CANADA

ELECTRICAL RESISTIVITY MEASUREMENTS ON WESTERN CANADIAN COALS

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**EPARTMENT OF MINES AND
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ELECTRICAL RESISTIVITY MEASUREMENTS ON WESTERN CANADIAN COALS

by

Lewis H. King*

ABSTRACT

Field resistivity measurements were made in advance of a coal face to determine the probability of encountering outbursts as the coal was mined. This field work led to the measuring of resistivity on laboratory specimens in order to ascertain the influence of adsorbed methane, carbon dioxide, and moisture. The laboratory work shows that moisture, but not adsorbed gases, can account for the large resistivity fluctuations encountered in the field. The field measurements apparently detect fracturing in the coal ahead of an advancing face when the fractures are saturated with moisture, but outbursts cannot be predicted from the measurements.

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Direction des mines

Rapport de recherches R 117

MESURES DE LA RÉSISTIVITÉ ÉLECTRIQUE DE CHARBONS DE L'OUEST CANADIEN

par

Lewis H. King*

RÉSUMÉ

Des mesures de la résistivité in-situ ont été faites en avant d'un front de houille afin de déterminer la probabilité des dégagements instantanés à mesure que progressent les travaux d'extraction. Ces travaux sur place ont amené l'auteur à mesurer la résistivité d'échantillons de laboratoire afin de determiner l'influence de l'adsorption de méthane, de bioxyde de carbone, et d'humidité. Ce travail au laboratoire révèle que l'humidité, mais non pas les gaz adsorbés, peut expliquer les importantes fluctuations de la résistivité notées sur place. Les mesures sur place décèlent apparemment les fractures au sein de la houille en avant d'un front avançant lorsque les fractures en cause sont saturées d'humidité, mais on ne peut pas prévoir les dégagements instantanés à l'aide des mesures.

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INTRODUCTION

An investigation into the electrical resistivity of coal was initiated in 1951 as part of a Mines Branch field program designated the Strata Stress Project. Electrical resistivity was first considered as a possible means for measuring the state of stress in coal, but later studies were directed to evaluating the possibilities of using it in "outbursting" mines as a method for detecting outburst zones ahead of advancing coal faces. The work was carried out during this period by J.G. Buchanan, of the Physical Metallurgy Division, in cooperation with field officers of the Fuels and Mining Practice Division (1, 2, 3). The field apparatus is fully described in these reports.

In the course of these earlier investigations, marked contrasts had been noted in the resistivity of the coal--in some instances the values had ranged from 10^5 to 10^{11} ohm-cm over relatively short lateral distances in the seams. The present investigation was undertaken to study the reasons for these large resistivity fluctuations. Observations have been made on the effect of sorbed methane and carbon dioxide, at various pressures, on resistivity measurements. An attempt has been made to study the role of moisture in the field resistivity measurements and to determine its influence on the performance of the field apparatus. Also, the influence of moisture on laboratory specimens has been investigated. Other factors which could influence the field measurements are also discussed in this report. Some of the data from previous reports have been embodied, and their significance in relation to outbursts is discussed.

BRIEF LITERATURE REVIEW

It is apparent from a number of previous studies, (4) to (12), that the resistivity of coal in situ or in the as-received state is highly variable and that there are many factors which contribute to the variability. There is, however, good agreement that moisture is the largest single factor contributing to the "apparent" resistivity of coal. On the dry basis, it has been shown that resistivity varies with rank (13). In the region of 90-95 per-cent carbon, the resistivity decreases rapidly with increase in rank because of the increasingly graphitic character of the material. Table 1, compiled from the results of McCabe (8) and van Krevelen (13), illustrates the variation in resistivity over the coalification range.

TABLE 1

Variation of the Resistivity of Coal with Rank

Rank	Main Petrographic Component	Resistivity, in ohm-cm		Investigator
		Dry 1/	Wet 2/	
Lignite	Vitrain	3×10^8	1.69×10^5	McCabe
Subbituminous B Coal	"	3×10^8	5.1×10^5	"
High Volatile C Bituminous Coal	"	3×10^8	2.74×10^5	"
High Volatile B Bituminous Coal	"	3×10^8		"
High Volatile A Bituminous Coal	"	3×10^8	1.48×10^5	"
Medium Volatile Bituminous Coal	"	3×10^8	2.2×10^4	"
93.7% Carbon	"	4.01×10^7		van Krevelen
94.2% "	"	6.09×10^4		" "
95.0% "	"	1.71×10^3		" "
96.0% "	"	6.43		" "
Fusain from High Volatile A Bituminous Coal	Fusain	6.5×10^3		McCabe
Fusain from High Volatile C Bituminous Coal	"	7		"

1/ - The limit of McCabe's bridge was 10^8 ohm-cm. The actual values for these coals are probably greater than 10^{10} ohm-cm. Measurements on clarain samples gave the same results.

2/ - Wet samples were prepared by soaking them in distilled water for 24 hours.

Table 1 shows that for most of the coalification range the vitrinite is essentially non-conducting whereas fusinite is a relatively good conductor. The values for wet vitrain are significant in that they show that in this condition, when conductivity is best, the vitrain exhibits a much higher resistivity than does dry fusain. In some instances this greater resistivity might be an important factor when considering the resistivity of Western coals, since petrographic analyses of these coals (14) usually show a combined fusinite and micrinite content in the order of 10 to 20 percent. McCabe's results (8) were obtained by compressing crushed coal in a conductivity cell at 6,000 psi, whereas van Krevelen (13) used solid cubes between two lead electrodes coated with graphite.

Freeman (10) also examined the effect of moisture on the resistivity of coal. By exposing dry cubes of coal to a humid atmosphere over a period of five months, it was found that the resistivity decreased about one-third to ten-fold in the anthracite samples and about one-half to many thousand-fold in the bituminous coals. He also found that most of the samples showed marked electrical anisotropy, depending on the orientation of the bedding plane. This was due to continuous fusain layers parallel to the bedding. Van Krevelen (15) noted a slight degree of anisotropy in pure vitrain samples of anthracites. In this case the anisotropy probably arises from the high degree of preferred orientation of the graphitic crystallites.

Much of the previous work deals with the behaviour of coal and coke on heating and is not pertinent to this investigation. No systematic investigation appears to have been carried out on the influence of moisture on resistivity, using controlled humidity conditions and various rank vitrains. Freeman's work (10) represents an attempt along these lines, but the samples were apparently badly contaminated with fusain. Millard (16) made a study of wet granular materials in which he included a number of coals. Whenever free water was present on the surface of the particles, the resistivity was of the order of 10^3 to 10^4 ohm-cm. McCabe's values were in the 10^5 ohm-cm range for saturated coals.

In general, the following conclusions can be drawn from the literature:

(1) The resistivity of bituminous coal is usually much greater than that of anthracite. Moisture conditions are not always specified, so it is difficult to evaluate departures from the trend of resistivity with rank.

(2) Anthracite and bituminous coal specimens are often electrically anisotropic. In many cases this is probably due to the orientation of fusain lenses.

(3) The petrographic constituents vitrain and clarain have a much greater resistivity than fusain.

(4) "Apparent" resistivity determined under field conditions is largely controlled by moisture.

INFLUENCE OF SORBED GAS ON THE RESISTIVITY OF COAL

Since it has been shown by Botham (17) that rather large quantities of gas are sorbed on the Western Canadian coals, it was decided to study the influence of these gases on the resistivity of coal under laboratory conditions. Methane and carbon dioxide were used, as both gases are present in significant amounts in the No. 3 and No. 4 Mine coals from Canmore Mines Ltd., Canmore, Alberta. The methane to carbon dioxide ratio is approximately 10 to 1.

The circuit for measuring electrical resistance employed a Rubicon high-precision, type B potentiometer and a Brown electronic galvanometer. The apparatus was set up as shown in Figure 1. The current was obtained

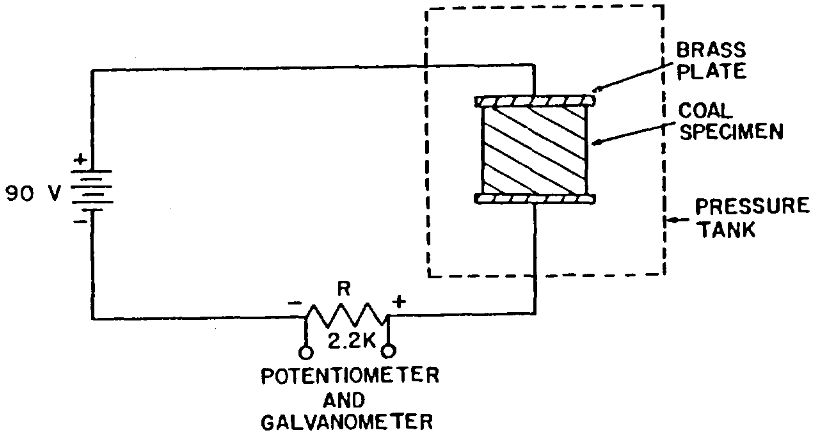


Figure 1. Circuit for measuring the resistivity of coal.

by accurately measuring the potential drop across a known resistor R, using the potentiometer for the measurement. Inasmuch as the voltage drop through the resistor R was negligible with respect to the accuracy required for the resistivity measurement, it was not necessary to measure the potential across the coal specimen. Using a 2.2K Ω resistor and a 90-volt battery, the working range was approximately 10^5 to 10^{11} ohm-cm. A 0.49-ohm resistor was used for measuring lower resistivities.

The coal specimens were one-inch cubes prepared on a disc sander with the aid of a templet. This technique of preparing regular specimens from friable coal proved much more satisfactory than did sawing or diamond drilling. The specimen holder was fitted with two one-inch-square brass plates which were pressed tightly to opposite surfaces of the coal cubes by means of a double-screw clamp. In order to reduce contact resistance to a minimum, electrodes were painted on the specimens, using conducting silver paint. The brass plates were insulated from the clamping device with a 3/8-inch layer of Bakelite and a 1/8-inch layer of Neoprene. The Neoprene served to keep an even pressure applied to the electrodes as the specimen changed shape under the experimental conditions. The specimen and holder were placed in a high-pressure tank (18) equipped with electrical outlets and a constant-temperature bath.

Six specimens of Canmore coal from the No. 3 and No. 4 Mines were selected for the gas sorption experiments on the basis of their megascopic structure, and ranged from blocky coals to highly sheared, friable coals. Bench resistivity measurements were made on the specimens before they were introduced in the pressure tank; the results are shown in Table 2.

The carbon content of these specimens is in the order of 91 percent (mineral-matter-free), so the resistivity values are slightly lower than one would expect from van Krevelen's results (15) for pure vitrains. The lower results might be attributed to their inertinite content. Moisture is not a factor, as the specimens were dried for 24 hours at 105°C.

The results of resistivity measurements under various pressures of carbon dioxide are shown in Figures 2 to 7. These measurements were made at 25°C, and the samples were evacuated for 24 hours prior to the introduction of the gas. The results are consistent in that they all indicate a decrease in resistivity of approximately one order of magnitude for a gas pressure change from 1 atmosphere to 1000 psi. However, the manner in which the resistivity decreases with respect to increasing gas pressure is quite erratic, as indicated by Figures 2, 4 and 7. In the case of sample 1 the rapid change occurs at 700 psi, while for samples 3 and 6 it occurs at 300 and 100 psi respectively. In samples 1, 2, 4, and 6 the decrease follows a smooth curve with respect to time, but for sample 3 the change is abrupt. The rate of change in resistivity is probably a function of the rate of diffusion of the gas, which is in turn dependent on the porosity and degree

TABLE 2

Bench Resistivity Measurements on Canmore Coals

Specimen No.	Location	Resistivity, ohm-cm	Megascopic Structure
1	No. 4 Mine, Canmore, Alberta	1.11×10^{10}	Blocky with well defined bedding parallel to direction of measurement.
2	No. 4 Mine, Canmore, Alberta	1.24×10^{10}	Prominent cleat at 45° to direction of measurement.
3	No. 4 Mine, Canmore, Alberta	1.13×10^{9}	Prominent cleat normal to direction of measurement.
4	No. 4 Mine, Canmore, Alberta	9.10×10^{11}	Friable coal.
5	No. 3 Mine, Canmore, Alberta	9.48×10^{11}	Very friable coal.
6	No. 3 Mine, Canmore, Alberta	1.01×10^{10}	Very friable coal.

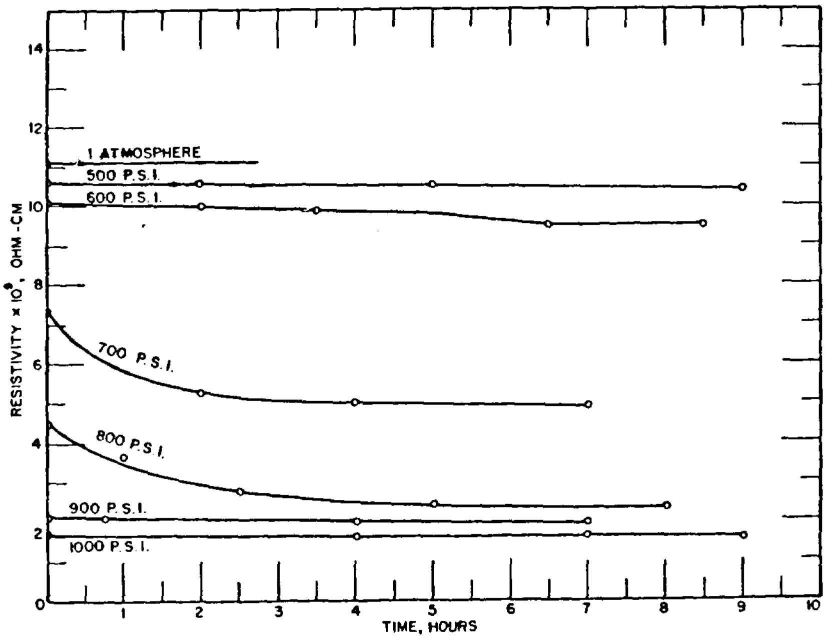


Figure 2. Variation of resistivity with time for different pressures of carbon dioxide - (Specimen No. 1).

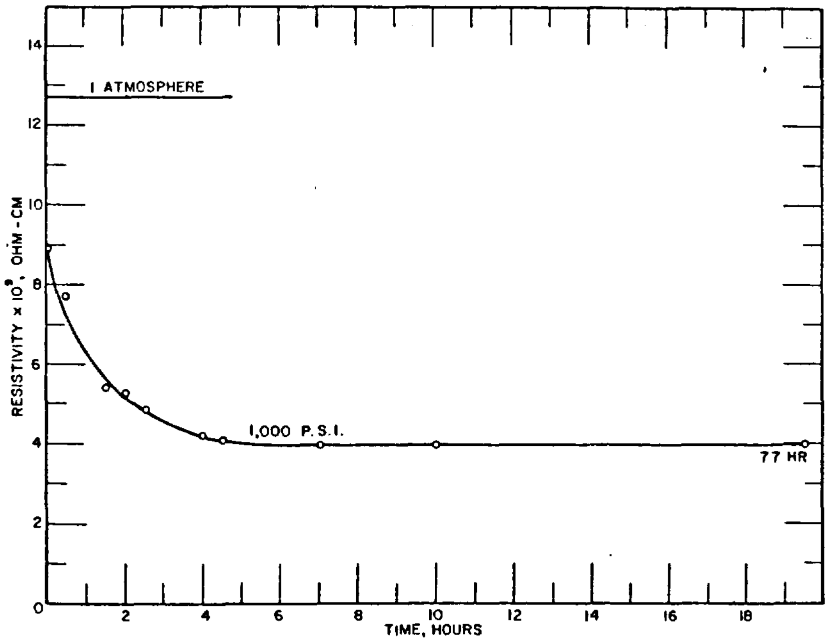


Figure 3. Variation of resistivity with time under 1000 p.s.i. of carbon dioxide - (Specimen No. 2).

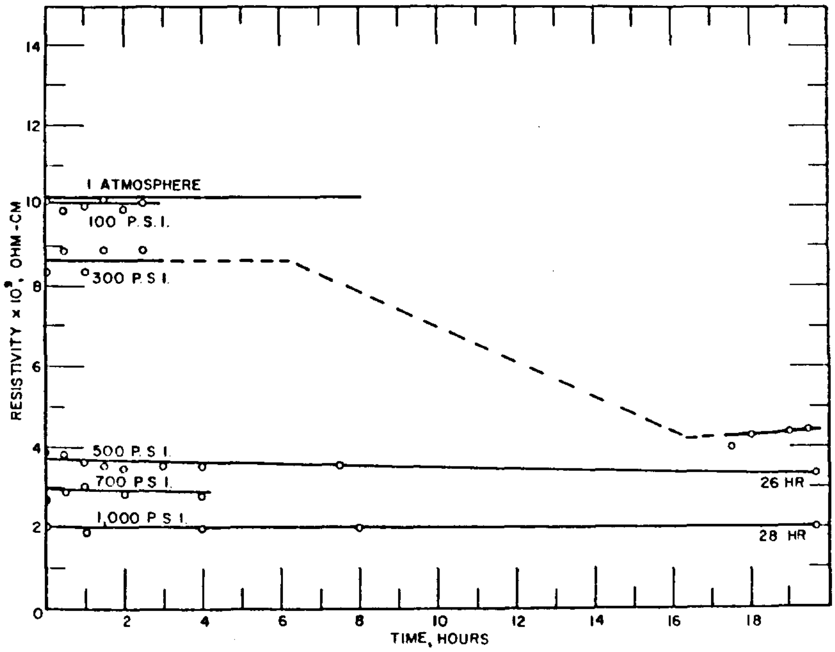


Figure 4. Variation of resistivity with time for different pressures of carbon dioxide - (Specimen No. 3).

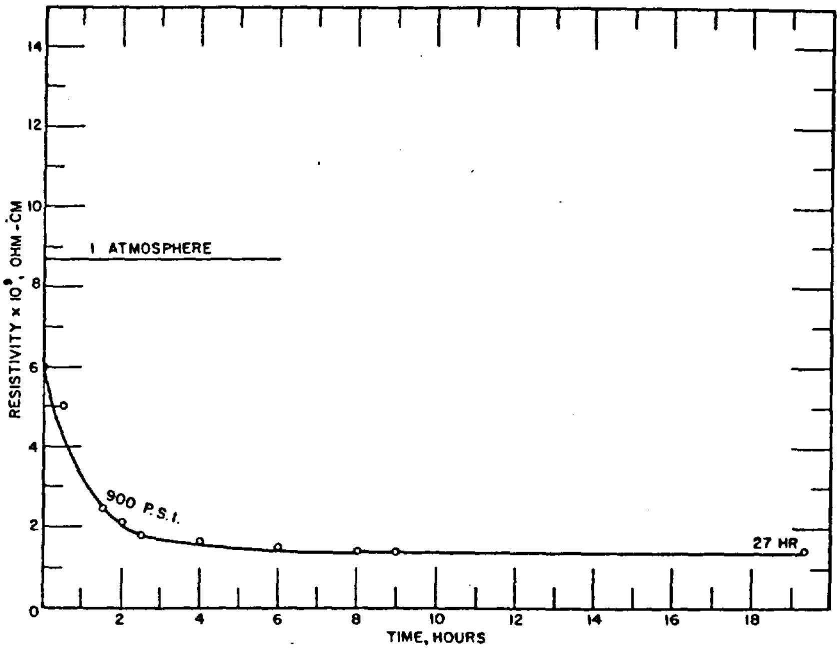


Figure 5. Variation of resistivity with time under 900 p. s. i. of carbon dioxide - (Specimen No. 4).

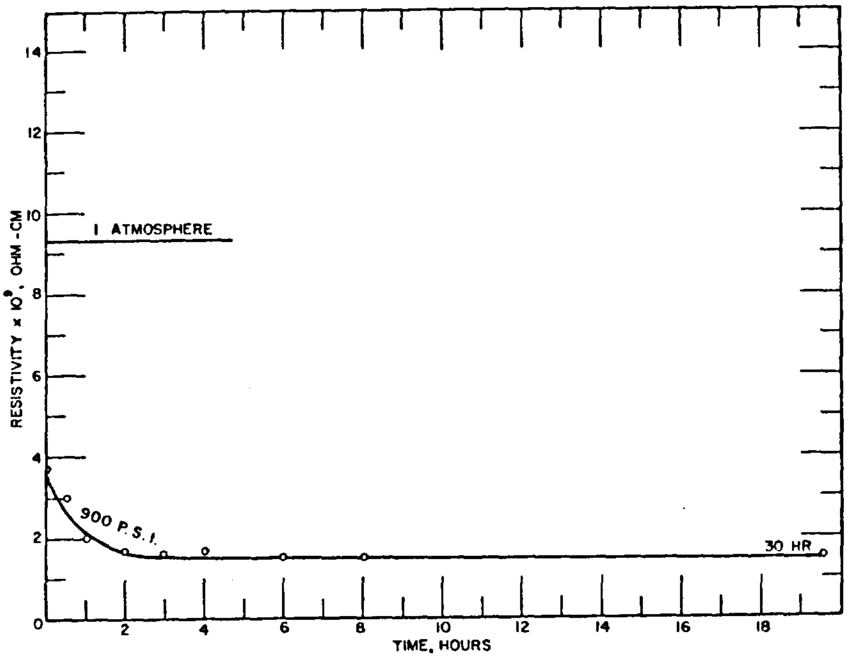


Figure 6. Variation of resistivity with time under 900 p. s. i of carbon dioxide - (Specimen No. 5).

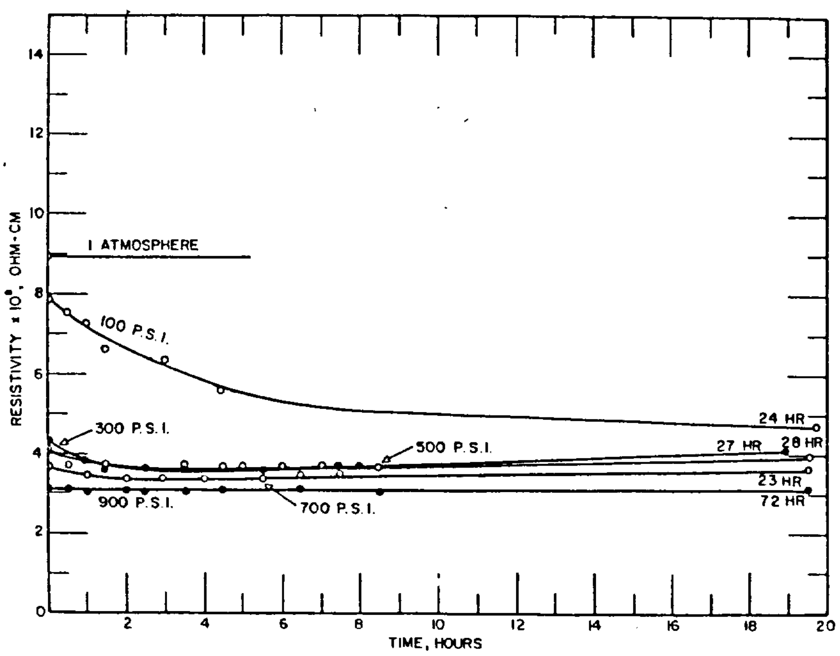


Figure 7. Variation of resistivity with time for different pressures of carbon dioxide - (Specimen No. 6).

of fracturing. Differences in the degree and nature of the fractures and in their behaviour under pressure possibly account for the erratic decrease in resistivity with respect to pressure. The initial diffusion rate is apparently very rapid, as indicated by the immediate response of the resistivity to a change in pressure. This is clearly demonstrated at zero time on all the curves.

It can be concluded, from this work, that the decrease in resistivity is not of sufficient magnitude to explain the large fluctuations in the field measurements. Furthermore, the actual carbon dioxide content of the gas adsorbed on the Canmore coals is only of the order of 10 to 20 percent by volume, and therefore its influence on the field measurements is likely to be much less than indicated by these experiments.

The samples were also treated with methane in a similar manner. In four cases no change in resistivity took place, but in samples 4 and 6 a very slight increase was noted.

The change in resistivity by the sorption of carbon dioxide is an interesting phenomenon from the viewpoint of semiconductors and catalysts, and possibly should receive further consideration. So far as is known, this phenomenon has not been observed previously on coal; however, it has been noted for a variety of adsorbates on active carbon (19) and other semiconductors (20) (21).

The present results show that the conduction does not take place through a carbonic acid film, inasmuch as the specimens were thoroughly dried and evacuated before the tests were made. It also appears that liquefaction of the carbon dioxide is not a factor, as one run was carried out at 35°C, 4°C above the critical temperature. Ionization of the carbon dioxide might be a mechanism, but it is also possible that the electronic properties of the coal are altered in the presence of the sorbed layer. Smeltzer and McIntosh (19) were unable to arrive at definite conclusions with regard to a mechanism to explain a reduction in resistivity through the sorption of a number of saturated hydrocarbons on active carbon; however, they suggest that the presence of physically adsorbed molecules on the surface of the carbon semiconductor alters the number, rather than the mobility, of the conduction electrons. It is interesting to note from their work that methane lowered the resistivity of the carbon, but with respect to coal no definite change was detected.

INFLUENCE OF MOISTURE ON THE FIELD RESISTIVITY MEASUREMENTS

In an attempt to evaluate the influence of moisture on the field resistivity measurements, samples of coal were collected for moisture determinations in conjunction with resistivity observations. The data were obtained in Canmore No. 3 Mine, 30 Slope, 5 Crosscut, by drilling ahead of the advancing face into the solid coal and noting the resistivity values at 2-foot intervals along the boreholes. (See refs. (1)(2)(3) for method of measurement.) The samples for moisture determination were collected from the cuttings in the boreholes and at newly exposed faces. These samples were placed in polyethylene bags and shipped to Ottawa for moisture determination. The limitations of this procedure for obtaining the total moisture were realized from the start, but for lack of a better method it was decided to make a few observations to possibly establish a trend. The results are shown in Figure 8 and indicate that the relationship is completely random. It appears quite possible that the lack of any trend results from losses in moisture before analysis.

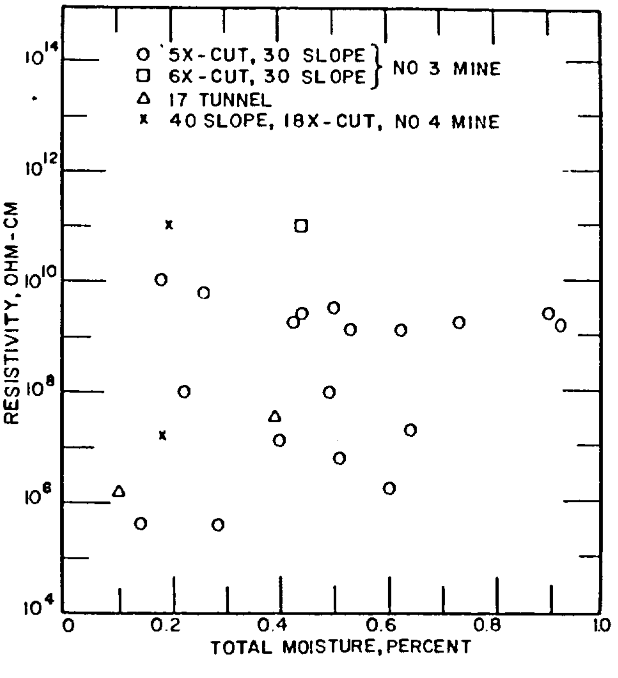


Figure 8. Correlation of field resistivity measurements with moisture content.

Resistivity measurements were also made on exposed faces in the mine, by holding the resistivity probes against the coal parallel to the bedding. Samples were collected at these points for laboratory resistivity and moisture determination and the results are shown in Tables 3 to 5. Many of the specimens were broken in transit, so that only a few could be prepared for laboratory resistivity determination. Once again, the correlation between the laboratory and field results is poor; however, the investigation was worthwhile since it showed that the resistivity is not necessarily constant from roof to pavement in a seam. In fact, it shows that low areas of resistivity sometimes occur in well-stratified planes of only a few inches thickness but of considerable lateral extent. It is also shown that high resistivity readings can be obtained while holding the probe in coal immediately adjacent to low-resistivity roof rocks. These observations suggest that the sphere of influence of the field apparatus might not be as large as considered by Buchanan (3) who contends that the method gives a value for the "apparent" resistivity of a volume of coal approximately the size of a sphere with 30-inch radius centred about the current electrode. Apparently this is not true for field conditions; otherwise, one would expect gradational readings between adjacent high- and low-resistivity media. In other words, the volume of coal represented by a given resistivity reading is also variable and is dependent on the electrical homogeneity of the seam. Thus, films of fusain and moisture between the potential and current brushes could greatly distort the theoretical volume relationship.

TABLE 3

Resistivity Data on Lower Marsh Seam (Face of #17 Tunnel)

Section	Sample	Field Resistivity, ohm-cm	Laboratory Resistivity, ohm-cm	Moisture %
Roof	C - 165	1.8×10^5		
Bright, hard and well banded coal	C - 145	2.0×10^7	1.2×10^8	0.41
	*	1.0×10^{11}		
3'10"	x	1.0×10^9		
	C - 146	1.0×10^8		0.16
Bright, fractured coal				
Parting 3'	C - 164	2.1×10^6		
Friable, sheared coal 5'	C - 147	6.4×10^5		0.49
Parting between upper and lower bench 7'	C - 165	9.0×10^5		

Influence of Moisture on Electrodes:

(*)	Dry electrodes	1.0×10^{11}
	Moisture on current electrode	1.0×10^{10}
	Moisture on both electrodes	1.2×10^9
(x)	Dry electrodes	1.0×10^9
	Moisture on current electrode	4.3×10^8
	Moisture on both electrodes	2.6×10^8
(Pavement)	Dry electrodes	9.0×10^5
	Moisture on current electrode	7.1×10^5
	Moisture on both electrodes	9.4×10^5
(Parting)	Dry electrodes	2.1×10^6
	Moisture on current electrode	2.1×10^6

TABLE 4

Resistivity Data on the Cairnes Seam (500' Below Main Air Intake)

Section	Sample	Field Resistivity, ohm-cm	Laboratory Resistivity, ohm-cm	Moisture, %
Hard, blocky coal 1'10"	C - 132	1.5×10^{10}	3.8×10^{8}	0.40
	C - 133	9.0×10^{9}	2.9×10^{8}	0.48
Parting 6"				
Hard, blocky coal 2'4"	C - 134	1.7×10^{8}	7.2×10^{7}	0.50
Highly sheared coal 10"	C - 136	6.7×10^{6}	9.8×10^{6}	1.38
	C - 135	7.5×10^{7}		0.41
Hard, blocky coal 2'	C - 137	1.3×10^{7}	4.7×10^{8}	0.66

TABLE 5

Resistivity Data on Upper Marsh Seam (No. 3 Mine, 30 Slope, 4 Crosscut)

Description	Sample	Field Resistivity ohm-cm	Moisture, %
Roof		1.0×10^6	
Slickensided band of coal just below the roof	C - 129	2.5×10^9	0.22
Band of grey, friable coal	C - 127	Above 10^{11}	0.28
Slickensided band of coal	C - 128	1.8×10^8	0.35
Very friable, sheared coal	C - 131	2.4×10^8	0.30
Sheared coal near pavement	C - 130	2.2×10^9	0.27
Pavement		6.2×10^7	

The data of Table 3 also show that the method is not independent of contact resistance. In areas of high resistivity the values can be changed by two orders of magnitude by introducing small amounts of moisture at the contact of the coal and electrodes. Such a situation might account for some of the sudden fluctuations in the borehole readings when the current electrode makes direct contact with a zone of extraneous moisture. Even larger effects can be visualized where moisture extends along fractures. The resistivity under these conditions would vary considerably, depending on the orientation of the cracks with respect to the electrodes. Local lenses of fusain would probably result in even greater fluctuations in resistivity.

It was also noted, while taking borehole measurements, that in some cases the readings would fluctuate as much as three orders of magnitude for a movement of approximately 1 inch in the position of the probe.

As a result, the reproducibility of replicate determinations is sometimes very poor; for example, in Figure 16 where readings were taken while advancing and withdrawing the probe in the hole.

Erratic effects such as those described in the two preceding paragraphs render questionable the significance of any local anomalies in the resistivity spectrum. In some cases the anomalies might represent a very small volume of coal. These points will be referred to again in the section entitled "Correlation of Outbursts with Resistivity Anomalies" (pp. 19-30).

INFLUENCE OF MOISTURE ON THE RESISTIVITY OF LABORATORY SPECIMENS

Since moisture seemed to be the most important single factor with respect to the field resistivity measurements, it was decided to investigate the influence of moisture on the resistivity of various ranks of coal under controlled humidity conditions.

The coal specimens were one-inch cubes prepared in the same manner as those used for the sorbed gas measurements. The apparatus used was the same as that shown in Figure 1, except that the pressure tank was replaced by a glass container sealed with a Neoprene stopper. The appropriate concentrated salt solution was placed in the container below the suspended specimen, to give the desired humidity. The equilibration time required to condition a sample with moisture varied from a few months, for friable coal, to at least six months for a solid specimen.

The moisture conditioning process was followed by taking periodic resistivity readings, which remained constant after equilibrium had been reached. The specimen was then removed and quickly weighed to obtain the moisture content. These experiments were repeated at a series of different humidities for each coal sample, and the samples varied in rank from lignite to anthracite. The fully saturated condition was obtained by soaking the specimen in water under water-pump pressure to remove all air, and the surface moisture was removed with a dry cloth just before the resistivity measurement was made. At the end of a series the sample was dried at 105°C and weighed for the moisture calculation. The dry resistivity was also noted.

At the very high moisture levels, polarization effects were noted making it difficult to obtain a null reading. This difficulty was overcome by rapidly noting the resistivity reading before drift could occur. These readings were checked by switching the terminals.

Measurements at low humidities could not be obtained in the low rank coals, because of crack development caused by loss of moisture. Difficulties were also encountered with the Eastern Canadian coals, which generally contain pyrite. Even small amounts of pyrite apparently introduced conducting ions and caused corrosion of the electrodes before equilibrium could be reached. As a result, these coals are not represented in the suite of samples.

The data showing the effect of moisture conditioning on the resistivity of various rank coals are illustrated in Table 6 and Figure 9. More than half the samples are from the Canmore, Alberta, area where the greatest number of outbursting coals occur. The other samples were included to provide a wider variation in rank. With the exception of the conducting Pennsylvania anthracite, all the samples fall in the semiconducting range when measured in the dry state.

The samples were also classified in a qualitative manner according to their physical condition. Since the majority of these coals are in a highly sheared state, it was difficult to obtain solid specimens and in the case of the Upper Marsh seam it was necessary to prepare a binderless briquet under high pressure in order to obtain a solid specimen.

The results indicate that at high humidities the rate of decrease of resistivity with moisture is greatest. For the Canmore coals the drop in resistivity is greatest for the friable specimens that have been completely

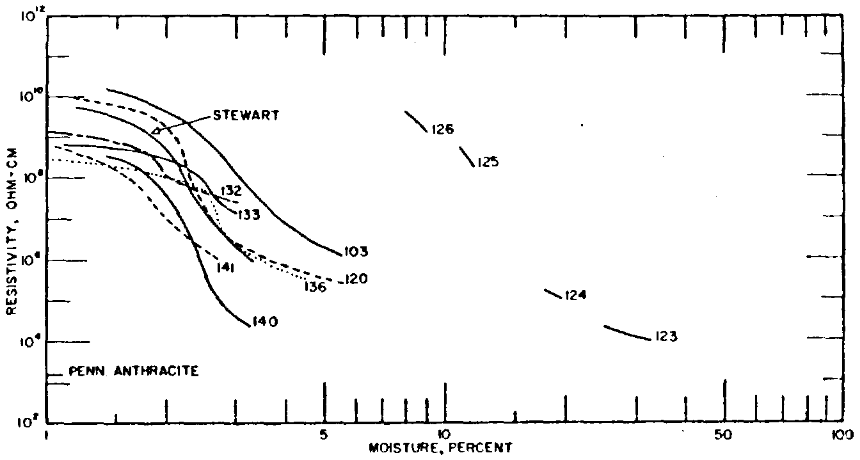


Figure 9. Variation of resistivity with moisture content for different ranks of coal.

TABLE 6

Effect of Moisture Conditioning on the Resistivity of Various Rank Coals

Sample Designation	Location	ASTM Rank	Megascopic Structure	Percent Moisture at Specified Relative Humidity at 20°C								Resistivity in ohm-cm. at Specified Relative Humidity at 20 °C								
				Sat. 1/	95%	91%	86%	76%	64%	55%	44%	Saturated	95%	91%	86%	76%	64%	55%	44%	Dry
C-103 Upper Marsh Seam	No. 3 Mine, 5 Crosscut, 30 Slope, Canmore, Alta.	sa - lvb	Friable and sheared	5.41	2.46	--	2.05	1.54	1.43	--	--	1.23×10^{6}	1.20×10^{9}		6.45×10^{9}	1.39×10^{10}	1.86×10^{10}	--	--	2.51×10^{11}
C-120 Upper Marsh Seam	No. 3 Mine, 5 Crosscut, Canmore, Alta.	sa - lvb	Very friable and highly sheared	5.67	2.54	2.29	2.16	1.92	1.55	1.40	1.17	4.47×10^{5}	1.48×10^{7}	1.60×10^{8}	2.24×10^{9}	4.44×10^{9}	5.79×10^{9}	8.46×10^{9}	1.10×10^{10}	3.15×10^{10}
C-120 Briquette	No. 3 Mine. 5 Crosscut, Canmore, Alta.	sa - lvb	Solid briquette, without binder	--	1.27	1.27	1.25	--	0.92	--	0.61	--	7.77×10^{8}	1.43×10^{9}	2.16×10^{9}	--	4.26×10^{9}	--	8.85×10^{9}	2.90×10^{9}
C-132 Cairnes Seam	Cairnes Mine, 500 feet from Fan on Airway, Canmore, Alta.	sa - lvb	Solid	2.87	2.42	--	1.85	--	1.56	--	0.98	5.02×10^{7}	9.86×10^{7}	--	5.69×10^{8}	--	8.97×10^{8}	--	1.73×10^{9}	8.55×10^{9}
C-133 Cairnes Seam	Cairnes Mine, 500 feet from Fan on Airway, Canmore, Alta.	sa - lvb	Solid	3.01	2.69	2.47	2.10	--	--	1.10	--	2.01×10^{7}	3.05×10^{7}	1.17×10^{8}	2.72×10^{8}	--	--	8.46×10^{8}	--	4.57×10^{9}
C-136 Cairnes Seam	Cairnes Mine, 500 feet from Fan on Airway, Canmore, Alta	sa - lvb	Friable and sheared	4.40	2.72	--	2.47	--	--	1.59	--	5.84×10^{5}	9.95×10^{6}	--	7.39×10^{7}	--	--	2.51×10^{8}	--	2.31×10^{10}
C-140 No. 4 Mine	No. 4 Mine, 14 Cross-cut, 40 Slope, Canmore, Alta.	lvb	Friable and highly sheared	3.26	2.24	--	--	1.69	1.40	--	0.95	3.66×10^{4}	7.57×10^{6}	--	--	2.73×10^{8}	5.37×10^{8}	--	1.76×10^{9}	1.07×10^{10}
C-141 No. 4 Mine	No. 4 Mine, 14 Cross-cut, 40 Slope. Canmore, Alta.	lvb	Fairly solid. well developed cleat	2.69	1.95	1.69	1.55	--	1.04	--	--	1.40×10^{6}	1.58×10^{7}	9.40×10^{7}	1.12×10^{8}	--	7.84×10^{8}	--	--	1.88×10^{10}
Stewart Seam	From stockpile at mine, Canmore. Alta.	lvb	Semi-friable to friable	3.27	2.20	2.07	1.86	--	1.58	1.18	--	1.23×10^{6}	6.07×10^{7}	2.38×10^{8}	1.11×10^{9}	--	1.38×10^{9}	6.93×10^{9}	--	2.51×10^{11}
Pennsylvania Anthracite	Jeddo Highland Mine, Germantown, Pa.	an	Solid	--	1.07	--	--	--	--	--	--	--	2.00×10^{3}	--	--	--	--	--	--	2.57×10^{3}
K-123	Western Dominion Coal Co. Souris Valley District, Saskatchewan	lig	Solid	--	32.7	32.3	29.9	25.0	--	--	--	--	1.02×10^{4}	2.49×10^{4}	1.97×10^{4}	2.94×10^{4}	--	--	--	--
K-124	Whitemud Creek Coal Co., Edmonton, Alberta	subC	Solid	--	19.5	19.1	19.0	18.2	--	--	--	--	1.12×10^{5}	1.22×10^{5}	1.77×10^{5}	1.94×10^{5}	--	--	--	--
K-125	Champion Coal Co., Champion, Alberta	subA	Solid	--	11.9	11.8	11.4	11.1	--	--	--	--	2.87×10^{8}	3.15×10^{8}	4.75×10^{8}	6.22×10^{8}	--	--	--	--
K-126	Lethbridge Colliery, Lethbridge, Alberta	hvCb	Solid	--	9.09	8.82	8.44	8.06	--	--	--	--	1.58×10^{9}	3.05×10^{9}	3.86×10^{9}	6.22×10^{9}	--	--	--	--

1/ Saturated by soaking in distilled water under water-vacuum pressure; surface moisture removed at time of measurement.

saturated, and they generally reach a low value of 10^4 to 10^6 ohm-cm whereas the solid specimens reach a steady value in the 10^7 ohm-cm range. The upper limits of resistivity are attained in the dry state and the friable specimens are in the 10^{10} to 10^{11} ohm-cm range, while the solid specimens generally have a resistivity of 10^9 ohm-cm. In other words, the resistivity of the friable specimens vary approximately 5 to 6 orders of magnitude between the dry and saturated states, while the solid specimens vary approximately 2 orders. For the Canmore coals these changes take place over the moisture range of approximately 0 to 4 percent by weight.

The change in resistivity apparently depends on the degree to which the pores are filled with moisture, and not on the actual moisture content. This becomes evident when coals of different rank, and hence different moisture capacities, are considered. This suggests that the mobility of the hydrogen and hydroxyl ions are restricted in the smaller pores and that they are not permitted to move freely until a fairly direct route is provided along the larger cracks. The results also indicate that at 95 percent humidity the largest fractures are, in the majority of cases, not completely filled. The very low rank samples are the exception to this rule.

The maximum range of laboratory resistivity measurements for Canmore coals, 6 orders of magnitude, is approximately the same as the maximum fluctuations in the field measurements. The field measurements apparently detect fracturing in the coal ahead of an advancing face, when the fractures are saturated with moisture.

CONSIDERATION OF OTHER FACTORS THAT CAN INFLUENCE THE FIELD RESISTIVITY MEASUREMENTS

The roles of moisture, fusain, and adsorbed gas have now been discussed. Other factors that might influence the field measurements are: stress, bulk density, mineral matter, and shale partings.

No direct measurements were made to evaluate the influence of stress and bulk density but their influence can be inferred from the field evidence. In the early work Buchanan reported (1) that low resistivity values were encountered in the mouths of all the boreholes. If either stress or bulk density were playing the dominant role, then high resistivities would be expected at the beginning of all boreholes, as the coal is de-stressed at this point and the bulk density is lowest. Further work has shown that both high and low readings can occur at the beginnings of boreholes. Furthermore, in a number of cases where boreholes overlapped during the process of following an advancing face, either high or low resistivity zones encountered at depth in the first borehole would again be encountered as such in the mouth of the second hole even though the stress environment had changed drastically. Examples of continuous and overlapping readings can be seen in Figures 10 and 12. It appears from these results that stress does not dictate the resistivity patterns. It should be noted, however, that the holes measured were up to 50 feet in length, drilled in friable coal, and it is possible that the walls of the holes were subject to varying degrees of stress relief.

The low resistivities encountered by Buchanan at the beginnings of boreholes might have been the result of a change in moisture content brought about by moist mine air circulating in the de-stressed friable coal. Most of the early holes were drilled in the rib, but the length of time the coal had been exposed is not known.

Since the mine rock consistently shows low resistivity values, it is thought that small partings and accumulations of ash encountered during drilling might be responsible for some of the resistivity fluctuations. Since these variable factors arise under inaccessible conditions and cannot be differentiated, the field resistivity method must be considered as being highly empirical.

CORRELATION OF OUTBURSTS WITH RESISTIVITY ANOMALIES

As stated previously, the purpose of the resistivity work at Canmore was to study the relation of outburst occurrences with resistivity profiles of boreholes ahead of advancing faces. Preliminary results were sufficiently encouraging to justify further work, as they indicated that outbursts were associated with high resistivity values. As work progressed, it was necessary to modify this opinion to the effect that outbursts occur in zones where resistivity values vary over a wide range within short lateral distances.

For purposes of facilitating discussion, previously reported data pertaining to the correlation (3) have been incorporated in this report (see Figures 10-14). Data subsequently obtained are shown in Figures 15 and 16. In the latter diagrams the reproducibility of the instrument is demonstrated by plotting both the inward and outward traverses, while in the previous diagrams the average is shown. Reproducibility is variable and depends on a very exact positioning of the electrodes. The measurements were all obtained in No. 3 Mine, Upper Marsh Seam, of Canmore Collieries Limited.

Figure 10 offers some evidence for the argument that outbursts are associated with high resistivity coal, the only inconsistency being that no outburst occurred at the 220 to 240 foot peak.

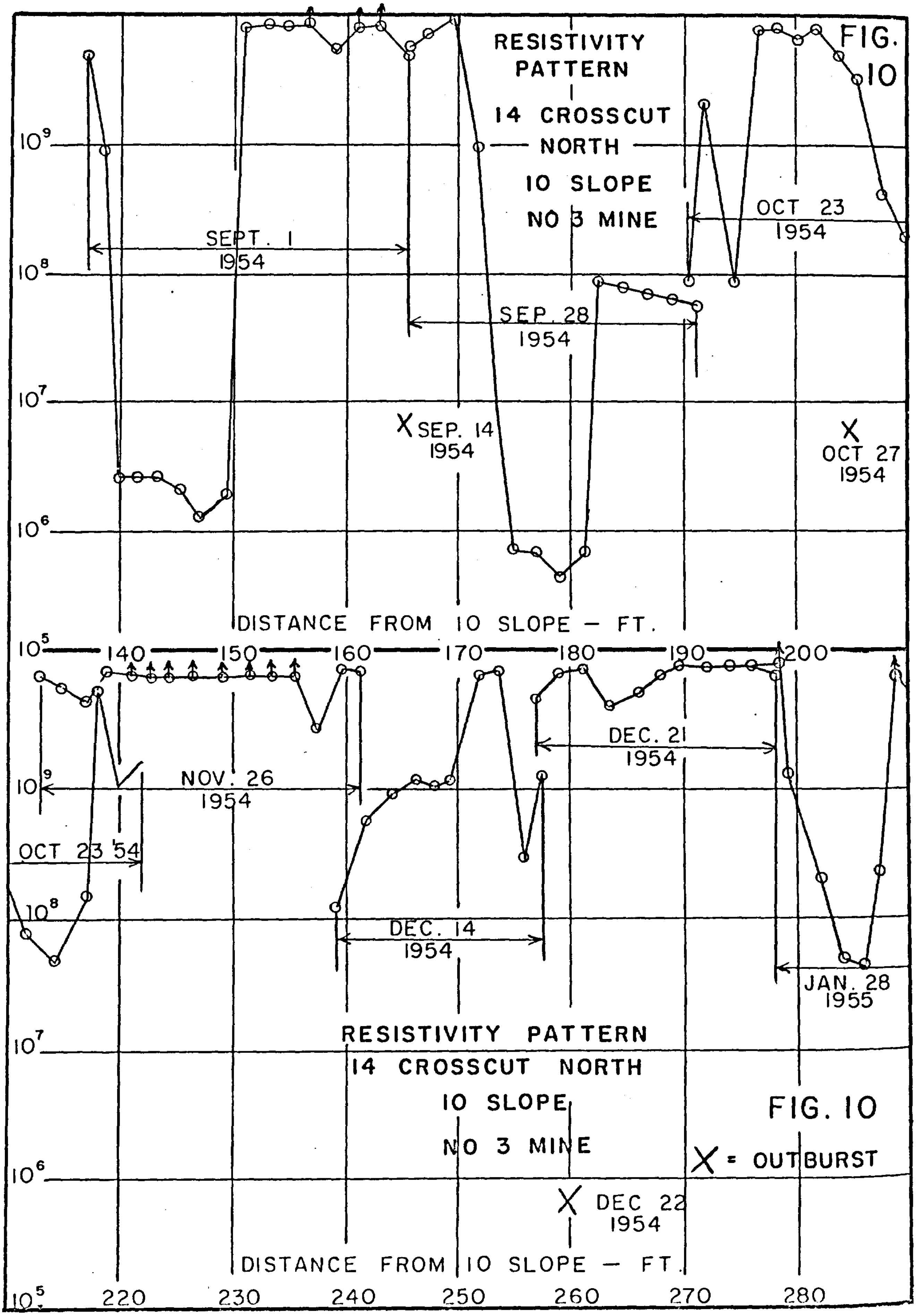


FIG. 10

RESISTIVITY PATTERN
14 CROSSCUT NORTH
10 SLOPE
NO 3 MINE
RESISTIVITY, OHM-CM
DISTANCE FROM 10 SLOPE – FT.
10^5
10^6
10^7
10^8
10^9
140
150
160
170
180
190
200
SEPT. 1 1954
SEP. 28 1954
OCT 23 1954
X SEP. 14 1954
X OCT 27 1954
RESISTIVITY PATTERN
14 CROSSCUT NORTH
10 SLOPE
NO 3 MINE
X = OUTBURST
RESISTIVITY, OHM-CM
DISTANCE FROM 10 SLOPE – FT.
NOV. 26 1954
OCT 23 '54
DEC. 21 1954
DEC. 14 1954
JAN. 28 1955
X DEC 22 1954
220
230
240
250
260
270
280

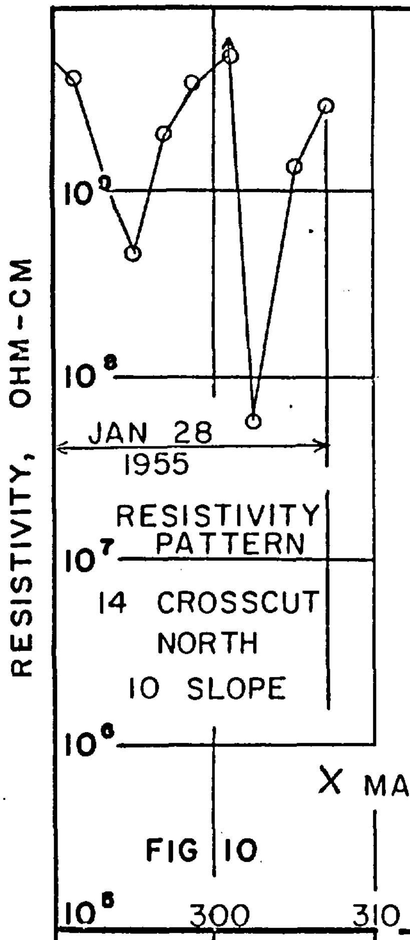


FIG 10

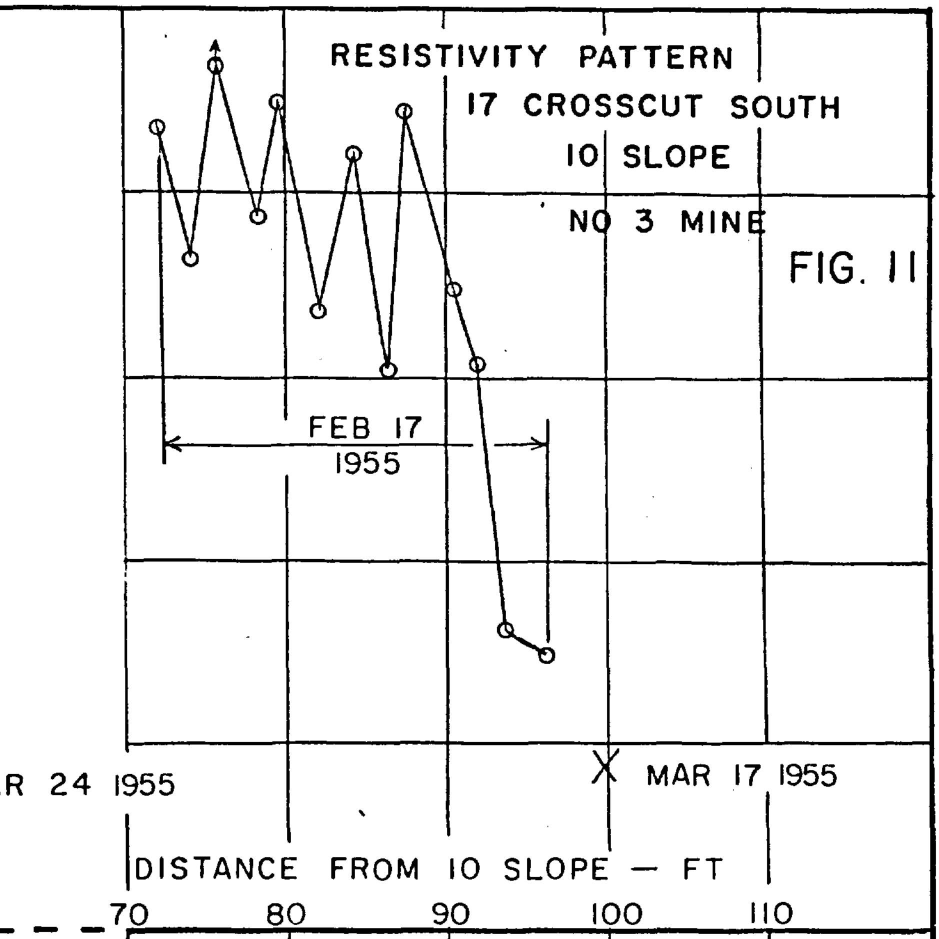


FIG. 11

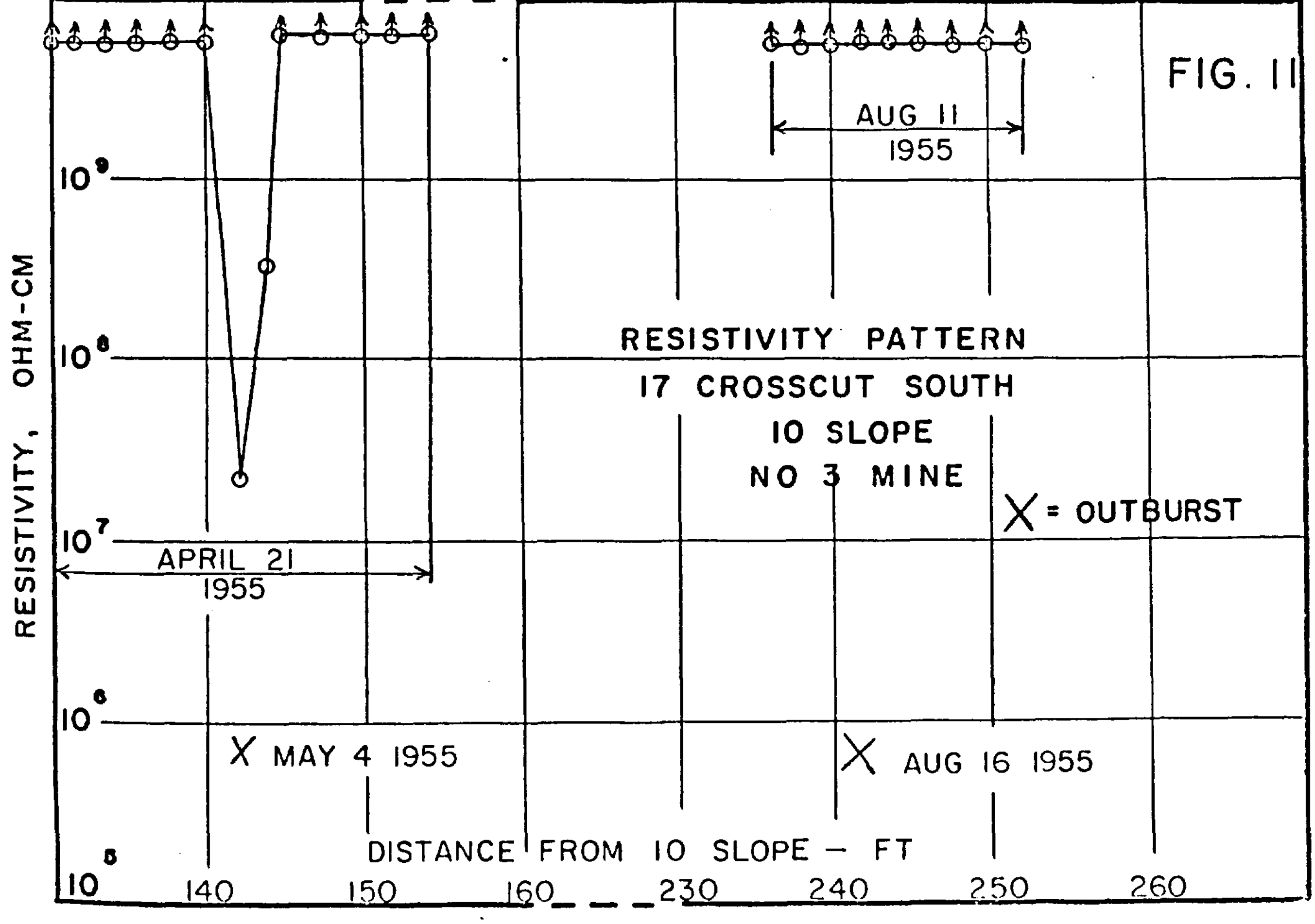
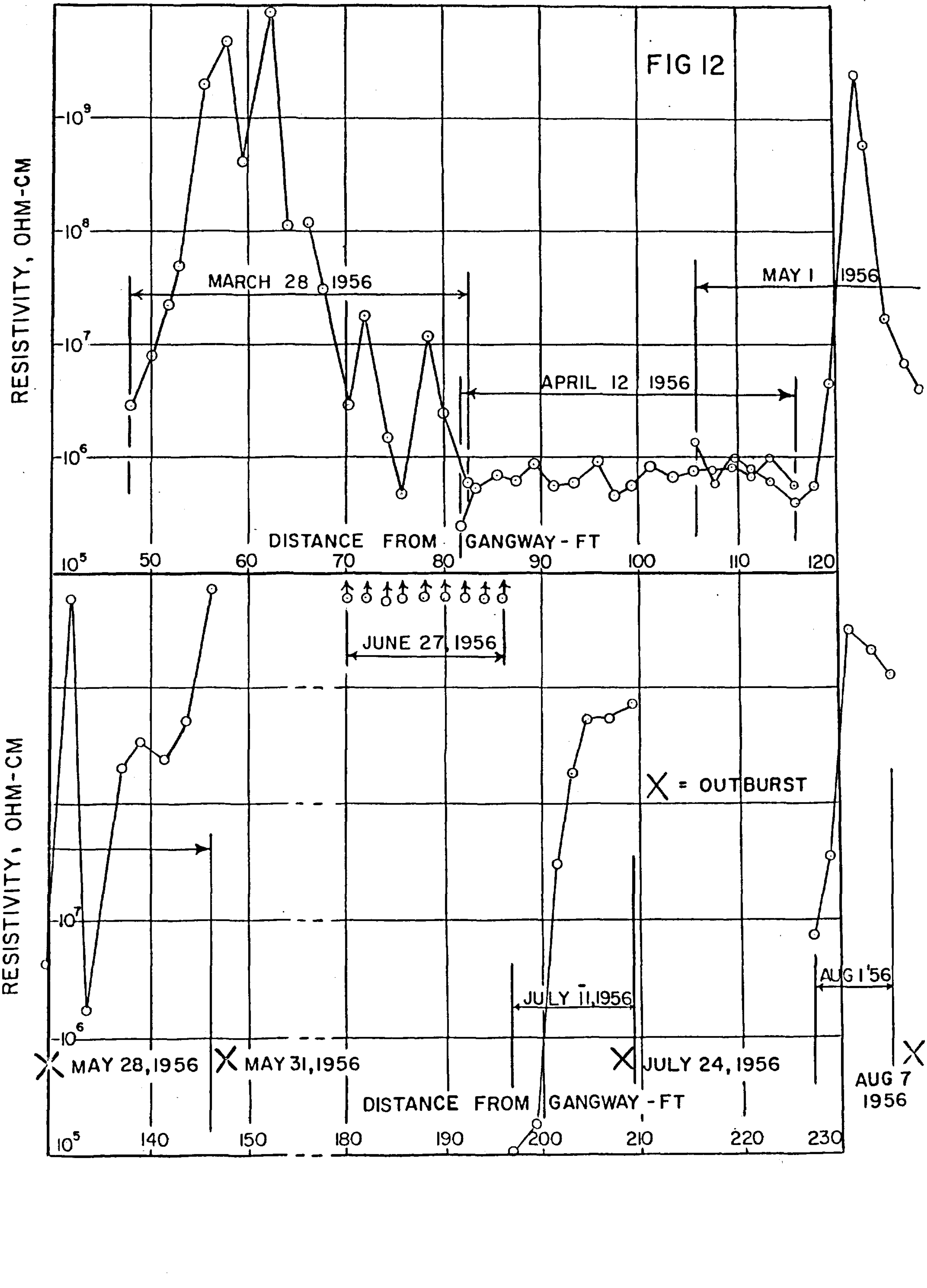
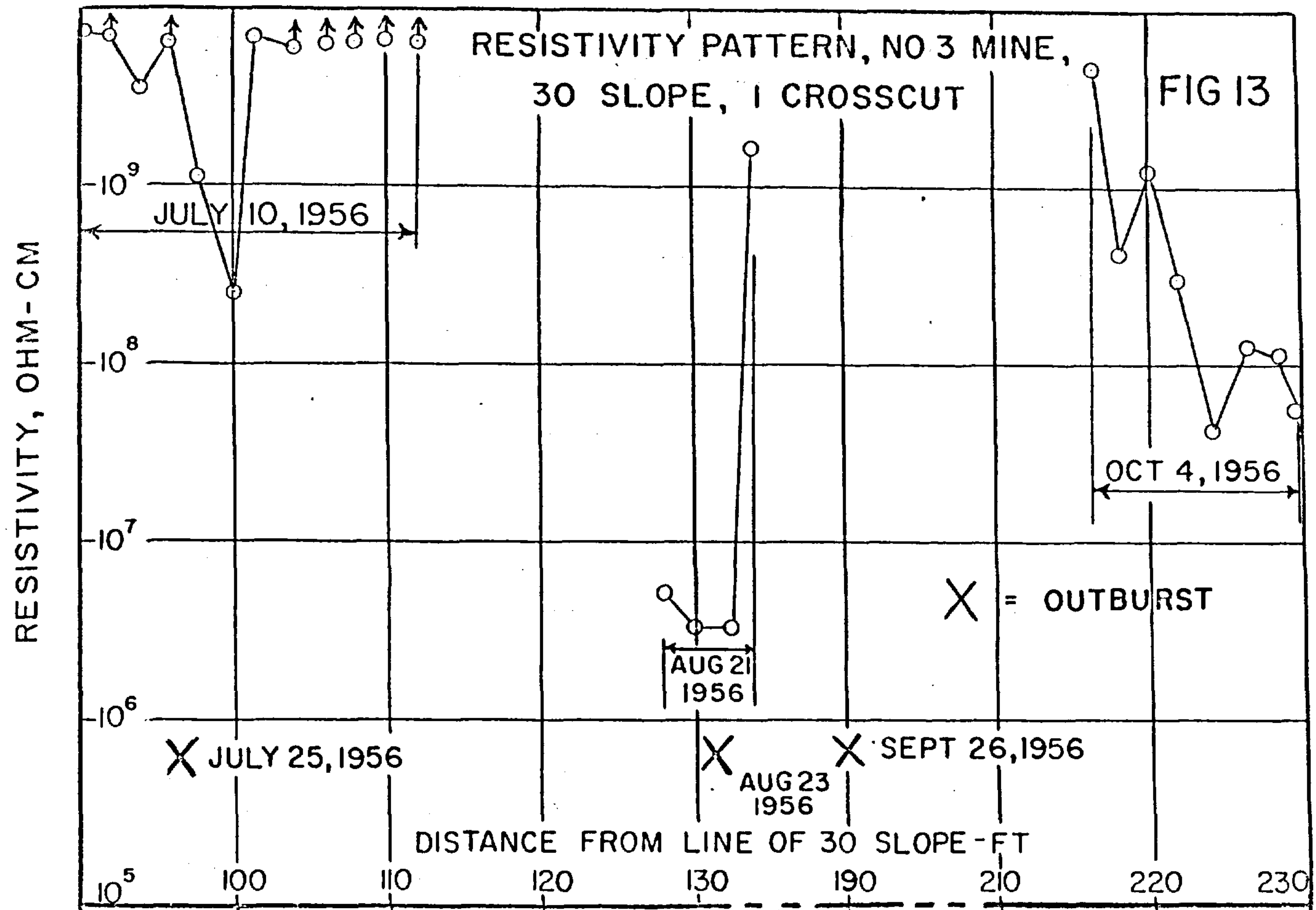


FIG. 11

RESISTIVITY PATTERN, NO 3 MINE, 30 SLOPE

FIG 12





RESISTIVITY PATTERN, NO 3 MINE, 30 SLOPE, 1 CROSSCUT

FIG 13

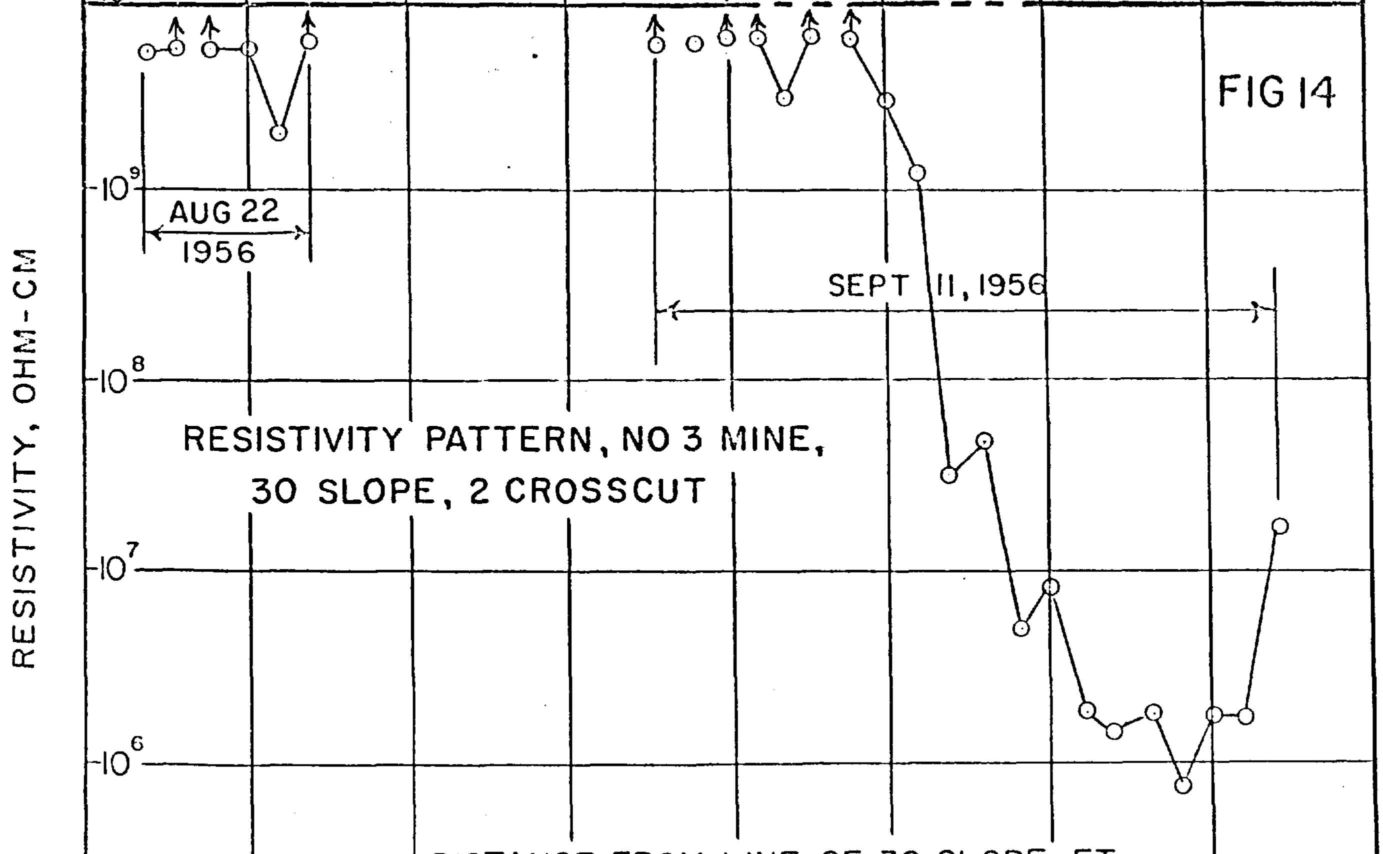


FIG 14

RESISTIVITY PATTERN, NO 3 MINE, 30 SLOPE, 2 CROSSCUT

RESISTIVITY PATTERN, NO 3 MINE, 30 SLOPE, 5 CROSSCUT

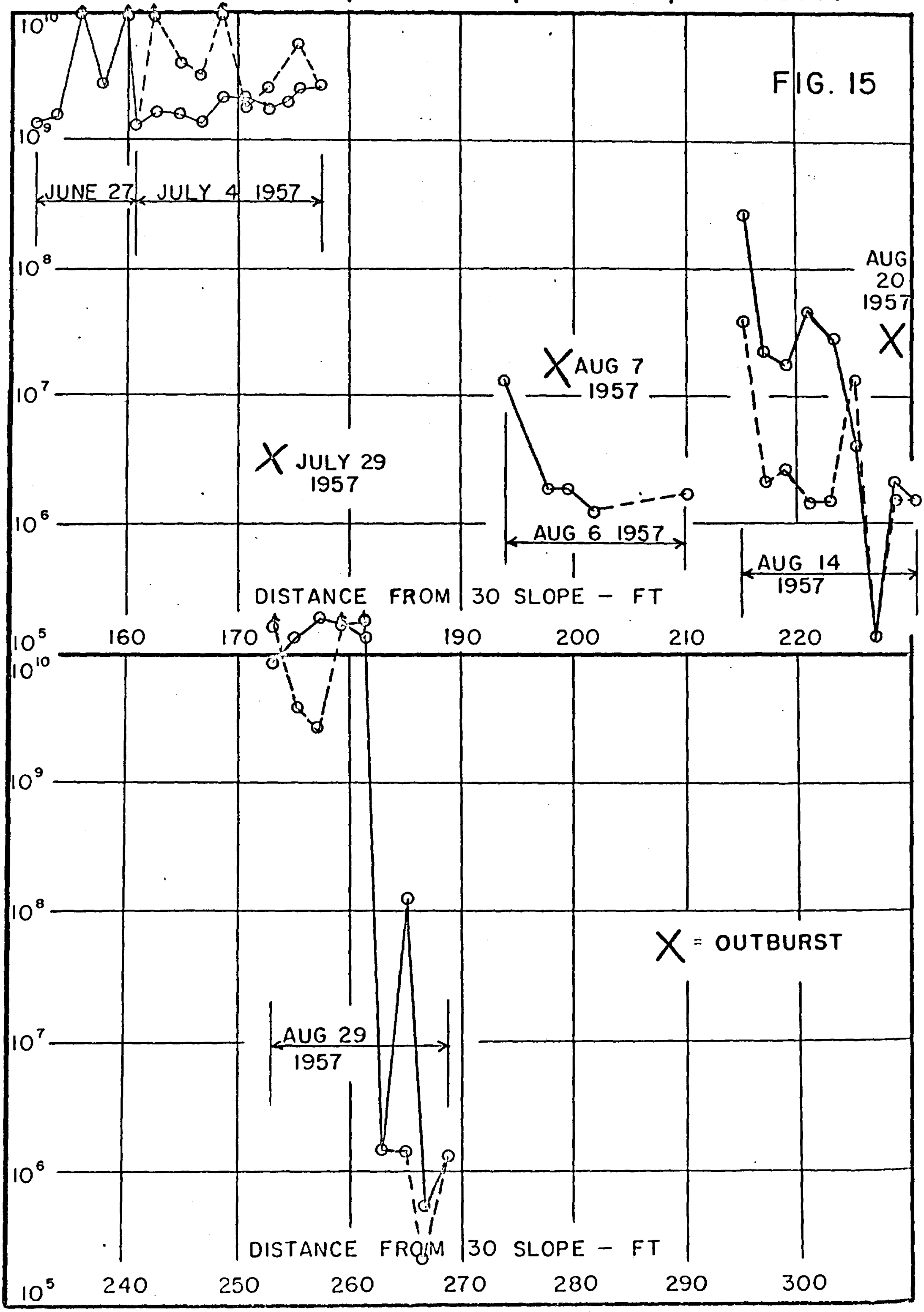
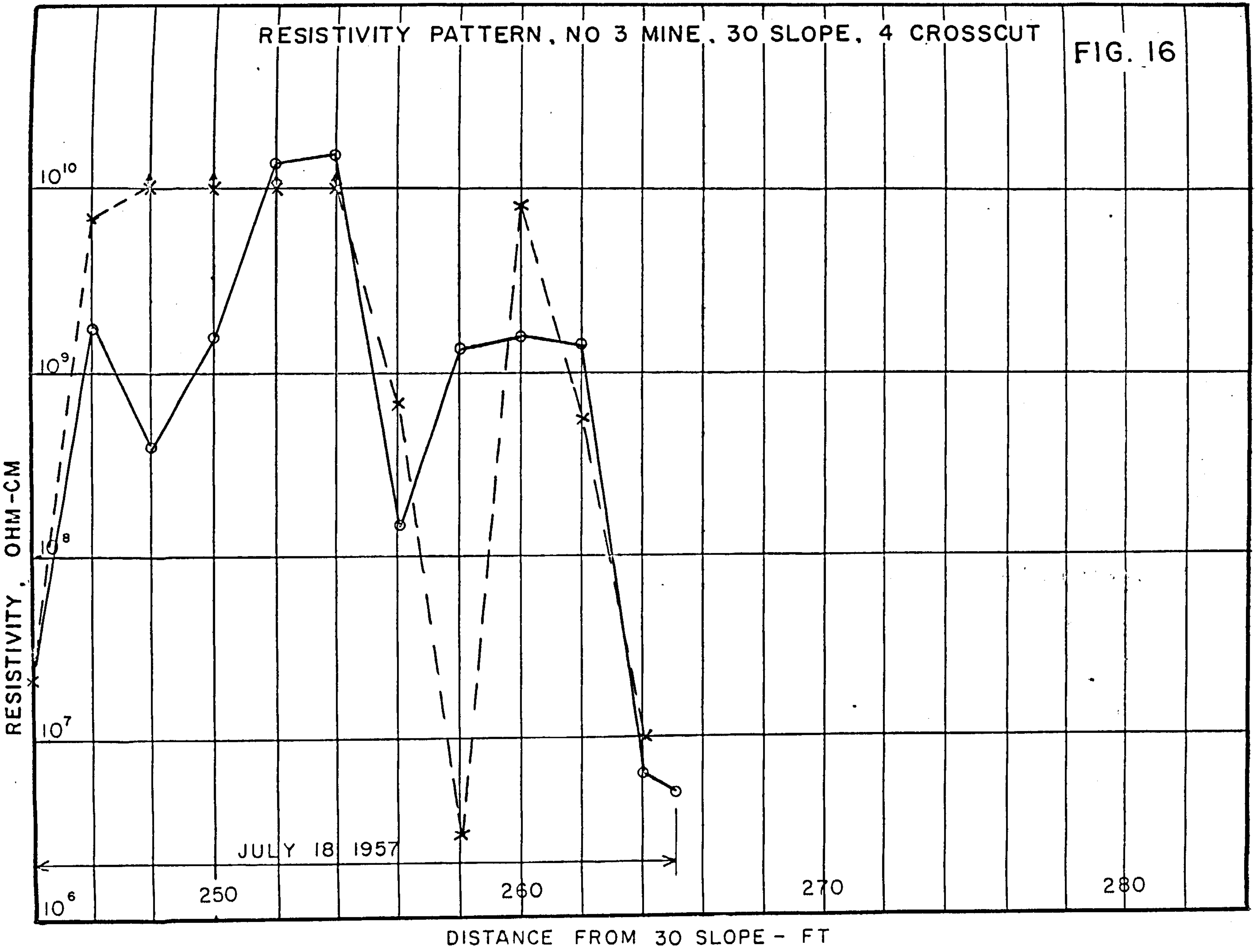


FIG. 15



RESISTIVITY PATTERN, NO 3 MINE, 30 SLOPE, 4 CROSSCUT

FIG. 16

The pattern shown in Figure 11 is, unfortunately, incomplete. The August 1 outburst occurred in high resistivity coal, whereas the May 4 outburst occurred at a resistivity low; however, the low zone is only represented by two points, so it is hardly significant. Furthermore, it is not possible to accurately locate the focus or point of inception of an outburst.

The data of Figure 12 show an outburst (May 28) in what is essentially a low but fluctuating area, and two in the high region of 10^9 ohm cm. In Figure 13 an outburst occurred at a high resistivity value and another at a low, but the low is not highly significant. Figure 14 shows both high and low zones but no outbursts occurred. In Figure 15 the measurements cover three outbursts, and it is significant that while one occurred in a high zone, the other two were in low areas. In 4 Crosscut, 30 Slope (Fig. 16), a fluctuating pattern was obtained but no outbursts occurred.

Considering all the data from the Upper Marsh Seam in the 10 and 30 Slope areas (Figs. 10-16), it can be stated that the resistivity pattern is highly variable and fluctuating; in some cases the peaks and valleys are well defined, while in others the resolution is poor because of very rapid fluctuations.

With regard to the correlation between resistivity pattern and outbursts, information on which to base a conclusion is rather sparse; however, the available data strongly suggest that there is no correlation. With further work in both outbursting and nonoutbursting mines it might be shown that such a fluctuating spectrum might be typical of an outbursting coal, but the present data hardly justify the use of any particular part of such a pattern for the prediction of outbursts in No. 3 Mine.

During the course of the resistivity investigation the greatest effort was concentrated on No. 3 Mine and, with the exception of International Mine, Coleman, Alberta, very few measurements were made in other mines for comparison. In the Cairnes seam (Fig. 17), consistently low resistivity readings were obtained, but they are not sufficient in number to safely categorize the seam. Furthermore, mining is not at sufficient depth to definitely classify the mine as outbursting or nonoutbursting. Figure 18 shows the resistivity pattern obtained during the development of F level in the International mine. This pattern is quite similar to that of the Upper Marsh seam, except that the readings never drop below 10^8 ohm-cm. In the light of these similarities, it is interesting to note that International is an incipient outbursting seam and, like Upper Marsh, is a very friable coal. The only other measurements are from No. 4 Mine and the Lower Marsh Seam (Figs. 19 and 20), but these are insufficient to establish any reliable pattern for these two coals.

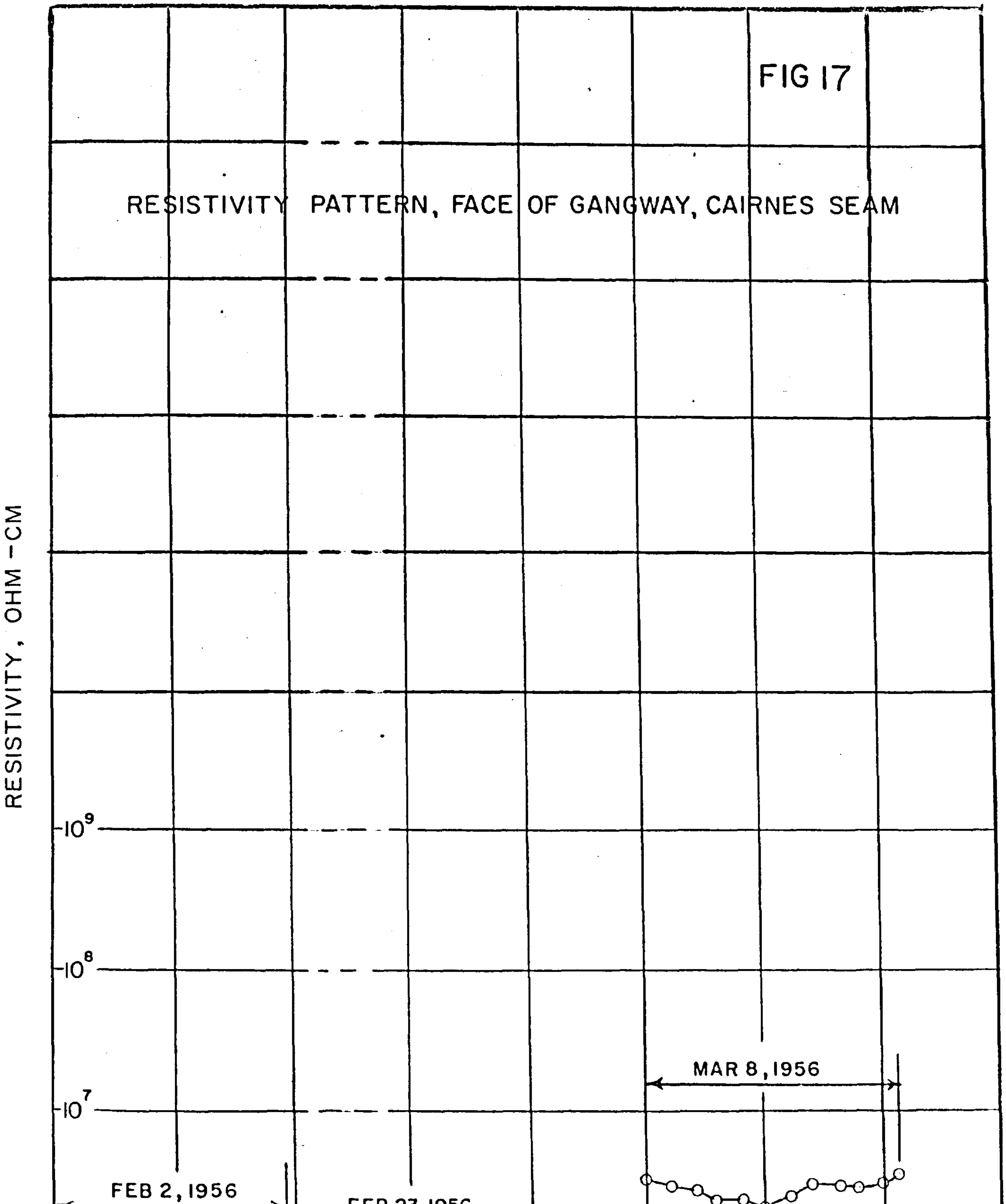


FIG 17

RESISTIVITY PATTERN, FACE OF GANGWAY, CAIRNES SEAM

RESISTIVITY PATTERN, INTERNATIONAL MINE, F DRAINAGE LEVEL

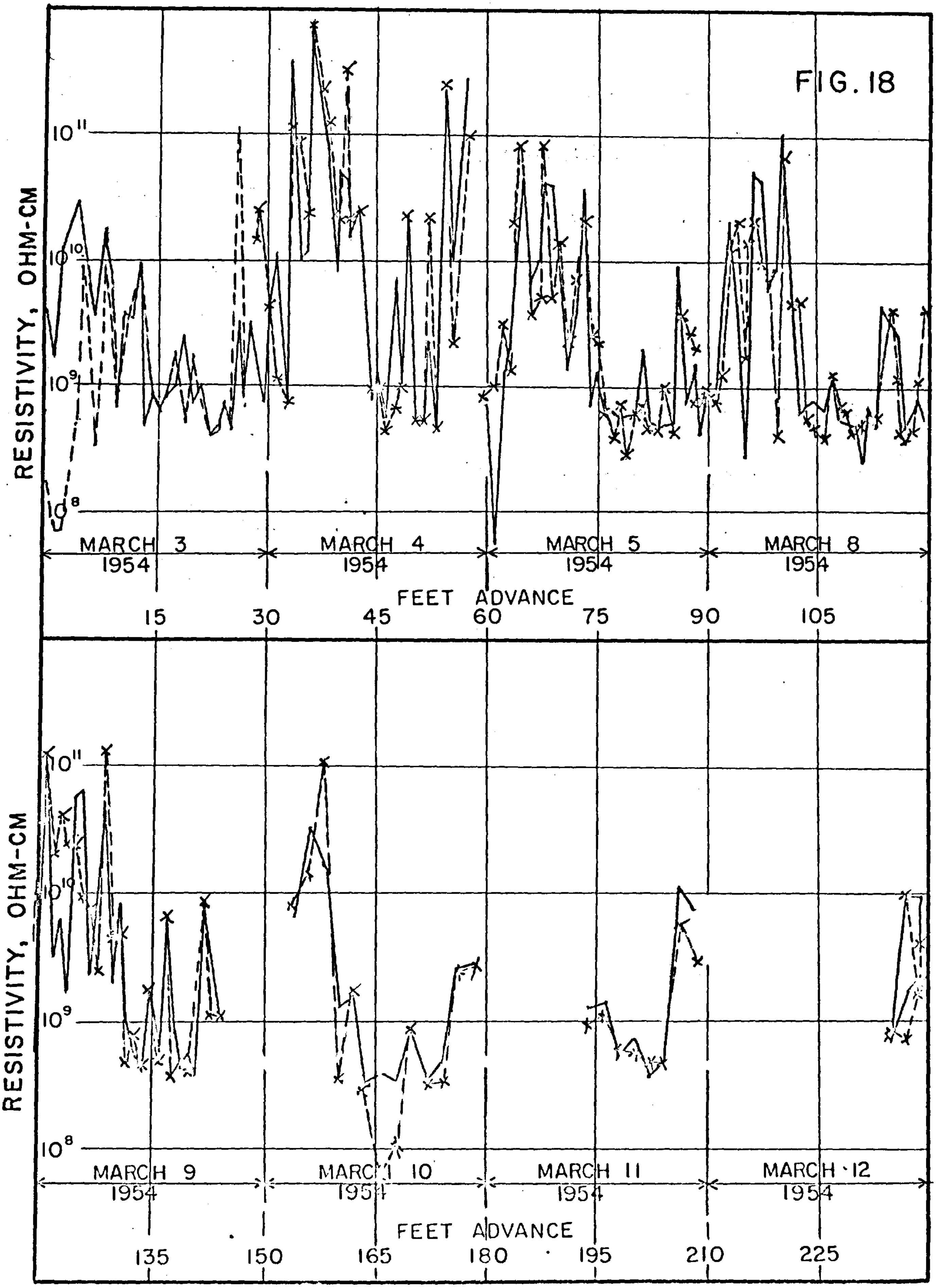
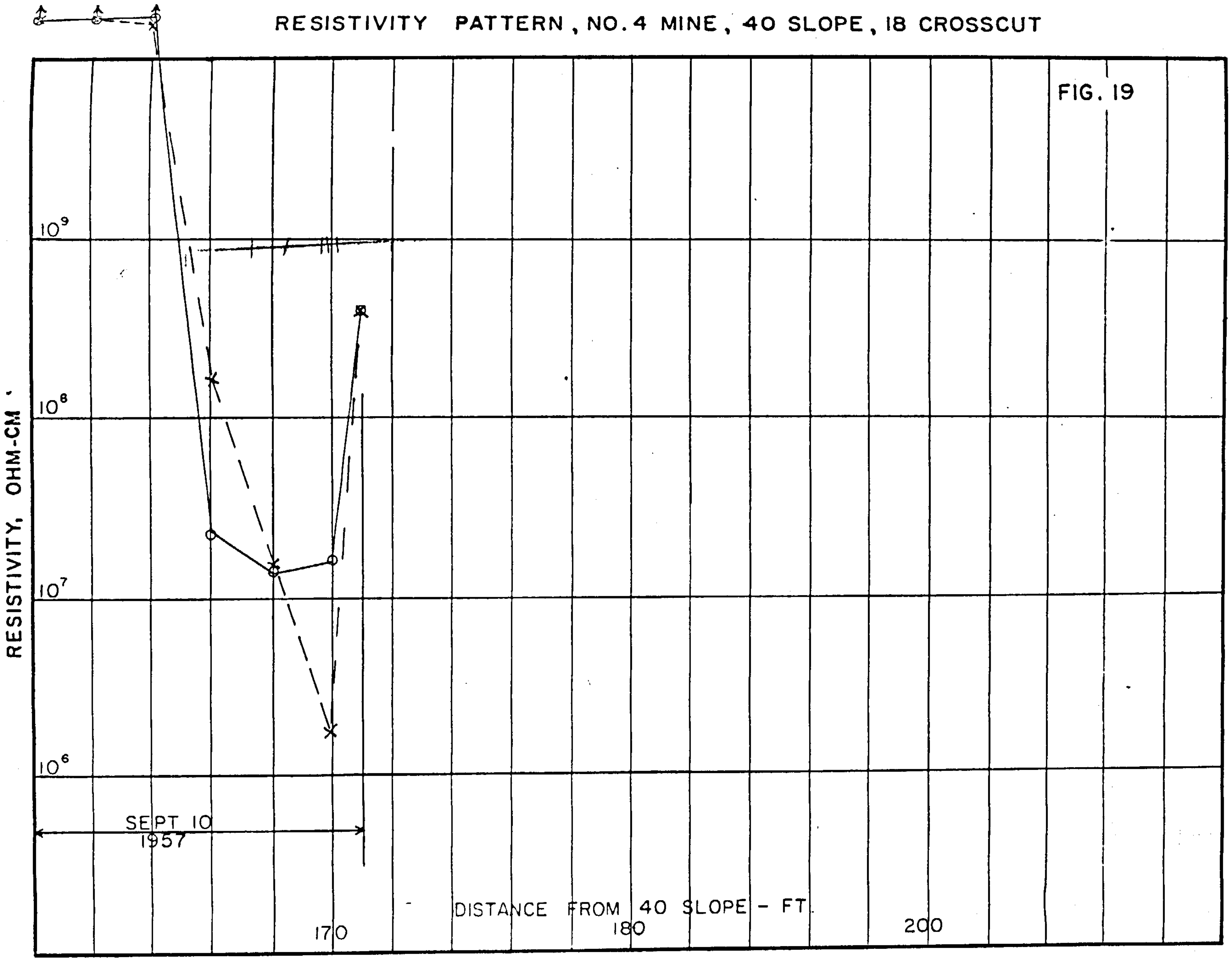
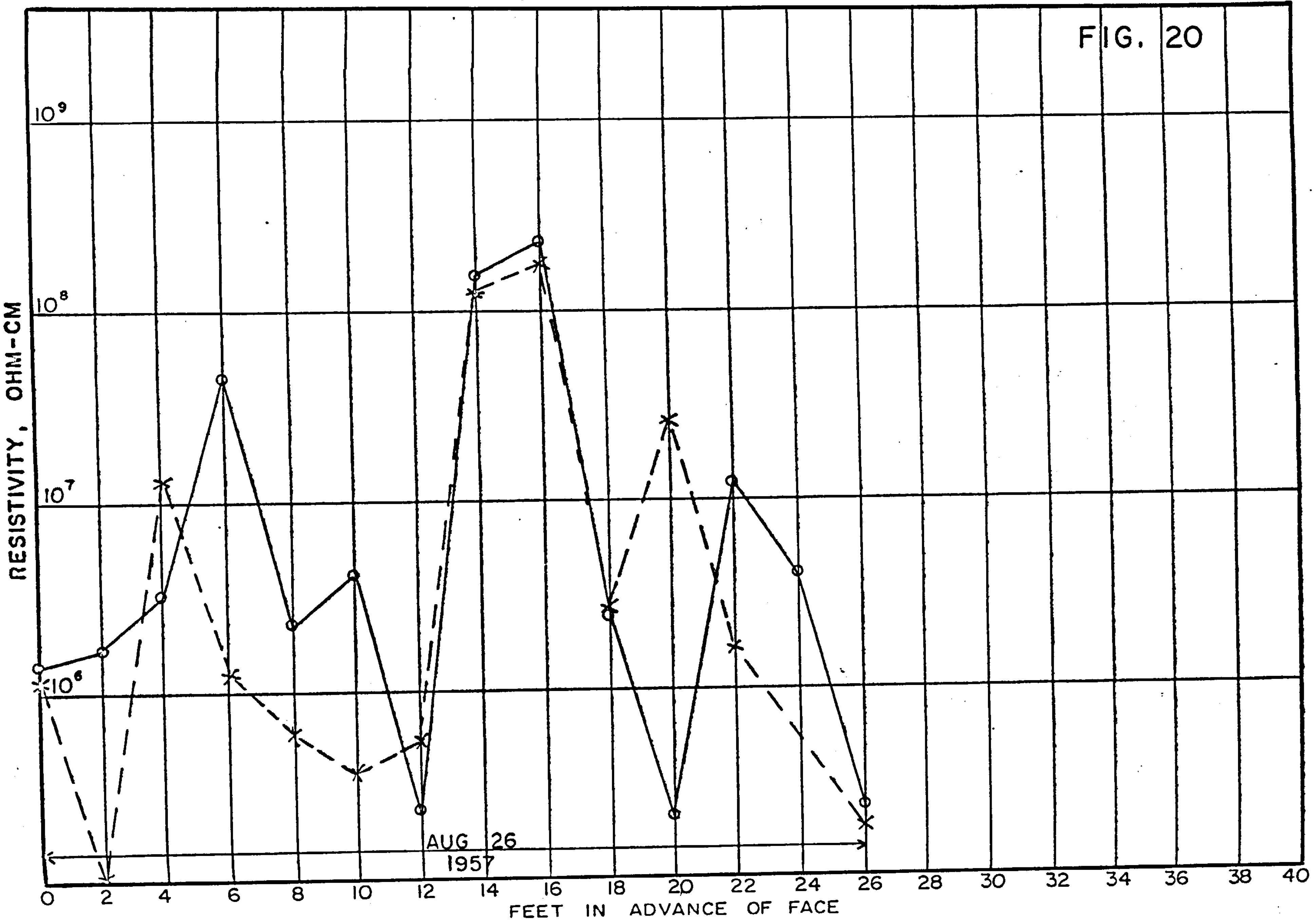


FIG. 18

RESISTIVITY PATTERN, NO. 4 MINE, 40 SLOPE, 18 CROSSCUT



RESISTIVITY PATTERN, LOWER MARSH SEAM, FACE OF 17 TUNNEL



CONCLUSIONS

1. The adsorption of carbon dioxide at 1000 psi lowers the resistivity of dry Canmore coal approximately one order of magnitude, but this is insufficient to explain the large fluctuations from 10^5 to 10^{11} ohm-cm in the field measurements.

2. Direct correlation of field measurements with moisture showed a random relationship. The lack of any correlation could be the result of the difficulties in obtaining representative samples and preventing changes in these samples during transit to the laboratory for moisture analysis.

3. Measurements at the face indicate that the seams can be stratified with respect to their resistivity and that these changes in resistivity between layers can be very abrupt, showing that the apparatus does not always give an apparent resistivity reading for a 30-inch-diameter sphere of coal centred about the current electrode. Under some conditions the volume of coal which is represented might be very small.

4. For high resistivity coals, the field apparatus is not independent of contact resistance.

5. A laboratory study of the relation of resistivity to moisture indicates that the maximum range for the resistivity measurements on friable coals, between the dry and saturated states, is approximately 6 orders of magnitude. This variation is of sufficient magnitude to explain the large fluctuations encountered in the field measurements. These fluctuations could arise from extraneous moisture along cracks.

6. Fusain lenses might produce the same effects as extraneous moisture.

7. There is no evident correlation between ground stress and resistivity.

8. Seam partings and accumulations of ash might in some cases influence the resistivity pattern.

9. There is no conclusive evidence to indicate a correlation between resistivity pattern and outburst occurrences in No. 3 Mine, Canmore, Alberta.

10. There are insufficient data from which to conclude that a fluctuating resistivity pattern is characteristic of outbursting seams.

11. The field resistivity technique is highly empirical.

ACKNOWLEDGEMENTS

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