

THE APPLICATION OF RADIO FIELD
INTENSITY MEASUREMENTS TO MAPPING
PRECAMBRIAN GEOLOGICAL STRUCTURES

THESIS FOR THE DEGREE OF M. S.

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CHARLES EDWARD KERMAN

1963

SUPPLEMENTARY
MATERIAL
IN BACK OF BOOK



**THE APPLICATION OF RADIO FIELD
INTENSITY MEASUREMENTS TO MAPPING
PRECAMBRIAN GEOLOGICAL STRUCTURES**

By

Charles E. Kerman

A THESIS

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ABSTRACT

A radio field intensity survey was conducted in the Marquette, Iron Mountain, Ironwood and Keweenaw areas of the northern peninsula of Michigan. The purpose of this study was to determine the applicability of radio field intensity measurements to mapping Precambrian geological structures in the Lake Superior region.

This method of geological mapping operates on the principle that a change in the underlying geology influences the intensity of radio waves at that point. These changes in intensity were permanently recorded on paper charts at the time the variations were observed. The recording was done continuously while the vehicle was in motion.

It is concluded that when a radio station can be received and there is a minimum of cultural interference, the radio field intensity method is applicable to geologic mapping in the Lake Superior region.

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SUPPLEMENTARY
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INTRODUCTION

The increased demand for mineral resources has spurred the search for new mineral deposits. Geophysical exploration methods, which detect hidden ore bodies or structures favorable for the occurrence of ore, have been the primary tools employed in this search because the vast majority of ore deposits that outcrop have already been found and exploited. A great variety of geophysical techniques are now being utilized in the search for mineral deposits. Although they all have their optimum place in the exploration industry, the reconnaissance methods which quickly and economically isolate favorable areas for intensified geophysical and geological studies have been the most useful.

The airborne magnetic and low-frequency electromagnetic methods have been particularly useful in reconnaissance exploration for mineral deposits. However, these methods do have limitations. The magnetic method is only applicable to the detection of horizontal variations in the magnetic susceptibility of rocks. Therefore, the method is limited to the detection of those ore bodies which are associated with concentrations of high magnetic susceptibility minerals such as magnetite, ilmenite, and pyrrhotite. Of course, not all mineral deposits are associated with detectable differences in

these minerals. The low-frequency electromagnetic methods have been successful in detecting hidden ore bodies that have a high electrical conductivity in contrast with the country rock. It is limited, however, to investigations on foot which are slow, or airborne studies which are very costly. In addition, the method is based on mapping variations in an electromagnetic field which is artificially generated and, therefore, requires a power source.

Another geophysical method which is potentially a valuable reconnaissance tool has not been fully investigated to determine its applicability to the detection of mineral deposits and geological structures. This is the radio field intensity method. It is based upon the measurement of the variations in the intensity of the signal carried by the surface wave from commercial broadcast band radio stations. The intensity of this wave is a function of, among other things, the electrical conductivity, dielectric constant, and magnetic permeability of the underlying earth formations. Therefore, unlike the airborne magnetic method, this technique is capable of detecting variations in the conductivity of earth material, and unlike the electromagnetic method, radio field intensity measurements can be made continuously from a moving vehicle, either ground or airborne, without having to produce the field which is investigated.

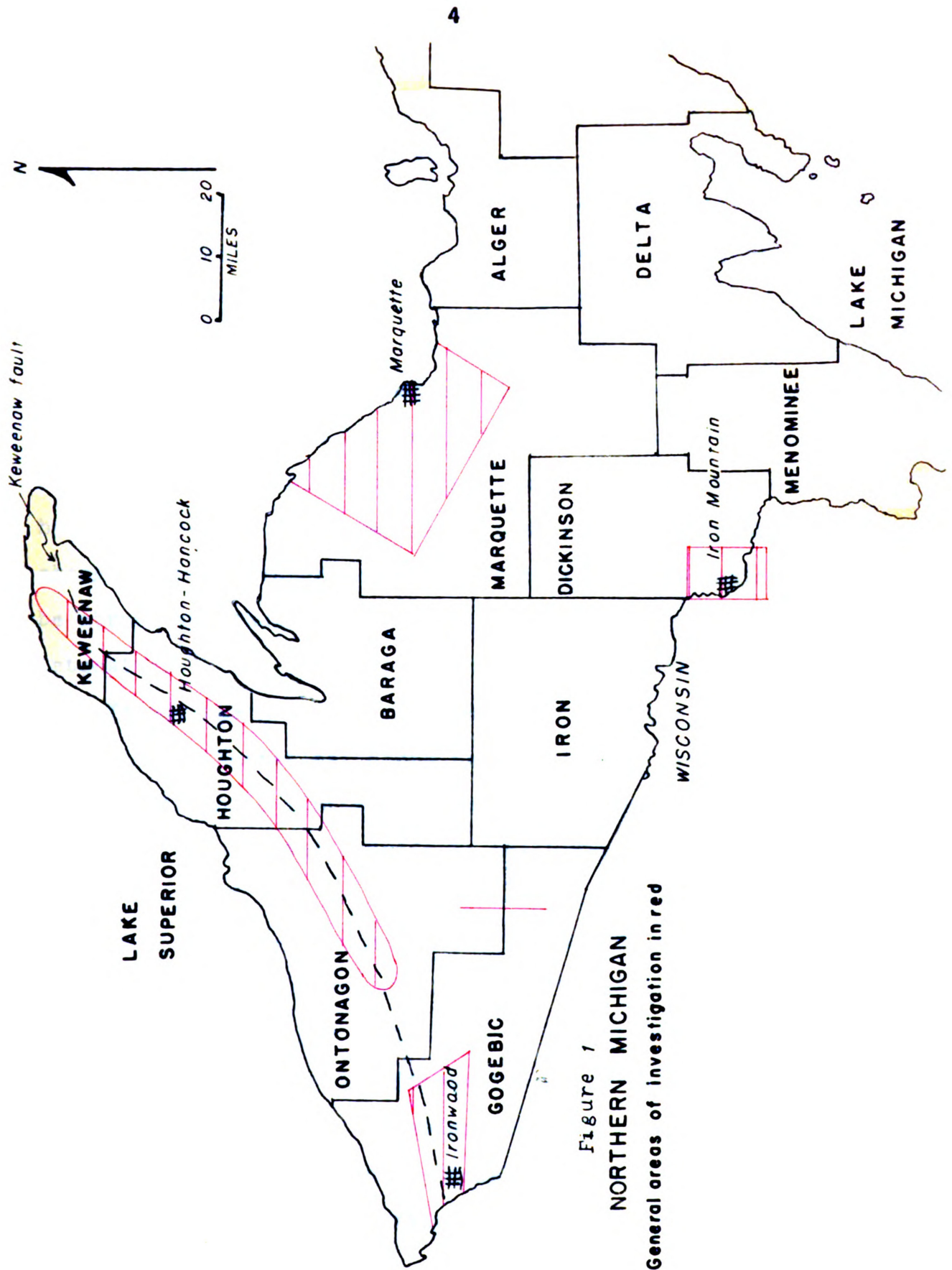
The purpose of this study was to determine the application of radio field intensity measurements in mapping Precambrian geological structures in the Lake Superior region.

This study was designed as a reconnaissance investigation of areas believed to be particularly well suited to this type of mapping. In the course of this study, during the summer of 1962, 350 miles of continuous field intensity records were made in northern Michigan and Wisconsin over a great variety of rock types and structures.

Some of the features investigated include the Keweenaw fault, granitic intrusions into lava flows, iron formations, the Wakefield fault, faults and Precambrian metasediments in a variety of locations in the Marquette syncline and adjoining areas, faults and metasediments in the Iron Mountain region, dikes and sills, and strongly magnetic features.

LOCATION

The field work was conducted in selected areas in the western half of the Northern Peninsula of Michigan and in adjacent parts of northern Wisconsin. The general locations of the areas of investigation are shown in Figure 1, and the specific locations of the traverses are given on the map in the folder at the back of the thesis.



The specific areas investigated were selected for a number of reasons. First, the geology is relatively well known. As the study was to determine the feasibility of geological mapping with radio field intensity measurements in this region, a good deal of geological control was needed to verify the results.

Second, geologic formations and structural features dip at high angles as a result of the intense structural deformation. In this type of mapping, it is desirable to have sharp contacts between adjacent rock types so the change in rock properties that affect the radio field will be abrupt and thus cause a distinctive change in the intensity.

Third, the glacial drift is thin in the areas investigated. The theoretical depth penetration of radio waves into the earth is limited, therefore the waves might not penetrate through thick drift to the bedrock. The desirability of thin drift in radio field intensity studies was pointed out by Gibbs (1939). On the basis of a survey in the Southern Peninsula of Michigan, he concluded that lithologic variations in the glacial drift were responsible for significant intensity changes.

The general level of geological knowledge, the sharp rock contacts, and the thin glacial drift provided excellent conditions for evaluating this method. In

addition, no comprehensive study of this method had been made in this area, and this method is potentially valuable in exploiting the mineral resources of highly deformed mineral districts.

PREVIOUS INVESTIGATIONS

Experimentation with radio waves in the earth began in the nineteen-twenties. Much of the first work dealt with the problem of radio communications within mines. As early as 1928, the U.S. Bureau of Mines published two technical papers on this subject; "Experiments in Underground Communications Through Earth Strata" by Ilsley, et al., and "Geophysical Prospecting: Some Electrical Methods" by Eve and Keys. Ilsley, et al., found evidence of radio wave penetration through seventy feet of earth, but were skeptical of the method of penetration. Eve and Keys, working at the Caribou Magnetite Mine, fifty miles from Denver, Colorado, found that KFEL, Denver, could be received at depths of 200 feet, and were of the opinion that there might be some reception at depths as great as 500 feet.

Eve, et al. (1929) continued their experiments in the Mount Royal Tunnel, Montreal, Canada. The most significant result of this work was the realization that long radio waves penetrate rock to a much greater extent

than short waves. That is, the lower the frequency, the greater the response deep in the tunnel. Later, Eve, Keys and Lee (1928), conducted similar experiments in the Mammoth Caves of Kentucky. The investigators thought that this would be a better test of the radio wave penetration because these caves did not have the wires, cables, and rails that were present in the Mount Royal Tunnel. Their work demonstrated that broadcast frequencies could penetrate at least 350 feet of rock.

Ernst Cloos (1934) accidentally noticed some disturbances in the reception on his car radio which did not seem to be related to cultural features such as power lines, steel bridges or telephone lines. As a result of this, he carried out a series of experiments in an attempt to relate these disturbances to the underlying geology. This was done using his automobile radio as a detection device, and listening for volume changes. He found that the results of his work agreed quite well with the known geology. He postulated that if the same area were run time and time again, and if the same non-cultural disturbances were recorded each time, then these might be a reflection of the underlying geology. Cloos found that there were 'dead spots' associated with faults and steeply dipping contacts. The results that Cloos obtained were excellent considering the type of equipment he used.

With the control of automobile traffic becoming a problem, the Ohio State Police had Higgy and Shipley (1936) run a radio transmission survey of Ohio to determine the best location, or locations, for their radio communications antennas. When the results of their work were plotted on a map of Ohio and the areas of similar conductivity shaded in, there was a remarkable correlation between this map and the geologic map of Ohio. The areas of best transmissive properties were underlain by Ordovician, Silurian, and Devonian limestones. The area with the next best properties was over Devonian and Mississippian shales. An area largely composed of Pennsylvanian and Permian sandstones was the third best area. A small section around Cleveland with thick Pleistocene deposits was the poorest area. This was probably the first time that the effects of the underlying rocks over a large area were fully realized.

Gibbs (1939) did a field intensity survey over the Howell Anticline in southern Michigan. In his conclusion he states that the bedrock had no effect on the field intensity because the glacial drift was too thick to allow penetration, and further, that the drift masked the bedrock response by its own changes in lithology.

B. F. Howell, Jr. (1943) ran radio field surveys over areas in southern California and New Jersey. He was not

too optimistic about the method because he found that some faults had weak fields associated with them but others did not. He was not able to determine the cause of the erratic response. He also stated that in populated areas there were too many man-made disturbances to render a good indication of the geology.

Larkin Kerwin (1946) was able to locate a dike with radio gear, and was then able to verify the location by field work. He also located several other anomalies and was optimistic about the future of the radio wave method of mapping. He concluded that topography had little effect on the field intensity in an area where the hills are gently rolling.

In 1948, McIlwain and Wheeler presented a paper to the convention of the Institute of Radio Engineers on the propagation of radio waves through the earth. Only the abstract of their report is available and in it they state: "The results show the limitations of radio waves for deep geophysical prospecting, though they may be useful for related exploration".

Haycock, et al., (1949) discussed the possibility of using radar for locating discontinuities within the earth. Their conclusion was that it probably would not be feasible to do this. However, they did think a phase shift measurement from a frequency modulated transmitter

might be of some value in this type of study.

Barrett (1949, 1952, 1953, and 1959) has done a considerable amount of work with a radio exploration method that he calls Radoil. In a demonstration at the Kleer Salt Mine at Grand Saline, Texas, he showed that radio waves with a frequency of 1,602 kc could penetrate 700 feet of earth materials.

The last major report in this field was by W. M. Pullen (1953). Pullen attempted to evaluate this method in all respects. He had a fair amount of success in mapping geology in Illinois using a method of continuous recording. Some of the features over which he found radio field intensity changes are the Shawneetown-Rough Creek fault, a cryptovolcanic structure, the Hicks dome, and the Inman East fault. In Illinois he found conflicting results over ore bodies of pyrite, sphalerite, and marcasite. He found little or no effect from soil or loess over glacial drift.

A major change that differentiates the more recent work from the older work is that since Kerwin (1946) all of the investigators have used a continuous recording method, and used only relative variations in the field intensity.

This research differs from that of Pullen's in that this is an attempt to determine the potential of the radio

field intensity method in the Precambrian areas around Lake Superior. This is, of course, a completely different geologic province than that in which Pullen made his investigations. Another difference, is that a tuned whip antenna was used whereas Pullen and most of the others used a loop antenna.

PHYSICS OF RADIO WAVES

INTRODUCTION

In the radio field intensity method of geological mapping the intensity of radio fields produced by commercial A.M. broadcast stations are measured. Many things affect the intensity of radio waves, one of these is the geology. By measuring variations in the intensity of the field, local changes in the underlying geology can be determined. These variations are caused by the interaction of the radio waves with the physical properties of the earth.

The radio waves that are utilized in this type of geological mapping are one form of electromagnetic radiation. Like the other forms, e.g. light, they travel at 300,000,000 meters or 186,000 miles, per second in free space.

When radio waves leave the transmitting antenna they can be classified into a number of waves depending on how

they are affected by the earth, and the path they travel in reaching the receiving antenna. The primary waves are the sky wave and the ground wave. The sky wave is that portion of the total wave that is directed toward the upper atmosphere. Depending on the time of day and the frequency of the radio signal this wave may or may not be reflected back to the earth by the ionosphere. This is primarily a nighttime phenomenon. As this wave does not interact with the earth it is of no interest to this investigation.

The ground wave is directed along the surface of the earth, is not reflected off the ionosphere, and is composed of one or more of the following waves: 1. the direct wave, 2. the ground-reflected wave, 3. the surface wave, and 4. the ground-refracted wave.

1. The direct wave is that component of the ground wave that travels directly to the receiving antenna from the transmitting antenna. This wave is primarily a line-of-sight wave. However, it can undergo a slight amount of diffraction in the atmosphere.

2. The ground-reflected wave is that portion of the ground wave which reaches the receiving antenna by reflecting off the earth. This wave is primarily important in short distance communication. When this wave is reflected it undergoes a phase reversal of 180 degrees, therefore at

close distances the ground-reflected wave and the direct wave may nearly cancel each other.

3. The surface wave is that portion of the ground wave that travels along the surface of the earth and follows the curvature for moderate distances. At near distances the direct wave and the ground-reflected wave can nearly cancel each other so that the primary form of transmission is by the surface wave. This wave is affected by the conductivity of the ground over which it passes.

4. The ground-refracted wave, for the purposes of this discussion, is that portion of the ground-reflected wave which enters the earth. This wave is refracted by the earth and travels within the earth until it is absorbed or until it is refracted or reflected back into the atmosphere. This wave is strongly affected by the electrical and magnetic properties of the earth.

As these waves are a form of electromagnetic radiation they follow the general laws of light. That is they can be diffracted, polarized, and reflected, and in accordance with Snell's law, they can be refracted.

FACTORS AFFECTING FIELD STRENGTH

Introduction

As the radio waves are emitted from the antenna they

spread out in accordance with the directional properties of the antenna. These waves consist of two fields, neither of which can be transmitted separately. These two fields, the electric and the magnetic, are mutually perpendicular to each other. The electrical field is vertically polarized and the magnetic field is horizontally polarized in waves emitted from commercial radio broadcast stations.

The intensity of these fields decreases as the wave travels away from the transmitting antenna as a result of the geometrical spreading of the wave and the absorption of the wave's energy. In addition, the intensity is affected locally by waves that are reflected and refracted within the earth. The surface environment including cultural, meteorological and terrain features, and secondary fields induced by the radio waves, also affect the intensity.

Geometrical Spreading

Geometrical spreading causes a decrease in the power per unit area, and therefore in the intensity of the waves as they travel outward from the antenna. When a wave is emitted from a transmitter it has a certain amount of power, and it is confined to a small area. As the waves spread out this initial power must now cover the increasing area thereby reducing the power per unit area. The power of these waves falls off as the square of the distance, while

the intensity decreases proportionally to the distance. In this investigation an attempt was made to orient the traverse at right angles to the direction of propagation, so that geometrical spreading would not unduly affect the results.

Absorption of Energy

As the waves travel away from the transmitting antenna the earth exerts an influence on them. Part of their energy is absorbed by the earth and is dissipated as heat. This loss of energy can be great and as a result of this the surface wave transmission is limited to moderate distances. As the surface wave travels along the surface of the earth it gives up energy to the earth and as a result there is a retardation of the wave front along the surface causing it to bend forward in the direction of propagation. Therefore the antenna does not pick up the maximum intensity of the electrical field, but rather a component of it, because the antenna is no longer parallel to the electric field vector. This tilting of the wave front has been measured and is as much as 32° from the vertical at broadcast frequencies.

Poorly conducting ground surfaces cause a greater dissipation or absorption of the radio wave energy than good conducting surfaces, hence a greater tilt of the wave front.

In an attempt to account for this absorption of energy by the earth Sommerfeld (Byrne, 1932) advanced the following equation:

$$E = y(\alpha) \frac{5.9 \sqrt{P}}{d} \quad (1)$$

where E = field strength in millivolts/meter at a distance of d miles
 $y(\alpha)$ = Sommerfeld's integral to account for earth effects
 P = doublet antenna power in watts
 d = distance in miles from transmitter to point of measurement.

Sommerfeld's integral, $y(\alpha)$, was approximated by Van der Pol to the following:

$$y(\alpha) = \frac{2 + 0.3 \alpha}{2 + \alpha + 0.6 \alpha^2} \quad (2)$$

where

$$\alpha = \frac{8.38 \times 10^{-10} d}{\lambda^2 \sigma} \quad (3)$$

where λ = wave length in meters
 σ = earth conductivity in esu
 d = distance in miles.

We can see from equation 3 that the conductivity is one of the earth's properties that affects the intensity. This conductivity is the total effect of all the various conductivities of the rocks over which the wave has passed. If a traverse should cross a particularly poor conducting body there will be an additional absorption and tilting of

the wave which will cause a further decrease in intensity.

Reflection and Refraction within the Earth

The intensity of the surface wave is also affected by waves that return to the surface after they have been reflected and refracted by discontinuities within the earth. The intensity of these waves which pass through the earth is rapidly attenuated by absorption of energy during propagation, and by dissipation of energy on reflecting and refracting interfaces within the earth.

The effect the ground-refracted wave will have on the surface wave upon recombination in the atmosphere is determined by the path within the earth, and by its velocity. The velocity of the electromagnetic radiation through a material is a function of the dielectric constant and the magnetic permeability of that material. The velocity of the wave within a medium can be expressed in terms of its speed in free space by the following equation which assumes a fixed frequency:

$$c_m = \frac{c}{\sqrt{\mu k}}, \quad (4)$$

where c_m = velocity in the medium in meters/second
 c = 300,000,000 meters/second, velocity in free space
 μ = magnetic permeability
 k = dielectric constant.

If the ground-refracted wave returns to the surface it may or may not be in phase with the surface wave because of

the path it has followed and the subsequent change in velocity. If it is 180 degrees out of phase there will be attenuation and an intensity low. If, however, the ground-refracted wave is in phase with the surface wave there will be a reinforcement and hence an intensity high. The path length is determined by the angle of incidence with which the radio wave impinges on the discontinuity, and the electrical properties of the medium through which it travels.

Induction

An electromagnetic field is induced in the conducting rocks where the radio waves enter the earth. As this field is 180 degrees out of phase with the inducing field it causes some attenuation of the surface wave and hence an intensity low over this location. The better the conductor, the stronger the induced field, and the lower the intensity. As the conductivity of the rocks decreases so will the strength of the induced field and therefore the amount of attenuation.

Surface Environment

The earth is only one of many things that affect the radio field intensity in this type of mapping. In general, the more pronounced and spectacular changes in field

intensity are caused by surface features. Fortunately these can be accounted for by close observation on the part of the operator.

Most noticeable of these effects are those caused by overhead wires of various types. Electric wires cause the largest changes in the intensity, telephone and guy wires cause changes of a lesser degree. Bridges, railroads and metallic culverts under the road also cause changes in the field intensity. In general, any metallic object that can act as an antenna will usually cause some sort of abnormal response in the meter, although wire fences along the road did not cause any noticeable changes in the intensity.

The type of response experienced by the meter from any given type of wire or object is not constant. It varies as a result of a number of factors. If the disturbing factor is an electric wire the strength of its field depends on how much current it is carrying. The amount of disturbance also depends on the relationship between the wire, the transmitting antenna location, and the vehicle's motion in relation to these factors. When driving in one direction under a wire the response may be large, however there may be little or no response from the same wire when driving in the other direction, or it may be in the opposite direction to the first response, even with the same station. See Figure 28.

In most cases the disturbance caused by a wire builds up as the wire is approached and drops off as the wire is left behind, with the greatest disturbance coming directly under the wire. This however, is not inviolable. There are some wires that give all of their effects on one side, regardless of the direction of the transmitter or the direction driven. This is the exception rather than the rule.

Topography may also affect the intensity if it is severe and close to the road. There seems to be some effect from swamps, but this is not something that can be relied upon. Woods were continuous on both sides of most roads and did not present any problems for this investigation although it is possible that they might affect the intensity under other circumstances.

The reinforcing in modern concrete highways has the effect of shielding the underlying geology so that the geology has little effect on the radio waves.

Meteorological conditions have been found to affect radio waves by Gracely (1949). He has shown that as the temperature increases the intensity decreases, and there is a specific temperature for which each individual frequency is attenuated the most. In this project the temperature had no affect because most of the traverses were short in distance and therefore in time. Pullen (1953)

states that meteorological effects are noticeable at low frequencies over long time intervals, or at high frequencies in short time periods. There are changes during the year, the winter apparently being the best time of year for reception. There seems to be no relation between magnetic storms and long wave field intensity. There does, however, seem to be a relation between intensity and sunspots, for as the activity of sunspots increases so does the intensity. The last two statements do not hold for short waves. All wave lengths are affected by bolts of lightning which result in erratic responses.

PENETRATION OF RADIO WAVES INTO THE EARTH

The depth to which radio waves penetrate the earth is primarily a function of their frequency. The higher the frequency the less the penetration. This is one reason why radar which utilizes very high frequency waves will not work in this type of investigation.

The relationship between the frequency and the depth of penetration of radio waves in the earth is controlled by the phenomenon called the skin effect. The skin effect is the crowding of current toward the earth's surface with increasing frequency. This is caused by the radio field inducing in the rocks another field that is 180 degrees out of phase. As the frequency of the radio wave increases

the intensity of the field that is induced in opposition also increases. As the intensity of this field becomes greater the current is limited to increasingly shallow depths.

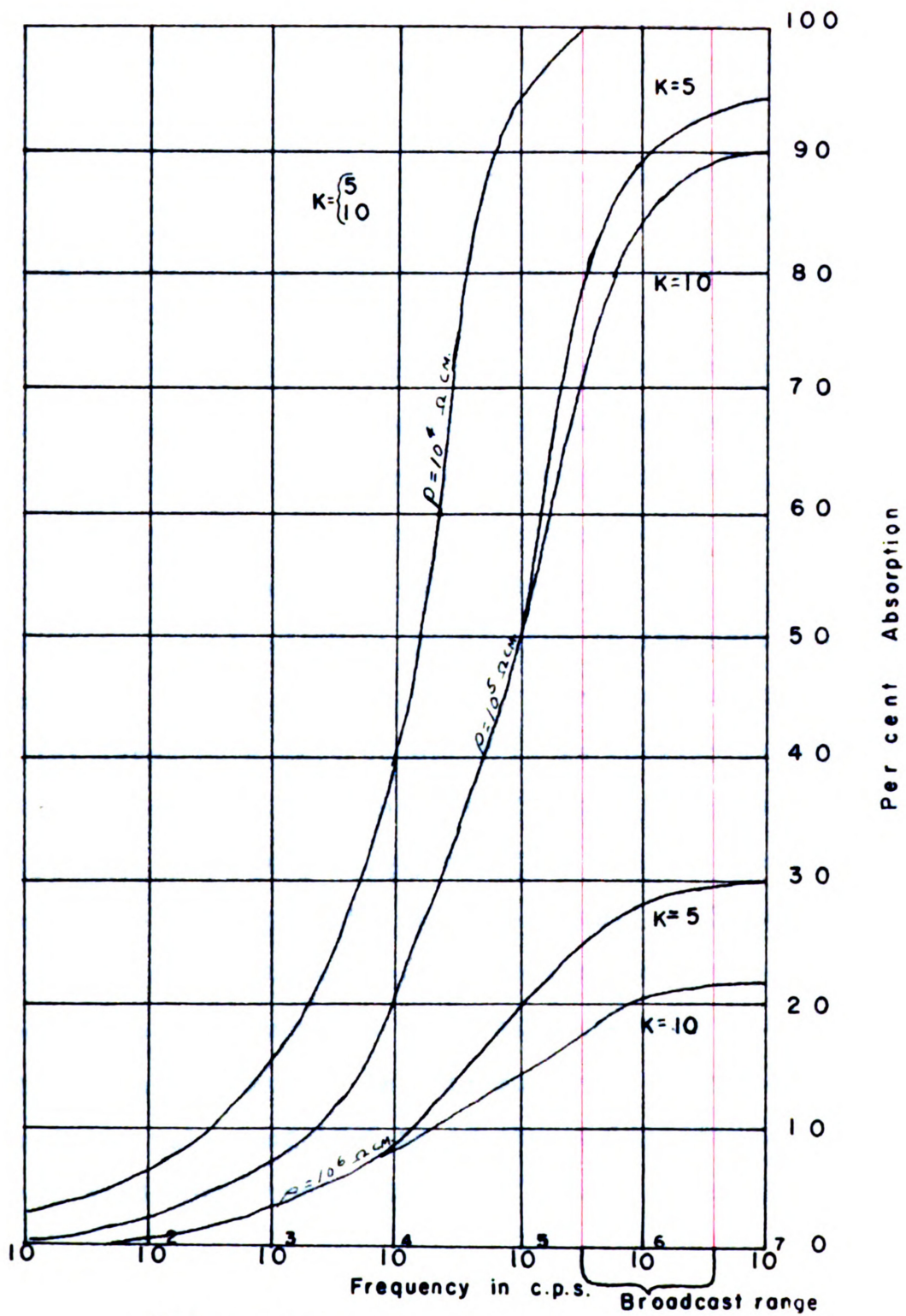
Joyce (1931) has related the absorption of electromagnetic radiation in the earth to the frequency of the wave, the dielectric constant, the resistivity and the magnetic permeability of the earth. He has expressed this as a ratio of the amplitude of the wave at a depth, d , to the amplitude of the wave at zero depth. This ratio is called the transmission factor and may be expressed as

$$T.F. = e^{-\frac{2\pi f d}{c} \left[\mu \left\{ \left(\frac{k}{2} \right)^2 + \left(\frac{1}{\rho f} \right)^2 \right\}^{\frac{1}{2}} - \frac{k}{2} \right]} \quad (5)$$

where d = depth in cm
 c = velocity of light in cm/sec
 k = dielectric constant
 f = frequency in cps
 ρ = resistivity in e.s.u.
 μ = magnetic permeability.

Joyce has made calculations using this relationship to show the percent absorption of the signal with varying dielectric constants, resistivities, and frequencies. Some of his results are shown in Figure 2. The depth for which these calculations were made is 124 feet, and the magnetic permeability is considered to be equal to 1. It can be seen from Figure 2 that as the frequency increases the

Figure 2



(After Joyce, 1931, page 4)

amount of absorption increases. It can also be seen that as the resistivity decreases, and as the dielectric constant decreases, the amount of absorption increases.

For a given frequency and resistivity the dielectric constant plays an important role, e.g., at $f = 10^6$ cps and $\rho = 10^6 \Omega\text{cm}$, doubling k reduces the absorption by almost 10 percent.

s

PERTINENT ROCK PROPERTIES

The radio field intensity method of mapping measures, to some extent, all of the electrical and magnetic properties of the earth. The distribution and the magnitude of the current induced in the subsurface depends on the type of electrical and magnetic properties the rocks possess. The most important of these properties is the resistivity. Resistivity, ρ , is defined as the resistance in ohms between parallel faces of a unit cube. This is usually measured in ohm-centimeters. The inverse of resistivity is conductivity. The conductivity, σ , is often used in equations expressing electromagnetic relationships. It is usually measured in mho-centimeters. Table 1 shows the range of values these two important physical properties have in some of the rocks encountered in this survey. Rocks that have resistivity values of 10^{-3} to 10 ohm-centimeters are considered good conductors, 100 to 10^{-9} are intermediate, and

10^{-10} to 10^{-17} are poor conductors.

Another electrical property to be considered is the dielectric constant of the rocks and minerals. The dielectric constant is a measure of the rocks ability to be polarized in an electric field. With an impressed electrical field, E , there is P , polarization per unit volume that is proportional to E , and ϵ , the electrical susceptibility. This is expressed as the total electric flux E_{tf} per unit area in the following equation:

$$E_{tf} = E + 4\pi P \text{ or } E(1 + 4\pi\epsilon) \quad (6)$$

The term $(1 + 4\pi\epsilon)$ is called the dielectric constant, k . The dielectric constant is an important electrical property when considering general electromagnetic wave theory, as seen from Joyce's curve, Figure 2.

The magnetic permeability is another rock property that must be considered. The magnetic permeability, μ , of a substance is the ease with which magnetic flux can be established in a material, or the ratio of the number of lines of force passing through the material to the number of lines in a like cross-section of air,

$$\mu = \frac{B}{H} \quad (7)$$

where H = intensity of field
 B = flux density.

The magnetic permeability is a consideration in determining

Table 1

**Pertinent Electrical Properties
of Rocks Encountered in this Survey***

Rock Type	Resistivity ohm-centimeters	Conductivity mho-centimeters
Basalt	2×10^6	0.5×10^{-6}
Diabase	2×10^3 to 2×10^6	0.5×10^{-3} to 0.5×10^{-6}
Gneiss	2×10^4 to 3.4×10^6	0.5×10^{-4} to 0.29×10^{-6}
Granite	3×10^4 to 10^6	0.33×10^{-4} to 10^{-6}
Quartzite	10^3 to 2×10^7	10^{-3} to 0.5×10^{-7}
Schist	5×10^2 to 10^6	0.5×10^{-2} to 10^{-6}
Syenite	10^4 to 10^7	10^{-4} to 10^{-7}
Trap Rock	1.5×10^4 to 3×10^5	0.66×10^{-4} to 0.33×10^{-5}
Glacial Drift	8×10^{-2} to 9.5×10^5	0.125×10^2 to 0.05×10^{-5}
Conglomerate	2.5×10^3 to 1.5×10^6	0.4×10^{-3} to 0.66×10^{-6}
Sandstone	3×10^3 to 10^7	0.33×10^{-3} to 10^{-7}
Hematite	5×10^4 to 10^7	0.2×10^{-4} to 10^{-7}
Magnetite	0.6 to 5×10^3	1.66 to 0.2×10^{-3}

* Source of Data J. J. Jakosky & F. Birch

Table 1 (continued)

Rock Type	Magnetic Permeability	Dielectric Constant
Basalt	1.0085 to 1.079	12
Diabase	1.0009 to 1.0526	--
Gneiss	1.0012 to 1.012	8 to 15
Granite	1.0012 to 1.012	7 to 12
Quartzite	1.0000	7
Schist	1.0012 to 1.012	11 to 12
Syenite	--	13 to 14
Trap Rock	--	18 to 39
Glacial Drift	--	--
Conglomerate	1.0012 to 1.012	--
Sandstone	1.0006	9 to 11
Hematite	1.00048 to 1.0012	25
Magnetite	26.0 to 1.5	--

the velocity with which an electromagnetic wave will pass through a substance.

Table 1 gives the range of values of these physical properties for some of the rock types encountered in this survey.

The exact manner in which the electromagnetic waves interact with the subsurface is not known. Therefore, by necessity, some of the considerations in this section are tentative and subject to further investigation.

EQUIPMENT

INTRODUCTION

The major components of the equipment employed in this investigation were borrowed from the Illinois Geological Survey. This equipment, which was used by Pullen in his investigations, was obtained in the summer of 1961. Field studies with the equipment were initiated at this time. These studies included 1. investigating the optimum speeds at which traverses should be run, 2. types of antennas best suited for this type of work, 3. the effect of cultural disturbances on the intensity of the radio field and 4. general operational procedures. As this was a continuing project technical problems that arose with the equipment during the summer were solved the following school year.

RADIO FIELD INTENSITY METER

The major component of the method is the R.C.A. 308-B Radio Field Intensity Meter. This is a six band receiver covering the frequency range from 120 kc to 18 mc. The meter contains, besides the receiving circuits, calibrating circuits to enable the operator to make absolute field intensity measurements. This meter is calibrated in microvolts per meter. This is defined as the voltage induced in a conductor 1 meter long when held so that it lies in the direction of the electric field, and at right angles to the direction of propagation and to the direction of the magnetic field. These circuits were not used, however, because relative variations are all that is needed for the purposes of this method and because the type of antenna used would not permit absolute measurements to be made.

POWER SUPPLY

The 308-B field intensity meter is normally powered by a 135 volt wet cell battery. Since there was no way of conveniently charging the battery in the field, a power supply was constructed that could be powered by a 12 volt automobile battery. This power supply was similar to one built by WKAR, Michigan State University Radio for an identical meter. The circuit diagram of this power supply is

supply is shown in Figure 3.

The power supply consists of three parts: an automobile battery, a converter, and a rectifier. A special 12 volt auto battery was procured with an extra 6 volt terminal. This battery was kept charged by connecting it in parallel with the vehicle's battery when the equipment was not in use. This battery ran the converter which took the 12 volts DC and converted them into 115 volts AC. The converter is a 90 watt A.T.R. (American Television and Radio Company) converter. The rectifier plugged into the converter. The rectifier changed the 115 volts AC to 135 volts DC and 90 volts DC to operate the plates and the screens, respectively, of the tubes in the 308-B. Filament power came from the special 6 volt DC terminal on the battery. The ground for the equipment came from the negative terminal of the battery. However, the filaments needed a positive ground and therefore had to be isolated from the car body while the charging of the equipment battery was in process. If this was not done a short circuit developed. This can be seen in Figure 4 which shows a schematic diagram of the connections between the various components. These power supplies, in addition to two 7.5 volt batteries in the meter, completed all of the necessary energy to operate the equipment.

RECORDER

The recorder used in this investigation was an Esterline-Angus, model AW, DC milliammeter. Full scale deflection of the meter was provided by a current of 10 milliamperes. The record of intensity changes is produced as an ink pen which is connected to the meter movement moves across a paper chart which is fed through the meter at a speed which is proportional to the speed of the vehicle. The synchronization of the vehicular speed and the chart is accomplished through the use of a Clark Speedometer Tee. The speedometer cable is disconnected from the back of the speedometer and is connected to the Tee. From the Tee there are two cables, one of which goes back to the speedometer and the other which goes to the recorder. This drives the recorder at a speed that is proportional to the vehicle's speed. In this investigation four inches of paper represented one mile of traverse.

Within the recorder there is, in addition to the recording pen, an event marking pen. This pen is activated by a 115 volt AC solenoid which is controlled by a key that was operated by the driver. This pen was used to mark cultural features that might disturb the radio field and also to mark features that were used to establish the

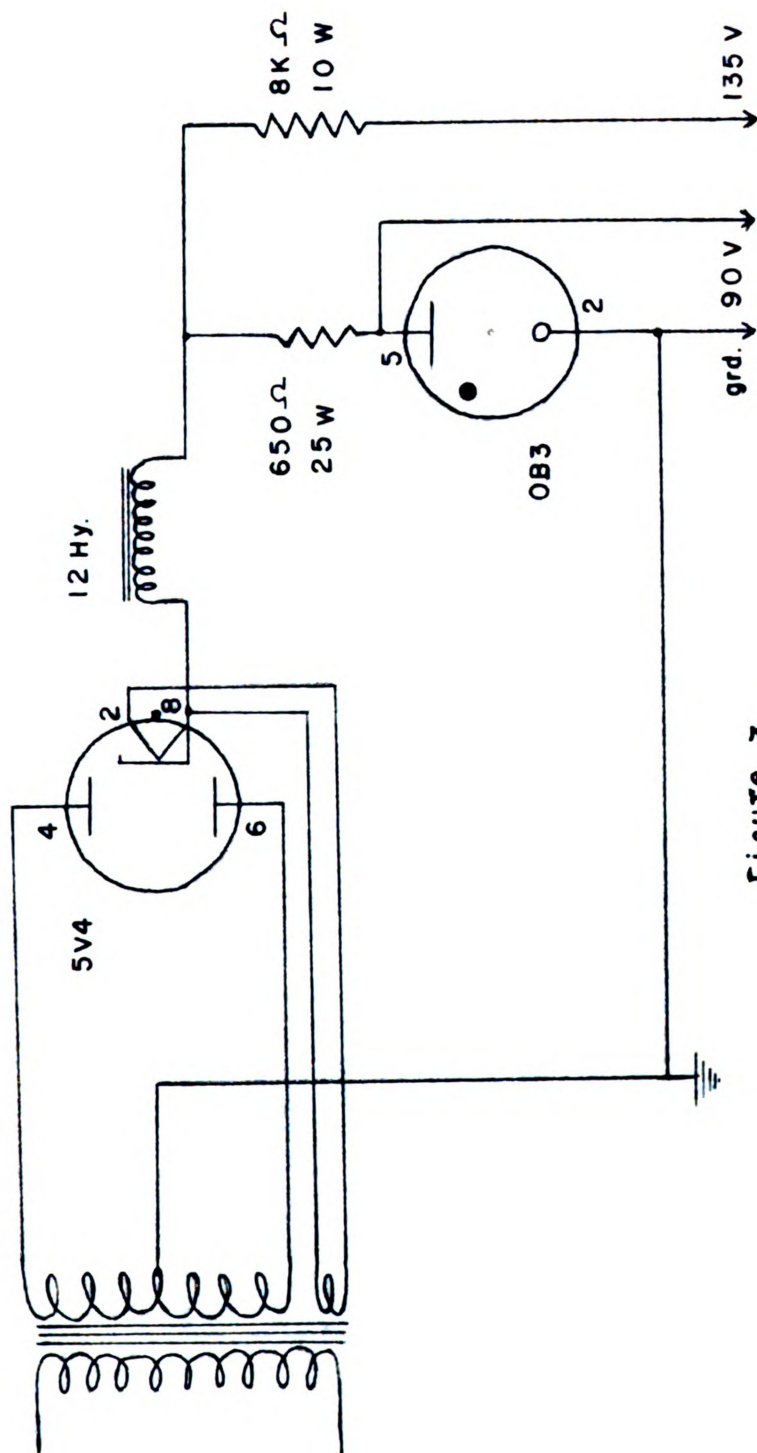


Figure 3
POWER SUPPLY

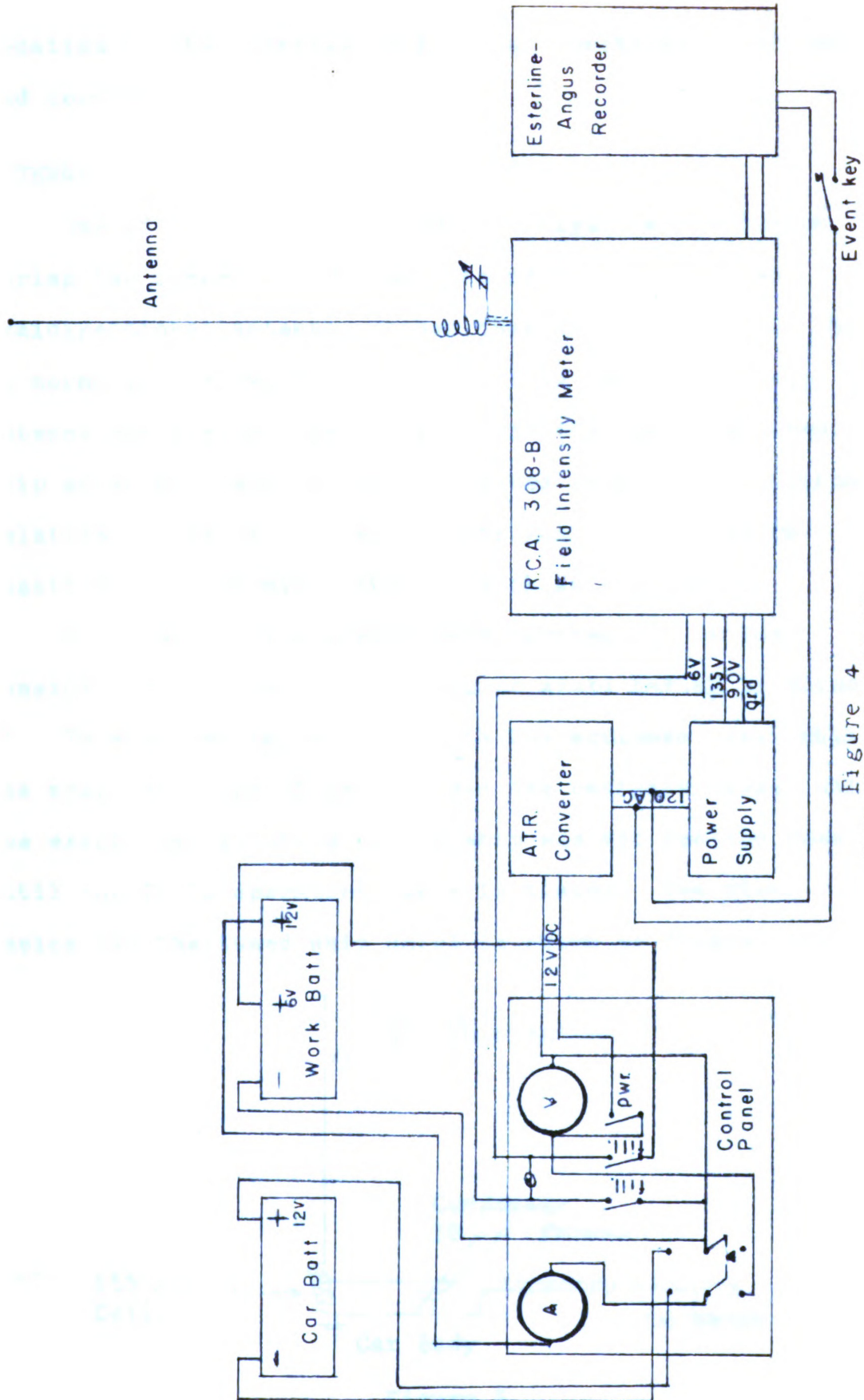


Figure 4
WIRING DIAGRAM

location of the traverse, e.g., road junctions, railroads, and county lines.

ANTENNA

One of the results of the investigations conducted during the summer of 1961 was the decision to use an omnidirectional antenna, rather than the loop antenna that is normally used with the 308-B. Even though the loop antenna has greater sensitivity than the omnidirectional whip antenna it must be kept oriented in a fixed position relative to the radio field. This would have been impossible in a one-man operation such as this one.

A number of experiments were carried out on the possibility of spinning the loop to avoid having to orient it. This proved impractical with the equipment available. The next best type of antenna was the omnidirectional whip. The exact configuration of the whip was not decided upon until the field operations were initiated. The final choice was the tuned whip which is shown in Figure 5.

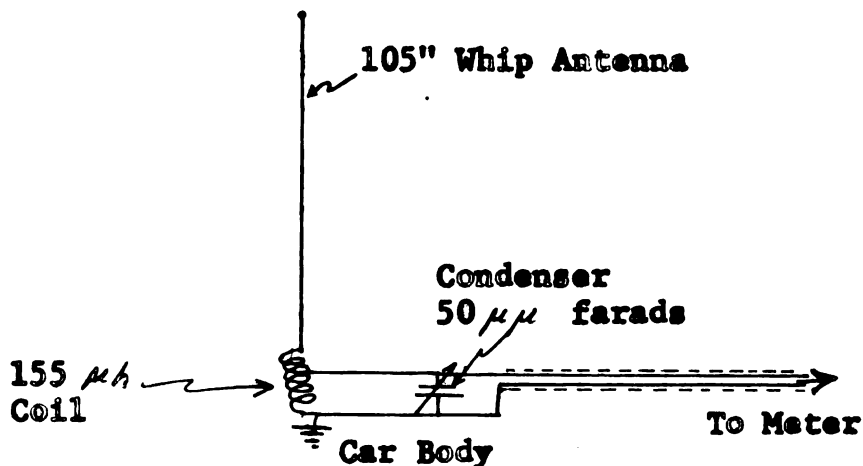


Figure 5

The antenna was attached to the back of the vehicle via a bumper mount. The antenna was kept rigid because if it swayed it caused an unwanted response on the record. This was done by use of a wooden pole to which the antenna was attached, and this was in turn fixed to the vehicle. This wooden pole also served as a mounting place for the coil in the antenna circuit. The condenser used to tune the antenna was fixed on top of the meter inside the vehicle.

FIELD PROCEDURES

This was a one man operation, therefore driving, observing, operating the event key and taking notes had to be done simultaneously. To alleviate this condition a magnetic tape dictaphone was used to record the field notes. The dictaphone was powered by a 30 watt A.T.R. converter that plugged into the cigarette lighter of the vehicle. The dictaphone was a DeJur Magnetic Tape Stenorette.

The general areas to be investigated were selected in the office on the basis of the conditions previously cited. On arrival at an area a general reconnaissance was made to determine whether radio broadcast stations were detectable and which roads were most suitable for traverses.

Investigations were carried out in the Marquette area, the Iron Mountain area, the Ironwood area, the Keweenaw area, and selected areas in Wisconsin. Examples of all traverses in these areas where the intensity changes correlated with the geology are shown and discussed in the section dealing with results and interpretations. Representative areas where the radio field intensity variations failed to correlate with the geology are also shown.

Some of the specific areas initially chosen were later changed because of the inability to receive radio stations, or because of cultural interferences.

The field procedure for making a traverse is given below.

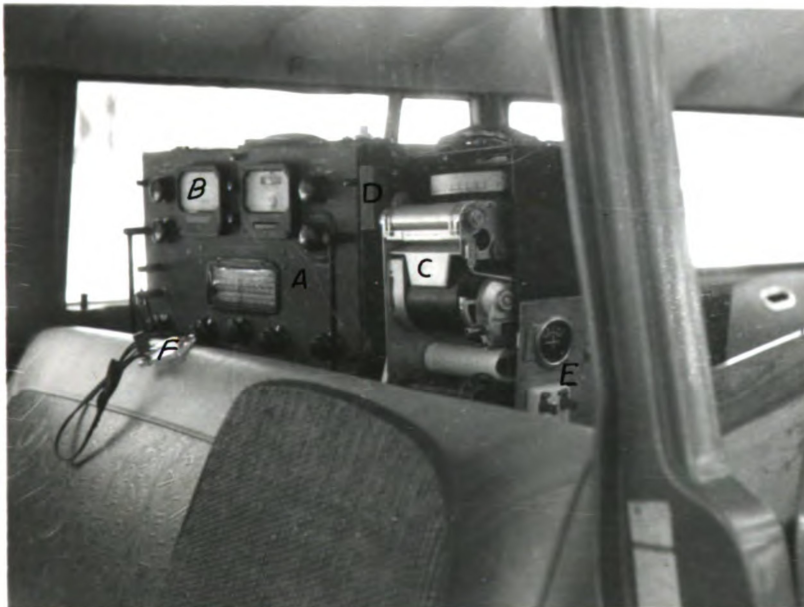
1. The road previously selected for investigation was located.
2. A reconnaissance of the road was made to see if it was feasible to make the traverse. The presence of many overhead lines was justification for disregarding a road.
3. If the traverse was feasible the equipment was warmed up and a station selected. A preferred station was one which gave a reading of mid-scale on the milliammeter in the 308-B.
4. As the traverse was run events were marked on the record with the event marking pen, and notes were recorded on the dictaphone. The events marked and the notes describing these events included orientation marks, culture, outcrops if any, and pertinent comments about other surface features.

5. At the end of each traverse an evaluation of the traverse was made to determine the success, and to see if there was a particular area in which closer visual observations should be made.
6. A re-run was then made using a different station if one could be received. There are only nine stations in the northern peninsula in the area in which the investigations were carried out, and these are all low power.
7. If a third station could be received successfully then the road was run again, etc.
8. Many times outcrops were available within easy access of the road, and the operator would get out and make a determination of the lithology and record it appropriately.

Figure 6

Equipment Mounted in Vehicle

- A. R.C.A. 308-B Field Intensity Meter
- B. Milliammeter
- C. Esterline-Angus Recorder
- D. Clark Speedometer drive
- E. Control Panel
- F. Event Key



RESULTS AND INTERPRETATIONS

INTRODUCTION

The results of this investigation are shown on the following pages. Not all of the records that were made are shown. Those shown are the ones most indicative of the successes and failures of the method. Sometimes the changes in the intensity and hence the geology, stand out very well. In other cases this is not so.

As this investigation was carried out in an area where the geology is relatively well known little attempt was made to introduce formations not on the present maps. At the same time, valid significant changes in the intensity level were not ignored. When more than one geological interpretation of an area was available the interpretation which best fit the intensity record was used. In every case an attempt was made to identify the geologic changes on the records before the geological maps were consulted. The final interpretation, however, was based on the maps available. The most detailed maps available were used in all cases.

The results are presented in groups from areas which have the same general stratigraphic sequence. The generalized geologic column showing stratigraphy and lithologies for each area is presented prior to the discussion of each

section. In the description of the records only the stratigraphic names are used. The basis for the stratigraphy was the Centennial Geologic Map of the Northern Peninsula of Michigan; (1939), publication 39, series 33.

In the discussion of each record the following information is given.

Number	A numerical sequence for cataloguing.
Date	Day on which the particular traverse was run.
Name	A geographical title for use in the field by the author.
Location	The range and township, and section(s) of the particular traverse. Sometimes it was more convenient to use the name or number of the road if the traverse is long and winding. In this case the location of the starting point is given.
Radio station	This identifies the radio station used, giving call letters, frequency, power, city, and distance and azimuth from the starting location of the traverse.
General topography	This is a general explanation of the topography if the topography is much the same along the entire traverse. Significant changes in the topography are noted.
Road type	The material with which the road is surfaced.
Vegetation	The type of vegetation along the traverse.

Geology and source	Geology refers to the formations and structures encountered along the road with the mileage given from the start of the traverse to the geologic feature. Source indicates the authority on which the geology is based.
Interpretation	A discussion of the correlation of the intensity changes with the geology.
Comments	Additional information on the record or its interpretation.
Scale	4 inches = 1 mile all records.

In the interpretation of the records it is important to know why the event key was operated. On every record just off the scaled paper is the trace of the event key. This is always on the low intensity side. The reason the key was operated is indicated by the coded letter next to its mark.

- 1. - Start of traverse.
- P - Power line crossing road.
- T - Telephone line crossing road.
- RR - Railroad with its wires.
- J - Road junction.
- RN - Side road to the north.
- RE - Side road to the east.
- RS - Side road to the south.
- RW - Side road to the west.
- B - Bridge.

- N - Of no importance in interpretation.
- G - Guy wire crossing road.
- TN - Traverse turns or bends north.
- TE - Traverse turns or bends east.
- TS - Traverse turns or bends south.
- TW - Traverse turns or bends west.
- TPL - Telephone lines start parallel to traverse.
- H - High hill next to traverse.
- A - Operator adjusted meter.
- E - End of run.

THE MARQUETTE AREA

The Marquette area was chosen for investigation because the geology is well known, there are a variety of rock types, and there is considerable structural deformation. Geologically this area is a series of subparallel synclines, which trend generally east-west.

In this area there are three radio stations: WDMJ, 1320 kc, 1 kw in Marquette; WJAN, 970 kc, 5 kw, and WJPD, 1240 kc, 1 kw, in Ishpeming. Unfortunately no two stations could be used on the same traverse. Most of the traverses in this area were run using WJAN, because of its high power and low frequency. The others were used where possible.

Generally the topography in the Marquette area is rugged. An attempt was made to pick traverses in level areas but this was not always possible.

Figure 7

Generalized stratigraphic column for the Marquette area.
(After The Centennial Geological Map of the Northern
Peninsula of Michigan, 1936).

QUATERNARY	Pleistocene		Glacial outwash and drift
		*****unconformity*****	
CAMBRIAN OR PRECAMBRIAN	"Lake Superior Ss."	Jacobsville sandstone	Red and brown sandstone with mottlings of white and grey. Red arkosic with a conglomerate at the base.
		*****unconformity*****	
		Michigamme slate	Grey slate, dark quartz slate to graphitic slate and graywacke.
		Clarksburg	Basic volcanics and pyroclastics with interbedded graywacke.
		Greenwood	Magnetic slaty quartzites, slaty iron formation, magnetic grunerite with laminae of green amphibole.
		Goodrich	Mainly massive vitreous quartzite with jasper conglomerate at base.
		*****unconformity*****	
		Negaunee	Iron formations. Silica and iron oxides, hematite and limonite; thin jaspillite; dominantly ferruginous cherts.
		Siano	Mainly thinbedded slates, locally with ferruginous quartzite.
		Ajibik	Quartzite; schists; granitic gneiss.
		*****unconformity*****	
		Wewe slate	Slate interlaminated with graywacke and quartzite.
ALGONKIAN	Huronian	Kona	Massive and banded cherty dolomite
		Mesnard	Quartzite, dense, light-colored and vitreous; conglomerate at base.
		*****unconformity*****	
		Laurentian	Shistose and gneissic intrusives in the Keewatin.
		Keewatin	Basic intrusives, highly metamor- phosed.
ARCHEAN	Keewatin Laurentian	Kitchi Mona	

Figure 8

Number	38
Date	June 21, 1962
Name	Deer Lake-5
Location	On the road that goes through Sections 33, 32, 29, 28, 21, and 16, T.48N., R.27W., Mich.
Radio Station	WJAN, 970 kc, 5 kw, Ishpeming, Michigan, 3 miles S20°W from starting point in NW $\frac{1}{4}$ of Sec. 33
General topography	Very hilly.
Road type	Blacktop.
Vegetation	Wooded on both sides of road.
Geology and source	1. start over Kitchi Schist. 2. 1.15 miles Kitchi-Ajibik contact 3. 1.31 miles Ajibik-Peridotite contact 4. 1.96 miles Peridotite-Kitchi contact 5. 2.95 miles Kitchi-Ajibik ? contact 6. 3.40 miles Ajibik-Siamo ? contact 7. 3.78 miles Siamo-Michigamme ? contact 8. 4.05 miles end of traverse
	U.S.G.S. Monograph XXVIII and LXX
Interpretation	Some of these contacts do not show up too well but others show up very well and agree with the geology. The reasons could be changing drift thickness, the effect of topography, or unmapped dikes or sills. Where the changes in intensity are not conclusive the geology is put in about where the maps show it to be. It is this uncertainty that is indicated by the question marks.
Comment	A repeat traverse was run with nearly identical results.

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CHART NO. 4331-X

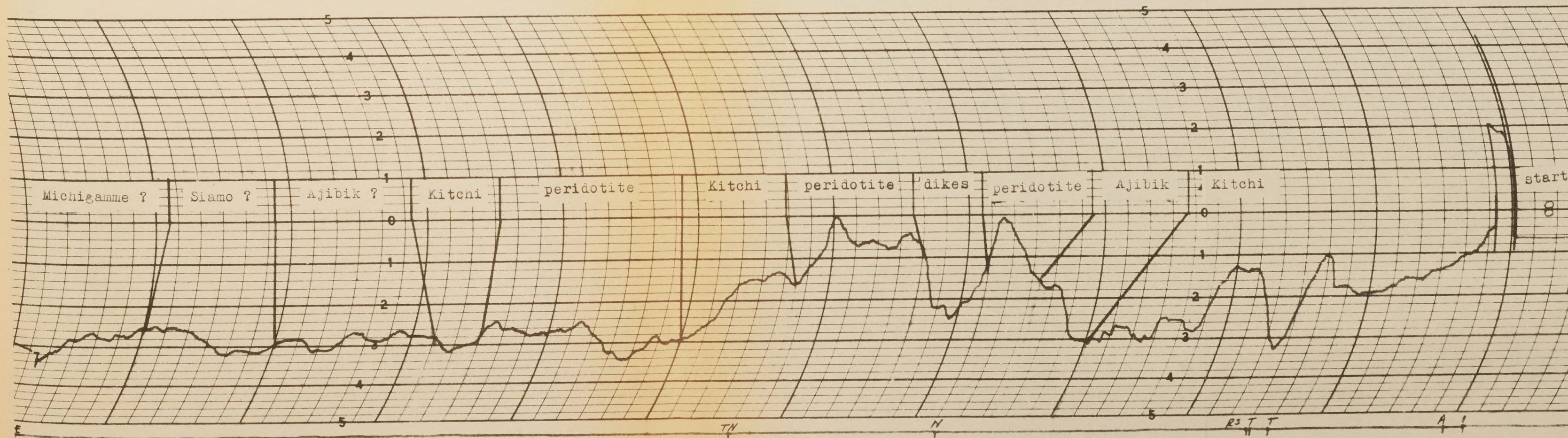
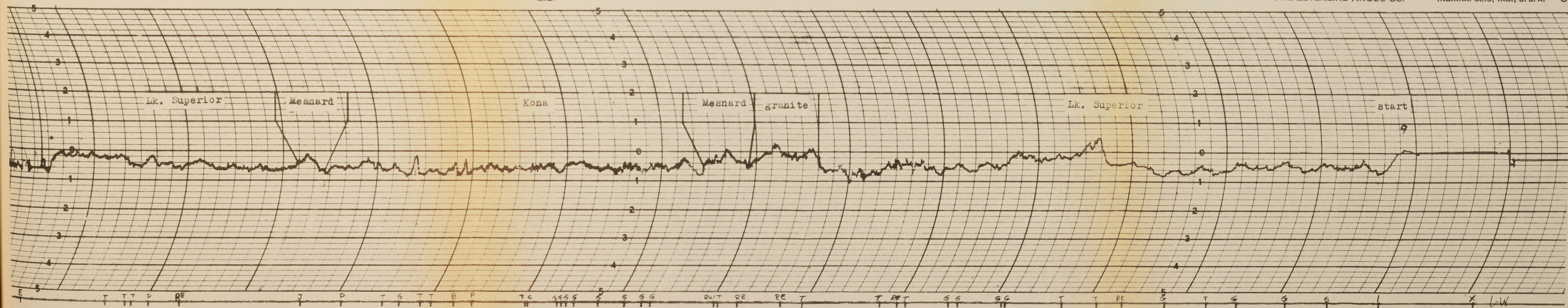


Figure 9

Number	51
Date	June 30, 1962
Name	M - 7
Location	On Marquette county road 553 from the junction of 553 and 480 north for 5.47 miles. The road junction is in Section 15, T.47N., R.25W., Mich.
Radio Station	WJAN, 970 kc, 5 kw, Ishpeming, Mich. 14 miles west of road junction and starting point.
General topography	Very hilly.
Road type	Blacktop; very winding.
Vegetation	Wooded on both sides of road.
Geology and source	1. start over Cambrian sandstones 2. 2.38 miles Lk. Superior-Granite 3. 2.65 miles Granite-Mesnard 4. 2.82 miles Mesnard-Kona 5. 4.32 miles Kona-Mesnard 6. 4.41 miles Mesnard-Lake Superior 7. 5.47 miles end of traverse U.S.G.S. Monograph XXVIII, Atlas plates XXXVIII and XXXIV.
Interpretation	The changes in intensity correlate very well with the mapped geological contacts. The fluctuation on this record could be due to topography as the traverse was very hilly. There were also a great number of telephone and guy wires which had only minor variations associated with them.
Comment	There was a repeat traverse which was nearly identical. The spot marked X (1.25 miles) may be due to a change in drift or sandstone lithology or a hill in the granite basement covered up by later sediments. The latter is most probable, because there is a field of high intensity associated with both and the basement rock undulates quite a bit as the outcrops indicate.

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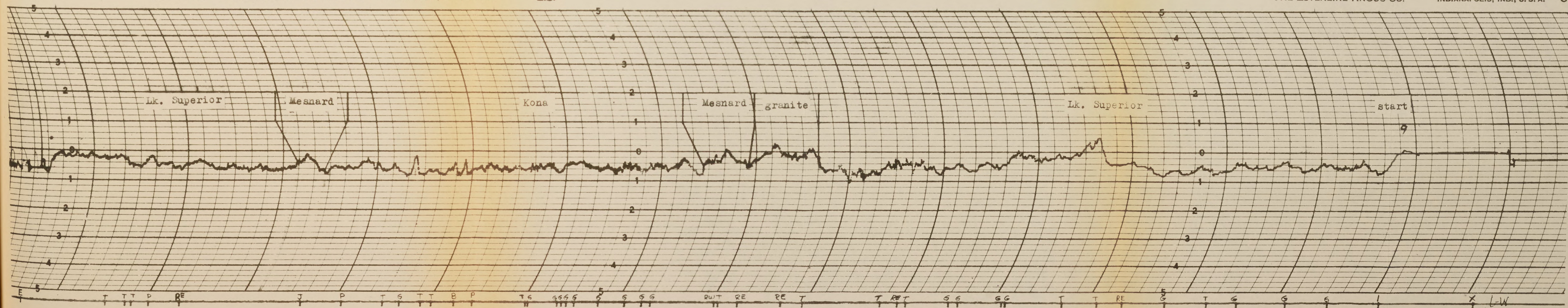


Figure 10

Number	50
Date	June 30, 1962
Name	M - 6
Location	On Marquette county road 480 from the junction of 553 and 480 north-west for 4.9 miles. The road junction is in section 15, T.49N., R.25W., Mich.
Radio station	WJAN, 970 kc, 5 kw, Ishpeming, Mich. 14 miles west of road junction and starting point.
General topography	Flat to gentle hills.
Vegetation	Wooded on both sides of road.
Geology and source	1. start at junction over Cambrian sandstone 2. 1.29 miles Lake Superior-Mesnard 3. 2.50 miles Mesnard-Kona 4. 2.63 miles Kona-Wewe 5. 3.43 miles Wewe-Ajibik 6. 3.59 miles Ajibik-Siamo 7. 3.79 miles Siamo-Ajibik 8. 4.32 miles Ajibik-Siamo 9. 5.05 end of run U.S.G.S. Monograph XXVIII, Atlas plates XXXVIII and XXXVII
Interpretation	This is an excellent example of how well the field intensity measurements can be applied to geologic mapping. The correlation between the geology and the intensity variations on this record are excellent. The small changes in intensity in the Wewe could be a facies change.
Comment	The traverse was repeated with nearly identical results.

No. 13

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CHART NO. 4331-X

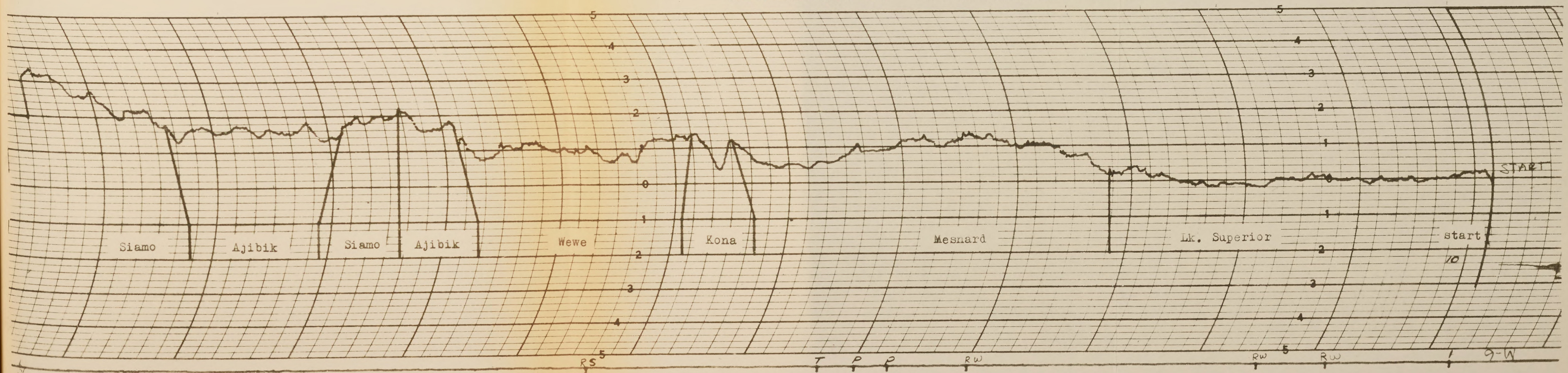
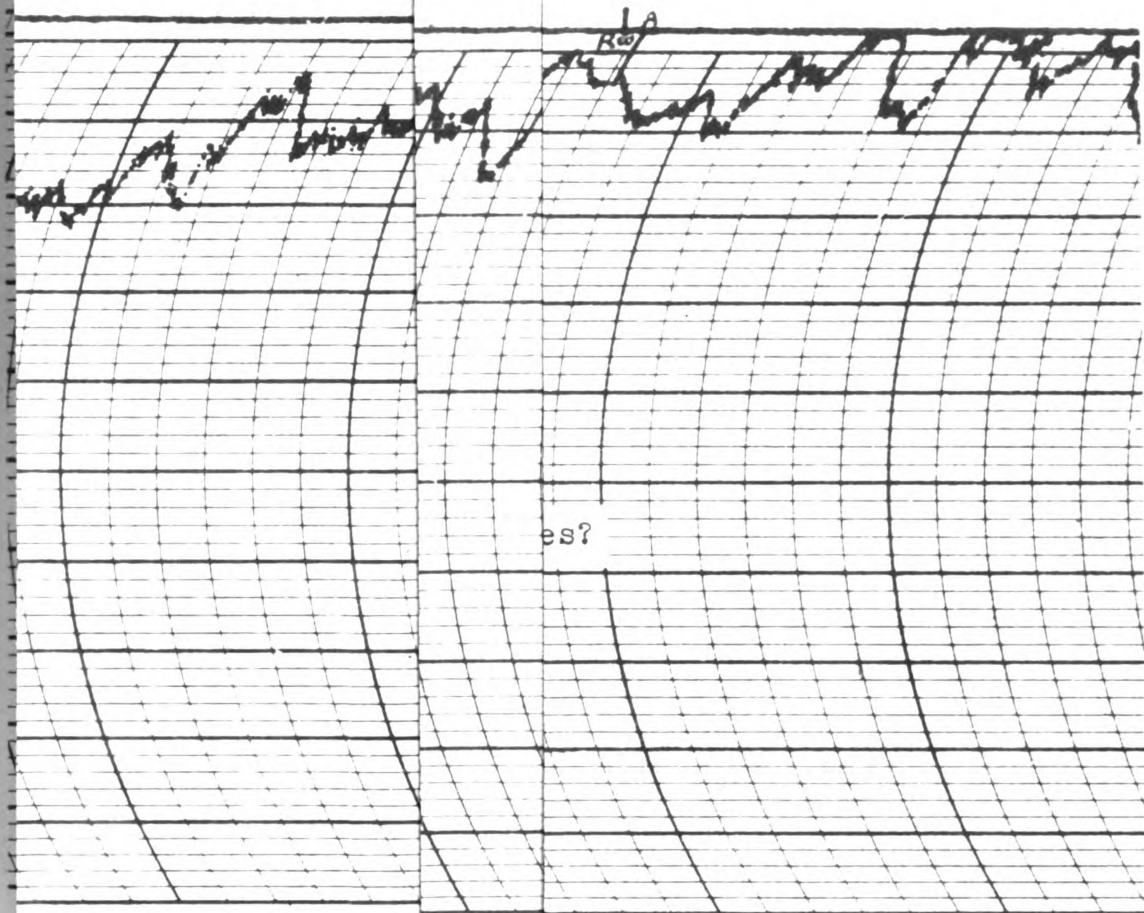


Figure 11

Number	63
Date	July 1, 1962
Name	Old M - 35
Location	On Marquette County road 510 from Midway, in Section 23, T.48N., R.26W., to Big Bay, Michigan. Complete traverse not shown.
Radio station	WJAN, 970 kc, 5 kw, Ishpeming, Mich.
General topography	Very hilly.
Road type	Black top to start with, then gravel.
Vegetation	Heavily wooded.
Geology and source	The geology along the road is not well known. The traverse crosses the end of the Dead River Basin about where the bridge is located. 1. start over syenite. 2. 1.61 miles syenite-Huronian sediments? 3. 2.10 miles bridge 4. 2.30 miles Huronian sediments-greenstone? 5. 3.00 miles fault along south side of Clark Creek Basin; Huronian sediments-Mona ? 6. 4.00 miles Mona-dike? 7. 4.10 miles dike-Mona ? 8. 4.25 miles fault ? 9. 4.40 miles blacktop road ends. 10. 10.76 miles south edge Clark Creek Basin 11. 11.45 miles north edge Clark Creek Basin
Interpretation	Before and after the Clark Creek Basin, the rocks are greenstones and granites. The reception was poor along most of this traverse.
Comments	The geology here is speculation by Dr. Justin Zinn and the author. There has been no recent work done in the area and the only known map (1936) is unavailable.



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THE KEWEENAW AREA

The Keweenaw area was chosen for the presence of the Keweenaw fault. Geologically the area consists of the fault trending generally north-east -- south-west. The "Lake Superior Sandstone" (Cambrian or Precambrian?) lies to the south, and the Keweenawan sediments lie to the north. The north side of the fault has moved up and all the Keweenawan sediments dip toward the north-east.

In the northern part of this area there are two radio stations. WHDF, 1400 kc, 250 watts, is in Houghton, and WMPL, 920 kc, 1 kw, is in Hancock. As WMPL was more powerful and lower in frequency it was used exclusively. East of the Eagle River no station could be received with this equipment.

The topography is quite varied in this area but it was generally level where the traverses were run.

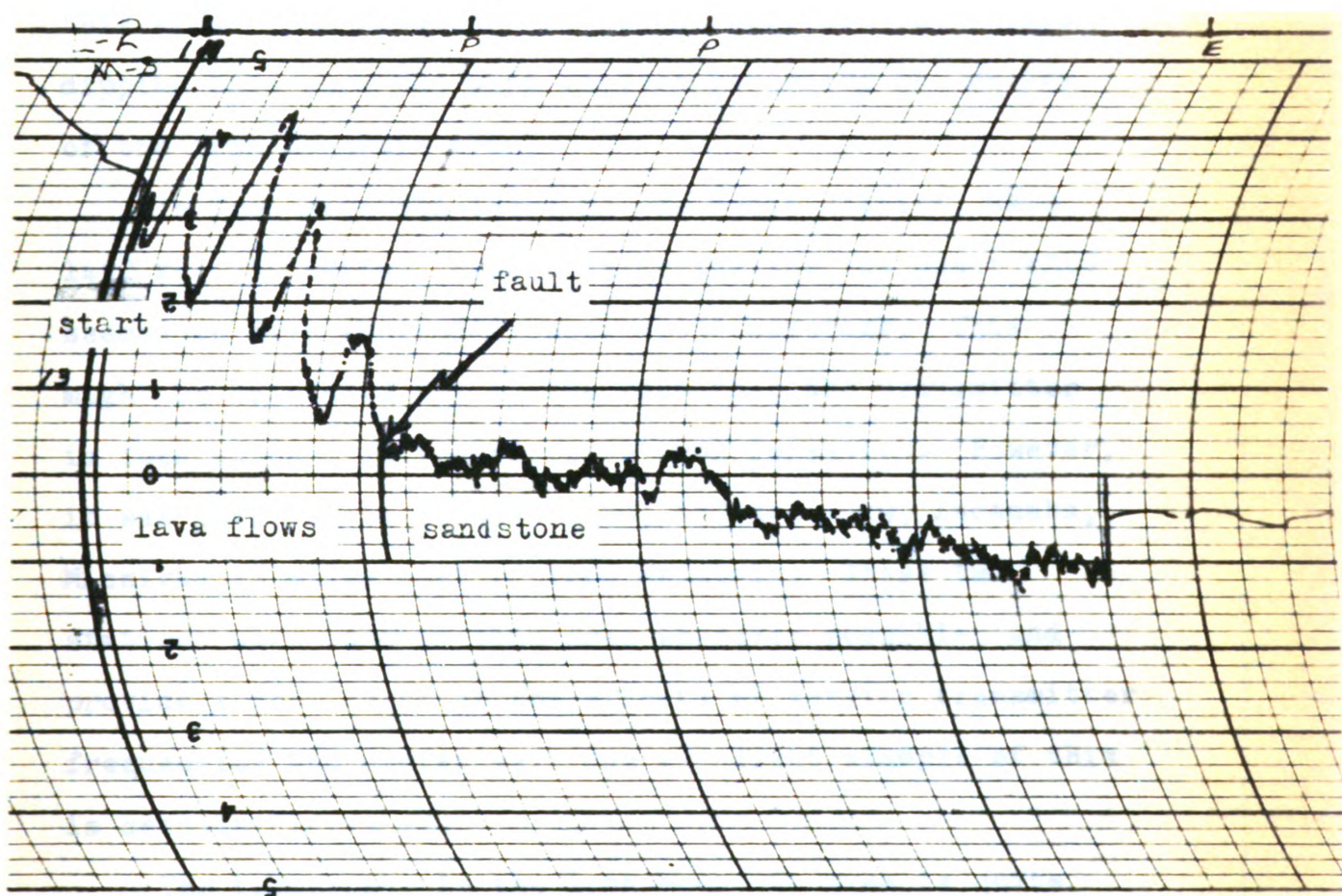
Figure 12

Generalized stratigraphic column for the Keweenaw area.
(After the Centennial Geological Map of the Northern
Peninsula of Michigan, 1936).

QUATERNARY	Pleistocene		Glacial outwash and drift
		*****unconformity*****	
CAMBRIAN or PRECAMBRIAN		"Lake Superior Ss."	Jacobsville sandstone Red and brown sandstone with mottlings of white and grey. Red arkosic with a conglomerate at the base.
		*****?unconformity?*****	
ALGOEIAN	Keweenaw	Upper	Freda sandstone Conglomerates. Red sand- stone, arkoses, shales.
			----- Nonesuch shale Dark shale and sandstone.
			Lake Shore Traps Thin basaltic lava flows, amygdaloidal.
		Middle	----- Great Conglomerate Coarse heavy conglomerate and quartzite
			*****unconformity***** Eagle River and Ashbed groups. Mesnard epidote Basic lava flows with many conglomerates and a few sandstone beds.
			Central Mine group No. 8 Conglomerate Bohemia Range group Mainly basic lava flows, intrusions of basic ig- neous rocks and granite.

Figure 13

Number	44
Date	July 13, 1962
Name	Laurium - 2
Location	Sections 10 and 3, T.55N., R.33W., Mich.
Radio station	WMPL, 920 kc, 1 kw, Hancock, Mich. 6.5 miles S.54°W. of starting point in SW $\frac{1}{4}$ of Section 3.
General topography	Very gently downhill to the south.
Road type	Gravel.
Vegetation	Open fields.
Geology and source	1. start over sandstone 2. 0.4 miles Keweenawan fault 3. 1.0 miles end of run. U.S.G.S. Monograph LII
Interpretation	We see here a completely different type of response over the Keweenawan conglomerates. This may be due to various thin beds of conglomerates. The change in field intensity agrees very well with the mapped location of the fault.
Comment	The traverse was repeated with nearly identical results.



THE IRON MOUNTAIN AREA

Geologically the Iron Mountain area consists of a parallel series of faults trending east-west. This faulting gives rise to repetition of beds from north to south. Most of the formations dip at very high angles in this area. The knowledge of the geology and the steeply dipping beds were the main factors governing the choice of the Iron Mountain area.

In Iron Mountain there is one radio station, WMIQ, 1450 kc, 250 watts. Even considering its low power WMIQ seemed to have abnormally poor areal coverage. This might be accounted for by the fact that the transmitter is located on highly conductive iron formation. However, it was possible to receive WDBC, 680 kc, 1 kw, Escanaba, Michigan 48 miles east of Iron Mountain. These two stations were used in this area wherever possible, and provide a good check of the effects of varying transmitter frequencies and distances. One excellent example of this is seen in Figure 19.

The topography in the Iron Mountain area is quite varied. The land ranges from very hilly with woods, to very flat with open fields.

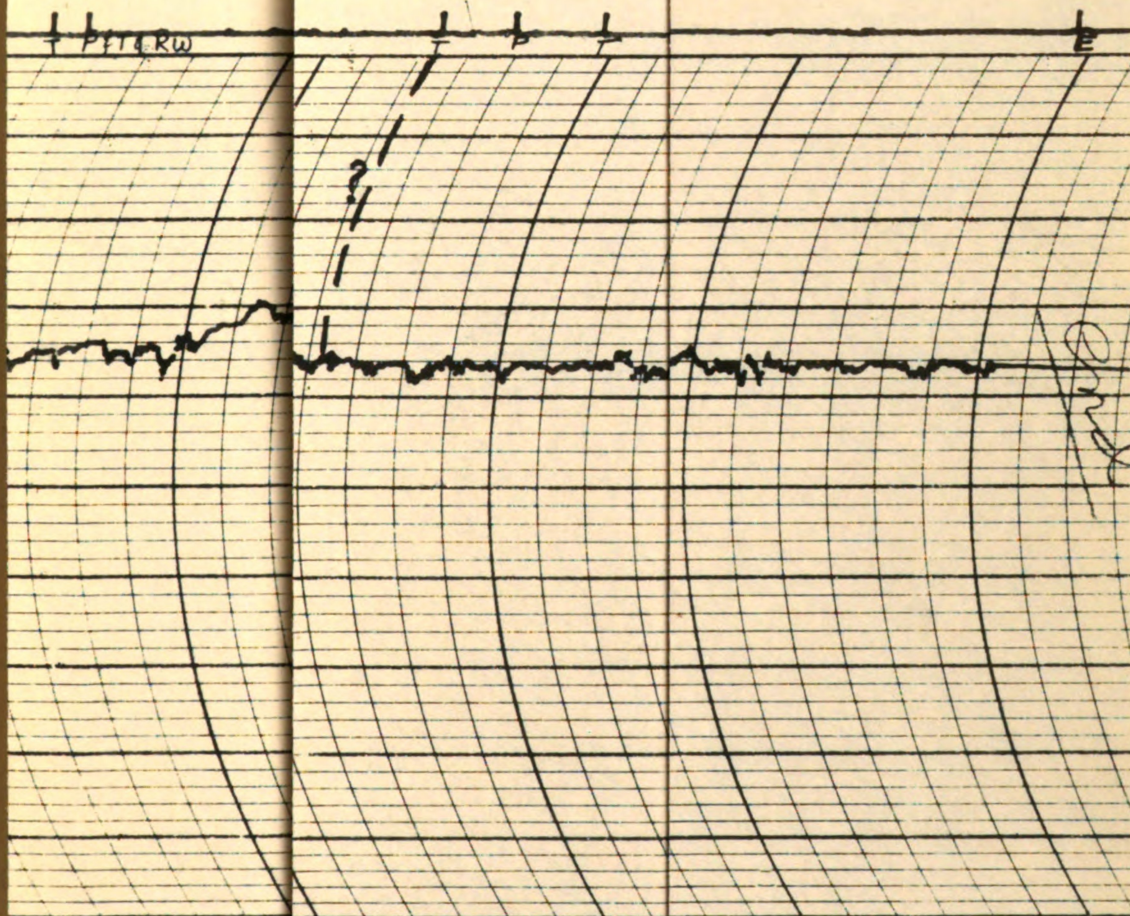
Figure 14

Generalized stratigraphic column for the Iron Mountain area. (After the Centennial Geological Map of the Northern Peninsula of Michigan. (1936).

QUATERNARY	Pleistocene		Glacial outwash and drift	
			*****unconformity*****	
CAMBRIAN OR PRECAMBRIAN	"Lake Superior Sandstone"		Jacobsville sandstone	Red and brown sandstone with mottlings of white and grey. Red arkosic with a conglomerate base.
			Badwater	Greenstone
		Upper	*****unconformity*****	*****
			Michigamme slate	Grey slate, dark quartz slate to graphitic slate and graywacke.
ALGONKIAN	Huronian	Middle	Quinnesec schist	Basic volcanic rocks, schists and greenstones. Intruded by the Hoskins Lake granite (?), and sills of metagabbro. (Wisc.)
			*****unconformity*****	*****
			Upper slate	Iron formations. Silica and iron oxides, hematite and limonite. Interbedded slates.
		Lower	Brier	
			Trader	
ARCHEAN	Laurentian	Lower	*****unconformity*****	*****
			Randville	Massive and banded cherty dolomite and marble, with beds of greenish slate and graywacke.
			Sturgeon	Dense vitreous light colored quartzites with conglomerate at base.
			*****unconformity*****	*****
			Laurentian	Shistose and gneissic intrusives in the Keewatin. Masses of syenite schist and gneiss rich in hornblend.

Figure 15

Number	5
Date	June 14, 1962
Name	#5
Location	On Dickinson County road 607 from Badwater Lake in the south to Randville in the north. The traverse starts in NE $\frac{1}{4}$ of Section 12, T.40N., R.30W., Mich.
Radio station	WMIQ, 1450 kc, 250 watts, Iron Mountain, Mich. 4 miles S.20°W. from start.
General topography	Hilly in the south, flat in the north.
Road type	Poor blacktop and gravel.
Vegetation	Wooded on both sides of the road.
Geology and source	1. start over Badwater greenstones 2. 1.46 miles Badwater-dike 3. 1.65 miles dike-Badwater 4. 2.10 miles Badwater-Michiganme 5. 4.12 miles Michiganme-granite fault 6. 6.21 miles granite-Michiganme 7. 7.82 miles Michiganme-quartzite fault 8. 10.00 miles end of traverse
	U.S.G.S. professional paper 310.
Interpretation	Most of these changes in intensity are easily seen. The place marked X (0.30 miles) may be another dike. North of Iron Mountain, once the Badwater had been left, the reception of WMIQ was very poor as can be seen on this record. This break was very abrupt. This held true on all of the runs just to the north of Iron Mountain.
Comments	One repeat traverse nearly identical.



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Figure 16

Number	10
Date	June 14, 1962
Name	Quinnesec #1
Location	Sections 21, 28, 27, and 34, T.40N., R.30W., Mich.
Radio station	WMIQ, 1450 kc, 250 watts, Iron Mountain, Michigan. 2 miles S.50°W. from start of traverse in section 21 at road junction.
General topography	Gently down hill to the south-east.
Road type	Blacktop with shallow curves to the south-east.
Vegetation	Wooded on both sides of road.
Geology and source	1. start over Upper Slates 2. 0.50 miles Upper Slate-Michigamme 3. 1.65 miles Michigamme-Randville fault 4. 2.80 miles end of run. U.S.G.S. Monograph XIX
Interpretation	The Upper Slates are poor conductors as indicated by the high level of intensity. There is a sharp drop in intensity as the Michigamme is approached and a still further decrease as the Randville is approached and crossed.
Comments	Point 2A (1.50 miles) on the record may have significance. The possible explana- tions are, in order of probability, as follows: 1. the fault 2. the Cambrian sandstone pinching out 3. the drift changing thickness 4. the soil type changing. Six repeat traverses were run, all very similar.

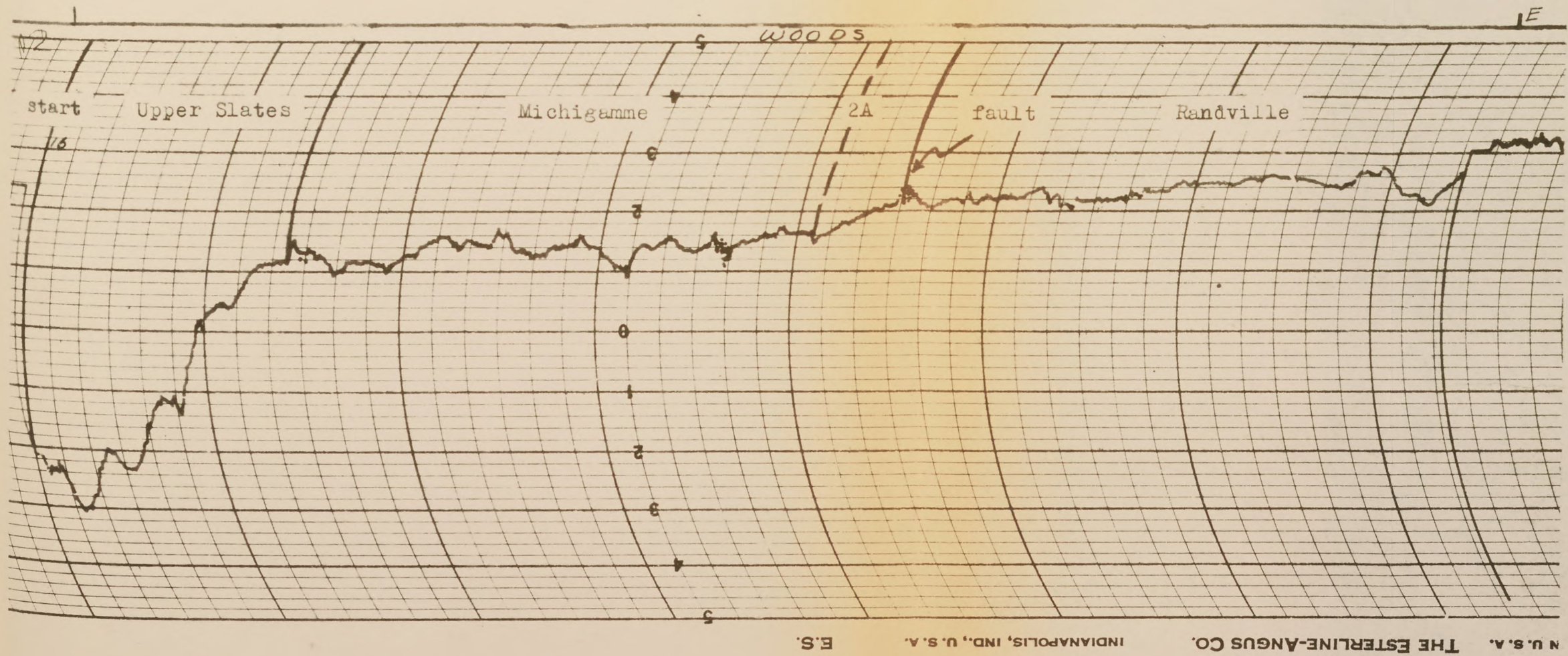


Figure 17

Number	13-B and 13-E
Date	June 14, 1962
Name	13 & 14
Location	Town line road between Breitung, T.40N., R.30W. and Norway, T.40N., R.29W., north from U.S. 2 for 3 $\frac{1}{4}$ miles, Michigan
Radio station	WMIQ, 1450 kc, 250 watts, Iron Mountain, and WDBC, 860 kc, 1 kw, Escanaba, Mich. WMIQ's transmitter is 5 miles due west of traverse start at Escanaba, and WDBC's transmitter is 42 miles due east of start.
General topography	Very hilly.
Road type	Blacktop straight north.
Vegetation	Farm land, open fields.
Geology and source	1. start over Brier 2. 0.18 miles Brier-Trader 3. 0.30 miles Trader-Upper Slate 4. 0.38 miles Upper Slate-Randville fault 5. 0.66 miles Randville-Michiganme fault 6. 1.63 miles Michiganme-Trader 7. 1.70 miles Trader-Upper Slate 8. 1.82 miles Upper Slate-Randville fault 9. 2.15 miles Randville-Upper Slate 10. 2.32 miles Upper Slate-Michiganme 11. 2.92 miles fault in Michiganme 12. 3.25 miles end of traverse U.S.G.S. open file report on Southern Dickinson County
Interpretation	This record shows the changes in the geology quite well. WMIQ's traverse is not too good because the station is quite weak here. One mile further west it could not be received. WDBC is very strong at this location.
Comment	A repeat traverse was run with nearly identical results.

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CHART NO. 4331-X

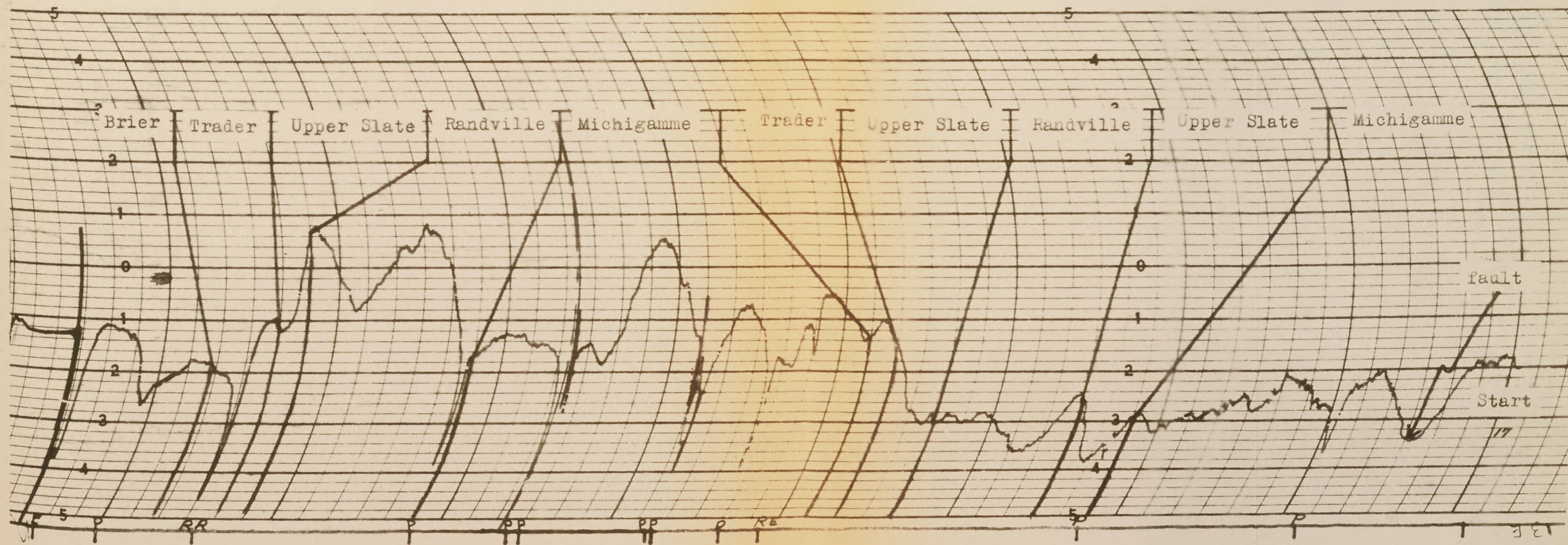


Figure 18

Number	24 A
Date	June 16, 1962
Name	Cowboy Lake
Location	From Power Plant in Section 3 along the township line between Sections 34 and 35, T.40N., R.19E., and sections 3 and 2, T.39N., R.19E., Mich. Traverse turns south at the north $\frac{1}{2}$ corner of section 2, just west of Iron Mountain, Mich.
Radio station	WMIQ, 1450 kc, 250 watts, Iron Mountain, Mich. Transmitter 4 miles N.78°E. from start of traverse at Power Plant.
General topography	Flat except for a low hill where traverse turns south.
Vegetation	Open fields except for hill where traverse turns south.
Geology and source	1. start over Quinnesec 2. 0.83 miles Quinnesec-Michiganne 3. 1.25 miles turn south 4. 1.65 miles Michiganne-Quinnesec 5. 2.00 miles end of traverse U.S.G.S. Monograph LII, plate XXVI.
Interpretation	There is some question as to the exact location of this contact. However, the intensity low seen on these records agrees very well with the placement by Monograph LII.
Comments	The low level of intensity at the start of the record is probably due to the power station and its associated wires by Cowboy Lake. The probable reason that the intensity over the contact is not the same on both records is that there was a minor fluctuation in the power of the station. This change in intensity is only 0.8 milliamperes.

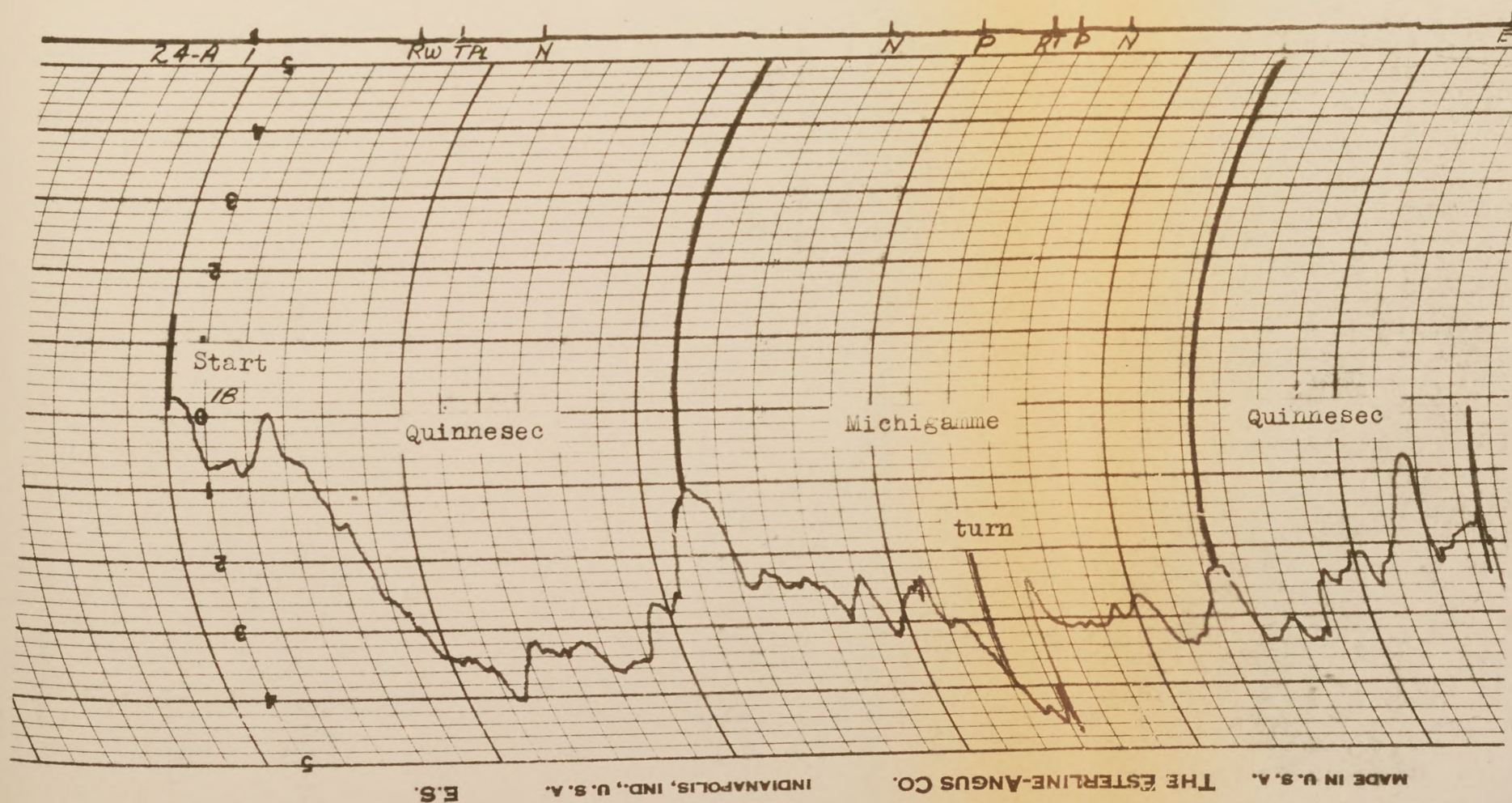
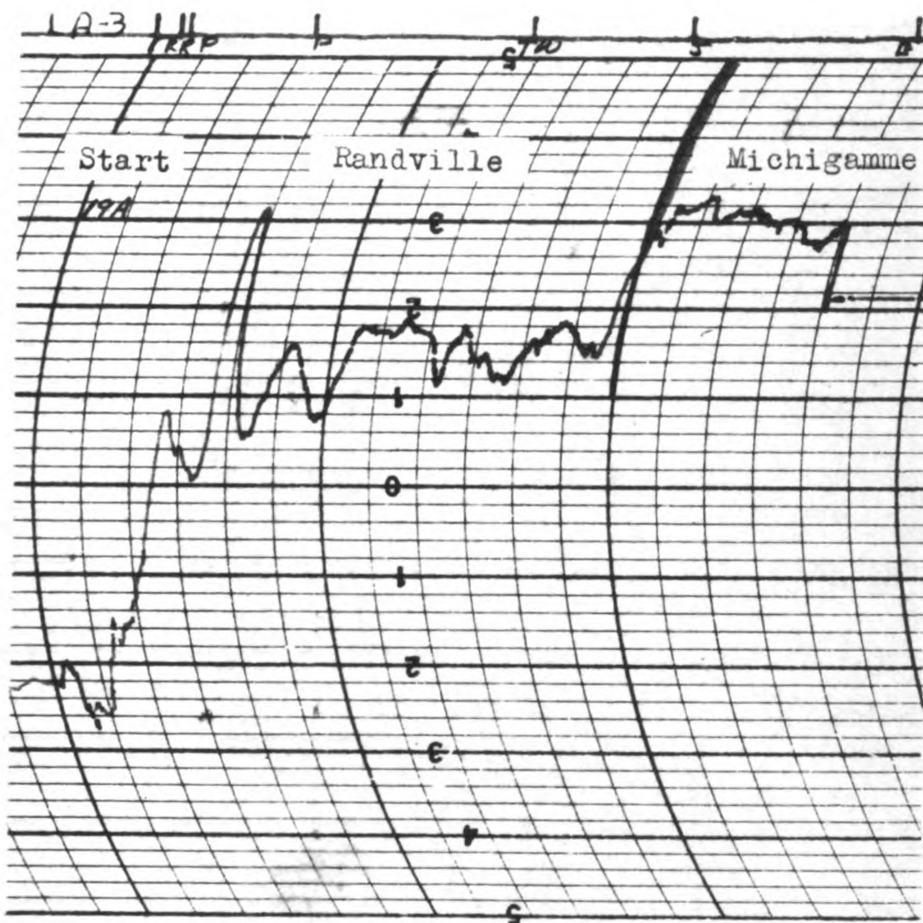


Figure 19

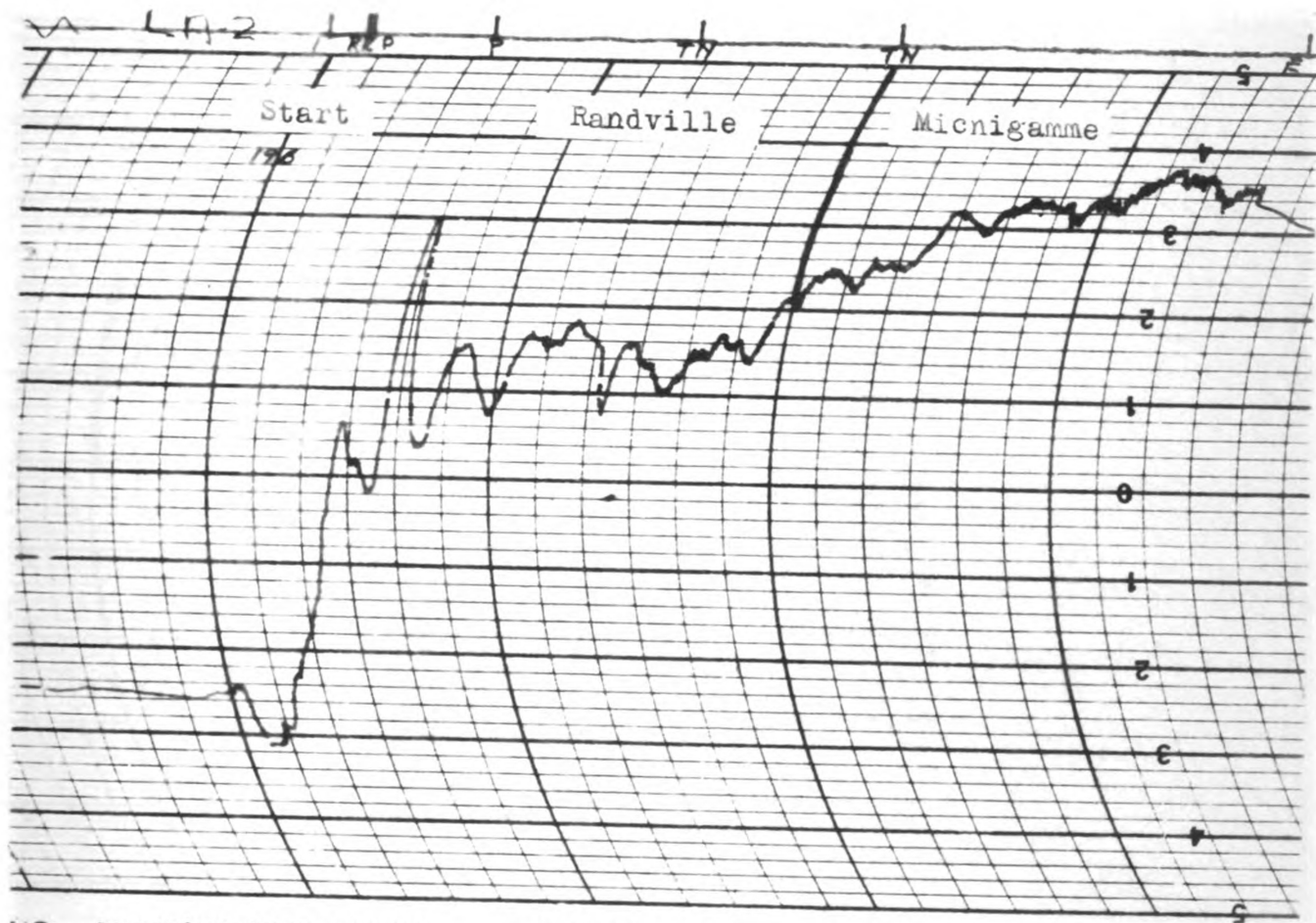
Number	65, 66, and 67-A and B
Date	June 14, 1962
Name	Lake Antoine 2, 3, and 4.
Location	No. 65 & 66 start in the SW $\frac{1}{4}$ of section 21, T.40N., R.30W., Michigan. No. 67 starts at U.S.-2 in section 19, and runs through sections 20, 17 and 8, T.40N., R.30W., Mich.
Radio station	No. 65 and 66; WMIQ, 1450 kc, 250 watts, Iron Mountain, Mich. No. 67-A; WMIQ, and No. 67-B; WDBC, 680 kc, 1 kw, Escanaba, Mich.
General topography	Hilly.
Road types	Blacktop, and gravel.
Vegetation	Generally wooded all along the roads.
Geology and source	No. 65 1. start over Randville 2. 0.70 miles Randville-Michigamme fault 3. 1.72 miles end of traverse No. 66 1. start over Randville 2. 0.70 miles Randville-Michigamme fault 3. 1.00 miles end of traverse No. 67-A 1. start over Randville going north 2. 1.35 miles Randville-Badwater fault 3. 3.15 miles end of traverse No. 67-B is a rerun starting over the Badwater going south U.S.G.S. open file report on Southern Dickinson County
Interpretation	In all of these records we see that the Michigamme has a much lower level of intensity associated with it. The fault does not show up too well on No. 65. Also notice that this fault does not give the same kind of response that Cloos and Howell have shown.

Figure 19 - Continued**Comment**

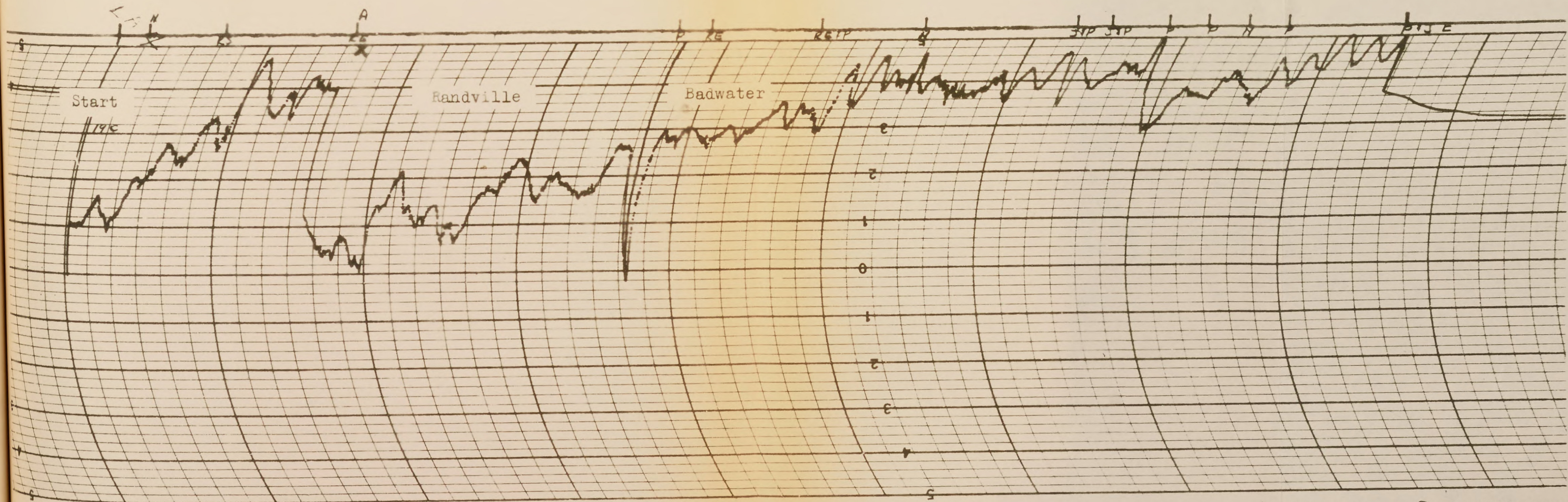
The X (0.58 miles) on record 67-A is where the operator had to increase the gain of the meter. Notice the difference between 67-A and B with the different radio stations. The response of the fault in 67-B is more like Cloos experienced in that there was a large change from the normal. In this particular instance the field of the fault was large.



U.S.A. E.S.

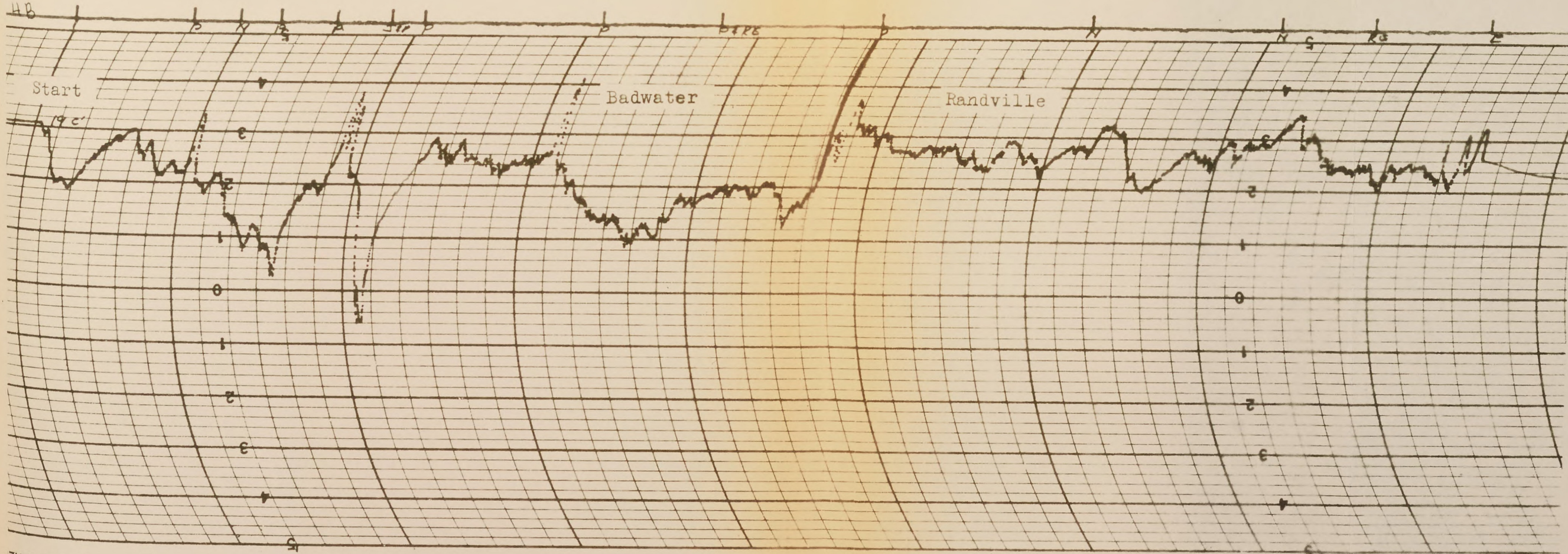


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Figure 20

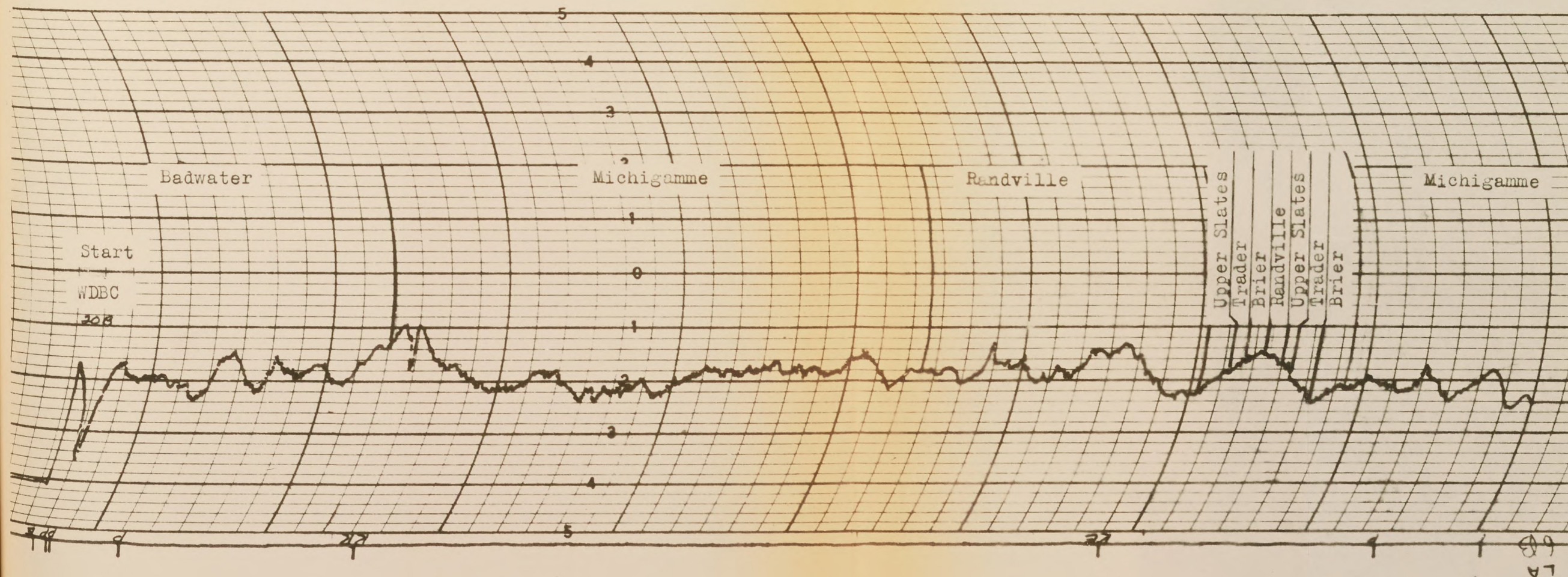
Number	69
Date	July 9, 1962
Name	Lake Antoine - 6
Location	Sections 26, 23, and 13, T.40N., R.31W., Mich. Starts at U.S. 2 via Section 13.
Radio station	1. WMIQ, 1450 kc, 250 watts, Iron Mountain, transmitter 3 miles S.20°E. from start of traverse in sec. 13. 2. WDBC, 680 kc, 1 kw, Escanaba, Mich. transmitter 48 miles due east from start of traverse.
General topography	Flat, except for Pine Mountain at the south end of the traverse.
Road type	Poor blacktop with shallow curves to the north-east
Vegetation	Open fields.
Geology and source	1. start over Badwater Greenstone in North. 2. 0.60 miles Badwater-Michigamme 3. 1.77 miles Michigamme-Randville fault 4. 2.40 miles Randville-Upper Slate 5. 2.43 miles Upper Slate-Trader 6. 2.49 miles Trader-Brier 7. 2.52 miles Brier-Randville fault 8. 2.57 miles Randville-Upper Slate 9. 2.61 miles Upper Slate-Trader 10. 2.66 miles Trader-Brier 11. 2.69 miles Brier-Michigamme 12. 3.20 miles end of traverse U.S.G.S. open file report on Southern Dickinson County
Interpretation	While the geologic factors do not show up to any great extent, this is still a very interesting set of records. These two records show very well the effect of frequency, distance and topography. Record 1 is very erratic. This is probably caused by the high frequency of WMIQ, the traverse's nearness to the transmitter and in part, the effect of

Figure 20 - Continued

Pine Mountain at the south end of the traverse. Under these conditions the intensity reacted more strongly to the rock's electrical properties than WDBC, which is much further away and therefore has a weaker field. Pine Mt. absorbed more of WMIQ's signal than WDBC's.

Comments

This points out the advantage of using stations more than a few miles from the traverse.



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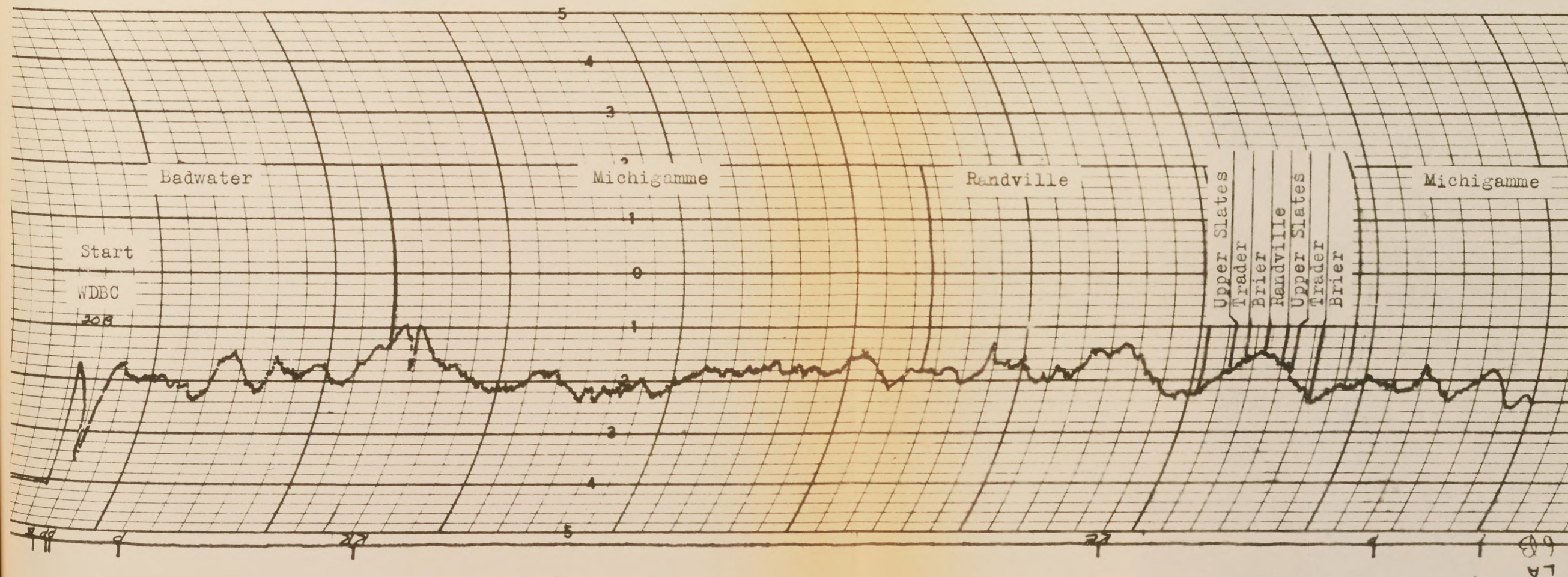
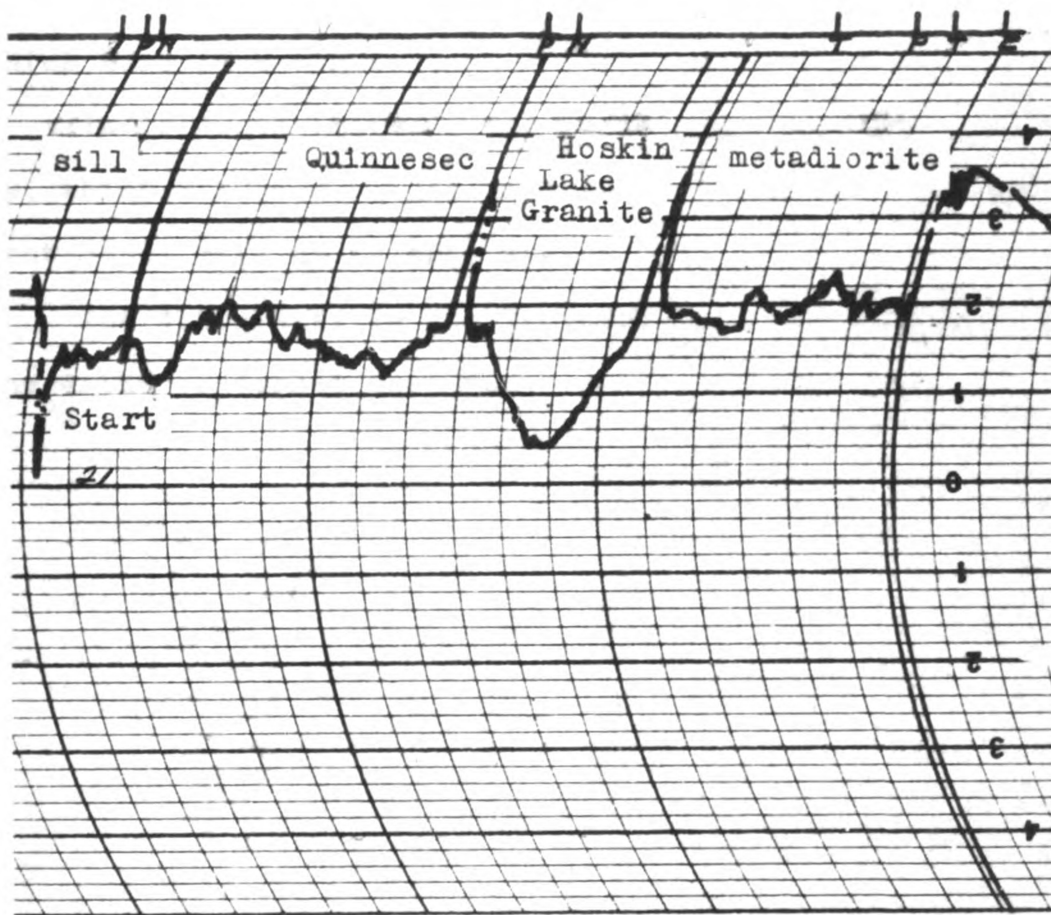


Figure 21

Number	77
Date	July 9, 1962
Name	Wisconsin #3.
Location	Sections 8 and 17, T.38N., R.20E. on County Road '0', Wisconsin.
Radio station	WDBC, 860 kc, 1 kw, Escanaba, Michigan. Transmitter 48 miles due east from start of traverse in section 17 at BM 1128.
General topography	Rolling.
Road type	Blacktop, generally straight, north-south.
Vegetation	Open fields.
Geology and source	1. start over Metadiorite 2. 0.31 miles metadiorite-Hoskinslake granite 3. 0.55 miles Hoskinslake-Quinnesec 4. 0.90 miles Quinnesec-Horseface sill 5. 1.08 miles end of traverse U.S.G.S. open file report on Southern Dickinson County
Interpretation	The metadiorite is a good conductor. The Hoskinslake Granite seems to be a poor conductor as indicated by the high level of intensity. The Quinnesec is only slightly better than the metadiorite, and the sill seems to be a little better than the Quinnesec.
Comment	Two repeat traverses were run, both of which are nearly identical to the original.



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THE IRONWOOD AREA

Geologically the Ironwood area consists of beds trending generally east-west and tilted toward the north giving rise to a cross-section of the Huronian sediments. To the north of the Huronian sediments there is an unconformable contact with the Keweenawan sediments. There are also faults in the area which were investigated.

In Ironwood there is one radio station, WJMS, 630 kc, 1 kw, which was used. This was the only station that the equipment could pick up in this area.

The topography in the Ironwood area was generally level where the traverses were run.

Figure 22

Generalized stratigraphic column for the Ironwood area.
(After The Centennial Geological Map of the Northern
Peninsula of Michigan, 1936.)

CAMBRIAN or PRECAMBRIAN	QUATERNARY			Glacial outwash and drift.
	Pleistocene			
ALGONKIAN			*****unconformity*****	
		"Lake Superior Sandstone"	Jacobsville sandstone	Red and brown sandstone with mottlings of white and grey. Red arkosic with a conglomerate at the base.
			*****unconformity*****	
			Eagle River and Ashbed groups.	Basic lava flows with many conglomerates and a few sandstone beds.
			Mesnard epidote.	
			Central Mine group	Mainly basic lava flows, intrusions of basic igneous rocks and granite.
			No. 8 Conglomerate	
			Bohemia Range group	
			*****unconformity*****	
			Killarney Granite (Presque Isle Granite)	Acidic intrusives, granite and granite gneiss with some diorite and syenite.
	Pre-Keveenan Post Huronian			
			Tyler slate	Graywacke and slate, locally very ferruginous. Chert with associated beds of siderite; black carbonaceous slates.
			*****unconformity*****	
			Ironwood	Iron formations. Silica and iron oxides, hematite and limonite; some slates interbedded.
			-----	-----
			Palms	Fine silty thin bedded green argillaceous slate with a clear, vitreous quartzite.
			*****unconformity*****	
			(con't)	

Figure 22 (Con't)

Generalized stratigraphic column for the Ironwood area.
Continued.

ALGONKIAN (con't)	Huronian	Lower	*****unconformity*****	
			Bad River	Massive and banded cherty dolomite and marble, with beds of greenish slate and graywacke.
ARCHEAN	Keewatin Laurentian		Sunday	Dense vitreous light colored quartzites with conglomerate at base.
			*****unconformity*****	
			Laurentian	Shistose and gneissic intrusives in Keewatin, masses of syenite schist and gneiss rich in hornblend.
			Keewatin	Basic extrusives, highly metamorphosed.

Figure 23

Number	25
Date	June 19, 1962
Name	Watersmeet - 1
Location	On U.S. 45 from 11.5 miles north to 4 miles south of Watersmeet, Mich.
Radio station	WBRL, 930 kc, Eagle River, Wisconsin, approximately 24 miles south of starting point at north end of traverse.
General topography	North of Watersmeet gently rolling, south of Watersmeet quite hilly.
Road type	Blacktop
Vegetation	North of Watersmeet open fields, south wooded.
Geology and source	1. start over Cambrian sediments 2. 1.9 miles Cambrian-Bohemian Range Group 3. 3.83 miles Bohemian R.G.-Michigamme 4. 8.75 miles Michigamme-Killarney granite 5. 10.63 miles Killarney-Michigamme 6. 14.10 miles Michigamme-Undifferentiated Precambrian
	U.S.G.S. Monograph LII
Interpretation	The correlation between the intensity changes and the geology are excellent. The interesting thing about this record is the depth of the bedrock, about 150'-200'. This is, however, a rare example of drift penetration. A magnetic anomaly of 10's of thousands of gammas lies just south of U.S. 2. There does not seem to be any indication of this anomaly. The contact between the Michigamme and the Undifferentiated Precambrian is not shown on the Centennial Geologic Map of the Northern Peninsula of Michigan. This change is too great to be ignored, it does show on the source map.

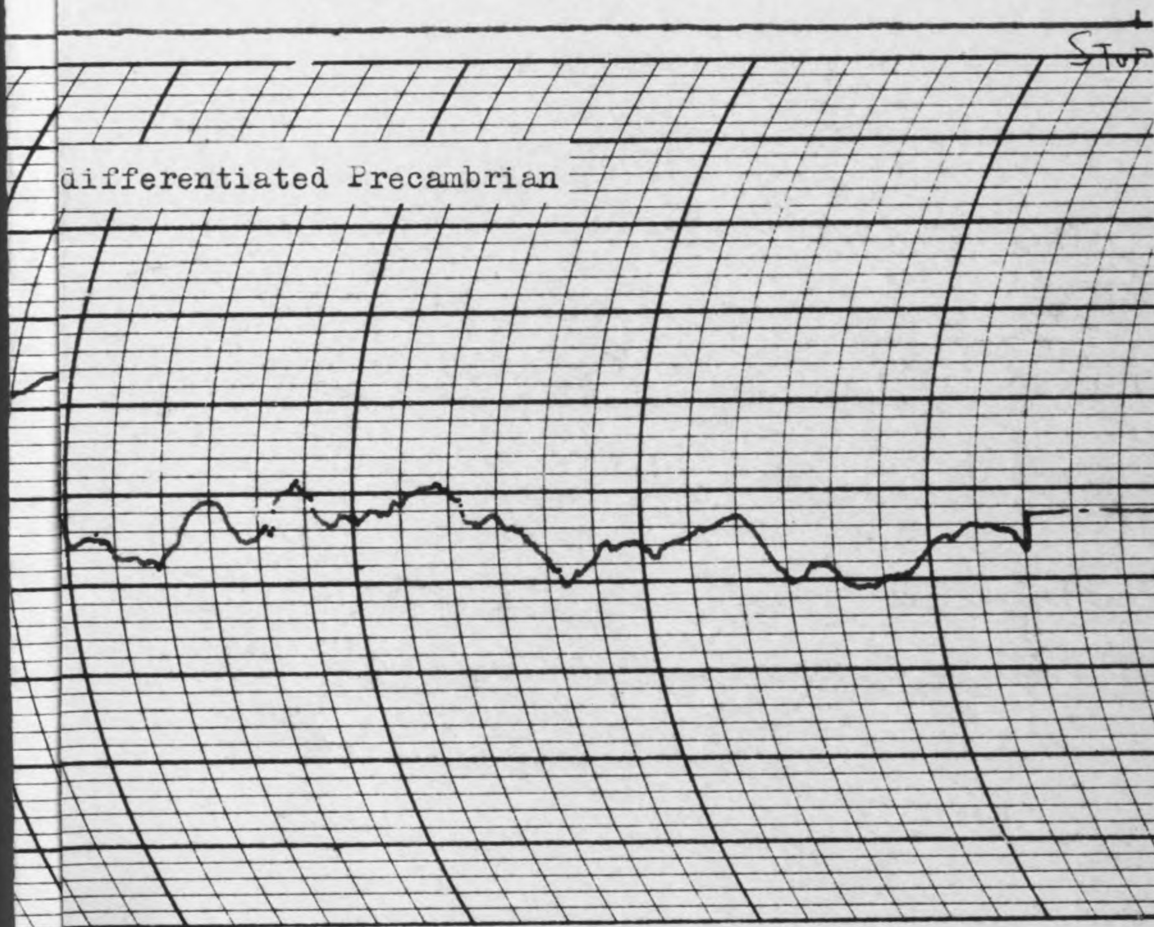
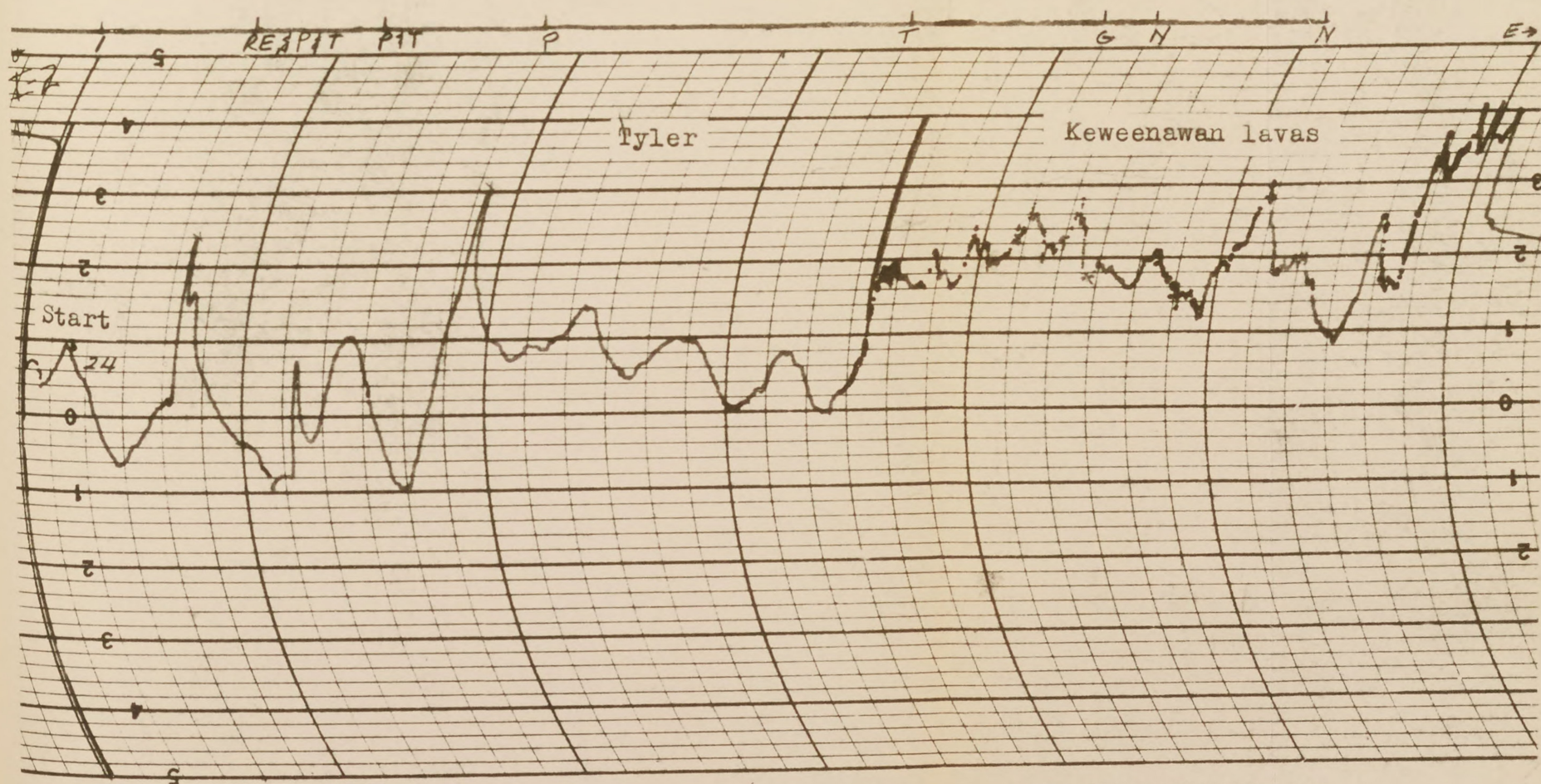


Figure 24

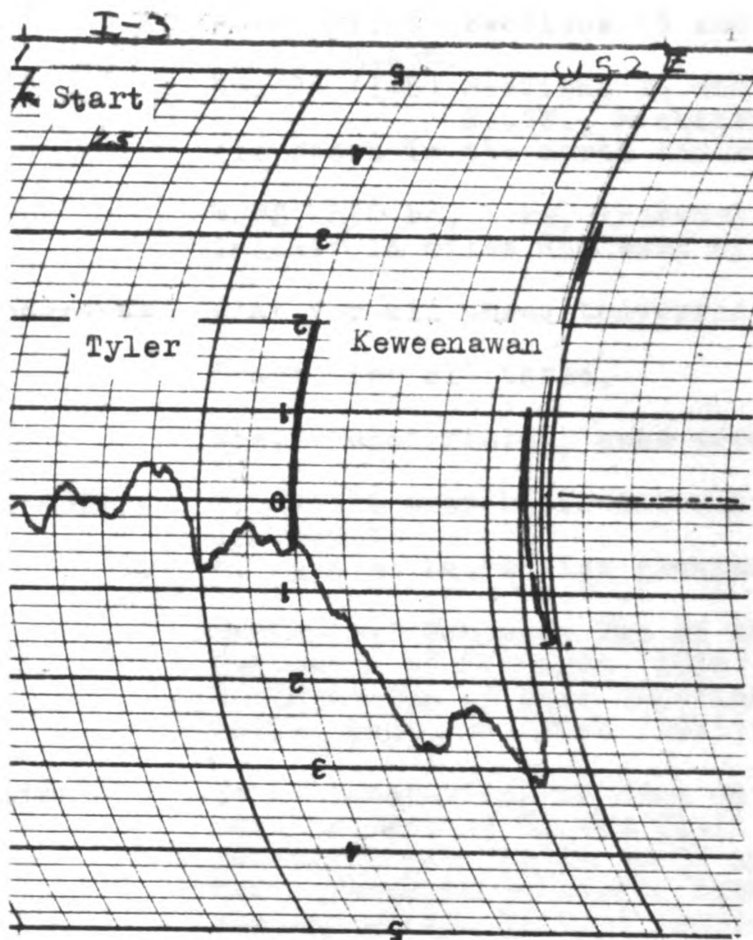
Number	29
Date	June 20, 1962
Name	Ironwood - 2.
Location	Section 36, T.48N., R.47W., and Sections 1, 12, and 13, T.47N., R.47W., Mich.
Radio station	WJMS, 630 kc, 1 kw, Ironwood, Mich. 2 miles S.35°W. from start at junction of US-2.
General topography	Gentle hills.
Road type	Gravel.
Vegetation	Open fields.
Geology and source	1. start at Tyler slates 2. 1.32 miles Keweenawan fault 3. Keweenawan lavas and conglomerates.
Interpretation	The fault itself does not seem to have any field change associated with it but the different lithologies of the beds on either side of the fault show up very well. These changes correlate very well with the mapped position of the fault.
Comments	Notice that on this record the Keweenawan formations have a low level of intensity, while on No. 30, Fig. 25, the Keweenawan has a high level of intensity. This is probably due to changes in the Tyler slate. The Tyler slate can be clay slates, graywacke and graywacke slates, or mica schist and mica slates.



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Figure 25

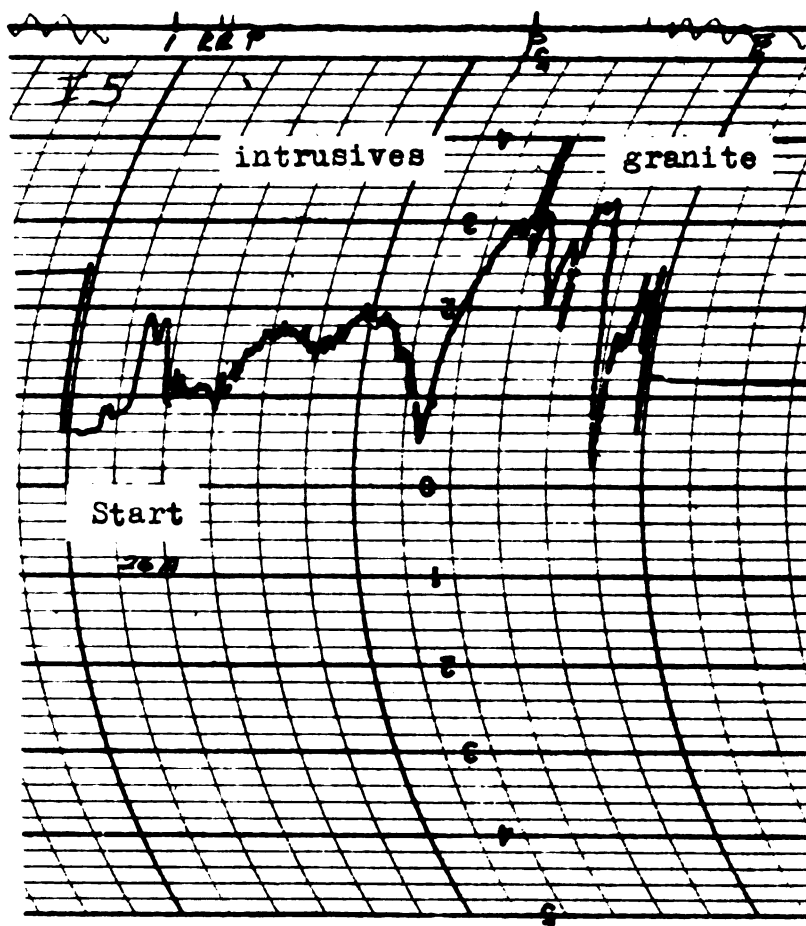
Number	30
Date	June 20, 1962
Name	Ironwood - 3.
Location	Sections 5 and 8, T.47N., R.46W., Mich.
Radio station	WJMS, 630 kc, 1 kw, Ironwood, Mich. 5 miles S.55°W. from start at US-2.
General topography	Low hills.
Road type	Gravel, oiled.
Vegetation	Open fields.
Geology and source	1. start in Tyler slates 2. 0.5 miles fault 3. stop in Keweenawan lava and conglomerates U.S.G.S. Monograph LII, p. 266.
Interpretation	The fault itself does not seem to have any field change associated with it but the different lithologies of the beds on either side of the fault show up very well. These changes correlate very well with the mapped position of the fault.
Comment	We see here a high level of intensity associated with the Keweenawan formation. On record 29 the Keweenawan has a low level of intensity. This is probably due to changes in the Tyler slate as discussed on No. 24. The traverse was repeated with nearly identical results.

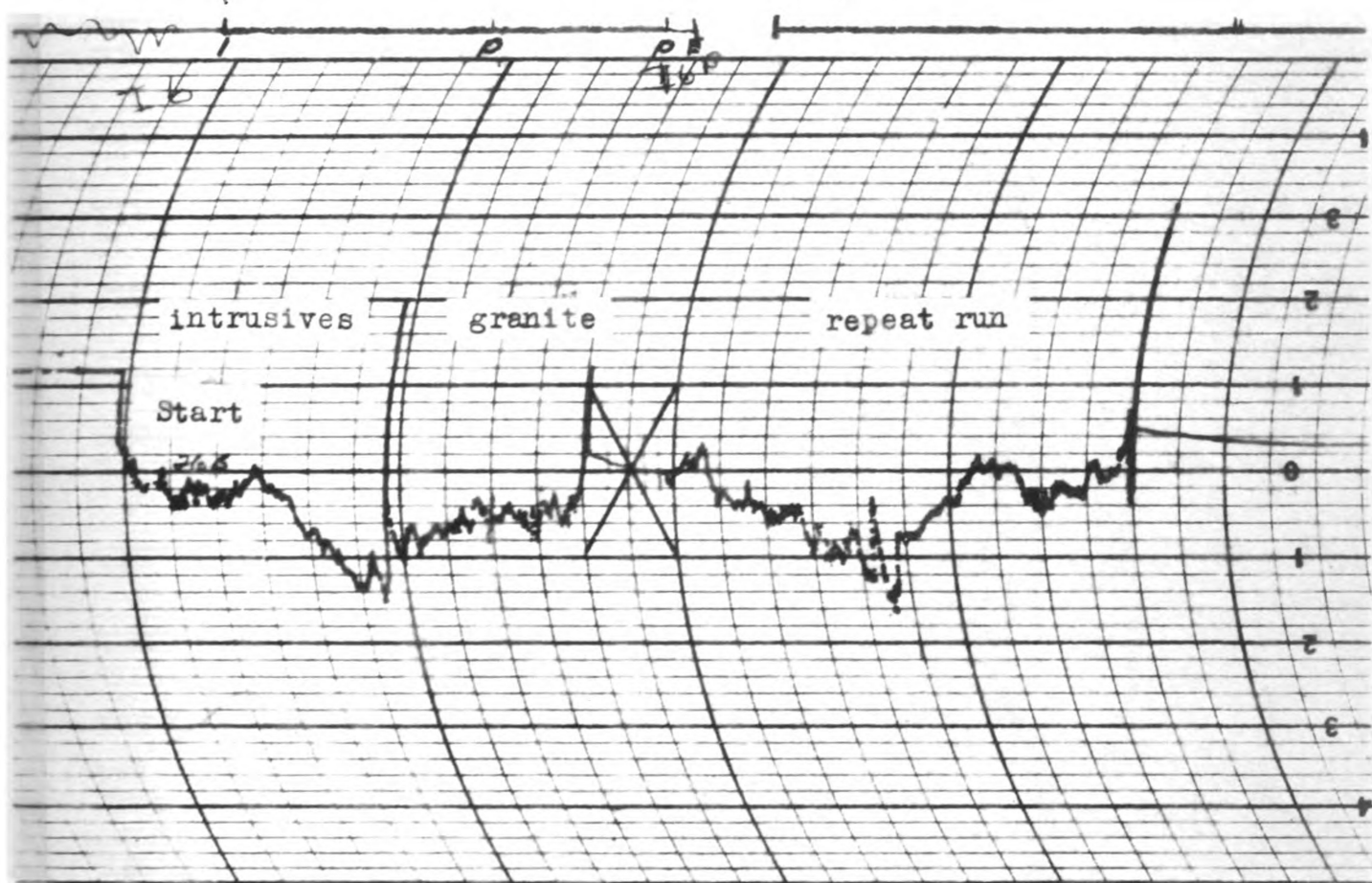


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Figure 26

Number	32, 33, and 35.
Date	June 20, 1962
Name	Ironwood 5, 6 and 8.
Location	No. 32 (I-5) Section 23, T.47N., R.45W., No. 33 (I-6) Sections 23 and 26, T.47N., R.45W. No. 35 (I-8) Sections 24 and 25, T.47N., R.45W., Michigan. All start in the north and run south.
Radio station	WJMS, 630 kc, 1 kw, Ironwood, Mich. approximately 14 miles due west of traverse.
General topography	Flat for all three traverses.
Road type	Gravel for all three.
Vegetation	Mostly open fields, some woods.
Geology and source	1. start over basic intrusives 2. fault 3. end in Laurentian granite. Centennial Geologic Map of the Northern Peninsula of Michigan (1936) and the Geologic Map of Lake Superior Region, Leith, Lund and Leith (1935).
Interpretation	It is interesting to note on these records that on 32 the fault shows an intensity low, while on 33 and 35, the fault shows an intensity high. This is similar to the kind of results Howell obtained. This could be caused by a change in the gouge material of the fault or in the moisture content.
Comments	This is a good example of how this method can be used for tracing a feature. One traverse was repeated for each, all were nearly identical to the original.





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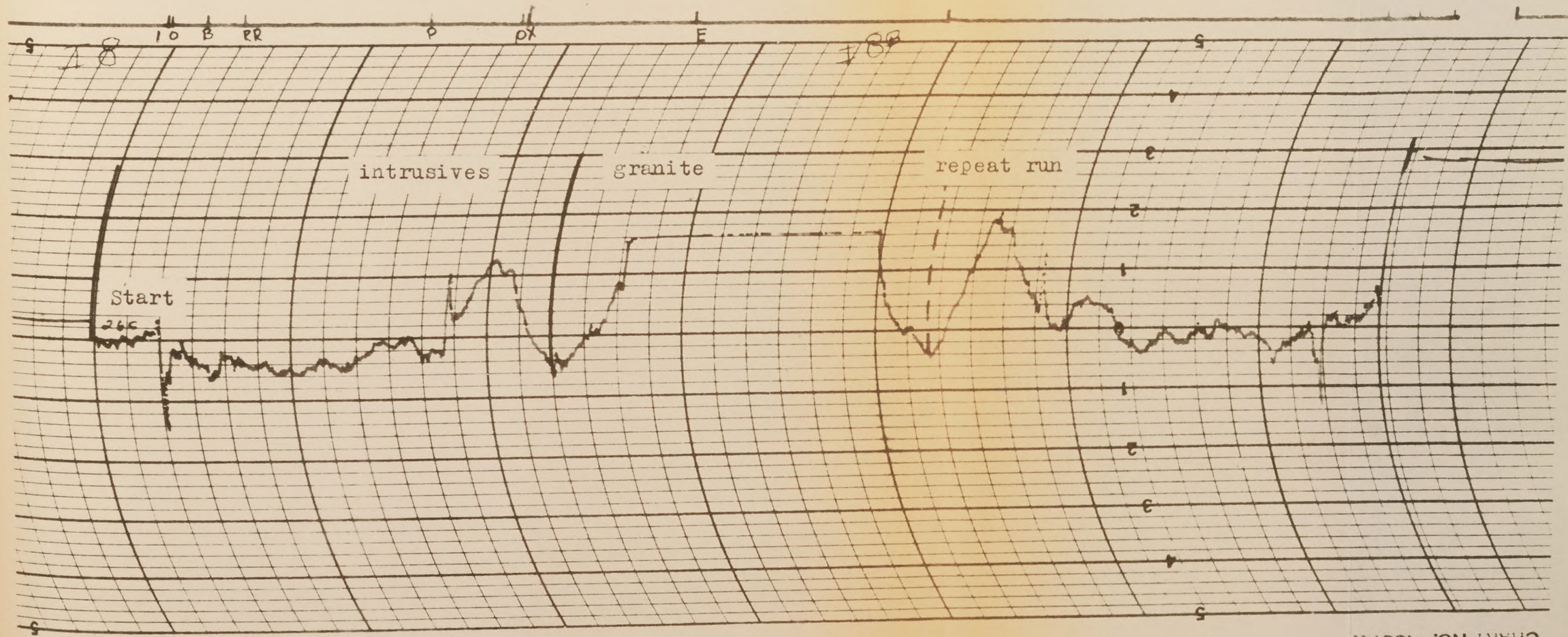


CHART NO. 4331-X

CONDITIONS UNDER WHICH THE METHOD FAILS

On the following pages are given examples of how certain conditions affect the records undesirably. These conditions include road type, presence of wires, and inadequate radio reception. Also included is an example of the method's failure to locate highly magnetic features.

All of the areas in Wisconsin were failures except in the Iron Mountain Area. The records are not included.

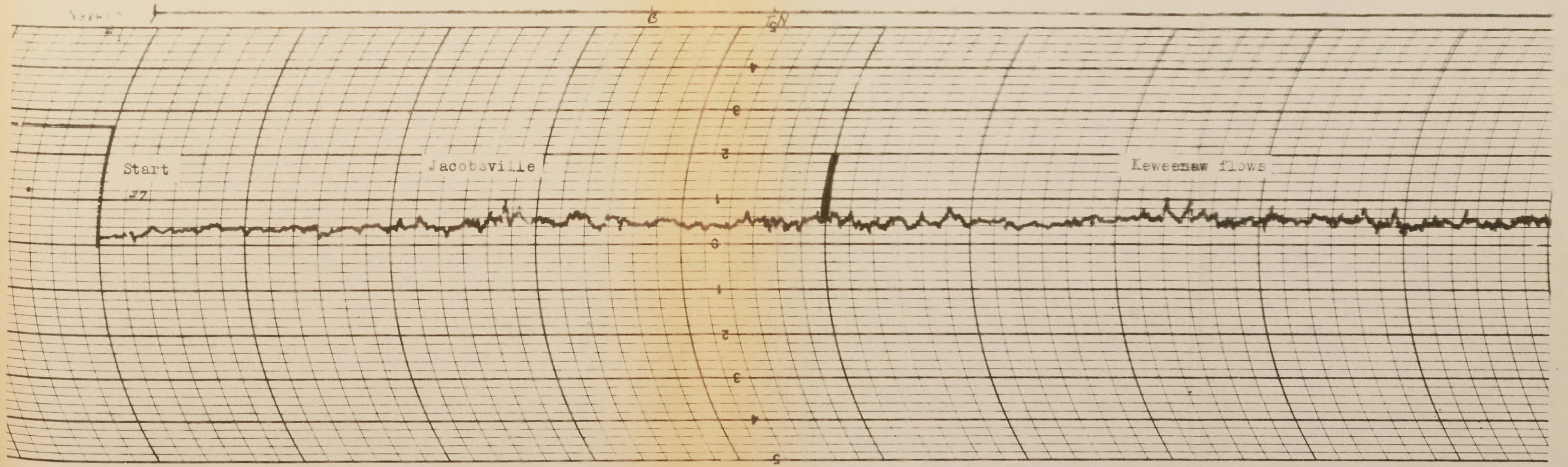
These areas are:

1. Pine Lake, T.44N., R.3E., sections 28, 21, and 20. Highly magnetic feature, no significant change in intensity.
2. Butternut, T.41N., R.1W., section 29. Highly magnetic feature, no significant change.
3. The McCaslin Mountain area. Could not receive a radio station with the equipment.

A possible source of failure, not knowingly experienced in this investigation, is where the rocks on either side of a fault or contact do not have significantly different electrical and magnetic properties to cause field intensity variations.

Figure 27

Number	37
Date	June 20, 1962
Name	Norwich - 1
Location	Sections 14-13, 11-12, and 2, T.49N., R.41W., Mich.
Radio station	WJMS, 630 kc, 1 kw, Ironwood, Mich. approximately 40 miles S.70°W from starting point on section line between 13-14.
General topography	Level to hilly, except where we pass through the Keweenaw fault scarp.
Road type	Gravel.
Vegetation	Open south of fault, wooded north of fault.
Geology and source	1. start over Jacobsville sandstone 2. 2.10 miles Keweenaw fault 3. end of run, over Keweenaw basic lava flows. Complete traverse now shown. The Centennial Geologic Map of the Northern Peninsula of Michigan
Interpretation	On this traverse the fault face could be seen clearly but there was no indication on the record. The fault face stood about 200 feet above the road.
Comment	This is a good example of a weak radio field not interacting with the rocks to any measurable extent.



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Figure 28

Number	62
Date	June 21, 1962
Name	Deer Lake - 1
Location	Section 29 and 32, T.48N., R.27W. and Sections 4 and 5, T.47N., R.27W., Mich.
Radio station	WJAN, 970 kc, 5 kw, Ishpeming, Mich. 2½ miles S.15°W. from start in section 29 at junction with Co. Rd. 573.
General topography	Very hilly.
Road type	Blacktop.
Vegetation	Wooded on both sides of road.
Geology and source	Undetermined.
Interpretation	This is a fine example of what too many electric, telephone, and guy wires can do. The needle never has time to estab- lish a level of intensity between wires, and thus the record is unusable.
Comments	Repeat traverse shown: observe that the changes in intensity during the south to north traverse are not as great as the north to south run. The event pen marked the location of the telephone and power lines.

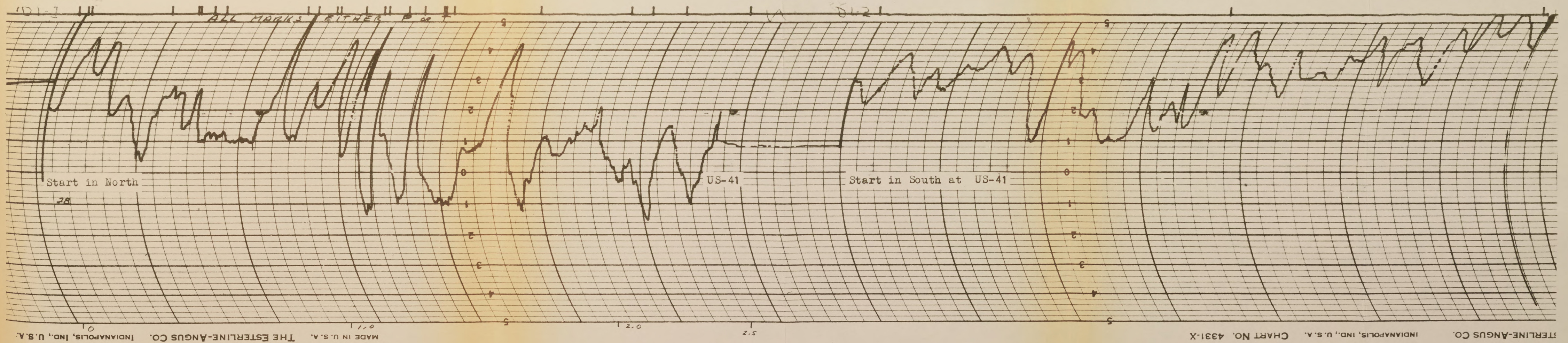
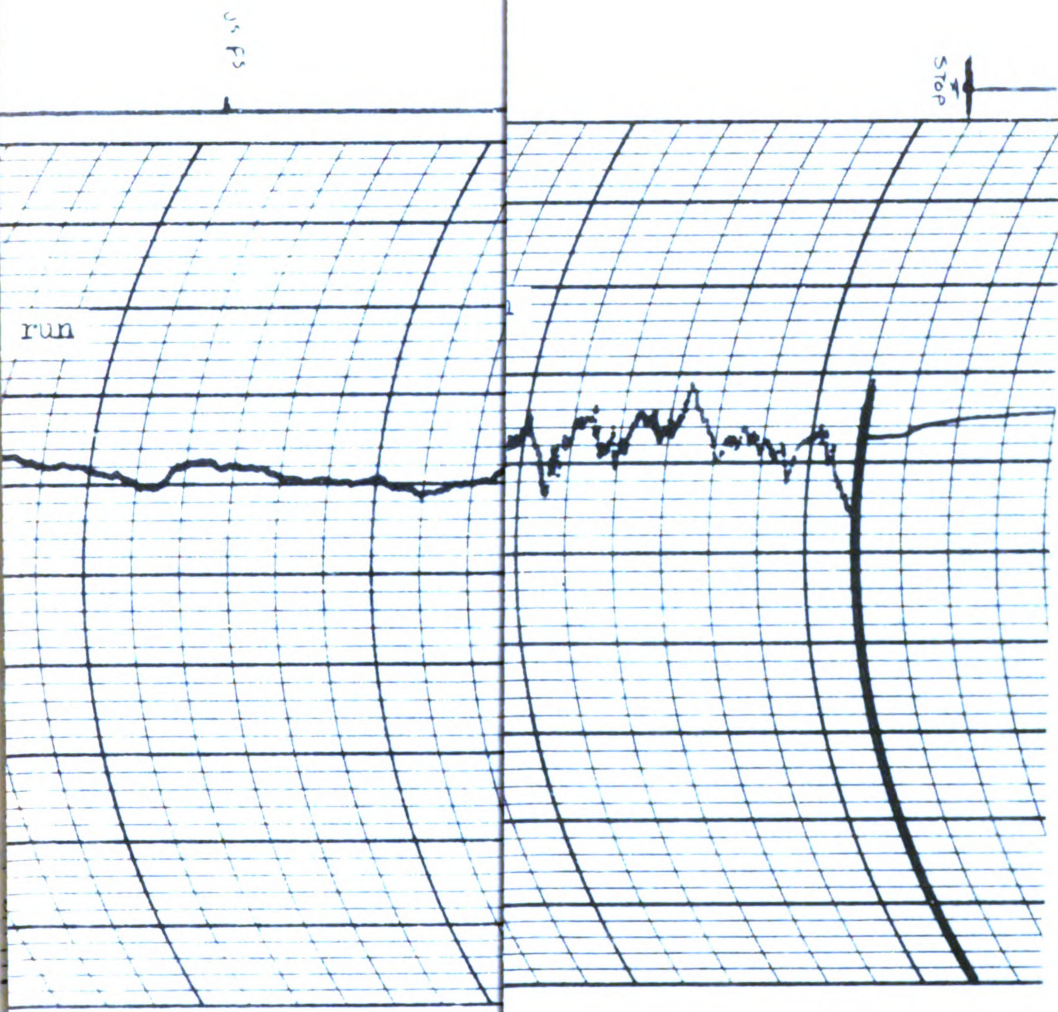


Figure 29

Number	26
Date	June 19, 1962
Name	U.S.F.S. - 116
Location	Sections 13, 14, 15, and 23, T.45N., R.41W., Mich., junction of U.S. 2 and U.S.F.S. 116.
Radio station	WBRL, 930 kc, Eagle River, Wisconsin, approximately 20 miles S.35°E. from junction.
General topography	Flat.
Road type	U.S. 2, concrete U.S.F.S. 116, gravel
Vegetation	Wooded
Geology and source	High magnetic area Robert C. Reed, Michigan State Geological Survey
Interpretation	The author experienced no success over magnetic features. Other traverses besides this one have been run and the results are all the same.
Comments	What is particularly interesting about this set of traverses is the vast dif- ference in response over the two roads, U.S. 2, and USFS 116. The reason for this difference is that U.S. 2 is a reinforced concrete road. The reinforcing mesh acts as an electrical shield for the rocks beneath. All we measured on U.S. 2 is the field intensity with very little effect from the geology. One repeat traverse was run with nearly identical results.



CONCLUSIONS

As a result of the radio field intensity survey conducted in the Lake Superior region the following conclusions were reached.

1. It is readily apparent that the radio field intensity method of geologic mapping can be of significant value. Generally speaking, in areas that were amenable to this type of mapping, the correlation between the changes in the intensity and the changes in the underlying geology was excellent.

2. There are several factors that make an area unsuited for this mapping method.

a. Before anything else is considered, if the road paving material is reinforced concrete there will be little or no success. This was postulated by Pullen and is here verified. (Figure 29)

b. Another factor is the intensity of the radio field at the area to be investigated. If there is not sufficient field strength the geology will not cause intensity changes. (Figure 27).

c. A third factor which interferes with this method is the presence of too many overhead wires. Just how many wires are too many is difficult to state. This is something which the operator must experiment with and learn to judge. The effect of many wires can be seen in Figure 28. At the same time we can observe from Figure 9 that sometimes a

large number of wires does not disturb the record. Therefore, unless there is an extremely high concentration of wires the traverse must be attempted before a judgement can be made.

d. The fourth, and most difficult factor to evaluate, is the topography. About all that can be done is to try and run traverses where the ground is level. If this is not possible it may be worthwhile to attempt a traverse as fair results can sometimes be obtained.

e. A fifth factor to be considered is the thickness of the drift. The theoretical depth penetration of radio waves, leads one away from attempting this method in heavily drifted areas. The Watersmeet record (Figure 23) is an exception.

3. There are a few traverses in which a fault or a contact has a field associated with it, e.g., Figure 26. Most of the time the only change noticed in passing over a fault or contact was in the level of intensity which correlated with differing formations on either side. It is possible that if the beds on either side of a fault or contact did not differ significantly no change in the level of intensity would occur.

4. It was also concluded that the transmitter should not be too close to the traverse. In some cases ten miles is too close. This depends primarily on the power of the station. The best results in this investigation were obtained

with stations of low power, 250 watts to 5 kilowatts, at distances greater than ten miles. Figures 21, 17, 10, and 9.

Pullen states that the best stations are ones 5-50 miles distant, depending on the frequency, and with a power of 250 to 1000 watts. He concluded that this was because weak fields are affected more by the geology than strong fields. This investigation found, on the contrary, that strong fields were affected more by geology than weak fields. Figure 22. Notice also the north ends of Figure 11 and Figure 15. These are weak field areas. Other examples are available but these are representative.

5. A number of highly magnetic features were investigated. The radio field does not seem to be affected by these fields.

Summary

Where field conditions are suitable, the radio field intensity method of geologic mapping offers promise of an economical and rapid method of reconnaissance mapping. It also has potential as a device for tracing and extending faults, contacts, and formations. Assuming the other conditions for suitability are met, the presence of glacial drift is the most serious drawback.

RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

As a result of this investigation the following recommendations can be made.

1. Before further studies are initiated in this field the equipment should be modernized. With the recent advances in electronics it should be possible to make the equipment lighter, more compact, more sensitive and with a lower power demand.

2. If in future investigations a whip antenna is used, it should be matched perfectly with the receiving meter. The antenna used in this study was the best the author could devise with the funds available and it worked very well, but possibly it is not the best arrangement.

3. With the improved equipment there are a number of intensity experiments that could be conducted which would be of value.

a. Rerun and expand the areas investigated in this study to see if results would be comparable, and if results in some areas could be improved.

b. With improved sensitivity it is possible that the low frequency (120 to 550 kc) aircraft range markers could be used as stations to be monitored.

c. This equipment might be suitable for airborne studies. This type of study is particularly appealing to the

author because it might eliminate the concern with cultural features, and would also make areas accessible which can not be reached by road.

d. Make a reconnaissance study of an unknown area and follow up with geological field work, to determine the value of the method.

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