any vein on a polished surface depends on the angle at which the surface cuts the vein.) There is some tendency for the banding to occur in the vicinity of sharp bends in the vein. The individual bands are too small to be reliably distinguished by the EBM beam, but a scan along one of them showed a rhythmic variation in nickel and iron content with nickel varying from about 2% to about 5% and iron varying inversely from about 58% to about 65%.

There are several instances in various meteorites where an oxide vein changes abruptly into a sulphide vein and one large vein in Potter has large remnant patches of sulphide. It is possible that many if not all oxide veins are actually replacements of sulphide (or metal) veins by oxide. The oxide grains do in many cases show "ghost" structures of the material replaced; the best examples of this are in Kingfisher where metal crystal boundaries are sometimes preserved as ghosts in the oxide. This may be the explanation of the banded oxide veins in Calliham.

The hydrated oxides are generally assumed to be of terrestrial origin, that is they are the result of corrosion of the meteorite after it landed on the earth. This is partly an assumption; however, it is supported by the fact that these oxides are clearly more abundant in "finds". It would be very surprising if hydrated oxides

had not formed in "finds". Proof that some of the oxide veins are of terrestrial

origin has been observed in a very few instances where the veins are present in the

fusion crust. The opposite case, of oxide veins apparently destroyed during the

formation of the fusion crust, has not been observed. The puzzling fact remains

that some meteorites which were picked up a few days or even hours after they

were observed to fall have extensive (though small) oxide veins and incipient oxide

replacements of grains. It is difficult to see how this could have happened on a

museum shelf.

3.2.2 Metal and Sulphide

The nickel-iron and sulphide grains were not studied in detail. No etching

was done, so that the relationships between the two possible nickel-iron phases

(taenite and kamacite) could not be seen. However, certain information can be

obtained from the shape of the grains, from the crystal sizes in the sulphide grains,

from inclusions in the grains, and from metal and sulphide veins.

The shape of these grains suggests unequivocally that they are interstitial

to the silicates; that is, they were the last material to solidify, although they may

originally have been present as solid grains in a breccia or angular "sand" of

silicates and metallic particles. They are highly irregular in outline and the finer

details of their shape appear to be determined by the shape of the adjacent silicate

grains. On well-polished surfaces one can often see very fine veins of metal or

sulphide extending from a grain into cracks in the silicates (Figure 13), sometimes

giving an overall "shredded" appearance to the borders of the metallic grains

(Figure 14). In a few chondrites the metallic grains contain fragments of silicate

crystals, usually somewhat rounded. This can be unmistakably seen in Hessle

(Figure 15); of course, most occurrences of "islands" of silicate in metallic grains

are due to the accidental plane of cutting in the sample. (A different situation is

seen in the achondrite Abee where the nickel-iron grains contain phenocrysts of

silicate which grew in the molten metal.)

Urey and Mayeda [3] found that the metal grains in chondrites contain taenite,

kamacite, and plessite (a fine mixture of taenite and kamacite) in various combina-

tions suggesting that the grains cannot have been molten after they arrived at their

present locations within the meteorites. This contradicts the findings set forth

above, and the two viewpoints are difficult to reconcile on the basis of the work we

have done. Urey and Mayeda's hypothesis supposes that the chondrites are random

mixtures of metallic and silicate materials, a view which is opposed by most

authorities on the basis of evidence from a large number of analyses which suggests

that most meteorites are in chemical equilibrium and that there is a rather smooth

variation in oxidation state of the iron and in nickel content of the nickel-iron among

all chondrites. (See, for instance, Ringwood [4] .)

The sulphide grains have in general the same mode of occurrence as the

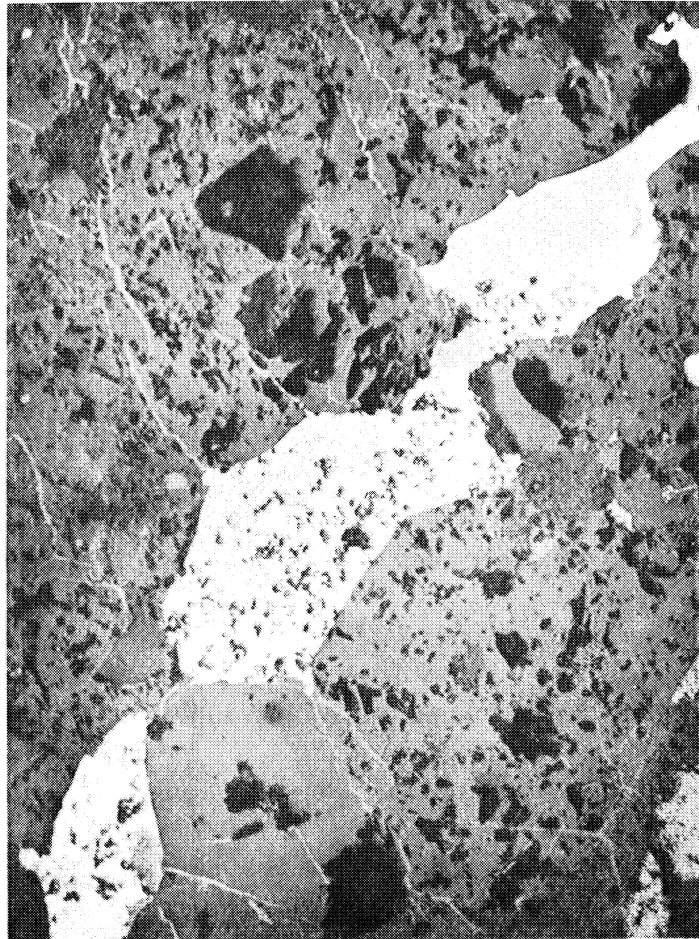nickel-iron and in different meteorites may be more plentiful or less plentiful

FIGURE 13: AREA IN HARRISONVILLE REMOTE FROM FUSION
CRUST AND DARK VEINS SHOWING FINE VEINS EXTENDING
FROM GRAINS. CLEAR WHITE AREA IS NICKEL-IRON.
PITTED WHITE IS TROILITE. GRAY GRAIN AT LOWER
RIGHT CORNER IS CHROMITE. MOST VEINS HAVE BEEN
REPLACED BY HYDRATED OXIDES. (X 250).
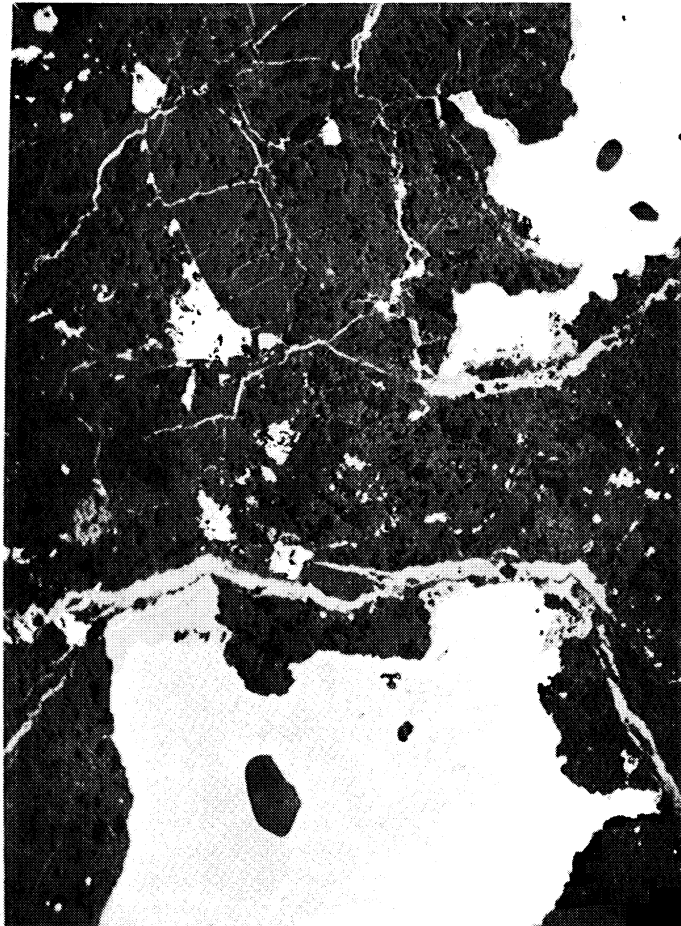
FIGURE 14: AREA IN PLAINVIEW REMOTE FROM FUSION CRUST
AND DARK VEINS SHOWING "SHREDDED" GRAIN
BOUNDARIES: THE TWO LARGE WHITE AREAS ARE
NICKEL-IRON. ALL SMALLER WHITE AREAS ARE
TROILITE. THERE ARE NUMEROUS HYDRATED
OXIDE VEINS, AND THE NICKEL-IRON IS PARTIALLY
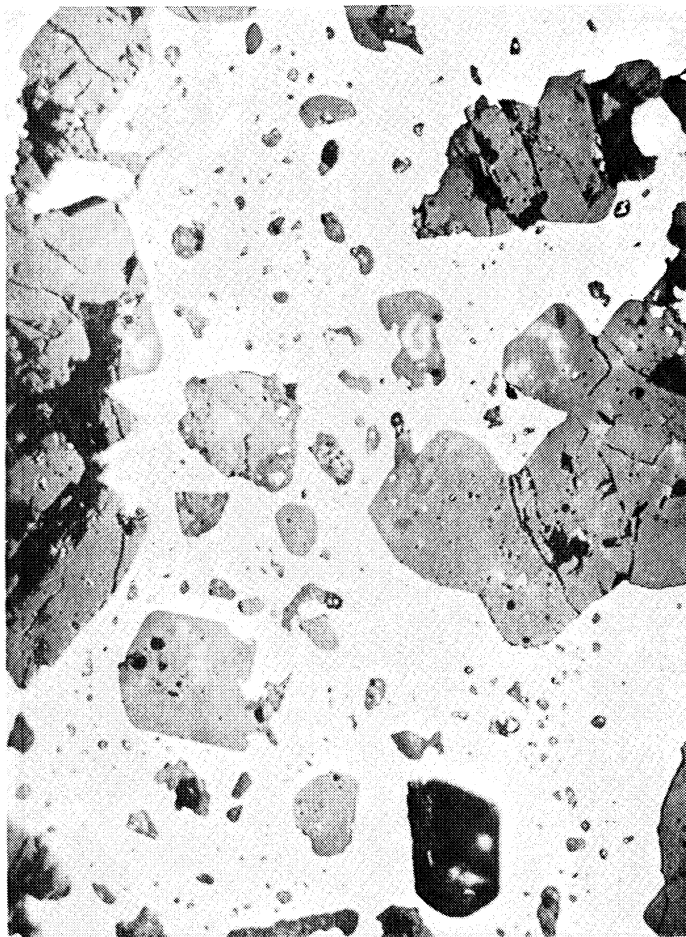REPLACED BY HYDRATED OXIDE. (X 250).

FIGURE 15: LARGE NICKEL-IRON GRAIN IN HESSLE CONTAINING
FRAGMENTS OF SILICATE CRYSTALS. (X 250).

than the metal. In some meteorites even the large grains are mostly monocrystalline (e.g., Calliham) while in others (e.g., Harrisonville) they are polycrystalline. It is rather common to see irregularly-shaped areas in a sample surface which are rich in small sulphide grains, as if a large grain had been partially dispersed. In some samples (e.g., Kingfisher) the large metal grains are often surrounded by a region of small sulphide grains.

The sulphide is nominally troilite (FeS), but is actually $(Fe, Ni)S$. The nickel content as determined by the EBM is generally about 1 or less, although in a few cases it was somewhat higher and in one case was about 25%. In Calliham the EBM identified one grain of pyrite (FeS_2); two nearby grains appear by their shape and optical properties to be the same. These are euhedral crystals and are in contact with troilite. The nickel content of the pyrite grain was about 0.5% and the adjacent troilite had about 5% nickel.

3.2.3 Chromite

This mineral occurs in inrregular grains similar to the metals and sulphides but without shredded boundaries. It is more rarely seen as euhedral crystals within metal grains. It occurs rather commonly as minute octahedra in small areas of glass (or devitrified glass). The octahedra generally occur in linear groups and are often associated with a normal large chromite grain which appears to have been partially melted. (See Figure 16)
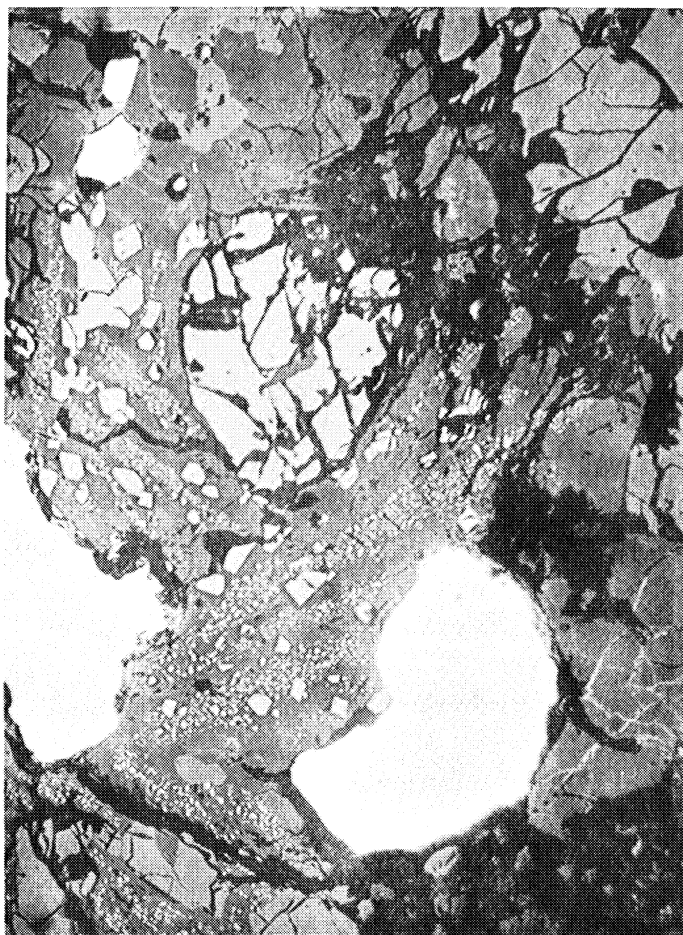
FIGURE 16: AREA IN MODOC WITH CHROMITE OCTAHEDRA IN
DIVITRIFIED GLASS. DARK GRAY IS GLASS, MEDIUM
GRAY IS SILICATE CRYSTALS, AND LIGHT GRAY IS
CHROMITE. WHITE AREAS ARE NICKEL-IRON. THE
CHROMITE OCTAHEDRA MAY BE DERIVED FROM THE
LARGE FRACTURED CHROMITE GRAIN NEAR THE
CENTER OF THE PHOTO. (X 250).

Chromite grains or octahedra were examined in four spots on Calliham and Modoc with the EBM. Chromium content was from about 12% to about 30% . One spot showed about 20% nickel, but the others had less than 1% . Aluminum was searched for in one large grain and in an adjacent crystal and was found in a concentration of about 5%.

3.2.4 Dark Veins

The dark veins which give "veined chondrites" their name appear dark to the naked eye and are opaque in thin sections. Under the microscope with vertical illumination they do not appear markedly different from the silicate "host rock" of the meteorite except that they usually contain many globular, spheroidal, or lacy inclusions of nickeliferous troilite and less commonly of nickel-iron. Figures 17 and 18 show typical examples.

In dark field illumination these veins appear distinctly darker than the host rock, being composed of glass or submicroscopic crystals. Boundaries with the host rock are distinct but smoothly rounded, and where crystals from the host rock have been entrained in the vein material their corners are rounded. The sulphide and metal in these veins has probably been entrained from grains in the host rock. Where a sulphide or metal grain forms part of a vein boundary the grain appears shredded with lacy extensions entering the vein material, and commonly there is evidence for flow with filaments of the grain material parallel to the vein walls.
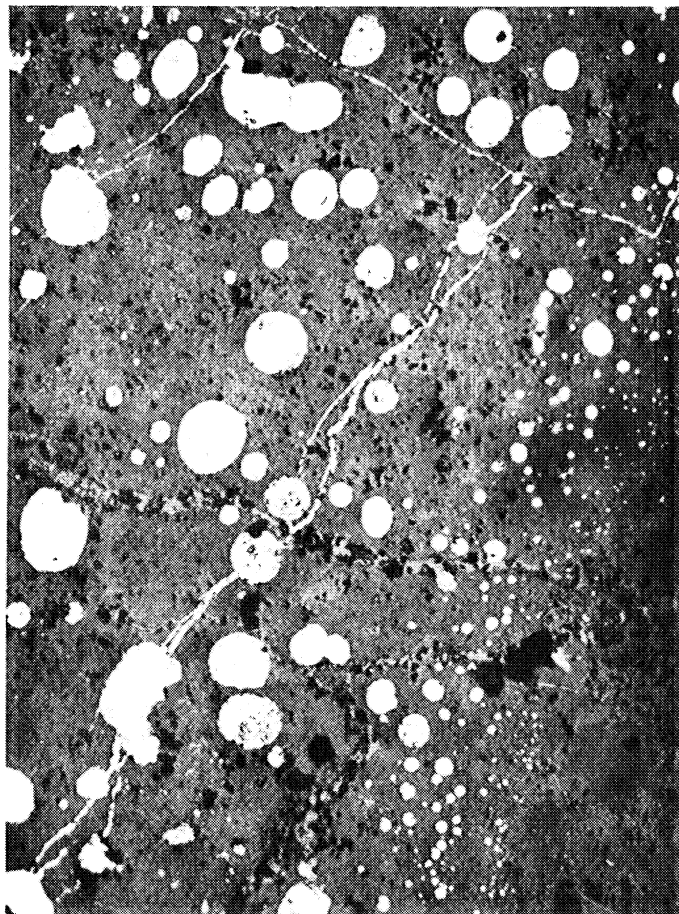
FIGURE 17: DARK VEIN IN HARRISONVILLE. THE SPHEROIDAL
GLOBULES AND THE VEINS ARE TROILITE. BOUNDARY
OF VEIN IS AT LOWER RIGHT. (X 250).

FIGURE 18: DARK VEIN IN FOREST CITY. LARGE NICKEL-IRON
GRAIN FORMS LEFT BOUNDARY OF VEIN. THE
SPHEROIDAL GLOBULES AND THE LARGE GRAIN
AT BOTTOM CENTER APPEAR TO BE MIXTURES OF
NICKEL-IRON AND TROILITE. (X 250).

The globules in the veins are mostly of sulphide with metal globules appearing only in close proximity to metal grains in the boundaries. The globules range in size from a few microns down to the limit of vision and the smaller ones are nearly spherical. There is a definite tendency for the globules to be larger in the central portion of a vein probably due to the fact that the central portion was the last to solidify and the globules had more time to coalesce. Small veinlets of sulphide often occur, generally as off shoots from globules or as connections between several globules. The material in the veinlets appears to be continuous with that in the globules and no doubt they are the result of cracking of the glassy vein before the sulphide solidified. Where a veinlet transverses a globule the two halves of the globule are sometimes displaced relative to each other.

The larger sulphide globules are very finely polycrystalline; it is not possible to see whether or not the smaller ones are monocrystalline. In veins where there are both metal and sulphide globules, some globules appear to have a eutectic structure of metal and sulphide; this was not confirmed with the EBM but the structure is very fine.

The bulk of the dark vein material in Harrisonville was shown by the EBM to be very rich in silicon (30-40%) with about 10% iron, 5% calcium, and traces of nickel and aluminum. In the two areas for which element scans were performed no magnesium or sodium were found.

The dark veins were probably formed in the meteorite parent bodies. They do not seem to be continuous with the fusion crusts and it is unlikely that such large and numerous cracks could have formed and been filled during a meteorite's flight through the earth's atmosphere without wholesale disintegration.

3.2.5 Glassy Areas

The small glassy areas found in most chondrites have been mentioned above as being the home of small chromite octahedra. (See Figure 16.) This material is probably in most cases a cryptocrystalline devitrified glass. In vertical illumination it appears slightly darker than the crystalline silicates and occurs interstitially to them, or occasionally as lamellae between partings of large crystals. In dark field illumination it appears distinctly lighter than the crystalline silicates; in thin section its glassy or cryptocrystalline nature is apparent. This material may in part be the so-called maskelynite or vitreous plagloclase mentioned in the literature. The EBM results on a few spots suggested the presence of higher aluminum, silicon, and calcium content and lower iron content than in the matrix crystals. The visually-observed structural relationships, and particularly the occurrence with included chromite octahedra from adjacent remelted chromite grains, indicate that the "glassy" areas may be the result of intense local heating followed by rather rapid cooling. It might be useful to investigate the possibility that shock waves are the responsible agents.

3.2.6 Fusion Crusts

Most of our samples of observed falls and some of the "finds" include portions of the fusion crust, which in all cases looks very similar. An example is shown in Figure 19. The crust is quite thin, approximately 0.5 to 1 mm, and appears to the naked eye as a black selvedge on the polished section. When observed under the microscope in vertical illumination it is seen to consist of two zones. The outer zone, which may be missing in some areas, is less than 0.5 mm thick and is a region of ablation and flow consisting of glass with many minute gray inclusions which may be magnetite; they are too small for their shapes to be resolvable, and too small also for identification with the EBM. The inner zone has been altered by partial melting of the constituents, with areas of glass and many veinlets of sulphide and metal filling a network of cracks in the crystals and glass. Chromite grains are often cut by these veinlets and evidently the chromite did not melt until it was reached by the ablation zone. There are very rare occurrences of metal or sulphide globules in the glass of the inner zone.

FIGURE 19: FUSION CRUST ON MODOC. THE BLACK RIM ALONG THE
OUTER EDGE OF THE CRUST AT RIGHT IS CAUSED BY
ROUNDING OF THE EDGE DURING POLISHING. OUTER
ZONE OF CRUST IS HERE ABOUT THE SAME WIDTH AS
THIS BLACK RIM. THE WHITE GRAIN NEAR BOTTOM
EDGE OF PHOTO IS SULPHIDE; OTHERS ARE NICKEL-IRON.
THE VEINS ARE SULPHIDE. THE OUTER EDGE OF THE
LARGEST GRAIN HAS A RIM OF SULPHIDE (NOT EASILY
SEEN IN THE PHOTO) WHICH IS PARTIALLY REPLACED
BY LIGHT GRAY HYDRATED OXIDE. ($\times$250).

IV

CONCLUSIONS

4.1 Electrical Investigations

All measurements of conductivity versus field intensity and temperature

with bulk samples showed non-linear relationships. Two meteorites had such low

conductivities that they could not be measured with the available equipment. For

temperatures below approximately 150° C the conductivity of most samples was

found to be a power function of absolute temperature for constant voltage and of

voltage for constant temperature. At temperatures above approximately 150° C

the behavior was complicated for most samples by the appearance of reversible and

irreversible changes in the form of the relationships, the cause of which was not

determined.

Probe measurements with a resolution on the order of millimeters showed

that the samples were electrically very inhomogeneous and that the conductivity was

probably due to the network of fine veins.

Two probe and four-probe measurements on polished 0.015-inch thick

samples with a resolution on the order of tens of microns showed that the veins

themselves were electrically inhomogeneous; the non-linear relationship between

conductivity and field intensity was usually observed for those regions which had

measurable conductivities.

4.2 Microscopic and Analytical Investigations

Techniques of preparing polished sections and polished thin sections of

friable meteorites were perfected. Powder samples from microscopic grains were

obtained by a drilling technique. Analysis of the samples was carried out by x-ray

diffraction analysis, by means of the optical microscope, and by the use of an

electron beam microanalyzer.

The veins which are responsible for the electrical conductivity of the

meteorites were found to be nickeliferous hydrated iron oxides, probably of

terrestrial origin. Evidence was found that the metal and sulphide grains in

chondrites have in most cases been molten since the meteorites achieved their

present configuration, and that perhaps many of the oxide veins are replacements

of metal and sulphide veins. The large dark veins in veined chondrites, which

contain numerous spheroidal globules of sulphide, and less commonly of metal,

are thought to be the result of invasions of the meteorite by hot liquid silicate with

resultant melting and entrainment of local metallic grains; a process which probably

occurred in the meteorite parent body rather than during the flight through the

earth's atmosphere.

Most chondrites have more or less numerous small areas of glass or of

cryptocrystalline devitrified glass which sometimes contains minute crystals of chromite. The chromite appears to have been derived from adjacent large grains by remelting and subsequent rapid cooling, and the glass may have a similar origin. It is suggested that shock waves may have been the responsible mechanism.

APPENDIX I

LIST OF METEORITES STUDIED

A. Samples purchased from American Meteorite Museum, Sedona, Arizona, and American Meteorite Laboratory, Denver, Colorado.

Name	AML No.	Class	Date Found
Beenham	414.71	Intermediate chondrite	1937
"	.82	" "	"
"	.172	" "	"
"	..223	" "	"
Brady	384.3	Chondrite	1937
Briscoe Co.	477.4	Gray chondrite	1940
Calliham	670.14	Chondrite	Recog. 1958
Harrisonville	176.34	Veined gray chondrite	1933
Holly	386.7	Chondrite	1937
Hugoton	280.48	Brecciated crystalline chondrite	1935
"	.335	" " "	"
Kelly	398.25	White to gray brecciated chondrite	—
Kingfisher	601.25	Black chondrite	1950
Ladder Creek	405.60	Spherical crystalline chondrite	1937
La Lande	464.181	Spherical crystalline chondrite	1933
Leedy	—	Chondrite	Fell 1943
Morland	282.1	Crystalline chondrite	1935
Norcatur	525.16	Veined intermediate chondrite	Recog. 1948
"	.18	" " "	"
"	.24	" " "	"
Plainview	92.1277	Fragments of spherical	1917
"	.1280	Chondrite embedded in	"
"	.1281	veined intermediate chondrite	"
"	.1290	"	"
"	—(?)	"	"
Potter	476.30	Brecciated veined gray chondrite	1941
"	.75	" " " "	"
Roy	234 K	Spherical crystalline chondrite	1933
Taiban	541.7	Black chondrite	1934

B. Samples loaned by University of Michigan Geology Department from Perry Collection

Name	P.C. No.	Class	Date of Fall
Alfianello	117	Intermediate hypersthene chondrite	1883
Beardsley	23A	Chondrite	1929
Forest City	11	Brecciated spherical bronzite chondrite	1890
Hessle	110	Spherical bronzite chondrite	1869
Linwood	190E	Iron, coarsest octahedrite	Found 1940-41
Modoc	73	Veined white hypersthene chondrite	1905
Pultusk	2301	Veined gray bronzite chondrite	1868
Richardton	100.41	Veined spherical bronzite chondrite	1918
Rose City	16 F	Brecciated black bronzite chondrite	1921

C. Samples loaned by Professor H. C. Urey, University of California, LaJolla.

Name	Class	Date	
Abee	Achondrite	Fell	1952
Allegan	Chondrite	Fell	1899
Carcote	Crystalline bronzite chondrite	Found	1888
Densmore	Chondrite	Found	1879
Estacado	Crystalline bronzite chondrite	Found	1883
Gilgoin Station	Crystalline bronzite chondrite	Found	1889
Mocs	Veined white hypersthene chondrite	Fell	1882
Modoc	Veined white hypersthene chondrite	Fell	1905
Tulia	Veined crystalline chondrite	Found	1924

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