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A laboratory study of some physical properties of sulfide ores in igneous and metamorphic rocks from the Burnt Nubble area, Somerset County, Maine

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Gordon R. Johnson and Lennart A. Anderson

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ABSTRACT

Laboratory measurements of resistivity, induced polarization, bulk density, and sulfide content were made on 72 core samples obtained from drill holes near Burnt Nubble, Maine. These different types of measurements were compared to reveal the interdependence of the respective data sets; such interdependence may be of value in the interpretation of geophysical field data. Sulfide content plotted against the induced-polarization response, normalized by resistivity and expressed as the effective metal-conduction factor, is considered the most useful for evaluating induced polarization surveys in terms of distribution and approximate content of sulfide minerals at the Burnt Nubble site.

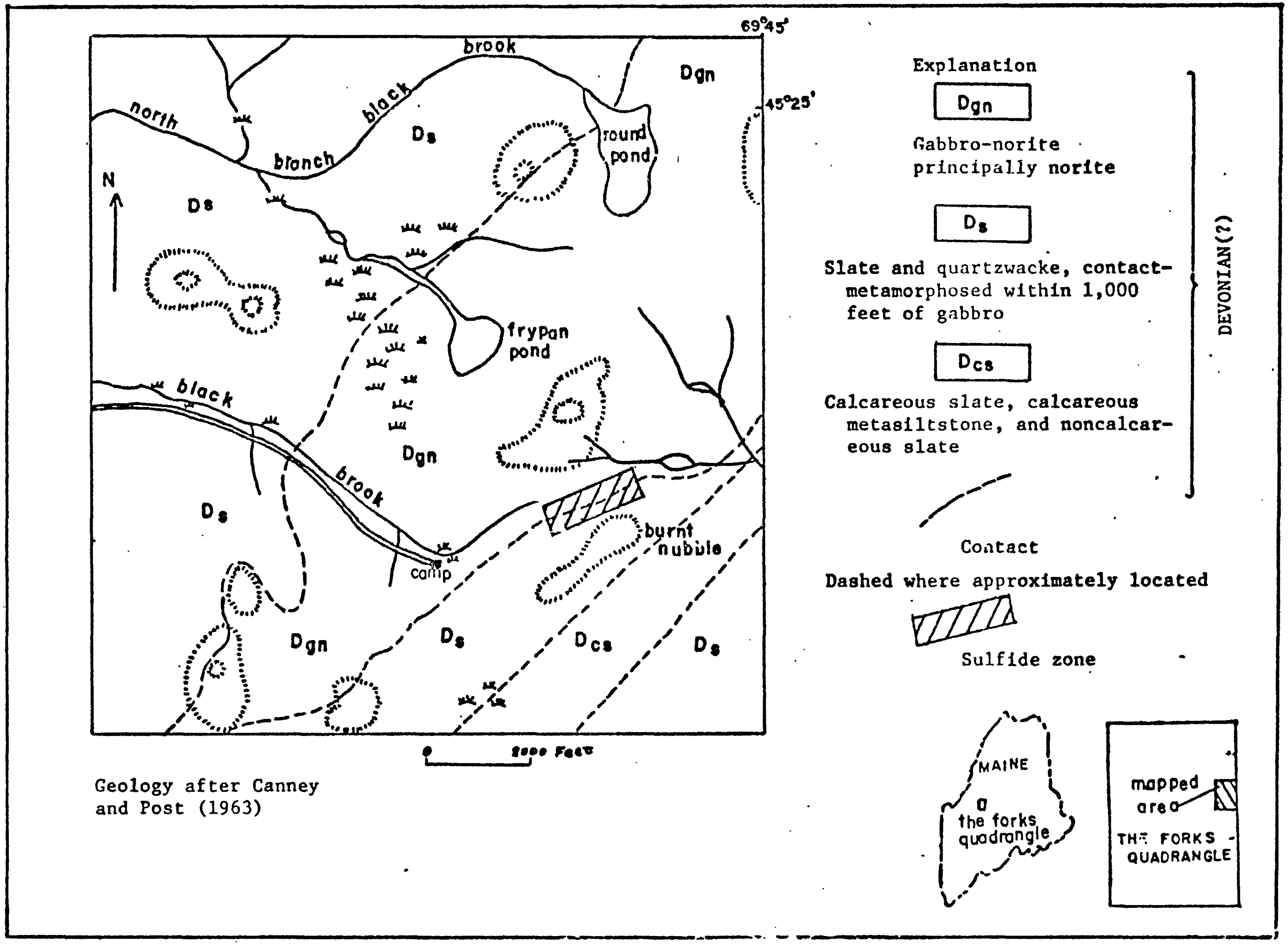
Introduction

A study of the interrelationship of certain rock properties, relevant to commonplace geophysical field techniques, was made on 72 diamond drill core samples obtained from the site of a sulfide prospect north of a topographic feature known as Burnt Nubble in The Forks 15-minute Quadrangle, Somerset County, Maine. Figure 1 shows its location and the general geology of the area as mapped by Canney and Post (1963). The principal geologic feature on the map is the norite-gabbro intrusive, which is part of the Moxie Pluton described in detail by Espenshade and Boudette (1967). The intruded rock is a fine-grained clastic metamorphic rock consisting of slate and quartzwacke that have been altered to hornfels in the vicinity of the intrusion. Sulfide minerals, primarily pyrrhotite, but including minor amounts of chalcopyrite and pentlandite, are found in both the intrusive and intruded rock within the indicated zone in figure 1. Localized pods of disseminated magnetite exist throughout the drilled section. Core samples, provided by Frank Canney of the U.S. Geological Survey, were of an altered norite, now mostly gabbroic in composition.

The object of this laboratory investigation was to provide background data that may be of value in the interpretation of geophysical surveys made in the area. Resistivity, induced-polarization (I.P.), and grain-density measurements were made on the samples. Emphasis was placed on the measurement of induced polarization and resistivity because these parameters can sometimes be used to define the manner of distribution of the sulfides and to some degree the relative bulk volume of sulfides within the host rock (Summer, 1976).

Cores were collected from four drill holes and samples taken at approximately 10-foot intervals. Each sample was selected so as to represent the sulfide distribution in that 10-foot interval from which it was taken.

The relationship between amplitude of polarization, or overvoltage, and current density was determined on a specimen of Burnt Nubble pyrrhotite before



Geology after Canney and Post (1963)

Figure 1 - Map showing location of the Burnt Nubble sulfide prospect and the generalized geology of the surrounding area.

I.P. was measured on the core samples. This was done in order to select a current density in the linear range of the I.P. response that could be used when measuring the induced polarization on the samples, thereby assuring that I.P. differences between samples would be a function of sulfide content rather than a variation in current density alone. After all physical and electrical measurements were made, a representative group of samples were crushed and the sulfide content of each sample determined by heavy-mineral separation and sulfur analysis.

Polarization characteristic of Burnt Nubble pyrrhotite

The amplitude of the induced polarization measured on a sulfide-bearing rock is dependent on the current density at which it is measured (Anderson and Keller, 1964). In induced polarization field surveys, the current densities used are so small ($<<10^{-7}$ amp/cm^2) that the nonlinear aspects of the polarization response can be ignored. However, in laboratory I.P. measurements a wide range of currents is available from the energizing source, and large variations in the amplitude of the measured effect can result solely from changes in current density. A determination of the polarization response as a function of the current density can therefore be useful in selecting current levels for measurements of induced polarization on core samples. The term overvoltage is often used in place of the more general term polarization to distinguish those effects observed at the interface of a metallic mineral grain and the surrounding electrolyte from those effects caused by restrictions in ion mobility within a rock, which is commonly called membrane polarization.

The procedure used in producing an overvoltage curve closely followed that described in Anderson and Keller (1964). Figure 2 shows a typical curve derived from individual measurements of the anodic and cathodic potentials across a sample of Burnt Nubble pyrrhotite and plotted as a function of the logarithm

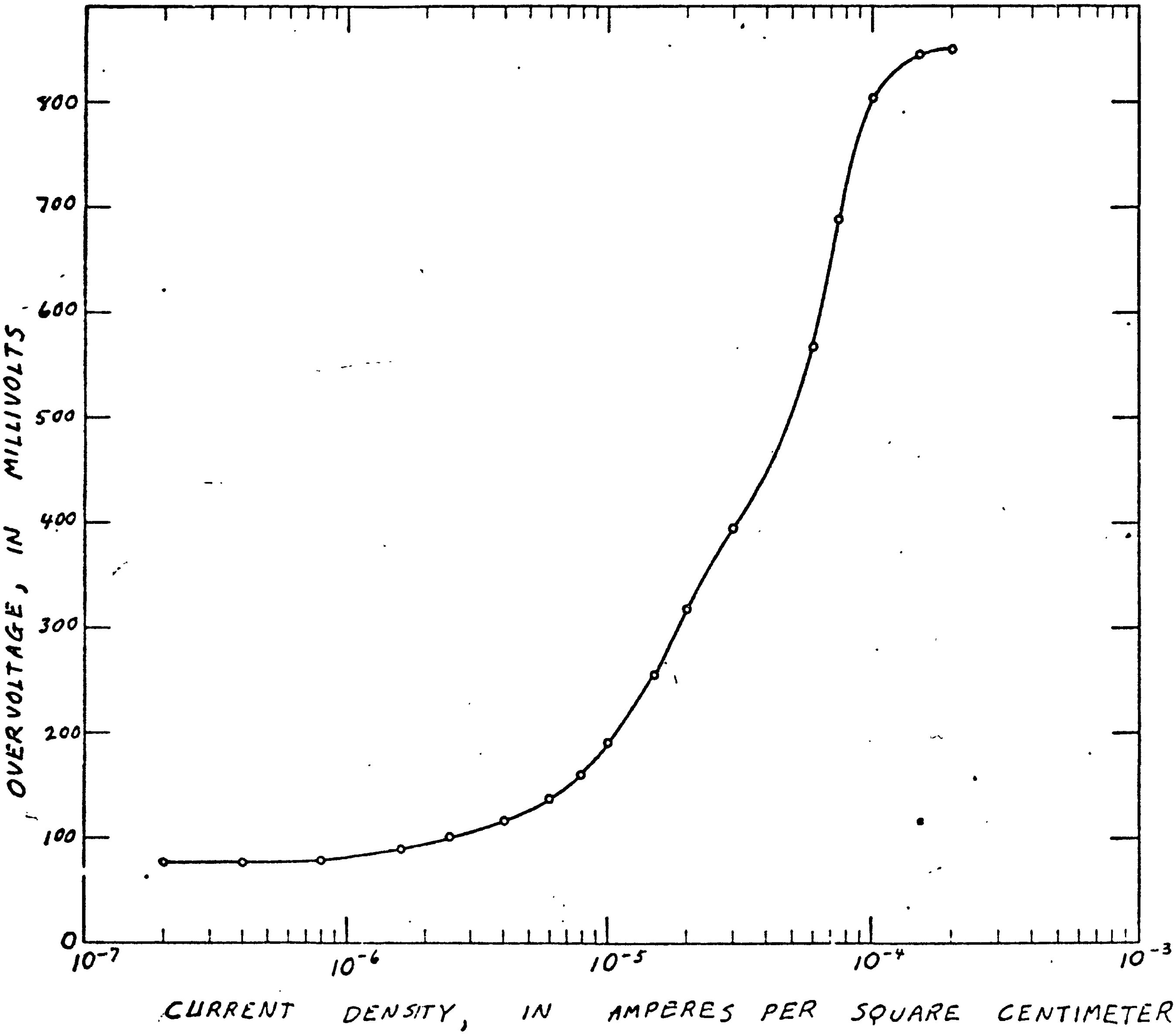


Figure 2. — Overvoltage measured as a function of current density for a sample of pyrrhotite from Burnt Nubble, Maine.

of current density. The measurements were made within a range of current densities from $2x10^{-7}$ to $2x10^{-4}$ $amps/cm^2$ with the sample in contact with a 0.05N H_2SO_4 solution. A charge time of 3 seconds was used at the respective current densities indicated on the plot. The curve illustrates the large variations in the overvoltage response that may occur with a very small change in current density, particularly at current densities in excess of 10^{-5} amp/cm^2. To minimize errors related to current variations, the I.P. measurements described herein were made at current densities less than $3x10^{-6}$ $amps/cm^2$.

Induced-polarization and resistivity measurements

The 1-5/8 inch diameter core samples were trimmed to a uniform length of 3 inches, placed in a dessicator, and subjected to a vacuum of less than 1.0 millimeter of mercury for a period of about 24 hours. After this procedure was completed, distilled water was introduced into the dessicator, and the rocks were permitted to soak for several days for maximum water saturation.

A schematic drawing of the equipment used in the I.P.-resistivity measurements is shown in figure 3. A core is first dried to remove excess surface moisture and then clamped into the sample holder between two lead-coated brass plates (current electrodes A and B). The surface of the core is exposed to air and dries quickly thereby negating concern over the flow of current around the surface rather than through the sample. To measure the small millivolt signals associated with a laboratory-induced-polarization experiment, particularly in the presence of a high ambient electrical-noise field, it was found that the best results in terms of reproducibility were obtained when the potential electrodes were in direct contact with the samples. This procedure tends to introduce a stray polarization at the potential electrodes (M&N), but by wrapping thin copper rods in gauze saturated with a copper sulfate solution the electrode polarization based on results obtained with barren gabbro samples

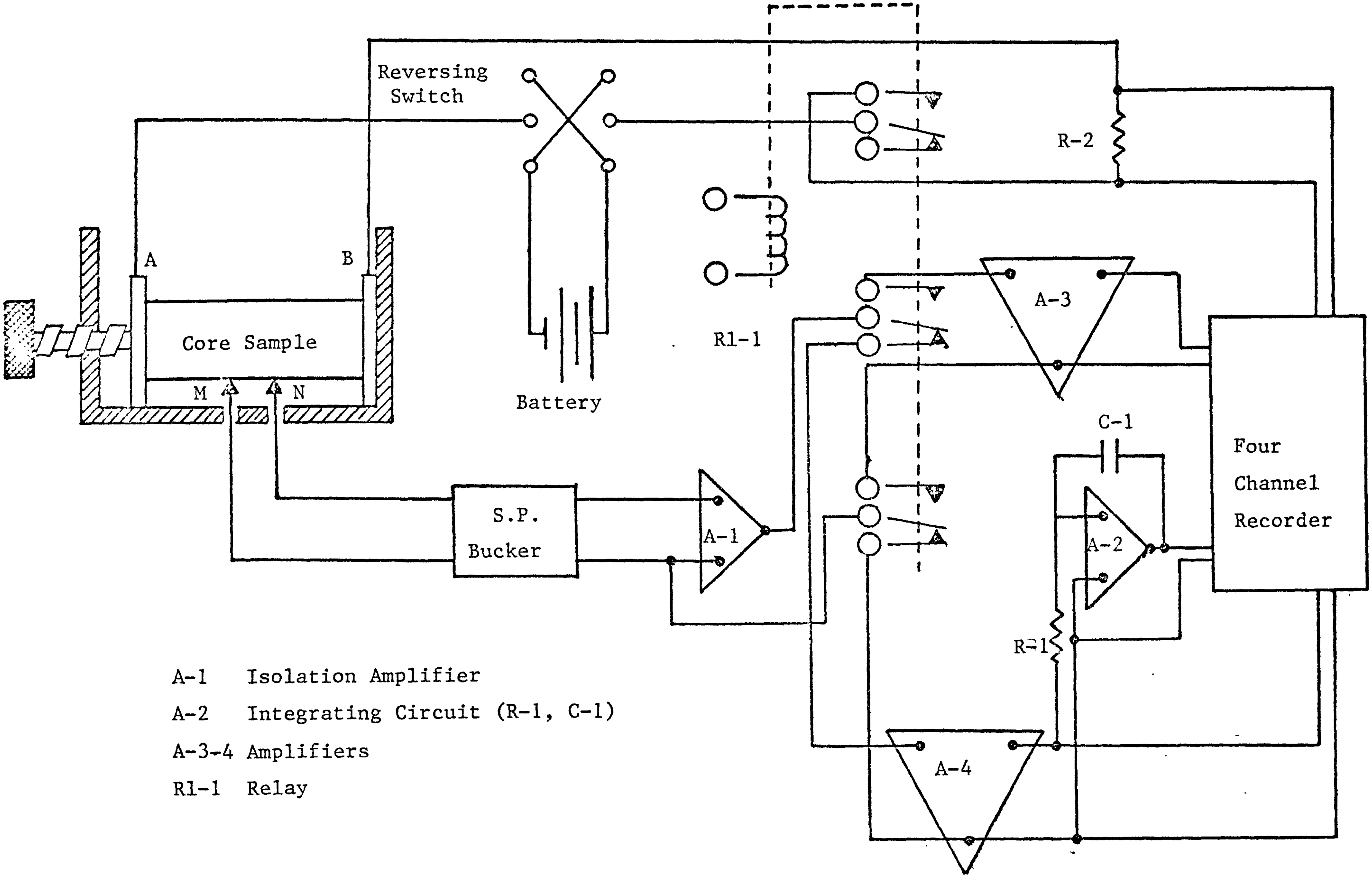


Figure 3---Laboratory apparatus for I.P. and resistivity measurements.

was at or below the general level of background noise.

Steady-state and transient signals were alternately measured by means of a triple-pole double-throw relay actuated by a time-controlled switch. The current through the sample and the steady-state potential between the measuring electrodes were recorded on two channels of a hot-stylus, four channel, graphic recorder. The transient voltage was recorded directly on the third channel and the transient voltage was electronically summed and plotted on the remaining channel of the recorder. A self-potential bucker was adjusted prior to an energizing cycle to compensate for d.c. offsets generated within the rock sample, and a reversing switch was used so that measurements could be made in both directions of current flow. The measurements on each sample were averaged before the various parameters were calculated.

A 3-sec current pulse was used with a 30-sec time interval allotted between pulses to allow the sample to reach an equilibrium condition, as indicated by the return of the transient channel stylus to its original bias level. The resistivity was calculated using the equation

$$\rho = K \frac{\Delta V_p}{I \times 100}$$

where K is the cross-sectional area (in square cm) of the core sample divided by the distance between the potential electrodes (in cm), ΔV_p is the potential difference at a time equal to 2.8 sec across the measuring electrodes in millivolts, and I is the current in milliamperes. The resistivity, ρ, is expressed in ohm-m.

The amplitude of the transient decay voltage 1-sec after termination of the current pulse was measured and this voltage (Vs) was divided by ΔV_p in order to express the induced-polarization effects in millivolts per volt. The relationship of the primary and secondary signals and their waveforms are shown in figure 4. Induced-polarization determinations made from the integrated

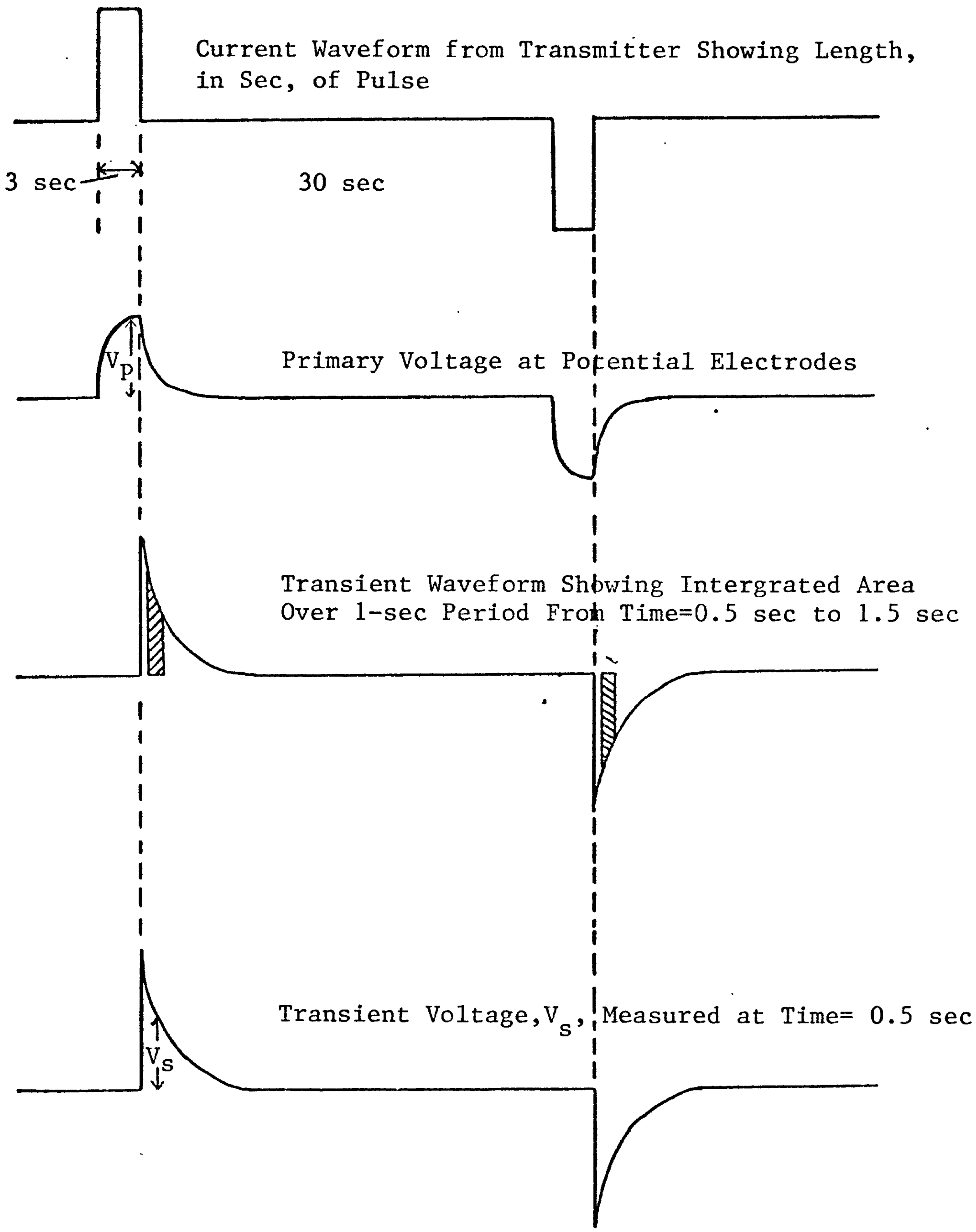


Figure 4---Relationship of signal waveforms used in resistivity and induced polarization measurements. Signal amplitudes are not to scale.

transient data did not reproduce as well as those determinations made from the transient decay voltage, possibly because of local noise problems, and therefore are not presented herein.

Results of I.P.-resistivity measurements

The I.P.-resistivity values determined for each rock sample are listed in table 1. To determine the specific relationship between the induced polarization and resistivity, the data were subjected to a curve-fitting procedure using the method of least squares. Best fit of the data was to a power curve for which a correlation coefficient of 0.84 was computed. Consequently only the power-curve plot defining the relationship between resistivity and induced polarization is shown in figure 5.

The formulated equation, $\ln IP = 8.054 - \ln \rho$, defines the manner in which the decrease in induced polarization occurs with increasing resistivity. Deviations from the fitted line are so much greater at the higher resistivities that a two-decade variation in the I.P. response may be expected in those rocks that contain only a few percent sulfides. For a very small volume fraction of pyrrhotite in a high resistivity rock matrix, the induced polarization may possibly vary as a function of the distribution and grain size of the sulfide minerals. However, according to Parkhomenko (1967), the presence of a small volume of conductive material within a high-resistivity rock would only result in a minor decrease in the bulk resistivity of the rock. In contrast, for low porosity rock (<2%) such as the norite-gabbros used in this study, a small variation in water content will cause large changes in bulk resistivity (Parkhomenko, 1967).

The line of regression cannot be extrapolated to include those samples containing high concentrations of sulfide minerals because the current flow is confined within interconnecting sulfide grains. Such a sulfide distribution reduces the effective metallic surface area and consequently the polarization

Table 1.--Electrical properties, bulk density, and sulfide content of core samples from the Burnt Nubble site, Maine

Sample number	Resistivity (ohm-m)	I.P. (mv/volt)	Effective metal factor (mho /m)	Bulk density (g/cc)	Sulfide content (percent)
BN-1-18	1177	3.8	3		
30	103	18	175		
36	89	195	2190		
53	3.3	2918	884000		
63	24	222	9250	3.09	7.4
70	13	367	28200		
80	128	22	172	2.91	1.1
93	33	15	455		
100	89	25	281		
283	96	42	438		
BN-4-26	91	73	800	3.01	5.8
32	259	21	80	3.02	3.6
43	140	105	750		
50	810	28	35		
56	12	433	36100		
63	253	50	198		
71	861	4.0	5		
89	348	22	63		
96	264	2.7	10		
108	329	11	33		
116	240	3.5	15		
125	324	1.3	4		
138	239	2.7	11		
152	321	4.8	15		
BN-4-165	883	0.3	0.3		
173	401	14	35		
198	714	0.7	1		
209	140	73	521		
216	227	36	160		
235	491	23	47		

Table 1.--Electrical properties, bulk density, and sulfide content of core samples from the Burnt Nubble site, Maine--continued

Sample number	Resistivity (ohm-m)	I.P. (mv/volt)	Effective metal factor (mho /m)	Bulk density (g/cc)	Sulfide content (percent)
BN-5- 17	136	12	88		
32	206	28	135		
41	25	32	1280		
49	109	32	294		
58	96	24	250		
66	21	128	6100	3.12	2.2
73	614	1.6	3		
85	17	291	17100	3.08	2.5
93	17	320	18800		
111	11	618	56200		
120	13	569	43800		
135	266	15	56		
147	279	13	47		
160	215	7	33		
172	355	13	37	3.05	0.4
188	170	0.9	5		
212	31	383	12400		
220	2.4	328	137000	3.36	19.2
BN-5-229	10	528	52800		
238	129	42.6	330		
239	22	447	20300		
247	5.6	432	77100	3.20	10.7
253	65	149	2290		
262	525	14	27		
280	201	4.8	24		
BN-7- 15	4540	2.6	0.6		
25	34	91	2680	2.94	2.7
36	6.8	438	64400	3.60	13.1
40	3.1	333	107000		

Table 1.--Electrical properties, bulk density, and sulfide content of core samples from the Burnt Nubble site, Maine--continued

Sample number	Resistivity (ohm-m)	I.P. (mv/volt)	Effective metal factor (mho /m)	Bulk density (g/cc)	Sulfide content (percent)
BN-7- 42	3.1	333	107000		
50	8.4	517	61500		
63	27	168	6220		
69	81	110	1360		
80	6.2	289	46600	3.64	28.8
85	7.3	455	62300		
87	9.3	478	51400		
94	273	33	121		
98	93	31	333		
109	12.9	456	35600		
116	70	3.8	54		
136	73	31	424		
141	85	35	412		

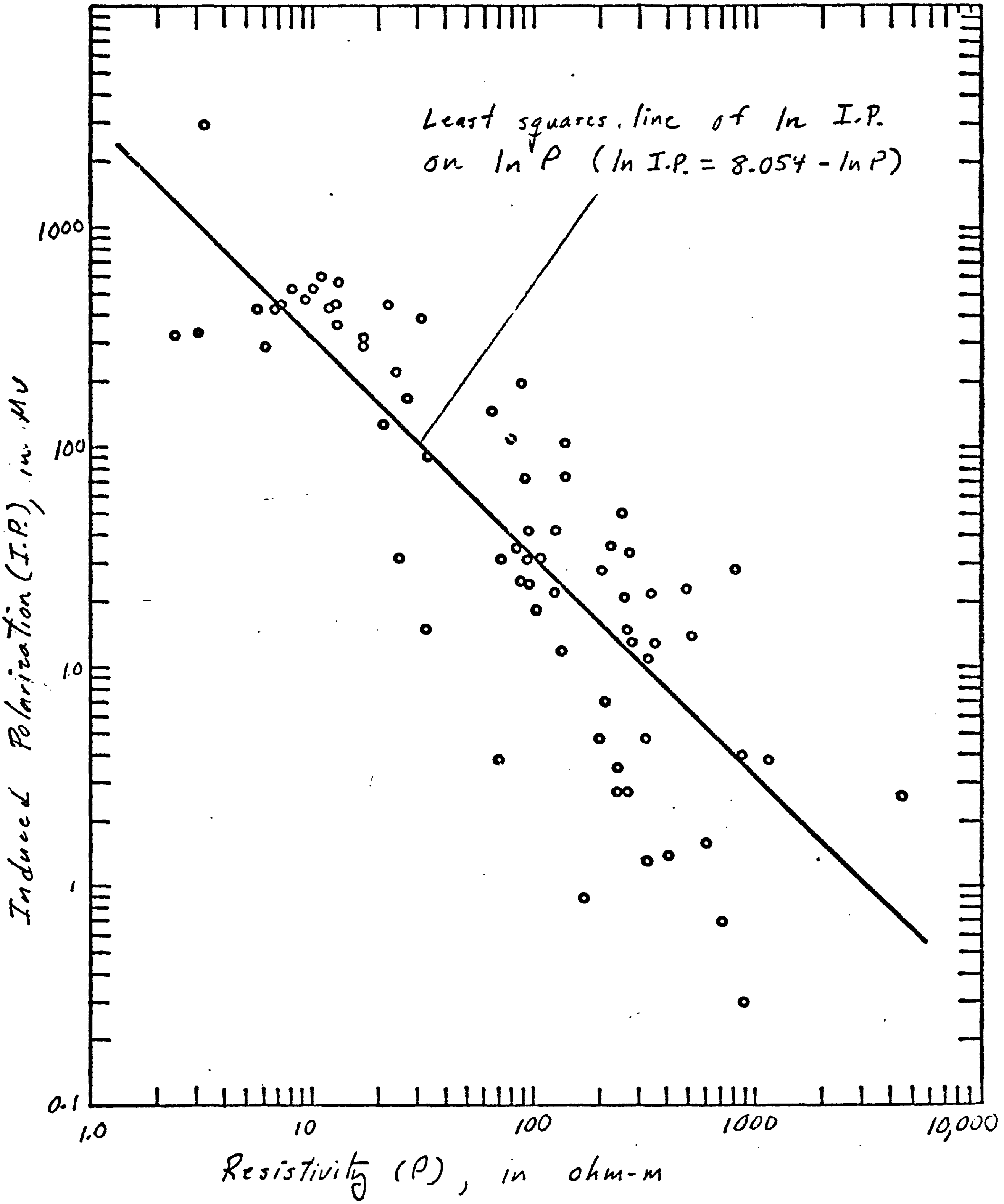


Figure 5 -- Correlation between electrical resistivity and induced polarization of sulfide-bearing core samples.

effect that occurs at the surface of the sulfides.

According to Marshall and others (1957), the usefulness of an induced-polarization measurement can be enhanced by converting the data to what is known as a "metal-conduction factor." This parameter provides a better indication of the total amount of polarizable material within igneous and metamorphic rocks by compensating for the resistivity changes caused by factors other than metal conduction. This metal-conduction factor is computed by normalizing the I.P. value obtained for a specific sample with the resistivity measured for that sample and multiplying by a 10^3 scaling factor. The term is typically used in conjunction with measurements made in the frequency domain but is equally valid in the time domain because units for each mode of measurement are in ohm-m. To distinguish between a frequency and a time-domain metal-conduction factor, the term "effective metal-conduction factor" is used in this report for time-domain measurements.

The data presented in figure 5 have been converted in the manner indicated above and used in figure 6 with the induced-polarization data in terms of effective metal-conduction factor plotted against resistivity. A least-squares fit gives the equation $\ln MF = 14.96-2.0\ln\rho$. A correlation coefficient for this equation of -0.95 as opposed to -0.84 for the equation fitted to the data shown in figure 5 indicates that, at least for these samples, the variation between resisitivity and the I.P. effect can be better predicted when the latter is expressed as effective metal-conduction factor.

Relationship of electrical parameters and grain density to sulfide content

Twelve samples that fall along the line of the plot of the equation derived for the data shown in figure 6 over the indicated resistivity range were arbitrarily selected and analyzed for sulfide content and bulk density

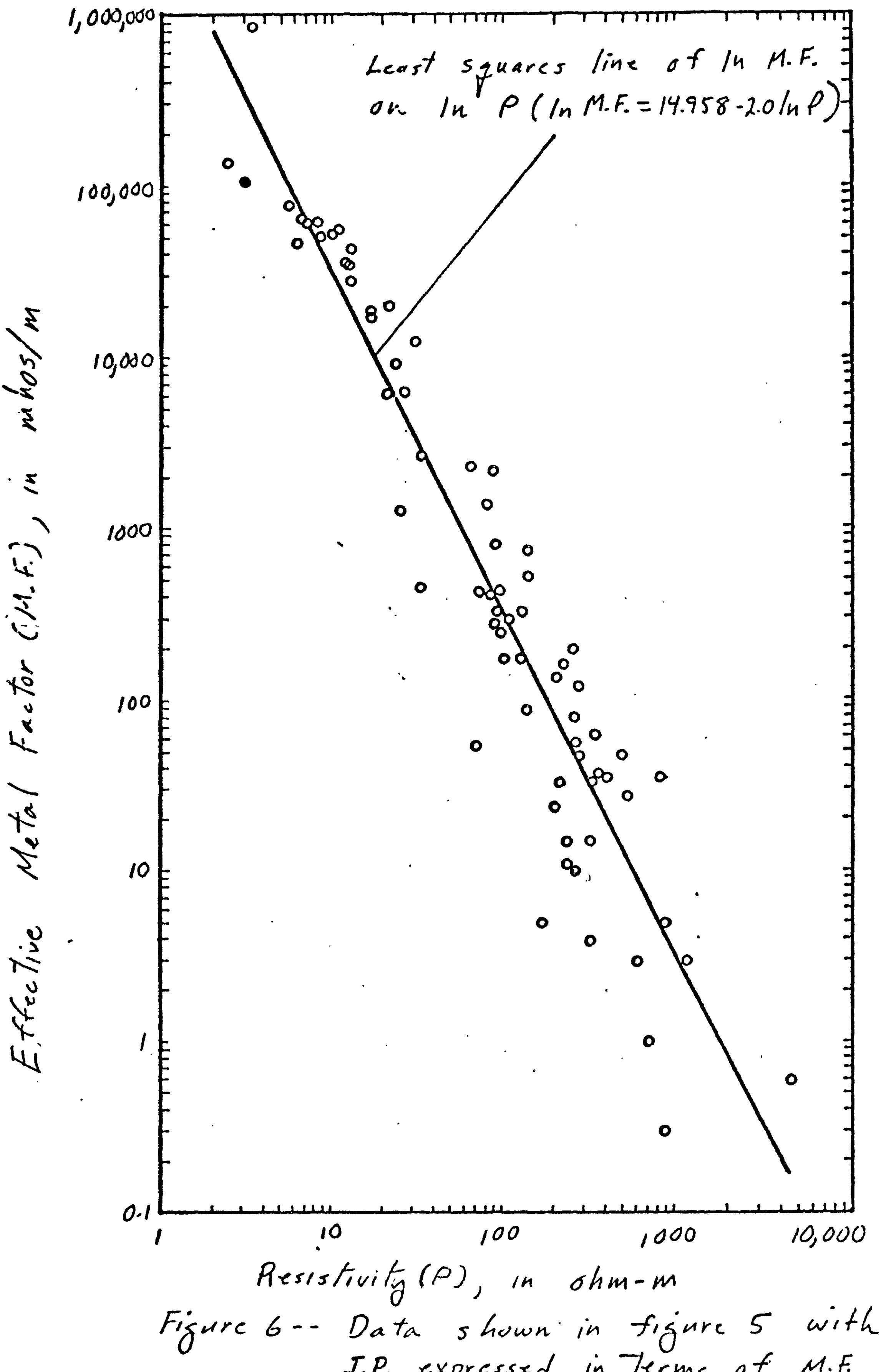


Figure 6 -- Data shown in figure 5 with I.P. expressed in terms of M.F.

(table 1). Density determinations were made on solid cores by direct weighing, and volumes were derived from measured dimensions, a technique that was designed to measure bulk density. Following density determinations, the core samples were crushed and heavy mineral separations were made. The heavy mineral concentrations were analyzed for total sulfur and their values used to approximate the original sulfide content based on the assumption that the sulfide mineral is primarily pyrrhotite. Figure 7 indicates the approximate manner in which the bulk density varies with increasing sulfide content. The cluster of points representing samples of low sulfide content shows variations in density related to varying amounts of heavy minerals such as epidote, garnet, and magnetite. Because sample SN-7-36 probably contained a higher than normal quantity of magnetite, it did not plot close to the correlation line established by the other data point.

Figure 8 illustrates a decrease in resisitivity with increasing sulfide content as expected. Pyrrhotite occurs within the interstices of the host rock forming a continuous vein structure such that only 3 to 10 percent of the sulfide is needed in order to make the rock highly conductive ($\sim$ 1.0 ohm-m) (Parkhomenko, 1967). A study by Anderson (1960) on a peridotite body near East Union, Maine, indicated that an 8-percent concentration of sulfides was needed to make the ore body appear electrically conductive. With the few data points plotted on figure 8, the best fit to the data is with a power curve given by the equation $\ln \rho = 4.884-1.04 \ln S$, where S is the volume fraction of sulfide. The correlation coefficient is 0.8, which is a reasonable measure of the correlation between the two variables. However, extrapolation of the line on figure 8 to achieve a conductivity of 1.0 ohm-m implies that the sulfide content must exceed 100 percent, which is, of course, erroneous. Obviously the quantity of data is insufficient to determine the realistic volume content of sulfides required to

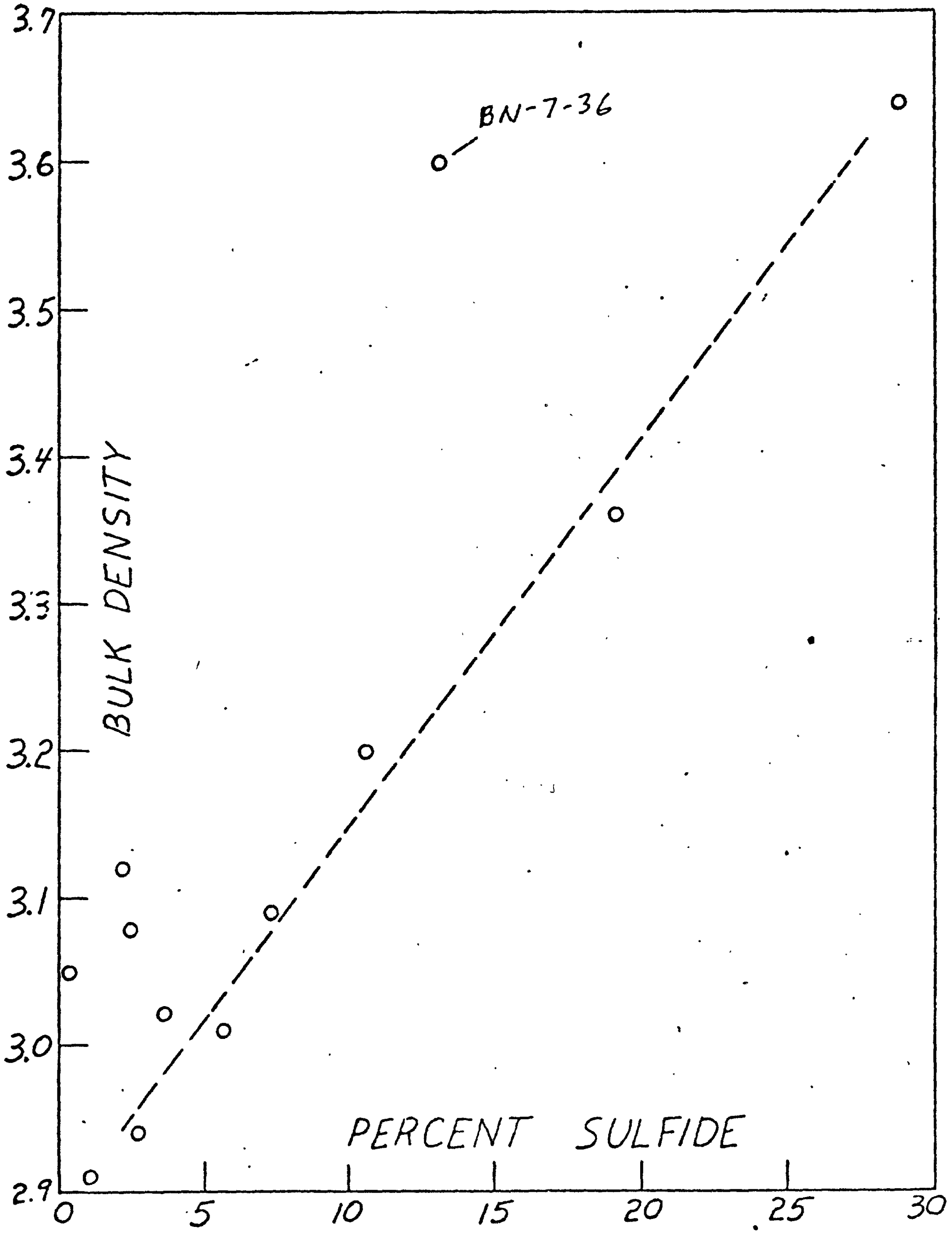


Figure 7-- Correlation between bulk density and sulfide content of selected samples.

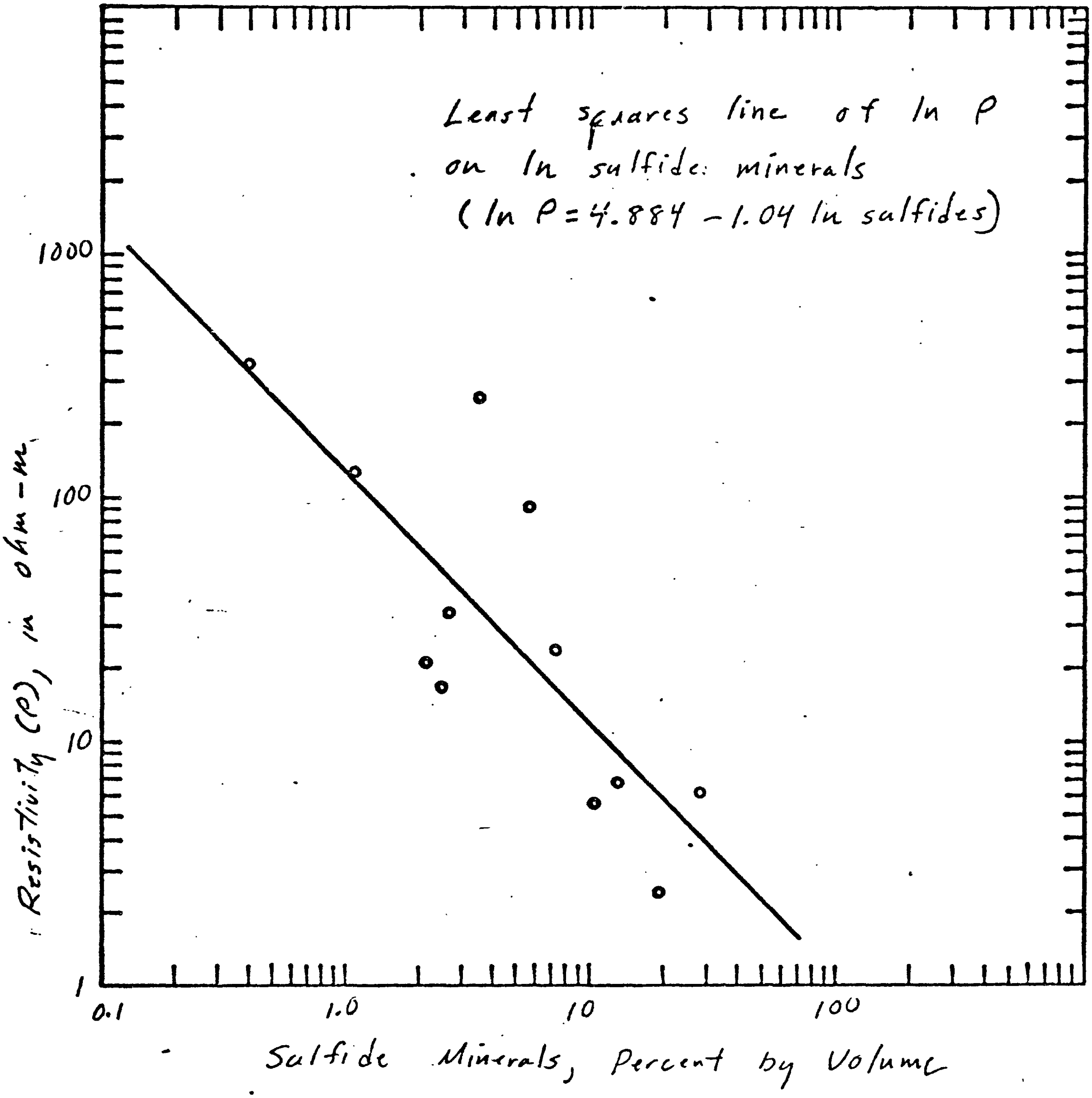


Figure 8 -- Correlation between ρ and sulfide minerals.

make the rock conductive. The sulfide-resistivity correlation is an important factor to be considered in the analysis of surface electrical methods in terms of the tonnage estimates and the subsequent economic significance of the ore deposit.

Induced polarization, in terms of effective metal-conduction factor, is shown plotted against sulfide content in figure 9. According to the study of Marshall and others (1957), this is an electrical parameter that can be measured both in the field and in the laboratory to obtain similar results. Laboratory-derived resistivity values are commonly higher than those measured in the field because of the one dimensional nature of the measurement; that is, the solid core used in the laboratory essentially by-passes the resistivity-controlling fracture zones found in nature thereby resulting in unrealistically high resistivity values. The fact that similar values of metal-conduction factor can be obtained in both environments makes this parameter an extremely useful one for interpreting field data. Figure 9 has too few sample points to adequately describe the variation of the effective metal factor with increasing sulfide content, although the least-squares fit to a power equation demonstrates a reasonable relationhip between variables. The data may, however, be useful for setting limits on the sulfide content within the host rock. An effective metal-conduction factor value below 200 mho/m suggests that less than 2 percent sulfides are present. From 800 to 10,000 mho/m, the range of sulfides varies from 2 to 8 percent and above 40,000 mho/m the sulfide content exceeds 10 percent. There are gaps in the data set but values may be interpreted in accordance with the indicated limits.

Summary and Conclusions

The laboratory study of selected physical properties on Burnt Nubble core samples was undertaken primarily to determine those methods that may possibly be utilized in further sulfide exploration in this area and, secondly, to

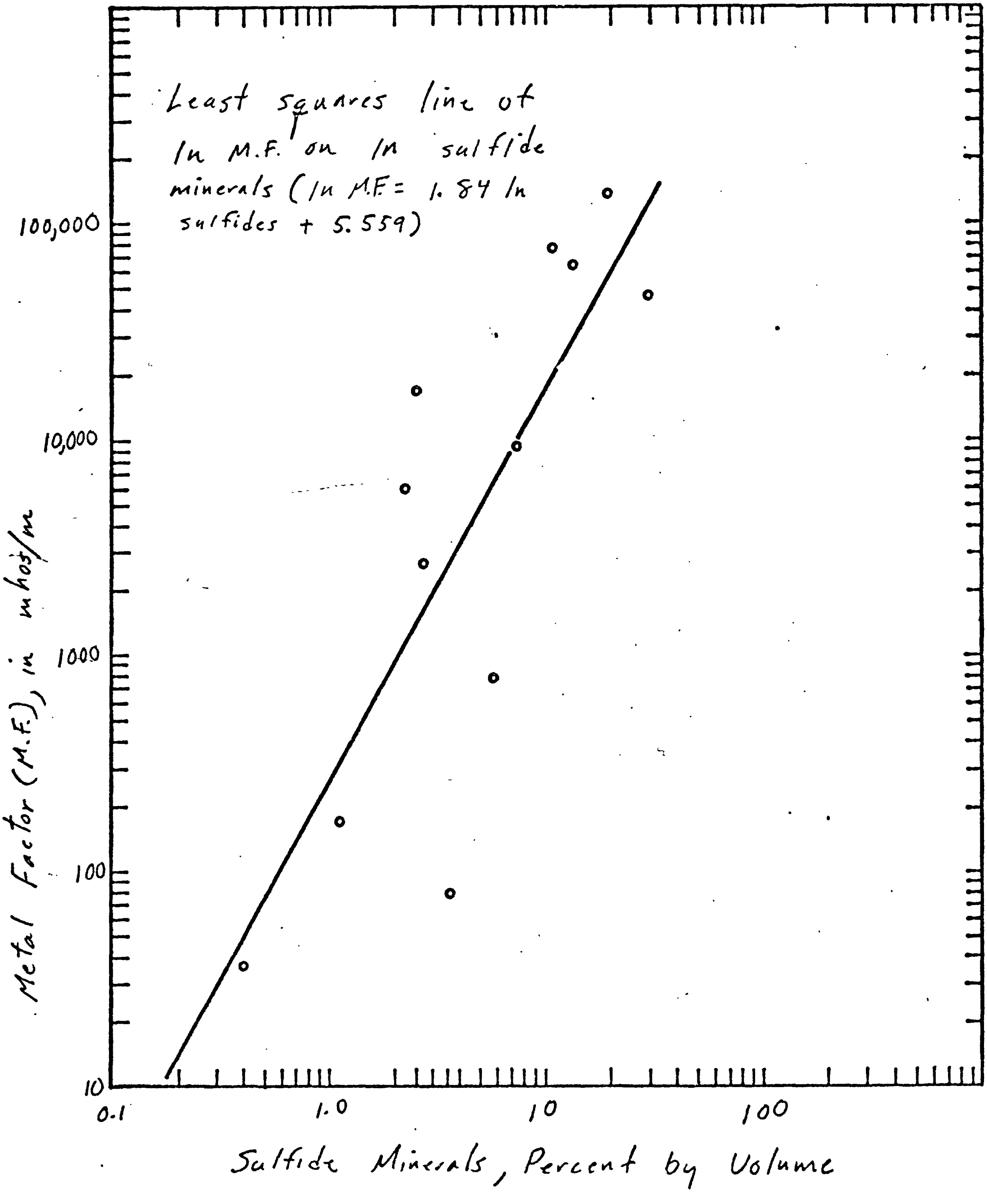


Figure 9 -- Correlation between M.F. and sulfide minerals.

determine the diagnostic qualities of the measured parameters. A summary of the results of the study are as follows:

1. It was established by sulfur analysis that pyrrhotite and minor amounts of associated sulfides constitute the bulk of the heavy minerals within the host rock. The sulfides have a significantly higher density than have the hornfels-norite; therefore, detailed gravity surveys may be useful in delineating these minerals, assuming they exist in sufficient quantities and that their gravimetric effects will not be obscured by short-period variations in the local gravity field. If gravity surveys should prove effective, then the density-sulfide content plot may, in subsequent modeling, help establish the distribution and abundance of contained sulfides.

2. Resistivity surveys and electromagnetic methods that sense the conductivity of the ore body can be used to good advantage to delineating the massive and electrically conductive parts of the sulfide mass. However, the data provided by laboratory methods are possibly of little value in determining the quantity of sulfides necessary to cause the rock to become electrically conductive.

3. Induced-polarization surveys over the Burnt Nubble ore body are considered to be the most effective tool for outlining the total distribution of sulfide minerals within the host rock. The diagnostic quality of the I.P. response when expressed in terms of metal-conduction factor allows a direct comparison of field and laboratory measurements such that some estimate of sulfide content is possible assuming that the frequency and current density with which the measurements are made are equivalent.

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