A PALEOMAGNETIC STUDY OF A MIOCENE TRANSITION IN SOUTHEASTERN OREGON

by

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ABSTRACT

Three sections of the Steens Mountain Basalt were sampled in detail in southeastern Oregon. The paleomagnetic directions were measured using a Spinner Magnetometer and the techniques of A.C. demagnetization. The measurements following demagnetization at 200 oersted are shown to be the most precise. A petrographic study was done on 27 polished sections. Basic experiments concerning the distribution of stability for TRM were initiated.

The results of this work indicate that the magnetic field reversed approximately 15.1 million years ago. In going from the reversed polarity to the normal, the field passed through a transitional phase as indicated by non-typical magnetic directions. These directions are shown to be representative of the magnetic field. The reversal appears to have taken place in three stages. The first

Abstract - continued

is shown by a rapid change in inclination. The second is represented by a series of non-typical directions. The third is shown by a rapid change in declination. Three widely separated areas show these patterns

The results of the stability experiments indicate that:

1) rock samples are easily modified by heating in air,

2) these changes are observable under a microscope,

3) there must be some basic relationship between stability and intensity of magnetization.

Thesis Supervisor: David W. Strangway

Title: Assistant Professor of Geophysics

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Chapter I - Introduction

History

The history of paleomagnetism extends back to the late eighteenth century (Irving, 1964), and some very basic observations concerning natural remanent magnetization (NRM) and thermal remanent magnetization (TRM) were made as early as 1853. However, progress in the field was slow, and it was not until about 1925 that interest really started to be aroused. Actually, most of the work in paleomagnetics has been done since 1950 and at the present time, progress in paleomagnetics and its closely related sister subject, rock magnetics, is accelerating at a tremendous rate.

The uses of paleomagnetic data are many and shed light on some of the major problems studied by earth scientists today. Such problems as continental drift, polar wandering, secular variations of the earth's magnetic field, stratigraphic correlations, origin of the earth's field, and the history of the field are a few. In fact, paleomagnetics, as the name implies, is the only source of data for studying the ancient history of the field. Magnetic observatory data only goes back approximately 400 years and, hence, is very limited in time.

Purpose

The purpose of this project was to study the history of the magnetic field during a transition period. It was hoped that by very detailed sampling in a selected area, some of the history of a reversal would be revealed. Mainly, the direction of the field was studied, however, some work was done on its intensity. Hence, a natural division of this paper.

It has been well documented (Irving, 1964), that the direction of magnetization recorded by rocks falls into two main categories or positions. These are called normal polarity and reversed polarity. Normal polarity is when the sampled direction is near to the direction of the present day field. Reversed is when the direction is rotated approximately 180 degrees. That is, when the north seeking pole points to the geographic south pole. The transition zone is represented by that time interval when the direction of magnetization was between normal and reversed.

Two concepts have been proposed for reversals. These are the ideas of self-reversals and the reversal of the earth's magnetic field. It has been shown by many people that generally the direction of permanent magnetization found in the rocks is the direction of the external field at the time of magnetization, and only rarely is the resulting direction found to be reversed from the field (Nagata, 1961). This last phenomena is the concept of self-reversal. It is an inherent property of a rock and in volcanic rocks is found naturally to exist only in the Haruna Dacite (Nagata, 1952). The theoretical aspects of self-reversals were discussed by Néel (1955). He proposed four general categories of self-reversal. Although plausible, all required some special physical or chemical make-up of the sample. But, it is well known that reversed magnetization is very common, and that all reversed samples do <u>not</u> fit Néel's criteria. The large amount of data available now strongly indicates that reversals are world-wide events and that by some mechanism the earth's field has reversed (Cox, Doell and Dalrymple, 1965).

In connection with this study, the fact that transitions or intermediate positions are found lends strong support to the concept of field reversals. For, if the magnetic polarity found in rocks depended strictly upon its physical and chemical make-up, then the intermediate magnetic positions showing progressive changes from one polarity to the other would be highly doubtful. Néel could not account for directions of remanent magnetization other than normal and reversed. There is no theoretical basis for assuming intermediate directions. However, a super-position of magnetic directions could result in an intermediate position. That is, by adding components of different magnitudes, but nearly opposite in direction, intermediate positions result. This, however, requires that the field reverses or nearly so. Intermediate directions could also be reflecting directions of the earth's field as it reversed. Thus, valid intermediate directions are good evidence for field reversals.

Review of Permanent Magnetization

The source and characteristics of permanent magnetization in volcanics is a gigantic subject and has been the essence of many studies by both physicist and geophysicist. However, it is felt that a brief discussion of some of the basic ideas is necessary. A short list of references for a more detailed discussion would include Nagata (1961), Neel (1955), Everitt (1961, 1962 a and b), and Kittel, (1956), Stacey (1963), Verhoogen (1959) and Chikazumi (1964).

Minerals show two distinct types of magnetism. One is the induced magnetism. Its magnitude depends upon the susceptibility of the specimen and the strength of the applied field. This type of magnetization does not exist in the absence of an applied field. The second type is called permanent magnetization. It is a phenomena exhibited by a few minerals, mainly iron oxides and some iron sulphides. This magnetization, as the name implies, persists in the absences of an external field. This is the type of magnetization which is pertinent to paleomagnetics.

Rocks can naturally acquire a permanent magnetization or natural remanent magnetization (NRM) by three principal and two minor means. The three main ways are: 1) cooling through some temperature interval in the presence of a magnetic field; 2) depositional or detrital; and 3) chemical processes. The application of high field strengths at a constant temperature and the application of low fields for a long time are the two minor methods. Of all of these methods, the first is the most important process in volcanic rocks.

It is well known that above a certain temperature, depending upon the magnetic mineral, no magnetism is present. This temperature is called the Curie temperature. Upon cooling below the Curie temperature, an intense permanent magnetism or thermoremanent magnetism (TRM) is acquired in the presence of a weak field. Volcanics, which usually contain a considerable amount of magnetic minerals, are generally extruded at temperatures of 1100°C to 1200°C. Curie temperatures are far below this. Examples of Curie temperatures are magnetite, approximately 585°C, and hematite, approximately 670°C. Hence, upon cooling, volcanics usually acquire a strong TRM.

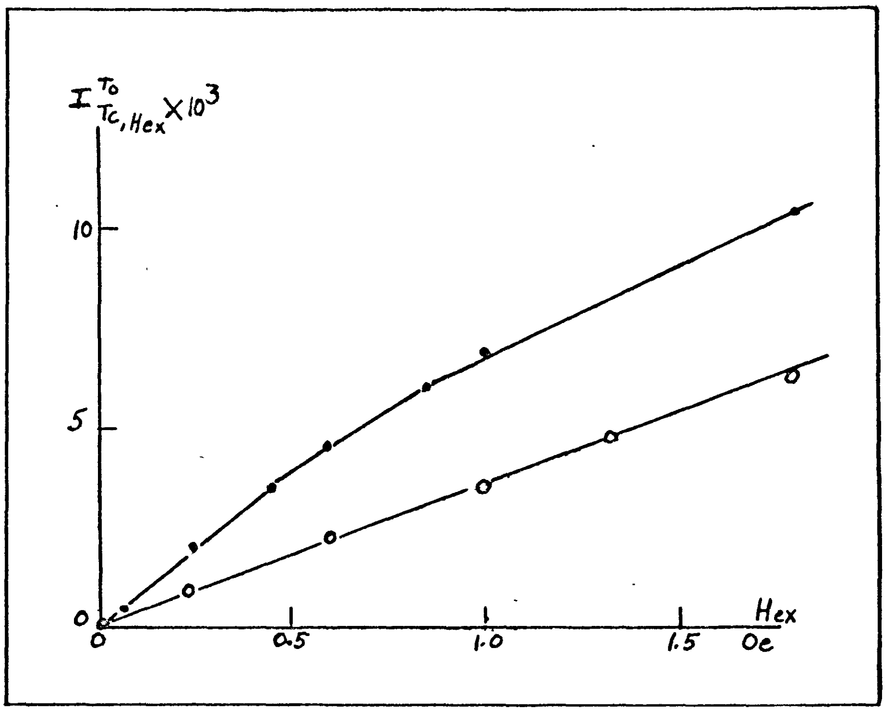
The physics of this phenomena is very interesting, but outside the scope of this paper. Of present importance, however, are the characteristics of this phenomena. Each characteristic will be briefly discussed. For a more complete discussion see Nagata (1961) or Irving (1964).

The first and very basic property of TRM is that, in general, the direction of the acquired magnetization is in the direction of the applied field. As mentioned earlier, there is only one known exception to this, the Haruna Dacite. A specific range of composition on the ilmeno-hematite phase line, from 45-60% ilmenite, has been shown to be self-reversing. This is believed to be an ordering-disordering effect due to negative exchange interactions across grain boundaries.

Also, some pyrrhotite is self-reversing. Therefore, by avoiding these known contradictions, it is possible to determine the direction of the magnetizing field by measuring the direction of the TRM.

Also of primary importance to paleomagnetism is the fact that in weak fields the TRM acquired is proportional to the applied magnetic field. This is the property of TRM which is the basis of all paleo-intensity studies. Above about 2 oersted this linearity breaks down. However, it is believed that the earth's field has always been small.

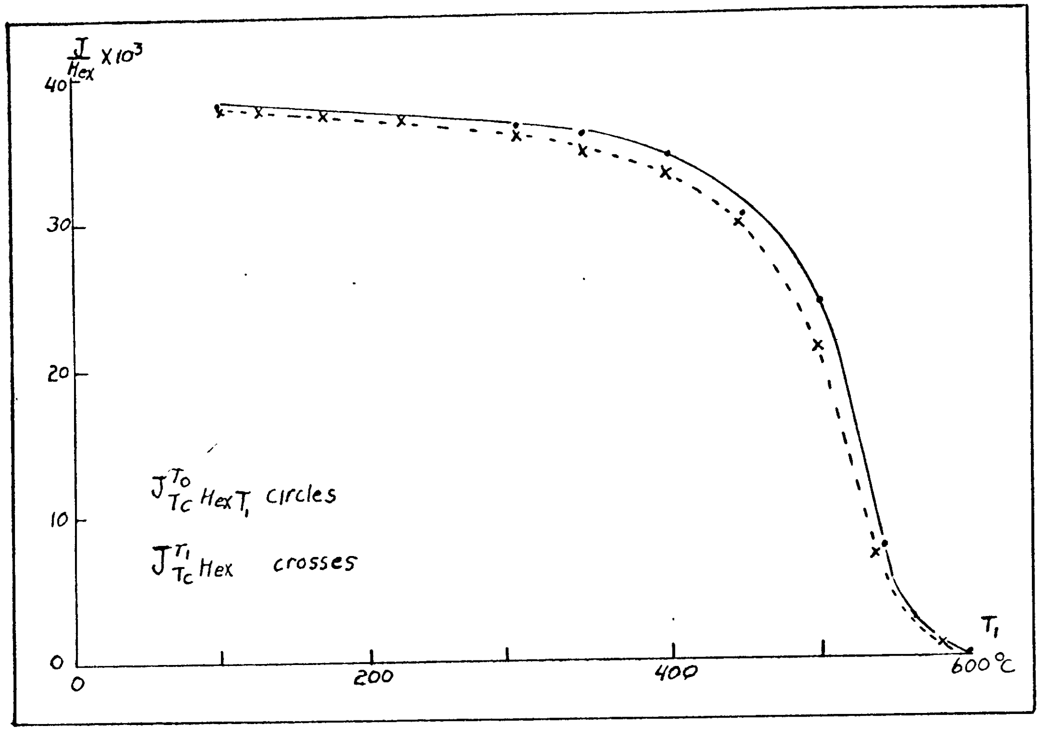
Figure 1-1



Linearity of TRM with field from Figure 5-5
Nagata, 1961

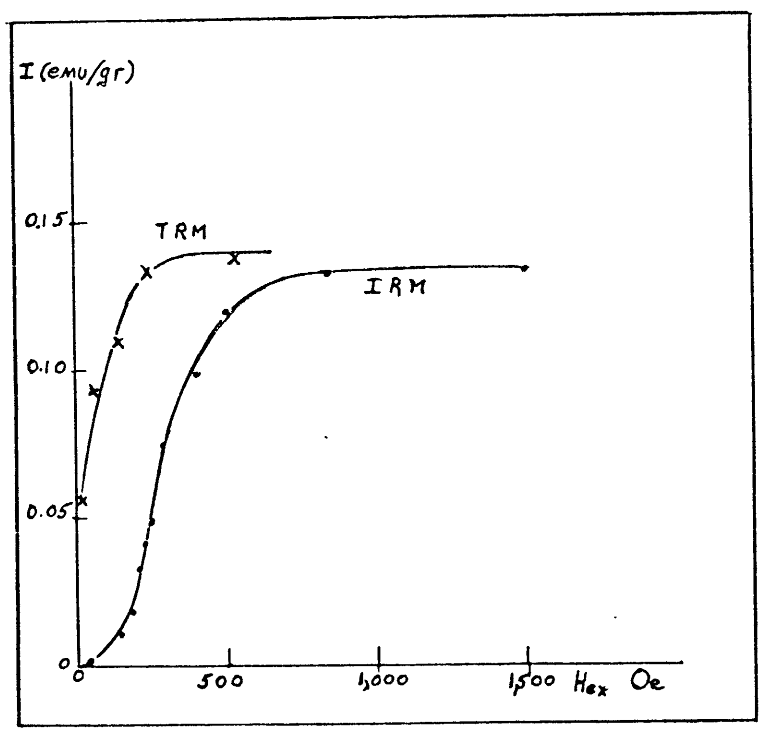
Concerning the magnitude of the acquired TRM, the magnitude not only depends upon the strength of the external field, but also the temperature range over which it was acquired (Figure 1-2). This subject will be discussed in greater detail in Chapter VI.

Figure 1-2



Temperature dependence of TRM from Figure 5-17,
Nagata, 1961

Figure 1-3



Comparison of saturation intensity for TRM and IRM
for powered magnetite (Figure 5-7, Nagata, 1961)

It has been shown, by many tests, that the TRM is very stable. That is, it is very resistant to change. TRM shows little or no change with time. Direct experiments are impossible to conduct on geologic time scales but the ideas of time stability are accepted. It can be demonstrated that TRM is very difficult to destroy by A.C. demagnetization or by a reversed magnetic field. TRM is also very resistant to thermal demagnetization. Except for some chemical remanence, TRM is the most stable form of permanent magnetization pertinent to paleomagnetics. IRM shows a change with time as a function of Log t.

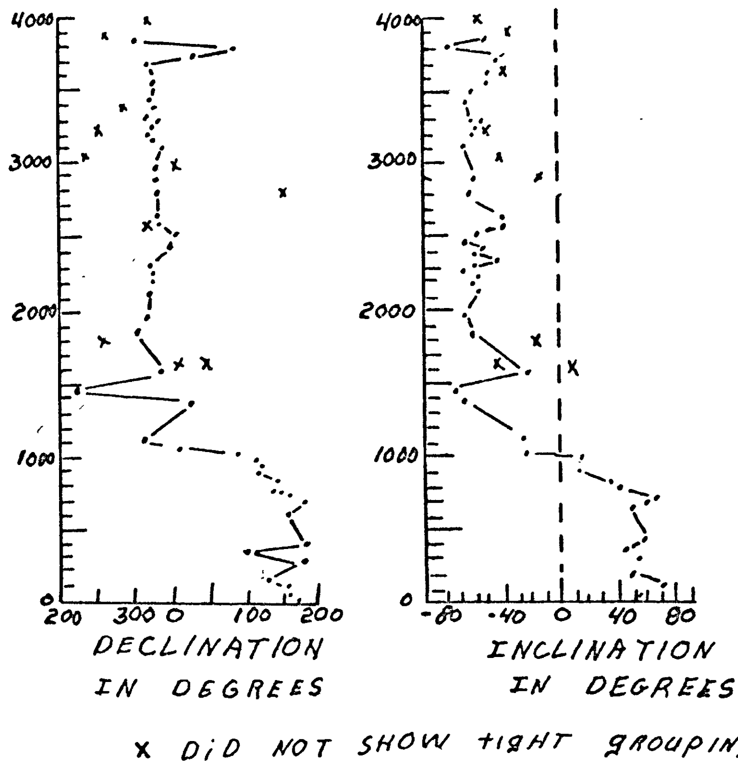
Another characteristic was shown by Roquet (1954). The saturation magnetization for TRM is reached at a much lower field value than for the true saturation (Figure 1-3). Also, TRM produced in weak fields is greater than the isothermal remanence or the induced magnetization. Lastly, it has been shown that generally the greater the coercive force, the greater the TRM. All these characteristics make TRM distinct and very useful in paleomagnetic studies.

Other Similar Studies

Detailed studies of transition zones in volcanics have been done by other workers. One of the first was done by Van Zijl, Graham, and Hales in 1962. They studied the

Trassic-Jurassic Stormberg Lavas in South Africa and found a progressive change in the direction of magnetization from reversed to normal. They also attempted to study the variation in the intensity of the earth's field. Their approach was to look at the NRM/TRM ratios. For small fields, the TRM acquired is proportional to the field. Therefore, by comparing the original NRM to the controlled TRM, it is possible to get some idea of the magnitude of the ancient field. However, this assumes that the measured NRM is a true measure of the original remanent magnetization, and that the NRM is all TRM. Further, it assumes that no changes took place in the samples during any of the laboratory experiments. Although attempts were made to support these assumptions, Thellier's method was not used and, as discussed in Chapter VI, sample changes are very easy to induce in the laboratory. One of the methods they used to improve the quality of the data was to compare NRM/TRM ratios after A.C. demagnetization. Thus the weaker or "softer" components were removed. They concluded that, during a transition, the field reduced to 1/4 or 1/5 its normal value and, also, there seemed to be periods of high intensity just before and after the transition. They also calculated the normal field at that time to be 0.42 oersteds.

Figure 1-4



Results of Stormberg Lavas at 219 oe. A.C. demagnetization

Another study of interest was done by Watkins (1965a, 1965b and others). He studied the Steen's Mountain basalts in southeastern Oregon, some of the same flows that were used for this study. He found a transition zone from reversed to normal spanning 19 flows. He also found that a peak A.C. field of 20 oe. was sufficient to remove the unstable components but the data at 200 oe. was reported. See Figures 1-5 and 1-6 for a summary of these results.

The data shows a definite grouping of the NRM directions over several flows and Watkins felt that this was due to irregular or pulsating volcanism. However, he

Steens Mountain - section one original NRM data, Watkins

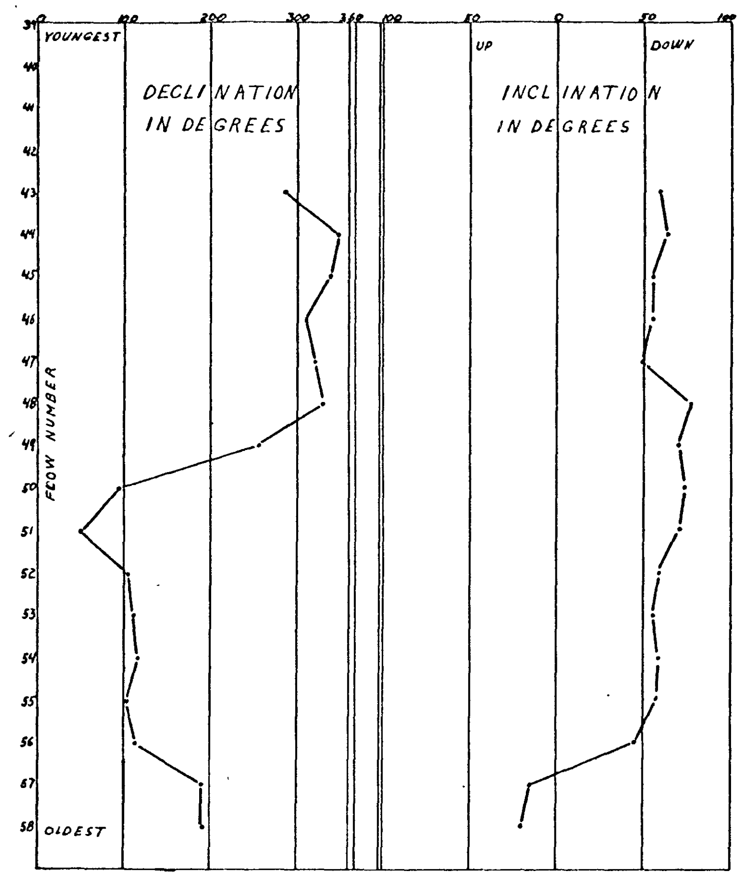


Figure 1-5

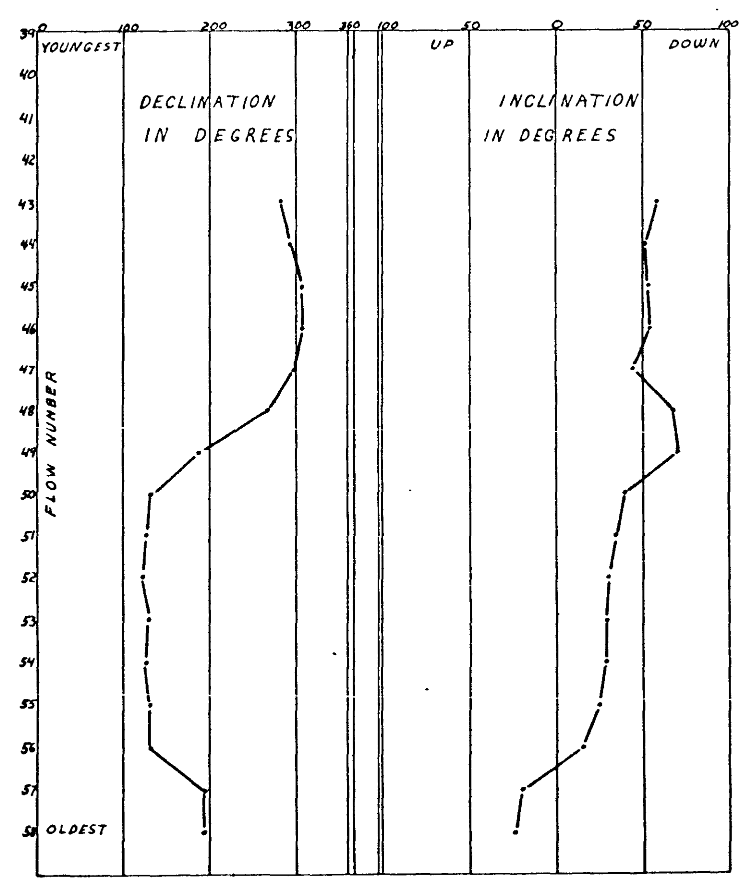


Figure 1-6

Steens Mountain - section one 200 oe. A.C. demagnetization, Watkins did not exclude the possibility of non-uniform movement of the field. Watkins also used this data to estimate the rate of extrusion. Taking the proposed (Cox et al., 1964) 10,000 years for a transition, Watkins concluded an average extrusion rate of one flow every 500 years. This is all highly speculative. As a final conclusion of this work, Watkins states that his results support Carey's (1965) oroclinal theory of tectonics.

In a more recent study, Watkins (1967) using samples of the Steens Basalts from the Guano Valley area in southern Oregon, attempted to correlate petrology with the reversal. He found that the samples from the transition zone contained maghemite and upon reheating he suggested that maghemite would convert to hematite creating a stable but erroneous NRM direction. Thus, Watkins suggested the possibility that the transition zone found in the Steens' Basalt is not real; rather, it is the result of a superposition of two stable magnetic components.

Other studies were done by Brynjolfsson (1957) and Momose in 1958 and 1963.

Chapter II - Field Site

Location

The area of interest is located in south-central Oregon in Lake and Harney Counties. Access to the area is somewhat limited. There are three paved roads in the area, U.S. Highway 395 from Lakeview, northeast to Burns, a road south from Burns to Frenchglen, and a road east from Lakeview to Winnemucca, Nevada. All other roads grade from good secondary roads to jeep trails (see index map, Steens Mountain Area).

General Geology

The area is very typical of the Basin and Range Province. That is, long parallel normal faults are the most dominant feature and they have divided the area into low valleys and high plateaus. The major faults trend nearly north-south or slightly east of north while the minor faulting trends N40-50W (Larson, 1965). All the faulting is normal and at a very steep angle. It appears that most of the major displacement took place quite rapidly during the post-Late-Middle Pliocene to Recent (Larson, 1965). The minor faulting, particularly in the N-W direction, appears to have taken place earlier, during

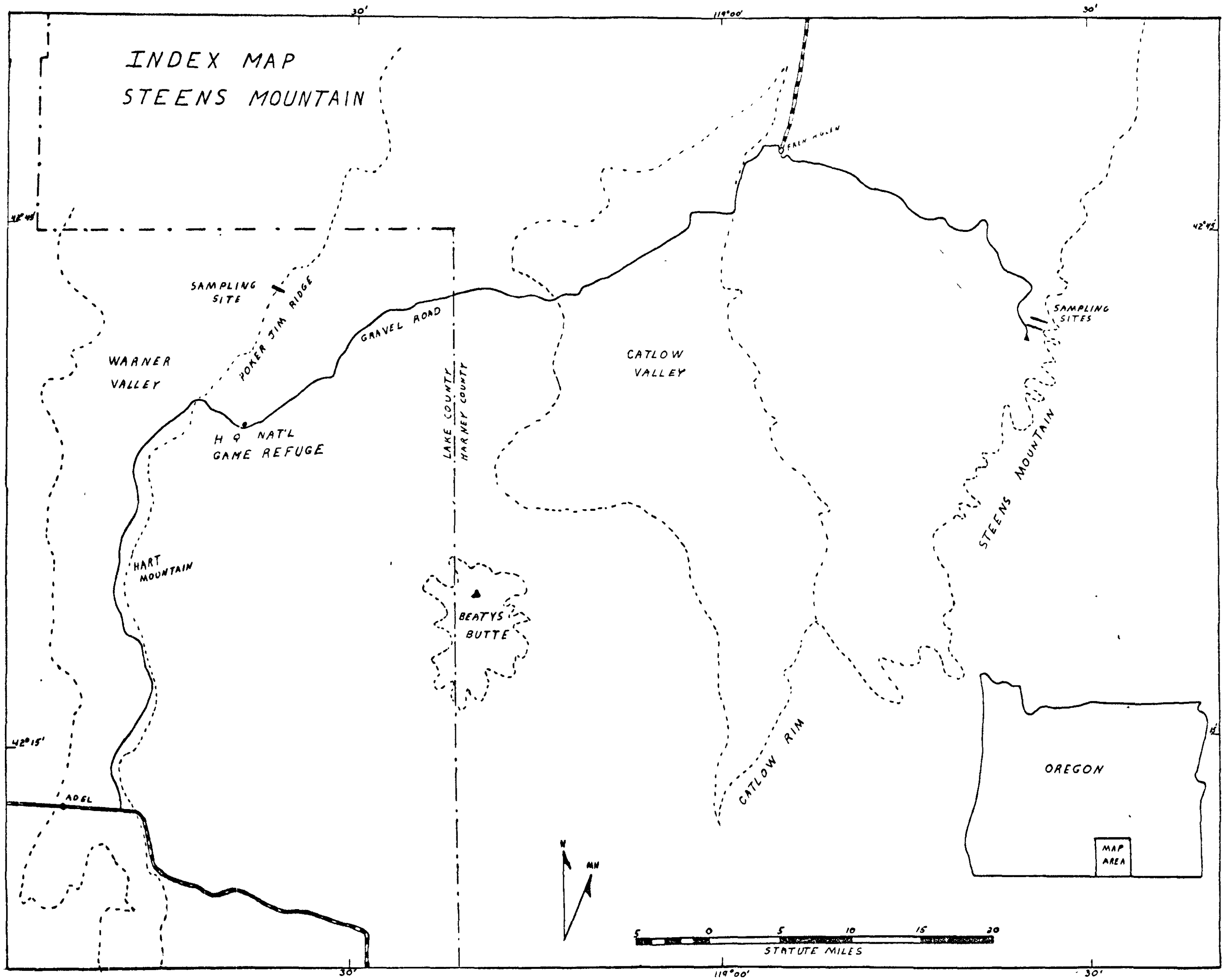

INDEX MAP
STEENS MOUNTAIN
30'
119°00'
30'
42°45'
42°15'
SAMPLING SITE
POKER JIM RIDGE
GRAVEL ROAD
WARNER VALLEY
H Q NAT'L GAME REFUGE
LAKE COUNTY
HARNEY COUNTY
CATLOW VALLEY
SAMPLING SITES
STEENS MOUNTAIN
HART MOUNTAIN
BEATYS BUTTE
CATLOW RIM
ADEL
OREGON
MAP AREA
N
MN
5 0 5 10 15 20
STATUTE MILES

Figure 2-1

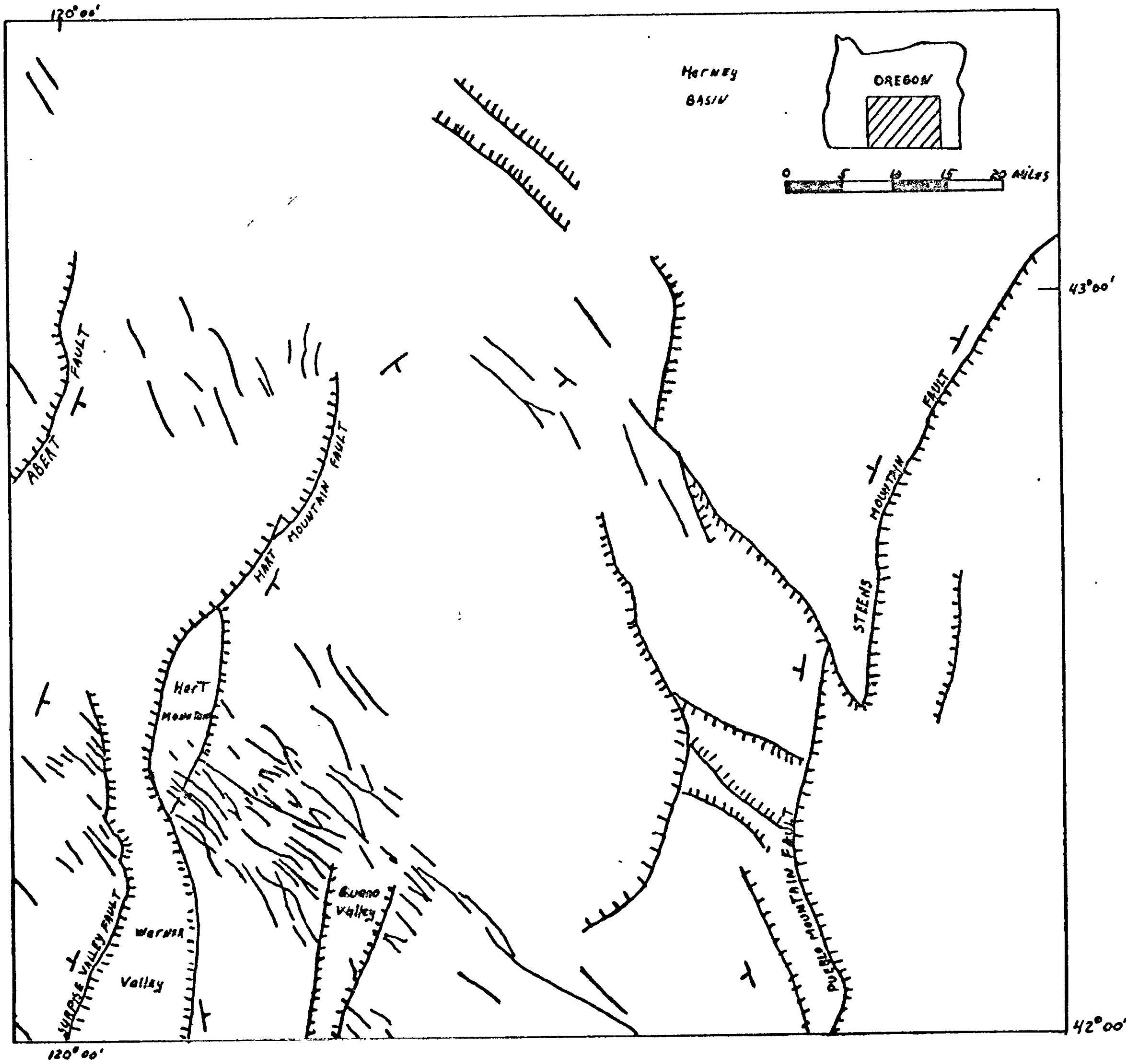


Figure 2-2

Generalized tectonics of the Steens Mountain area

Larson, 1965

the time span of late Miocene to post-Late-Middle Pliocene (see generalized tectonics of Steens Mountain Area, Larson, 1965).

The major faults have exposed thick sections which are principally volcanics. These volcanics are generally flat lying or gently-dipping and show very little weathering. Although several volcanic sequences are exposed by the faulting, only the Steens Mountain basalt is of interest in this study. This basaltic sequence is described in detail by Larson (1965) and the following is a brief summary.

The Steens Mountain basalt is a fissure basalt, varying up to 4000 ft. (Fuller, 1931) in thickness. It is composed of a series of medium-grained olivine-rich basaltic flows. Each flow unit is generally quite thin, average thickness is about 10 feet; and highly irregular in the lateral direction. Flora and fauna of the same age as the Steens Mountain basalt have been dated at 14.6 and 15.0 million years. The dating was principally done by Evernden and James (1964). Recently Baksi et al. (1967) dated the Steens transition at 15.1 ± 0.3 million years. These dates place the Steens basalt in the Middle to Late Miocene.

The Steens basalt appears to be quite uniform in composition. Basically, it is composed of plagioclase, clinopyroxene, olivine, opaques and apatite. Of particular interest are the opaque minerals since here lies the source of all paleomagnetics.

The primary opaque minerals are magnetite, ilmenite, and some hematite. Also, very minor amounts of maghemite and pseudobrookite were found. The opaques make up from approximately 2% to 10% of the rock. More discussion of the opaques will follow in Chapter IV.

From the work of Larson (1965) and Watkins (1965a and b) it appears that the flows came in rapid succession. However, some of the flows are characterized by large plagioclase phenocrysts. These phenocrysts are usually about one inch long. Larson suggests that this is due to cooling at depth prior to eruption and, hence, such zones mark a time break or period of non-volcanism.

Sample Collection

On the basis of the work done by Larson (1965) and Watkins (1964), two collection sites were selected. One site is located on the north end of Poker Jim Ridge, 42.6°N, 119.6°W, in Lake County, Oregon. The second site is in the central portion of Steens Mountain, 42.8°N, 118.5°W, in Harney County, Oregon. At Steens Mountain, two separate vertical columns, about 1000 feet apart, were sampled. These were designated as Steens (1) and Steens (2).

These sites were selected for a variety of reasons. The most important reason is that Watkins (1965a and b) had found a reversal on Steens Mountain and Larson (1965) found what he believed to be the same reversal on Poker Jim Ridge. All of Larson's work in the area indicated that the basalts on Poker Jim and Steens Mountain are of the same age and that the reversal can be used as a time marker in both locations. Also of great importance is the fact that the flows show evidence of very rapid succession. Hence, it was felt that there was a good chance, by careful detailed sampling, to find some flows marking the transition from the reversed position to normal.

Other factors made this area very desirable. The geology is relatively simple. That is, the volcanic flows are flat lying or gently dipping (less than 2^{o}) and the faults are high angle normal. Regional tectonics, specifically the concept of oroclines, were not considered pertinent. No folding could be found at the sampling sites, thus, serious data corrections due to the geologic history were eliminated. The Steens basalt shows little evidence of weathering and, hence, fresh rock samples are easy to obtain. The last pertinent reason for selecting these sites is their horizontal separation. These sites are approximately 55 miles apart and, hence, effects of the local setting are greatly reduced.

The method of collection was quite simple. The desired interval was located by the use of a very light (approximately 1 lb.) portable flux-gate magnetometer. The circuit design was done by Doell and Cox (1962) at the USGS and the sensing head is a standard item sold by Sharpe Instruments #MF 1-27 with non-magnetic tube (see appendix C). This was a very useful device in that rough magnetic directions were easily obtained in the field, and, hence, only the sought after transition zones were selected for drilling. This saved a considerable amount of field time and work. Having located the transition zone, rock cores about 1 inch by 3 inches were taken using a portable, water-cooled core drill. Before a core was detached from the flow, the dip and strike of the core was measured. This is done by slipping a special brass tube over the core which allows the upper surface of the core to be marked. Then using a standard Brunton compass, the dip and strike are measured. The dip and strike should be accurate to a few degrees. After recording this information, the dip-line, the outer or upper surface, and an identification number were marked on the core. Thus re-orientation was assured.

At least four individual cores were taken from each flow. Care was taken to insure both lateral and vertical separation of the samples within each flow. Also, because of the minor N-W faults and lateral discontinuity of the flows, care was taken to insure that the same flow or the same time interval was not sampled twice. This sampling technique should reduce the effects of minor mineralogical changes as well as the effects of weathering and reheating. Over 200 cores were taken in the manner described.

Chapter III - Data Collection

Measurement

Each of the drilled cores was cut into cylindrical samples approximately 1 inch by 1 inch, and the original NRM of each sample was measured. This was done using an air-driven spinner magnetometer in field free space.

Briefly, a nylon rotor with a half black, half white top is used for the sample holder. By passing pressurized air under the rotor, the sample is spun at 100 cps. Two vertical coils are used for the signal detection. These coils are positioned so that variations of the background magnetic field in the laboratory is cancelled out, but the desired signal is still detected. That is, the second coil is placed further from the signal source than the first coil, and then the signal at the second coil is subtracted from the first. The magnetic moment varies as $1/R^3$. Hence, very little of the desired signal is detected by the second coil and the background field is essentially cancelled. By the use of a phase lock amplifier (Princeton Applied Research Model J.B. 6), 90^{o} components of the signal are measured. Three different combinations of axes are measured to insure accurate measurements. Directions of the resultant vector are probably accurate to 1^0 while 5% is estimated for the magnitude. A photo cell directed at the top of the rotor serves as a reference signal. For a more detailed description of the spinner magnetometer and its operation, refer to Koch (1966).

The NRM data was calculated and plotted using Fortran IV program by Grommé (1965) and this program has been revised by R.D. Watts, M.I.T. graduate student. The program calculates the direction and intensity of each sample. Part of the program is designed to plot this data on a computer constructed stereo-net. The average declination, inclination and intensity for each flow is calculated. Then, the Fisher statistics are calculated and, also, the paleo longitude and latitude.

A brief explanation of Fisher statistics might be helpful in understanding some of the work that follows. The basic reference for this discussion is Fisher (1953). The basis for this statistical approach is the assumption that the directional vectors of each sample are independent samples of a gaussian distribution about the true position on a sphere. The assumed density distribution is $e^{\kappa \cos \theta}$ where κ is a measure of the internal precision and θ is the angular displacement of the vector from the true position.

This leads to an absolute element of frequency $df = \frac{\kappa}{2 \sinh \kappa} e^{\kappa \cos \theta} \sin \theta d\theta$. It is obvious that the density distribution is a maximum when $\theta = 0$. When κ is zero, this implies a uniform distribution of points on the sphere. As κ gets large and approaches infinity, this implies that the distribution is approaching a two-dimensional isotropic gaussian distribution and κ is approaching 1/variance. Large kappa's are desirable in paleomagnetics.

In the case of N-R <2, the probability function can be expressed as $P = \left(\frac{N-R}{N-Rc}\right)^{N-1}$ where N is the total number of independent unit vectors used, R is the vector sum of the N vecotrs and c is cos θ. A better form is $1 - c = \frac{N-R}{R} \left\{ \left(\frac{1}{P}\right)^{\frac{1}{N-1}} - 1 \right\}$ and κ now equals $\frac{N-1}{N-R}$. This form allows the calculation of any desired confidence limit. In paleomagnetics, the 95% confidence limit is in general usage. This confidence limit is the solid angle which, when projected on a sphere and centered around the assumed correct point, gives a 95% probability that the true position lies within this circle.

A.C. Demagnetization

The results of the initial NRM data indicated a reversal with many flows in the transition zone, but scatter was evident in the data. Therefore, A.C. demagnetization spectra were done on at least one sample from every flow. The selected peak A.C. field strengths for the spectrum was 0, 100, 200, 400, 600 and sometimes 800 and 1000 oersteds.

The A.C. demagnetization apparatus is quite simple. A rotating (approximately 1 cps) hollow cylinder is placed inside a solenoidal coil. The coil is capable of generating fields greater than 1000 oe. The inside of a round ball was machined to hold the rock sample. This ball is rapidly forced up and down the rotating cylinder by a rubber "kicker" at one end and a rubber "bouncer" at the other. By this simple method, a fairly random motion of the ball is produced. Power for the coil is supplied by a variac auto transformer through a smoothly varying resistor and a capacitor. The variable resistor is a flask of salt water with two copper electrodes. As the water is slowly siphoned away, the resistance increases approaching infinity. Actually, the resistance varies from about 70 ohms to 40,000 ohms. The entire apparatus is placed inside a field free space created by a single set of square Helmholz coils.

The application of extensive A.C. demagnetization seemd to improve the data. Some samples did not form a tight grouping, and, hence, seem to be unstable samples. If only one value of the A.C. field was selected and used on all the samples, these unstable samples would not have been detected. Also, the highly viscous components were obviously removed by this procedure (see examples in Appendix A).

Susceptibility

The susceptibility of at least two samples from each flow was measured. This was done using a Geophysical Specialties Model MS-3B magnetic susceptibility bridge. The measurements are taken at 1000 cps. By knowing the susceptibility, it is possible to get a "feeling" for the intensity of magnetization found in the sample. This will be discussed in Chapter IV.

Chapter IV - Discussion of Results

General Comments

In general, the results of all three sampling sites are approximately the same. The same patterns or changes of inclination and declination were found at all three sites. However, each site will be discussed separately.

The results have been plotted by sampling site, Steens Mountain - section one; Steens Mountain - section two; and Poker Jim Ridge. The plots show inclination and declination versus the flow number, counting from the oldest to the youngest flow. Three different graphs have been made for each section. These are the results of the original NRM data, the total A.C. demagnetization spectrum, and the values at 200 oersteds peak A.C. field. For the original NRM data, all the results from one particular flow have been averaged. If one core was cut into two or more samples, these samples were first averaged together. Then they were used in the over-all calculations for that flow. The computed value for alpha 95 was taken as a measure of the precision for each flow and was plotted as a bar on the declination curve. It is plotted here as a matter of convenience and does not imply that all of the variation is due to differences in the declination.

For the total A.C. demagnetization charts, the results from each successive demagnetization of the samples were used in the calculations. The same calculations were performed on these data as were done on the original data. The computed alpha 95 was again used and plotted as a measure of the precision. Using this averaged data is really assuming that each of the individual A.C. demagnetization results is of equal value or worth. That is, the results after demagnetization at 50 oersteds is "just as good" or is "just as representative" as the results after demagnetization at 200 oersteds. This is <u>not</u> in full agreement with the ideas of A.C. demagnetization. By removing the "softer" components of the remanent magnetization, the remaining remanence should be closer to a true representation of the ancient field. However, in many cases (see Figure A-8) a tight grouping of directions did not develop as a result of A.C. demagnetization. Because of this, it is felt that straight averaging the data is of some worth and gives some idea of the change in the direction of magnetization.

The third plot, the results of the A.C. demagnetization at 200 oersteds peak field, is thought to be the most reliable of the three types, and to be the most diagnostic of the changes during the transition. It was felt by As and Zijderveld (1958) that 300 oersted peak field and 150^{o}C was sufficient to "clean" most rocks. Van Zijl et al. (1962a) felt that 219 oerted peak field was sufficient to remove all the soft components. Other workers have shown that low peak A.C. field strengths have been sufficient to clean the data.

In this investigation, it was felt that 200 oersted field was the best value for two reasons. It was felt that it is big enough to remove all of the unwanted magnetization and yet it is not so big as to add spurious components. It is obvious from all the scatter in the original data that there must be soft components present, and, hence, must be removed. In many cases there seems to be a tendency for the results from the 100 oe. and 200 oe. A.C. demagnetizations to group together (see Figure A-7). The results of Watkins (1965b and c) show 20 oe. to 50 oe. was sufficient. However, A.C. demagnetization spectra were done only on a few samples from a section. Then the peak field was selected on the basis of these results. Therefore, on the basis of the present and past information, it is felt that a 200 oe. A.C. field is sufficient to clean the data.

Critically looking at the results of the A.C.

demagnetizations, it was noticed that in many cases radical changes in either the intensity or direction of magnetization occurred with fields above 200 oe. Possibly the samples are very unstable or soft and only have a very small stable component, or maybe the demagnetizer adds unwanted components to the samples. Whatever the cause, above 200 oe. the data seems to show an increase in scatter. For these two reasons it was felt that 200 oe. is the best value for the A.C. demagnetization.

To demonstrate that the 200 oersted data gives the most internally consistant results for a flow, and also to demonstrate that the alpha 95 derived from the A.C. demagnetization of a sample is some measure of the internal precision of the flow, a critical experiment was done. Four flows were selected for this test on the basis of the preliminary data only. Two of the flows were Steens Mountain - section one flows 19 and 20. These were predicted to represent stable flows. That is, flows for which very reliable directions could be measured. The other two flows were 8 and 15 from Poker Jim Ridge. These were predicted to be unstable, or unreliable directions.

For these four flows, samples from every core were demagnetized at 0, 100, 200, 400 and 600 oersteds. For the results see Appendix A, Figures A-1, A-2, A-3 and others.

Each of the Steens Mountain samples showed a good grouping of directions upon A.C. demagnetization and for the Poker Jim samples, each showed a loose or poor grouping of directions. The individual cores from Steens Mountain showed a large kappa value and a correspondingly small alpha 95 while those from Poker Jim Ridge showed small kappa values and large alpha 95 values.

To show the consistency within each flow, the kappa and alpha 95 values were calculated using all the data for one flow taken at a specific A.C.field value. Because a large kappa implies a small alpha 95 and vice versa, it was decided to plot the kappa values instead of alpha 95. The results are shown in Figure 4-1.

All of the curves except Poker Jim 8 show a peak in the kappa value at 200 oe. This demonstrates the validity of taking the 200 oersted data as the most representative of the flow. Also, these results show that the flows predicted to be unstable on the basis of individual A.C. demagnetization spectra have very little internal consistancy, and, hence, do not give very reliable directions.

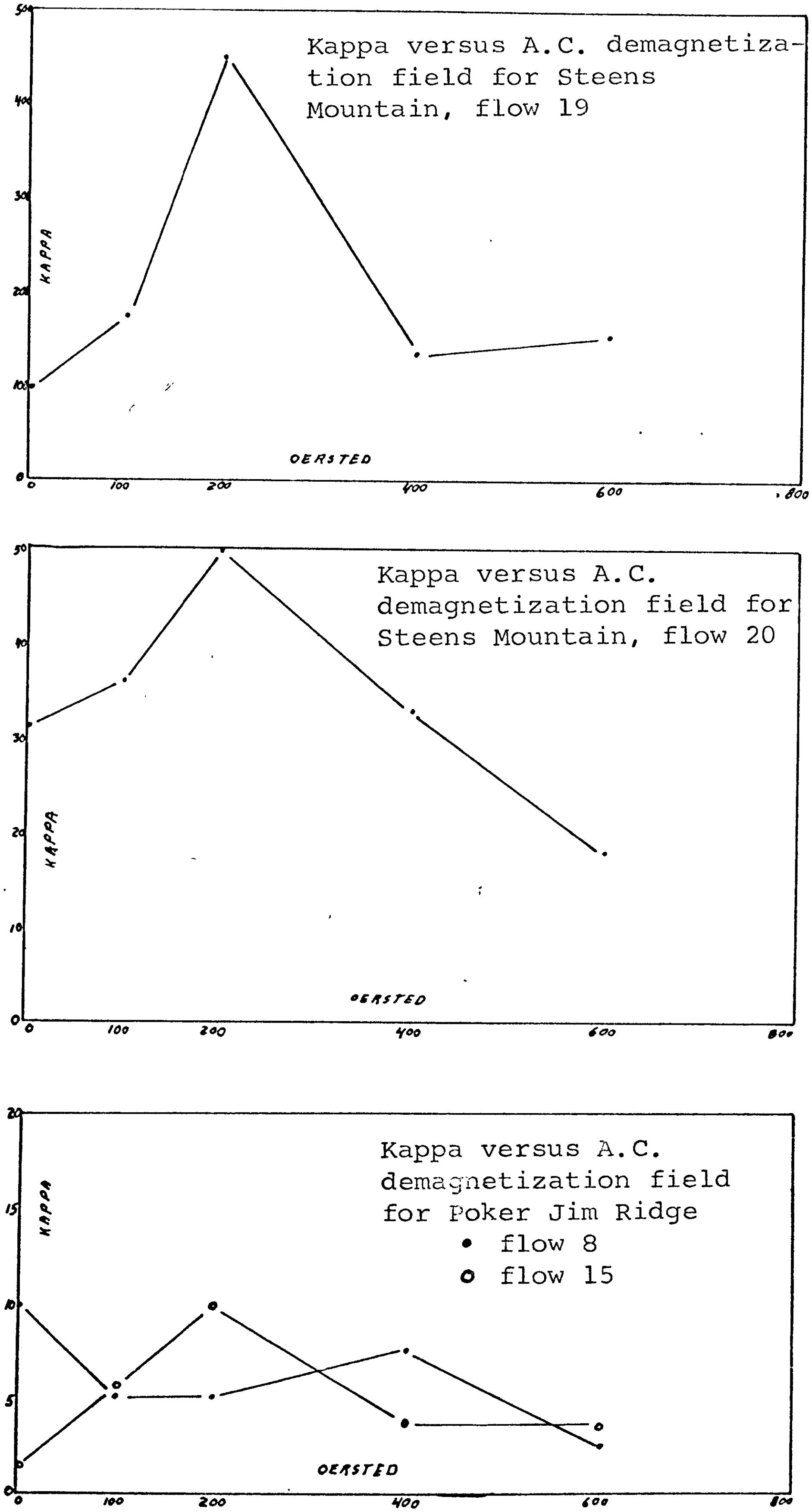

Kappa versus A.C. demagnetization field for Steens Mountain, flow 19
KAPPA
OERSTED
0
100
200
400
600
800
Kappa versus A.C. demagnetization field for Steens Mountain, flow 20
KAPPA
OERSTED
0
10
20
30
40
50
0
100
200
400
600
800
Kappa versus A.C. demagnetization field for Poker Jim Ridge
• flow 8
o flow 15
KAPPA
OERSTED
0
5
10
15
20
0
100
200
400
600
800

Figure 4-1

Steens Mountain - Section One

The results from Steens Mountain section one show a reversal from reversed polarity to normal polarity starting at flow number 2 and probably ending at flow number 17 (see Figures 4-2, 4-3 and 4-4). Flow 17 was selected as the end point because the original NRM data shows a sharp change in inclination there. This change also appears on the demagnetization graphs but it is not as sharp. Depending upon the definition of a transition zone, the maximum span of the transition would be from flow 2 to beyond flow 20 and the minimum would be from flow 2 to 13. The range from flow 2 to 17 was picked strictly on the pattern. The reversal seems to have taken place in steps or phases. This is with respect to flow numbers which do not necessarily represent time. This will be discussed later. Momose (1963) and Watkins (1965a) also noticed that during a transition, the changes seem to take place in stages. The first step is shown by a drastic change in inclination from a negative 25 - 30 degrees to eventually a positive 50 degrees. For the northern hemisphere a negative inclination is when the north seeking pole points upward and a positive inclination is when it is pointing downward. At the same time, the declination seems to have rotated counter-clockwise from

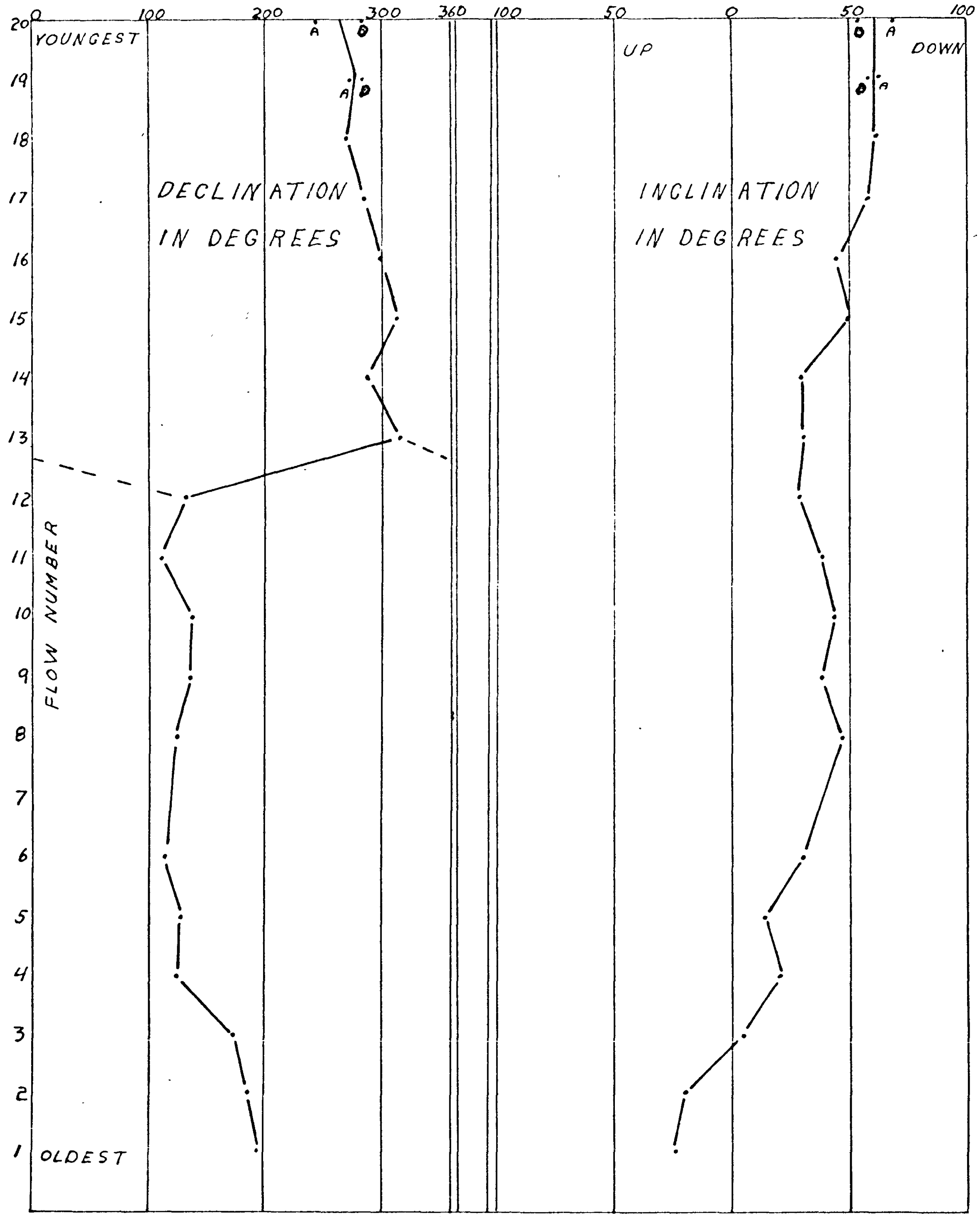
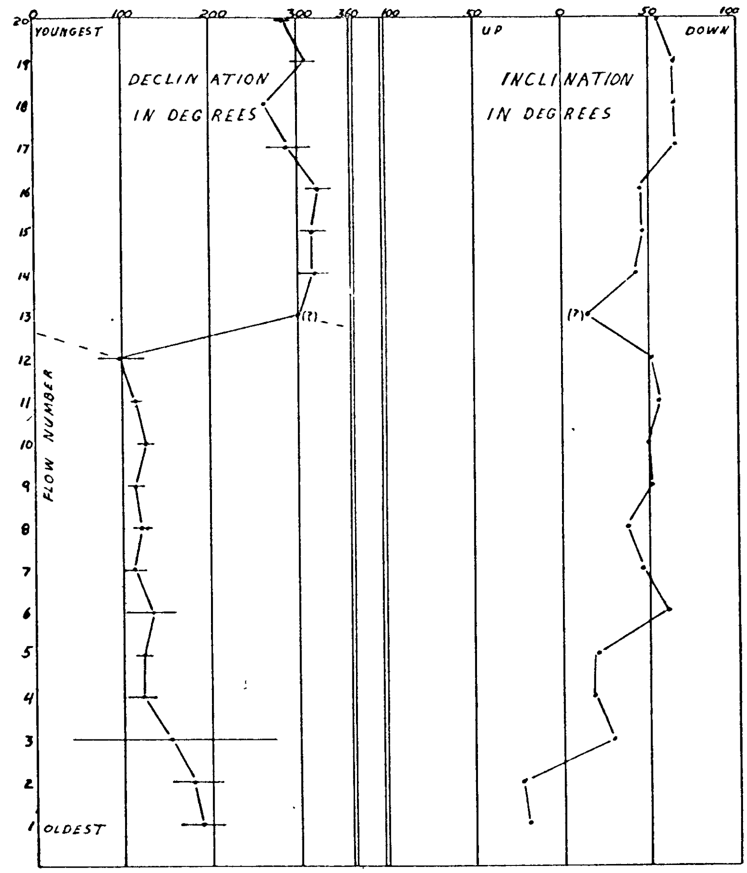


Figure 4-2

Steens Mountain - section one 200 oe. A.C. demagnetization data

Figure 4-3

Steens Mountain - section one
original NRM data



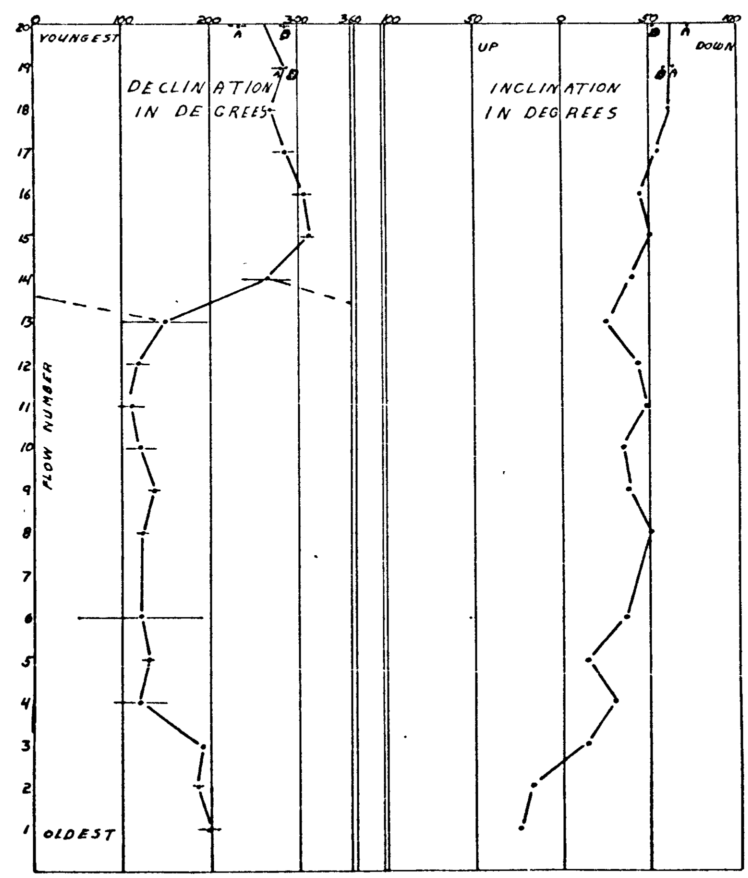


Figure 4-4
Steens Mountain - section one
total A.C. demagnetization data

about 180° to approximately 120°. This first step took about four flows to complete.

The second phase lasted for six or seven flows. This is shown by the apparent consistent or stable, but non-typical, direction of magnetization of east-southeast and down. Generally, paleomagnetic directions are either north or south, rarely are they found in any other direction. It is surprising to find six or seven non-typical directions in a row. As discussed earlier, mechanisms for self-reversals have been demonstrated but no reasonable explanation except the reversal of the field has been proposed to explain these odd directions.

The third phase lasted for four or five flows and is shown by a large change in declination and a minor change in inclination. There is some choice as to the path taken from flow 12 to flow 14. On the basis of this data, it is difficult to tell whether the declination moved in a clockwise or counter-clockwise sense from 100° to 320°. The motion in the first phase suggests counter-clockwise movement and so do the results from Poker Jim Ridge.

Considering the large alpha 95 in the original NRM data, it is immediately noticed that the values for flows 3 and 13 are exceedingly large, 119° and 128° respectively.

For flow 3 the original data consists of three points, two of which are very flat lying. The initial intensities are in the expected range and the A.C. demagnetization curve is similar to the typical TRM demagnetization curve (see Figures A-9 and A-10). Hence, this large separation of data points could be the result of a rapidly changing field or rebaking. As stated in the discussion of the sampling procedure, lateral and vertical separation was maintained between samples within each flow. This flow marks the first big change in directions. From petrological studies, this flow contains some unaltered magnetite and, therefore, it may be that the large deviations are due to unstable components. See the section on petrology for a detailed discussion of these results.

For flow 13, three widely separated points make up the original data. The intensity is slightly higher than would be expected and the A.C. demagnetization curve shows a rapid decrease in intensity with increasing field. Therefore, it is a possibility that this large dispersion is due to a lightning strike, or possibly a very unstable sample for some reason. From the petrological examination, unaltered magnetite was found.

The value of alpha 95 as explained in Chapter III can be considered as a measure of the precision of the data. Although there are many values of alpha 95 around 20^{o} and larger, the general pattern of declination and inclination should persist.

The data taken after A.C. demagnetization at 200 oe. shows the same general pattern as the original data. The changes may take place at slightly different places, but the changes seem to be smoother. The first change in inclination seems to be a more gradual continual change spanning possibly five flows. In the original data, the change is not very smooth and covers four flows. After 200 oe. demagnetization, the rapid change in declination now seems to occur between flows 12 and 13, whereas the original data placed the switch between 13 and 14. Thus, the demagnetization data suggests that the first phase lasted five flows, the middle phase five flows, and the last phase four flows. This data is probably more representative of the actual reversal.

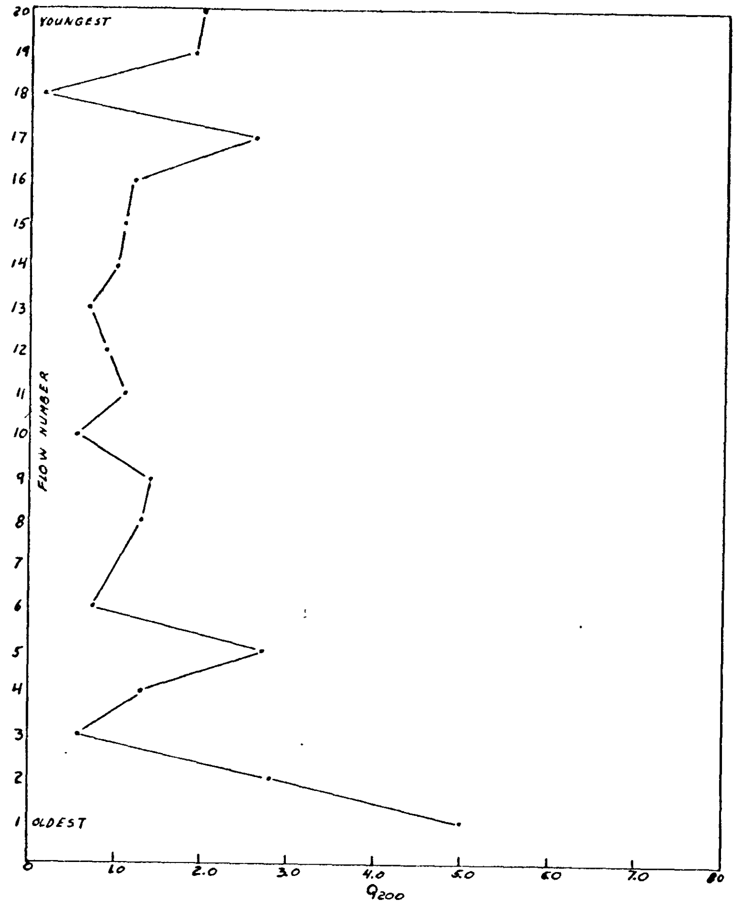
By knowing the susceptibility of a sample and its intensity, it is possible to calculate the Q_n of the sample. Q_n was first defined by Königsberger (1938) as $Q_n = J_n/KH_o$, where Q_n is usually greater than 1 for volcanics. J_n is the intensity of the remanent magnetization, K is the susceptibility and H_o is the normalizing field strength. This is an attempt at normalizing the intensity measurement and to give some idea of the magnitude of the magnetizing field. Too many variables such as the history and chemistry of the sample are involved for Q_n to be a true measure of the ancient field. But, as stated, it may give some hint to the field variations.

Taking the intensity after demagnetization at 200 oersted and using H_o equal to 0.6 oersted, Q_{200} was calculated and plotted against flow number (see Figure 4-5). For the Steens Mountain - section one graph, the center portion seems to have a smaller average value of Q_{200} than the ends. The values for flows 5 and 18 are highly anomalous. The demagnetization curves for both samples indicate that they are stable and probably represent TRM. Also, the susceptibilities for both are within the expected range. Although these two values are anomalous, they certainly appear to be valid data points. The fact that the center portion of this curve is depressed may suggest that the earth's field was reduced during the transition. Other workers have suggested this phenomena, but the data is not overwhelmingly convincing, Van Zijl,

Figure 4-5

Steens Mountain - section one

Q_{200} at 200 oe. A.C. demagnetization; Ho = 0.60 oe.



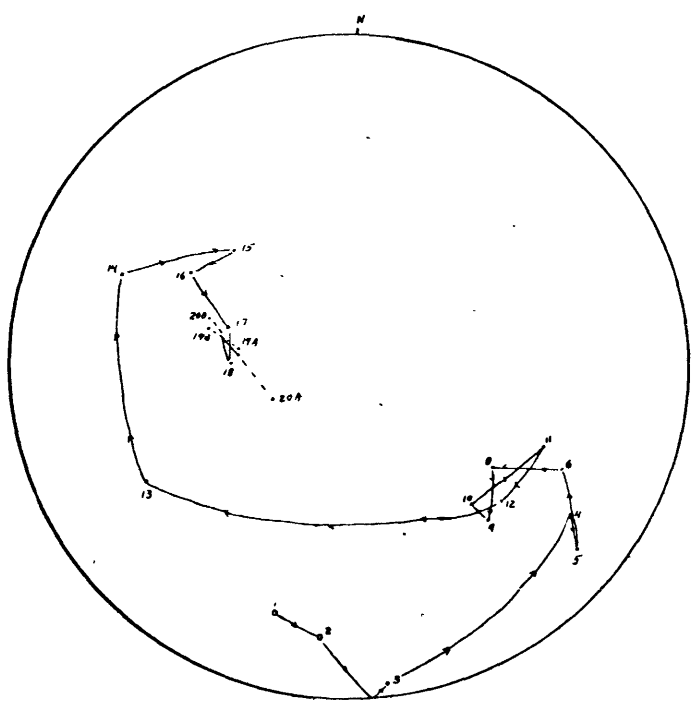


Figure 4-6

Steens Mountain - section one

Virtual dipole path at 200 oe. • down o up et al., 1962b and Momose 1963. See Appendix B for any supplementary data concerning Steens Mountain - section one.

All flows except 1, 2, 8, 9 and 20 contain large plagioclase crystals. Larson (1965) describes this texture and stated that the texture was evidence for pre-cooling of the melt before eruption. Hence, this indicates a time lag in the succession of flows. Thus, it is very difficult to describe the periodicity of the flows or the time sequence involved in the change of polarity. Very accurate dating procedures would be necessary to give this type of information.

Steens Mountain - Section Two

The results for Steens Mountain - section two are very similar to those for section one (see Figures 4-7, 4-8 and 4-9). The same three phases of the transition are present. By comparing the results at 200 oe. from sections one and two, it appears as though flow 2 of section one and flow 3 of section two correspond and flow 12 of section one corresponds with flow 11 of section two. This makes it likely that flow 13 of section one corresponds to flow 12 of section two. Similar to flow 13, flow 12 shows a poor grouping of original TRM's, a poor A.C.

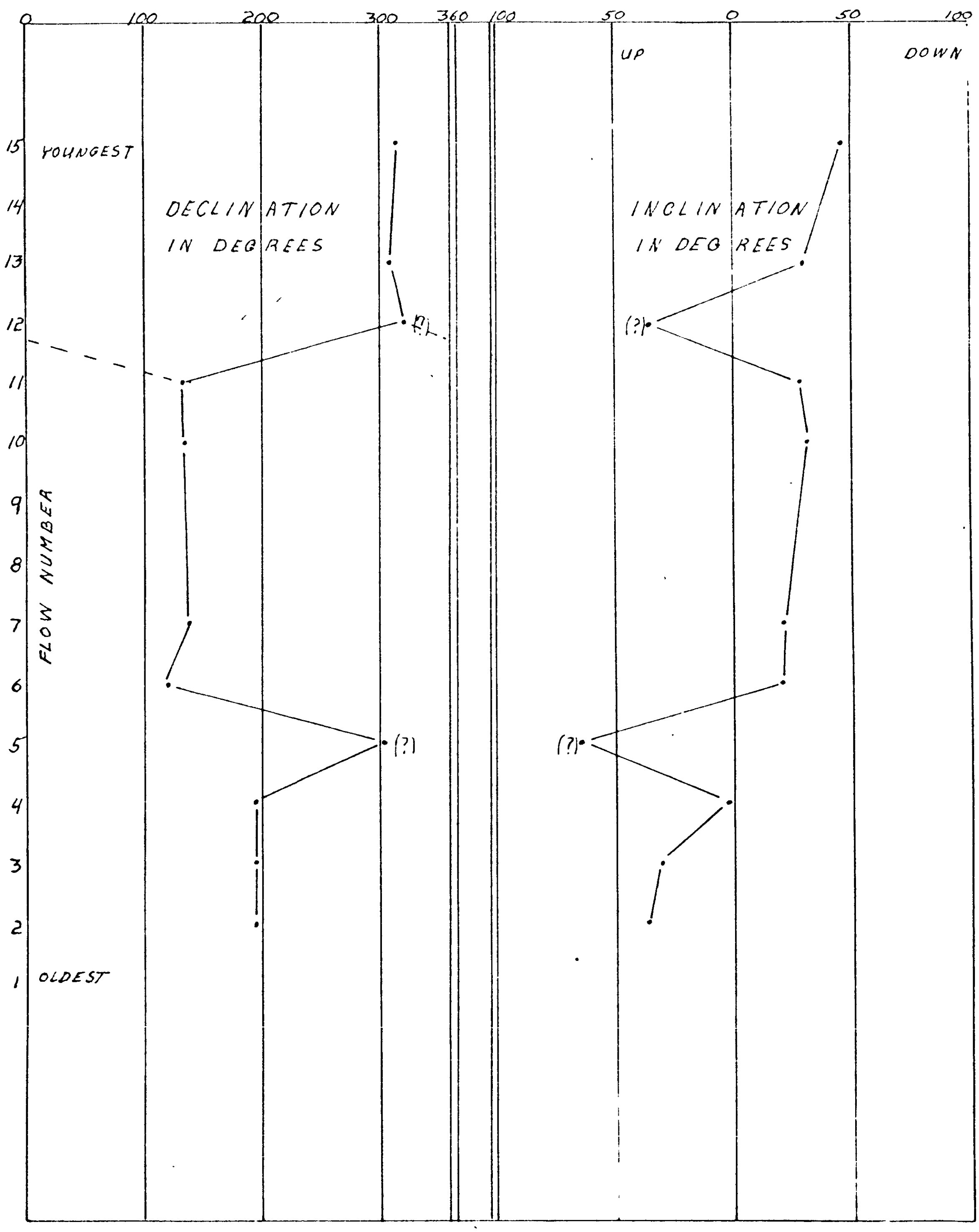


Figure 4-7

Steens Mountain - Section Two

200 oe. A.C. Demagnetization data

Steens Mountain - section two
original NRM data

Figure 4-8

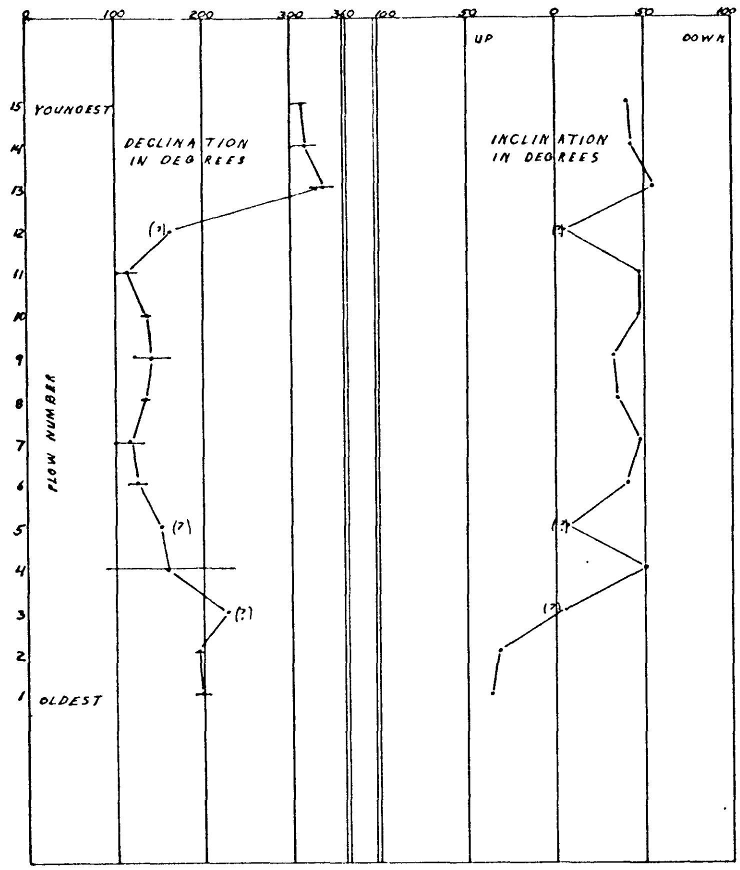
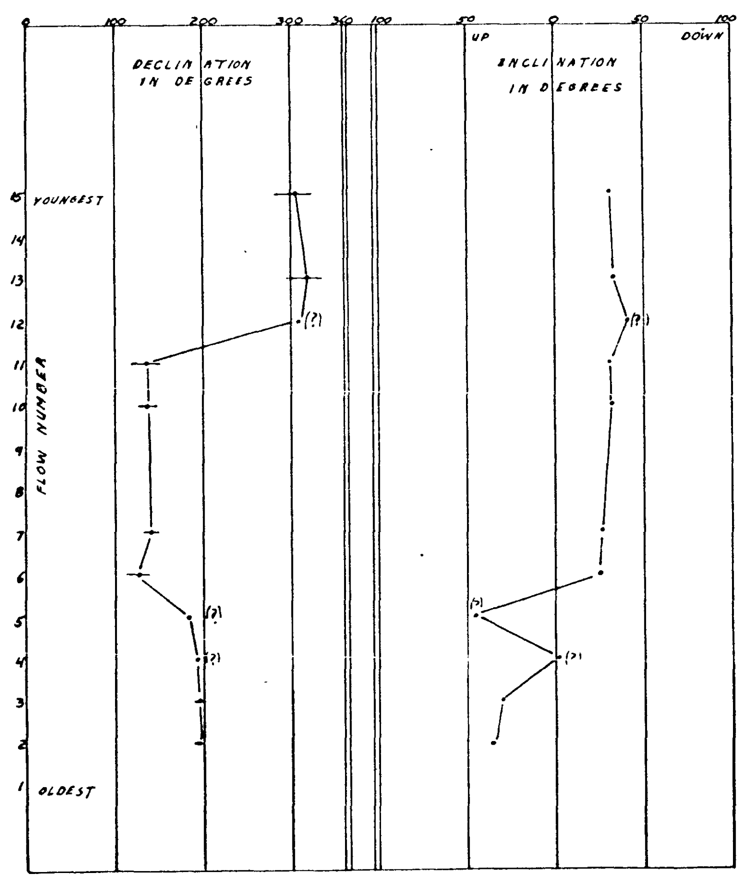


Figure 4-9



Steens Mountain - section two
total A.C. demagnetization data

demagnetization spectrum and a rapid decrease in intensity with increasing A.C. field. Similar to flow 13, flow 12 marks one of the rapid changes in direction. Because these two sampling sites are 1000' apart, it is believed that the instability displayed is not lightning strikes as suggested above, rather it is either a property of that particular flow or the magnetic field at that time. As pointed out by Larson (1965) the flows in the Steens Mountain basalt are very discontinuous laterally. This is shown in these data by the different number of flows in the transition zone even though the two sections are only 1000' apart.

As found in section one, the directional change during the first break seems to have occurred in a counter-clockwise sense. The change could have occurred in either direction for the last break.

Q_n was again calculated using the intensity value after 200 oe. demagnetization (Figure 4-10). The plot of these data suggests a decrease in Q_n during the transitional stage and higher values during the times of normal and reversed polarity. As stated earlier, Q_n is not a direct reflection of the field, but this does suggest that the field may have been reduced during the transition.

Steens Mountain - section two
Q_{200} at 200 oe. A.C. demagnetization
H_o = 0.60 oe.

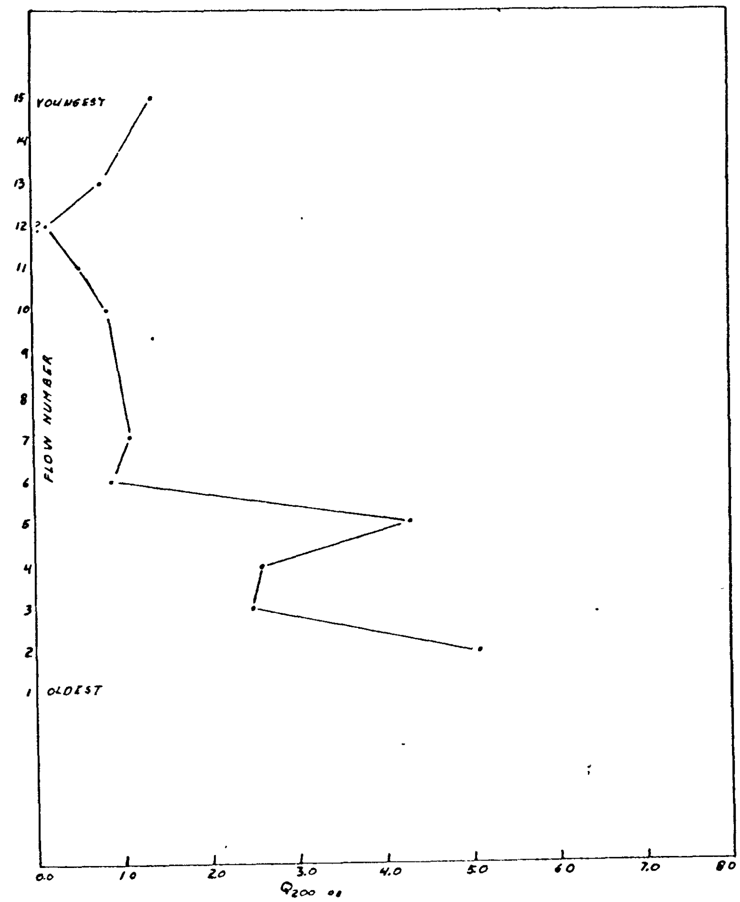


Figure 4-10

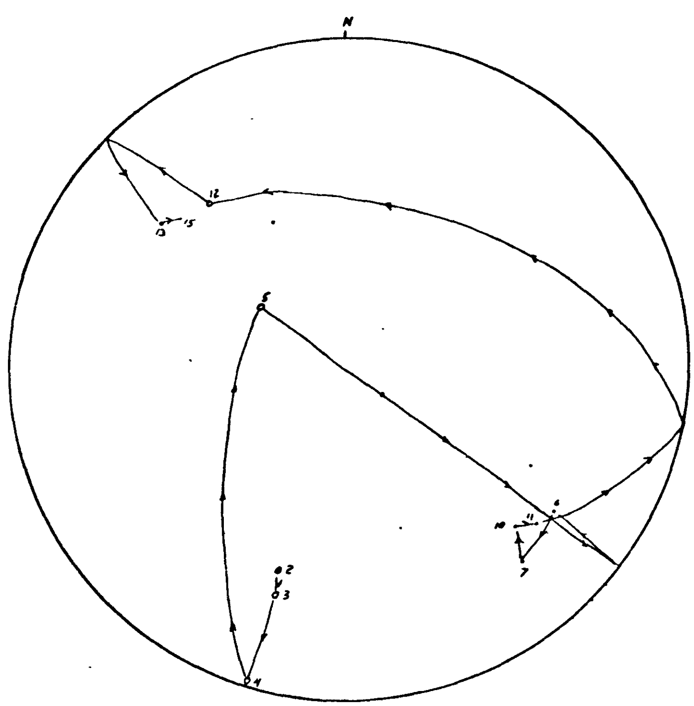


Figure 4-11

Steens Mountain - section two
Virtual dipole path at 200 oe. A.C.
demagnetization • down o up

As discussed for section one, many of the flows have large plagioclase crystals, and, hence, the time sequence involved is difficult to describe.

Poker Jim Ridge

The data from Poker Jim Ridge shows the most scatter of any of the sections. Many of the samples were difficult to demagnetize in that a good grouping of directions never resulted. The three phases of the reversal are not as distinct as on Steens Mountain, but the same general trend is apparent (see Figures 4-12, 4-13 and 4-14).

The very bottom of this section starts at a steeper angle of inclination and further to the west than the other two. This is because more samples were taken in the reversed section. The angles of inclination and declination just before the start of the reversal are approximately the same as those found at Steens Mountain. Taking the same break as before for the start of the transition, it appears that the transition starts at flow 5; this is where the big change in inclination starts. The middle portion of the Poker Jim Ridge section does not show the consistent non-typical directions as well as Steens Mountain did. Many of the samples from this zone did not show tight groupings

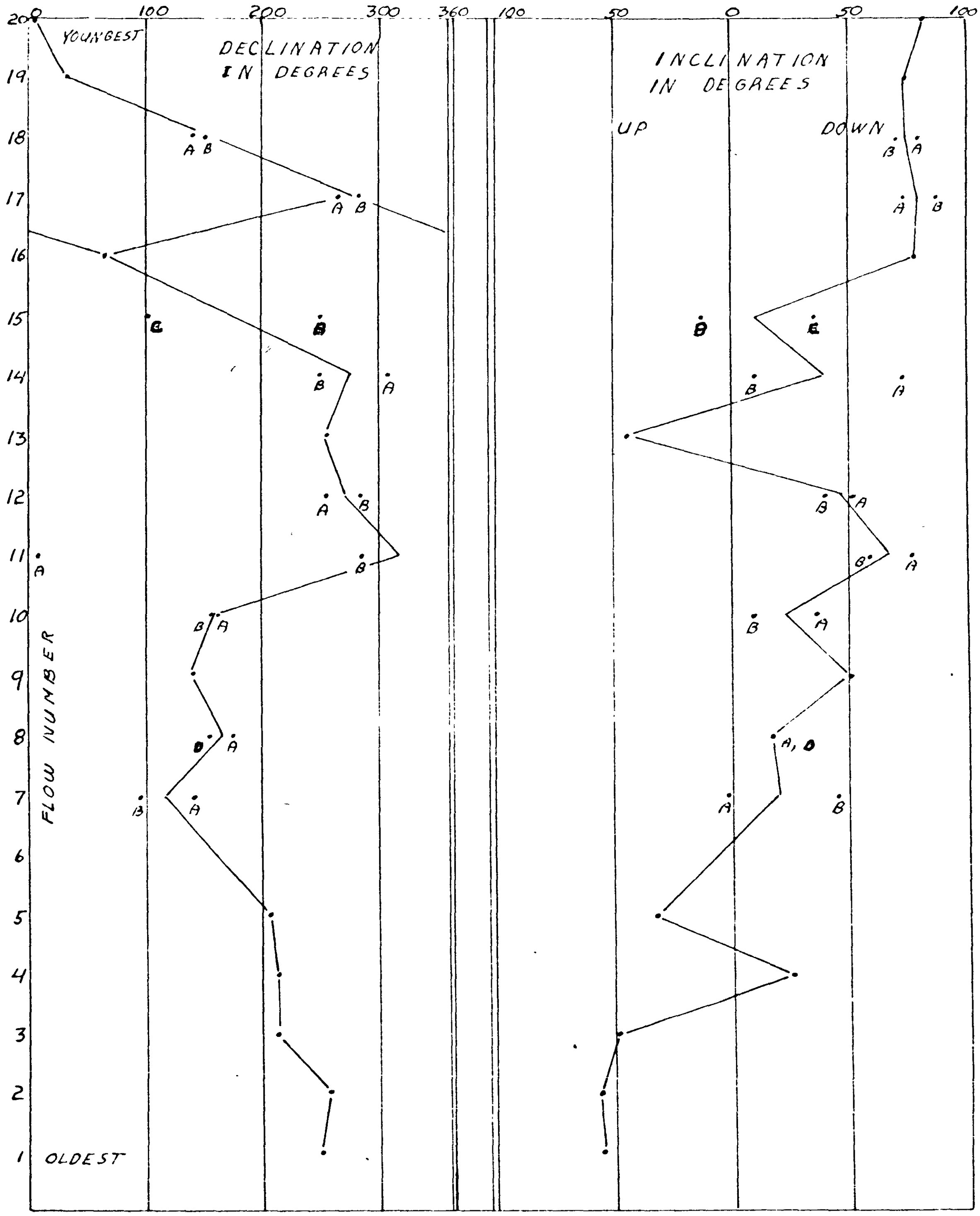


Figure 4-12

Poker Jim Ridge 200 oe. A.C. demagnetization data

Poker Jim Ridge original NRM data

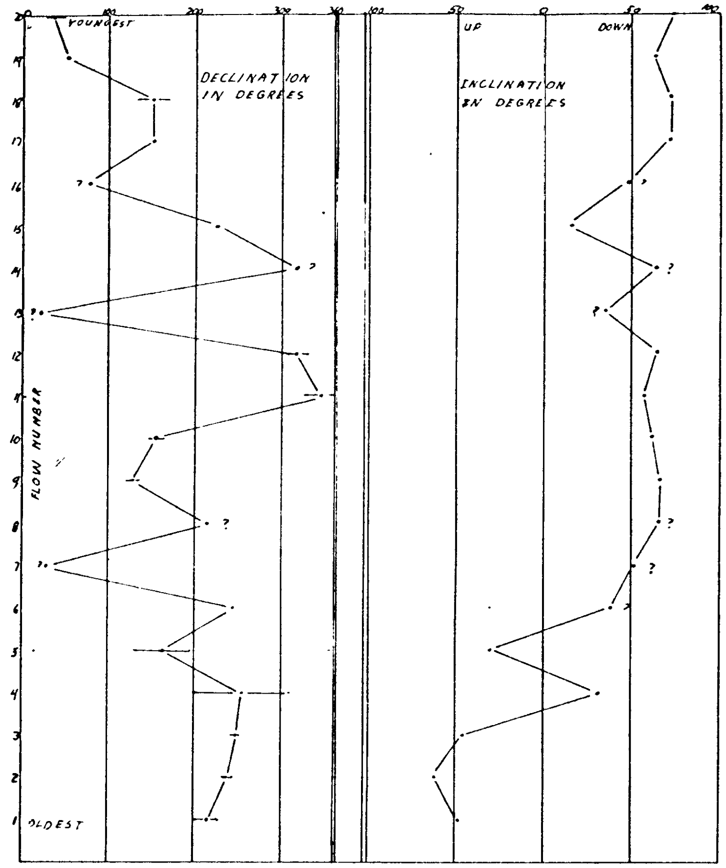


Figure 4-13

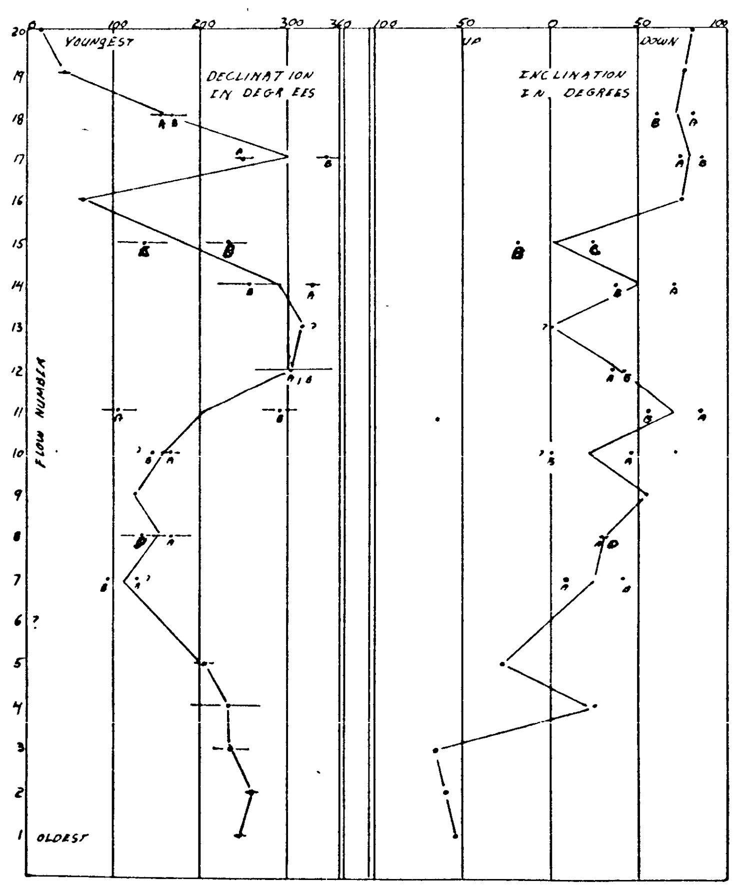


Figure 4-14

Poker Jim Ridge total A.C. demagnetization data upon A.C. demagnetization, hence, large discrepancies from the true direction could be present. However, this middle portion is still recognizable and corresponds to the second phase found at Steens Mountain. The maximum extent of the transition would be to flow 19. The data indicating the rapid change in declination from flow 14 to 19 seems to suggest a counter-clockwise motion for the change. This fits in with the other changes in direction as discussed for Steens Mountain sections one and two.

Q_n at 200 oersted was again plotted against flow number (see Figure 4-15). There seem to be many rapid changes, typical of the apparent instability of these data, but the ends still seem to be somewhat higher than the middle.

The section at Poker Jim Ridge contains a number of flows which have large phenocrysts of plagioclase. These are flows 8, 9, 10, 11, 12, 13 and 14. Therefore, once again, the time sequence involved in the transition is not revealed by these flows.

As defined earlier, Q_n is proportional to the intensity and inversely porportional to the susceptibility, and may be some measure of the magnetizing field. The susceptibility is a quantitative factor which reflects the amount and type of magnetic material present. The intensity, if all the

Poker Jim Ridge Q_{200} at 200 oe. A.C. demagnetization

H_o = 0.6 oe.

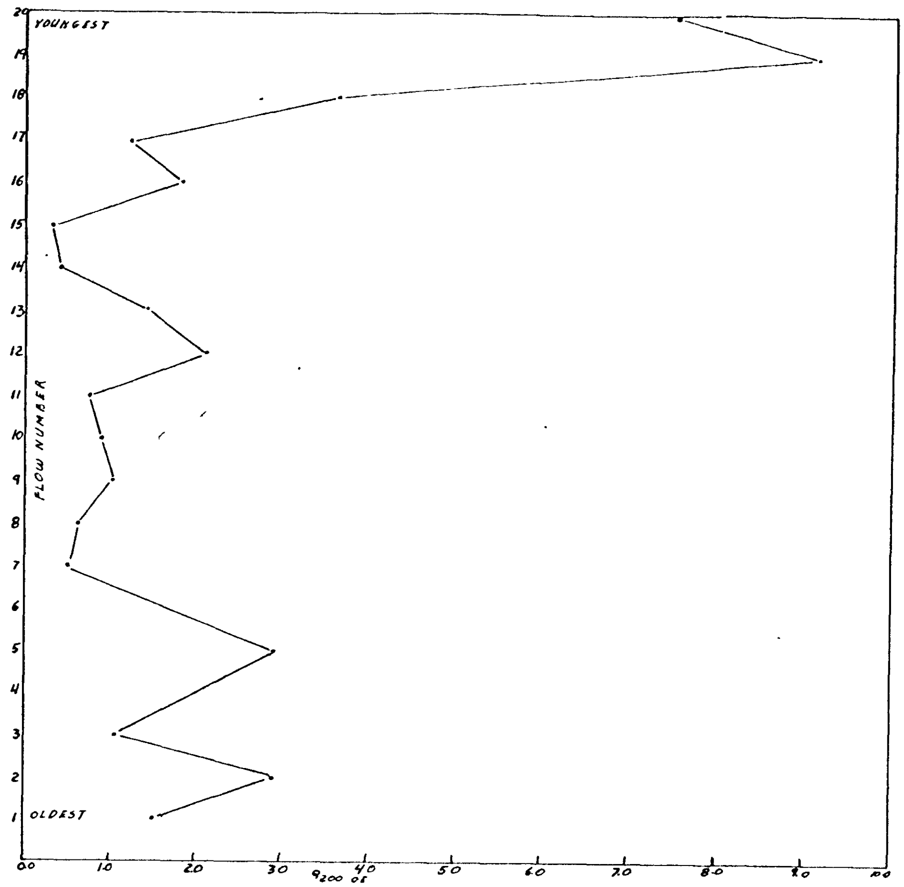


Figure 4-15

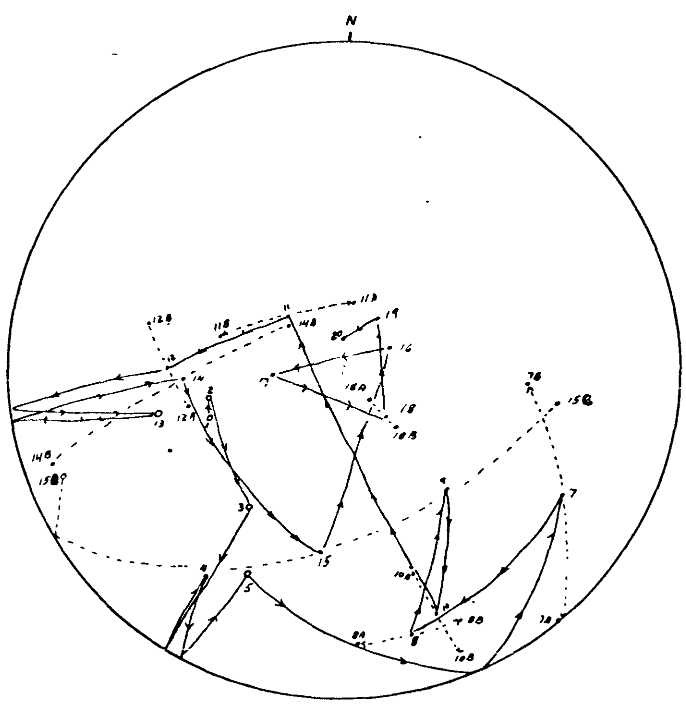


Figure 4-16

Poker Jim Ridge virtual dipole path 200 oe.
A.C. demagnetization • down o up

remanence is due to cooling in the presence of an external field, should be a refelction of the type and amount of magnetic material plus the external field. There are too many variables involved for Q_n to be a direct measure of the magnetizing field, but the results from this work are interesting.

The intensity of magnetization after A.C. demagnetization at 200 oersteds has been plotted versus flow number. Hopefully, this intensity is a measure of the TRM. Also, the susceptibility of each flow has been plotted. The results from Steens Mountain - section one are the most interesting (see Appendix B for this data). The intensity seems to decrease during the transitional period and is generally higher during the time of normal and reversed polarity. The susceptibility graph has many spikes and appears to be independent of the transition zone. Therefore, why does the Q_n at 200 oe. show a good correlation with the transition zone? Maybe in this case Q_n 200 is displaying a decrease in the field during a transition. The patterns are not as distinct in the Poker Jim Ridge and Steens Mountain - section two data.

To get an acceptable answer to this intensity problem, extensive work should be done using Thellier and Thellier's method or modifications of it. Then and only then will good evidence be available to describe the changes in the magnitude of the field during a transition.

Q_{200} Results

It was noticed, while performing the A.C. demagnetization spectrums, that the magnetic directions seen to group together better for the normal and reversed polarity samples than for the transitional ones. The alpha 95 values have been plotted as bars on the declination graphs, and it is seen that, in general, the largest alpha 95 values are in the transition zone. As already discussed, the largest values correspond to the most drastic directional changes. These large values are possibly due to either very unstable samples in which it is easy to add or remove viscous components or a result of rapidly changing field.

To show the relationship between the consistency of a sample's directions and its "hard" magnetization it was decided to plot a scatter diagram of Q_{200} at 200 oe. versus alpha 95. The criteria for a stable sample, as used here, would be one for which a consistent magnetic direction was reached upon A.C. demagnetization and, also, one whose intensity did not rapidly decrease with increasing A.C. field. Using these criteria, Q_{200} represents the intensity and alpha 95 represents the direction. Figure 4-17 shows

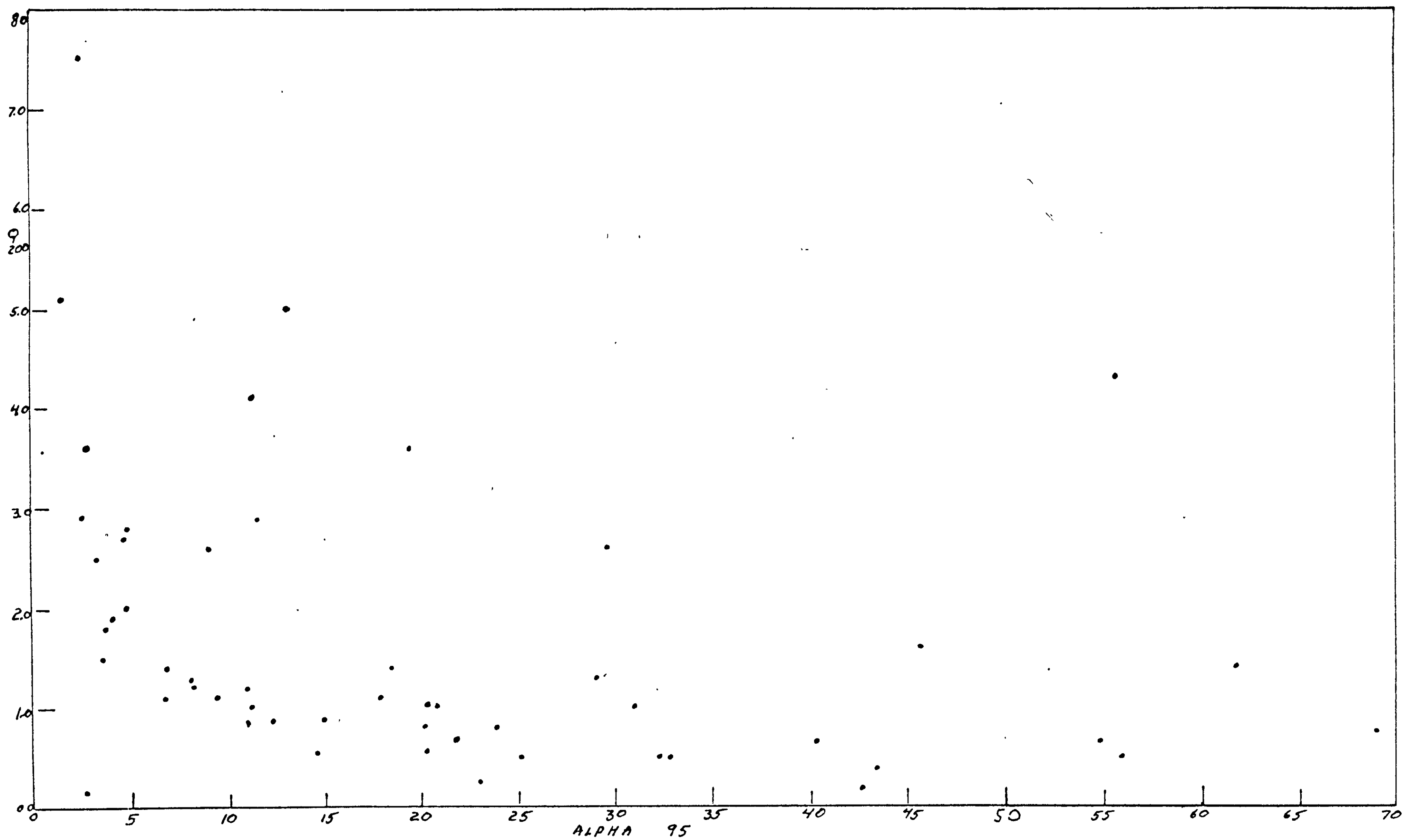


Figure 4-17

Q_{200} at 200 oe. A.C. demagnetization versus alpha 95 of the total A.C. demagnetization spectra that for decreasing alpha 95, or better increasing precision, the Q_n 200 increases. This is a predictable result based on the characteristics of thermoremanent magnetization.

Comparison of Results

For a review of the results of the previous work by Watkins (1967) on Steens Mountain - section one, see Figures 1-5 and 1-6. By comparing Watkins' data after 200 oe. A.C. demagnetization to the present data; it is obvious that the same patterns are present. However, there are some minor discrepancies. The samples were taken essentially side by side, yet there appears to be two more flows in the middle zone of the present data. Care was taken in the collection of the cores to insure that each flow was sampled. Because the flows pinch-out laterally, at times it was necessary to move horizontally slightly to fill in the complete time scale.

Watkins' data shows a more gradual change in declination from flow 50 to 47 (Watkins' flow numbers) and the data suggests a clockwise motion. In the present data, this switch occurs over one flow and it is difficult to determine the direction of rotation. The initial break, shown by the rapid change in inclination, is about the same in both sets of data.

Probably the most pertinent point of both independent sets of data is that the three phases of the reversal are present in both. That is, two totally different sets of measuring apparatus, coupled in with the human factor, give approximately the same results for a transition zone. This gives great strength to the validity of the data.

Petrology

As a basic part of this invesigation, 27 polished sections were made. Six of the samples were randomly picked from Poker Jim Ridge and the remaining were taken from Steens Mountain - section one. On Steens Mountain at least one sample from every flow was selected, usually a sample that had been A.C. demagnetized. These polished sections were studied under a reflecting microscope at 2000 magnification. Also, photographs at 1000 magnification displaying the typical mineralogy were taken of the Steens Mountain samples. The summary of these results are shown in Tables I and II and Figures 4-18, 4-19, 4-20, 4-21 and 4-22.

It is seen that the samples which show a predominance of high temperature oxidation are generally stable. That is, upon A.C. demagnetization, a tight grouping of

Table I

Description of Polished Sections

Sample	Description	Prediction	A.C. Demagneti-ization results
S.M. 1	Mostly hematite-pseudobrookite silicates are very red; highly oxidized	stable	general grouping of directions
S.M. 2	Hematite-pseudobrookite magnetite-hematite silicates very red; highly oxidized	stable	tight grouping
S.M. 3 Figure A-9	Some magnetite-ilmenite in which ilmenite has gone to pseudo-brookite. Some magnetite-hematite and some relatively un-oxidized magnetite. Silicates are generally red.	some unstable components	some scatter in points, no tight grouping developing
S.M. 4	Highly oxidized magnetite-ilmenite with ilmenite to pseudobrookite. Some inclusions of hematite. Silicates red.	stable	all points group together except at 600 oe.
S.M. 5	Highly oxidized magnetite-ilmenite which has gone to pseudobrookite. Some hematite, silicates red.	stable	tight grouping

Table I - continued

Sample	Description	Prediction	Results
S.M. 6	Some magnetite-ilmenite where ilmenite has gone to pseudo-brookite, some hematite, some relatively unaltered magnetite, silicates red.	some unstable components	no tight grouping developed
S.M. 7	Lots of unaltered magnetite, a little hematite, some red silicates	unstable	not demagnetized
S.M. 8	Magnetite-ilmenite which has gone to pseudobrookite. In places, lots of hematite, silicates very red, highly oxidized, rutile present, dendritic texture	stable	tight grouping
S.M. 9	Magnetite-ilmenite with some hematite. Ilmenite has gone to pseudobrookite, some skeletal magnetite, silicates very red.	stable	tight grouping
S.M. 10	Hematite-ilmenite, magnetite-ilmenite to pseudobrookite, silicates red, some magnetite and ilmenite grains with no lamella developed. A few magnetite grains.	minor unstable component	a loose grouping with 600 oersted far out

Table I - continued

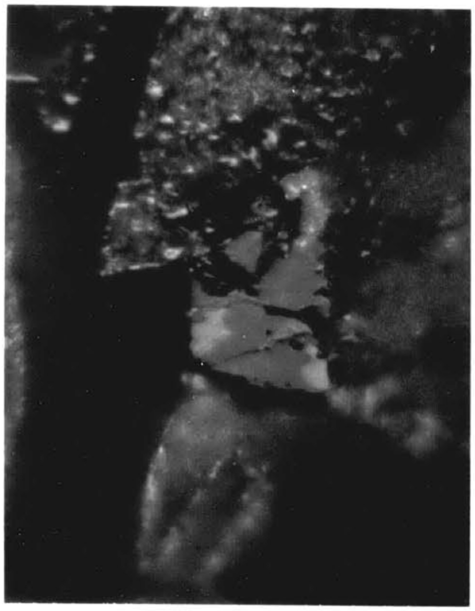
Sample	Description	Prediction	Results
S.M. 11 Figure A-4	Magnetite-ilmenite to pseudo-brookite and hematite silicates highly oxidized.	stable	grouping with 600 oe. far out
S.M. 12	Magnetite-hematite, hematite and ilmenite, poor lamella development, unaltered magnetite, silicates red.	unstable component	very loose grouping
S.M. 13 Figure A-9	Magnetite-ilmenite, some hematite poor lamella development, unaltered magnetite.	unstable components	no positive grouping possibly lightning effects present
S.M. 14 Figure A-8	Mostly magnetite-ilmenite with poor lamella development, some hematite, some magnetite, silicates red.	unstable components	no grouping developed
S.M. 15	Magnetite-ilmenite with some hematite. In some cases ilmenite lamella very difficult to see, silicates red.	stable	tight grouping except at 400 oe.
S.M. 16 Figure A-7	Magnetite-ilmenite with some hematite. The lamella structure not clear; lots of unaltered magnetite.	unstable component	loose grouping

Table I - continued

S.M. 17	Pseudobrookite-hematite magnetite-ilmenite, skeletal magnetite, highly oxidized.	stable	tight grouping except 600 oe.
S.M. 18	Pseudobrookite-hematite skeletal magnetite, highly oxidized.	stable	tight grouping
S.M. 19a Figures A-1; A-6	Magnetite-ilmenite with hematite. Spinel rods still visible in magnetite, silicates very red, some hematite-pseudobrookite	stable	tight grouping except at 400 oe.
S.M. 20a Figures A-1; A-2; A-6	Pseudobrookite hematite, silicates oxidized, some rutile, highly oxidized	stable	tight grouping
Poker Jim 7a Figure A-8	Large unaltered magnetite grains very few ilmenite lamella; minor amounts of small hematite and magnetite grains	large unstable component	no grouping of directions unstable
Poker Jim 8b Figures A-2; A-3; A-5; A-7	Generally large mostly unaltered magnetite grains, minor amounts of hematite and ilmenite	large unstable component	tendency for 50, 100, and 200 to group. The intensity decreases more rapidly than normal

Table I - continued

Sample	Description	Prediction	Results
Poker Jim 11a	Large magnetite grains showing lamella of hematite and ilmenite sample has a "pitted" surface due to oxidation	large stable component	0, 50, 100, 200 show a tight grouping
Poker Jim 14-1	Some magnetite grains show oxidation, some grains just a little oxidation, olivine is oxidized to Iddingsite	should have a moderate un-stable component	not demagnetized
Poker Jim 14b Figure A-5	Most magnetite grains show oxidation, some, however, do not, some pseudobrookite is present	should have moderate un-stable component	seems to have spread in the data not too good of a prediction transition zone
Poker Jim 19	Mostly oxidized magnetite, ilmenite and hematite	stable component	good prediction



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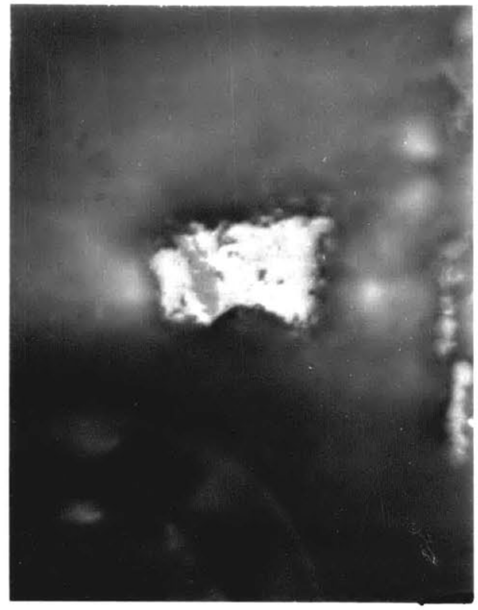

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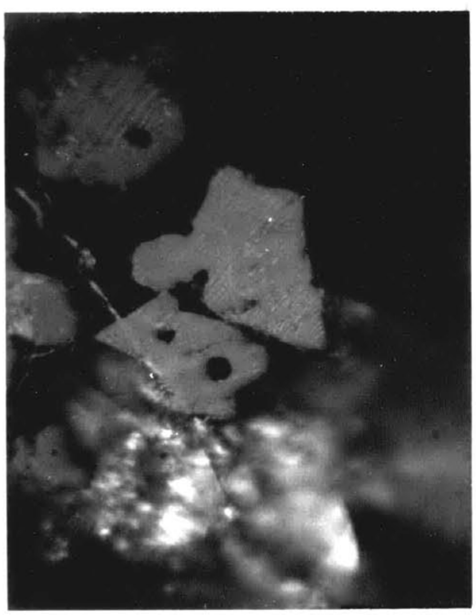

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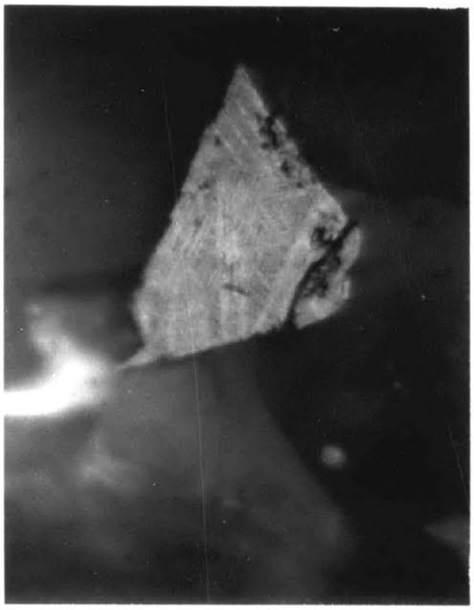
Figure 4-18



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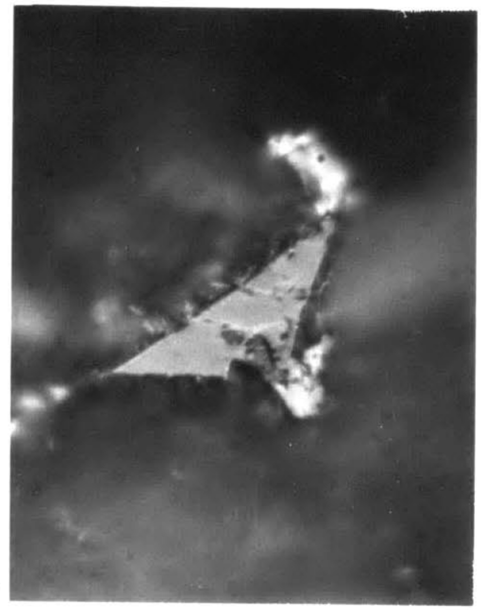

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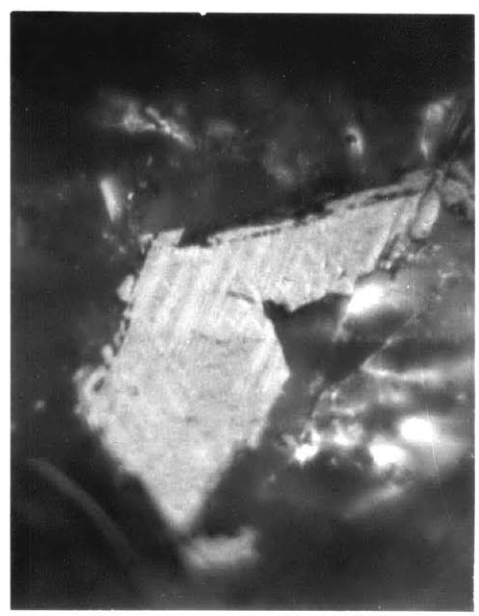

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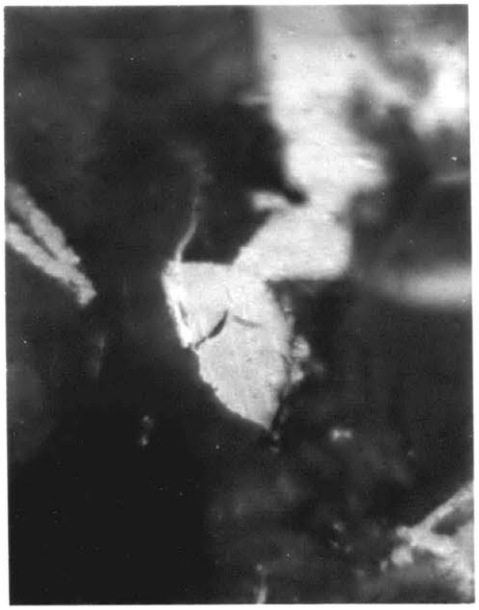
Figure 4-19



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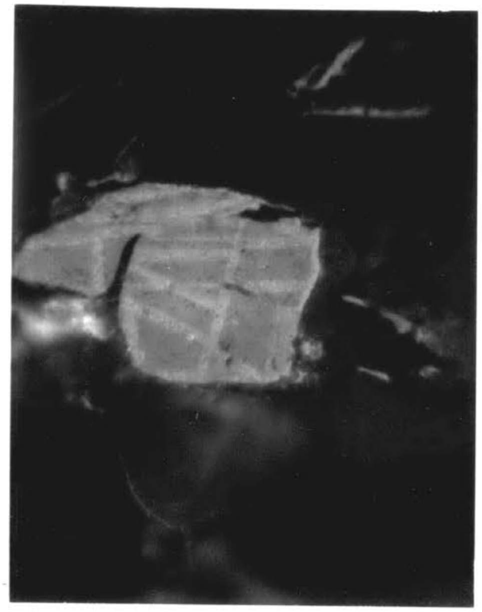

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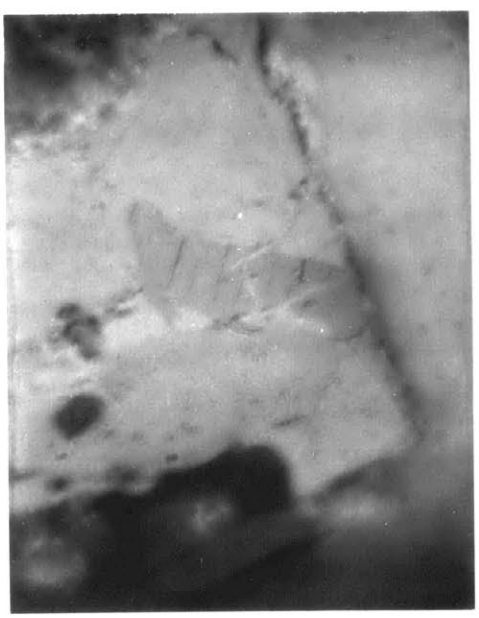

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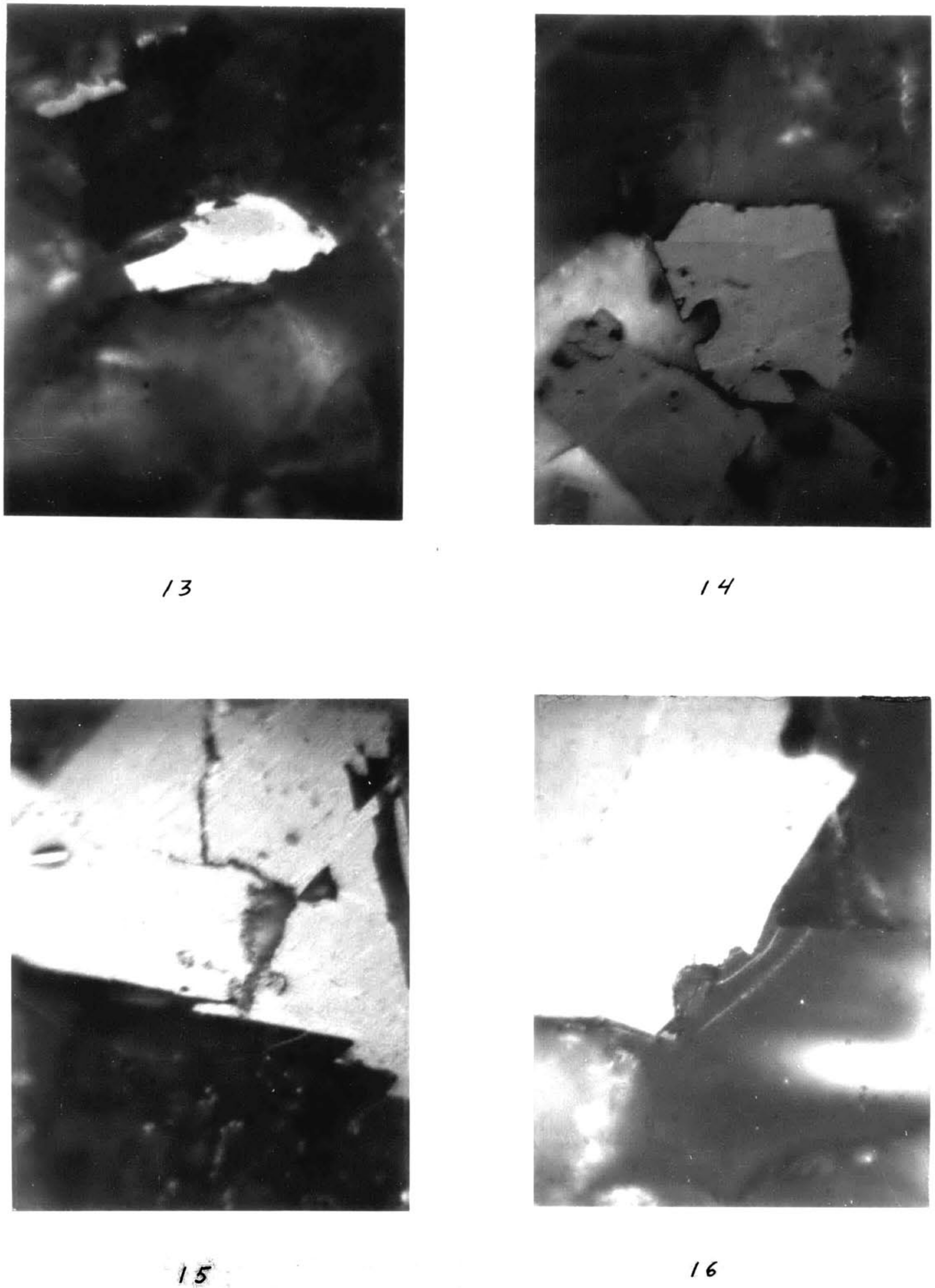
Figure 4-20



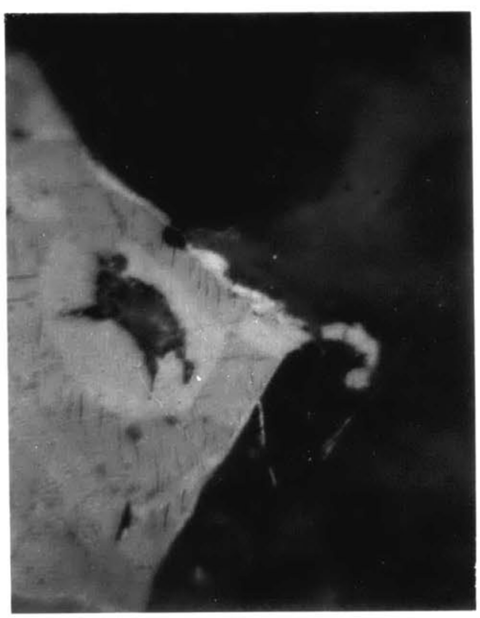
13 14

15 16

Figure 4-21

17

18



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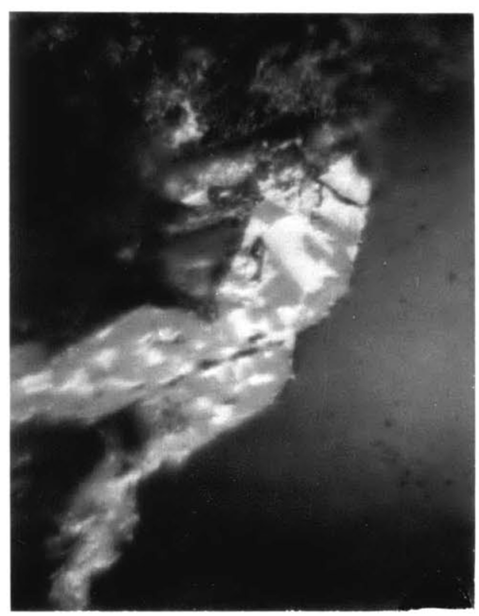

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Figure 4-22

Table II

Description of Photographs

1	Hematite - pseudobrookite (dark)
2	Hematite - pseudobrookite (dark)
3	Magnetite - ilmenite to pseudobrookite white spots are hematite
4	Highly developed magnetite - ilmenite where ilmenite has gone to pseudobrookite Some hematite is present
5	Magnetite - ilmenite where ilmenite has gone to pseudobrookite Magnetite is dark patches, pseudobrookite is light
6	Pseudobrookite dark and hematite white This sample has lots of relatively unaltered magnetite
7	Magnetite - ilmenite; dark spot is ilmenite, light streaks are hematite
8	Magnetite - ilmenite; ilmenite to pseudobrookite
9	Magnetite - ilmenite; ilmenite to pseudobrookite White edge is hematite
10	Magnetite - ilmenite in which ilmenite has gone to pseudobrookite Some spinel rods still visible in magnetite
11	Magnetite with spinel rods, dark center White streaks are hematite Gray background is pseudobrookite
12	Magnetite - ilmenite Lamella is present White streaks are hematite

Table II - continued

13	Magnetite - ilmenite Poor lamella development White band is hematite
14	Magnetite - ilmenite, the lighter portion in the center White streak is hematite No lamella development
15	Magnetite - ilmenite with some hematite Lamella is better developed than in 16
16	Magneite - ilmenite Very stable lamella structures Some hematite
17	Skeletal magnetite oxidized to dark gray Pseudobrookite and hematite are white lines which formed on the ilmenite lines (111) Dark background center is oxidized silicates High state of oxidation
18	Skeletal magnetite interbedded in highly oxidized silicates The dark areas are pseudobrookite and the bright white is hematite A very high state of oxidation
19A	Magnetite - ilmenite Magnetite is darker zone with black lines (spinel rods) In center is light area showing wiggly white lines which is hematite
20A	Dark gray blobs are pseudobrookite, white spots are hematite The dark fuzzy area in left center is oxidized silicates

directions develops and the intensities slowly decrease with increasing field. However, other ideas concerning the importance of oxidation have been proposed.

Wilson and Watkins (1967) were attempting to show a correlation between states of oxidation and the polarity of magnetization. They defined five classes or states of oxidation, class V being the most oxidized. These classes are based on the high temperature phenomena, not the low temperature or weathering effects.

Taking their data from Steens Mountain only and plotting it in a slightly different manner, it becomes apparent that a definite correlation between oxidation and polarity is not very obvious (see Figures 4-23, 4-24). Figure 4-23 shows the average petrological class, by their classification, for each flow plotted against the flow number. The average of the class numbers seems justified to use because of the minor mineralogical variations in each flow. The average should be more characteristic of the flow.

The different definitions of the reversal or transition are shown. The break in inclination from negative to positive dip was used by Wilson and Watkins. In an earlier paper, Watkins (1965b) defined this transition zone

Petrological class versus flow number for Steens Mountain

Wilson and Watkins, 1967

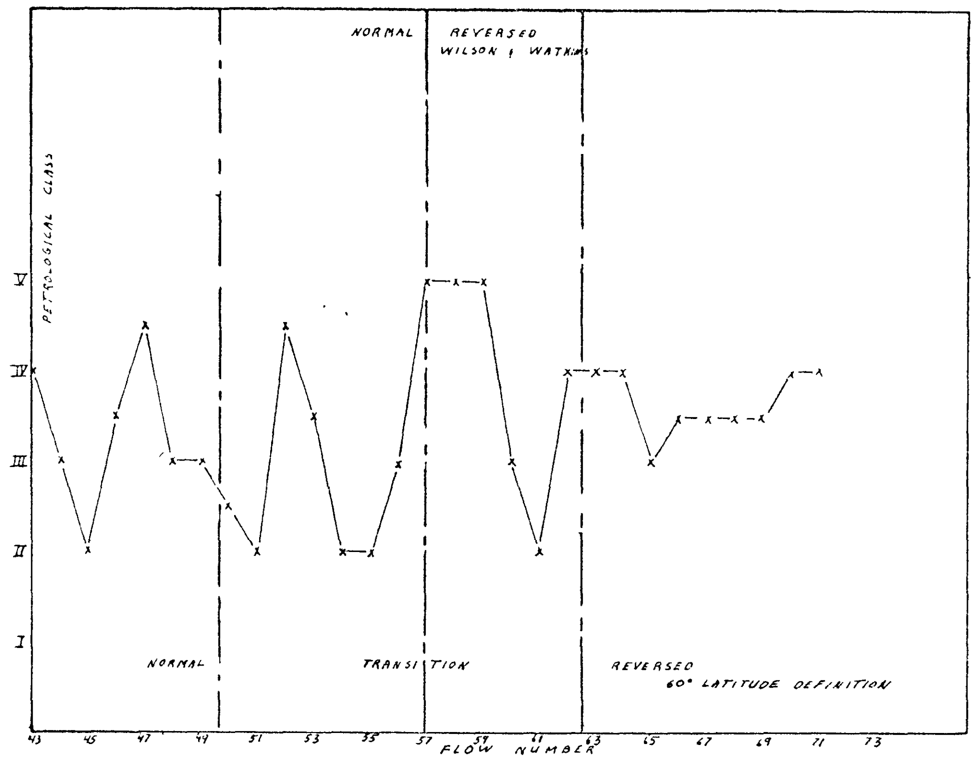


Figure 4-23

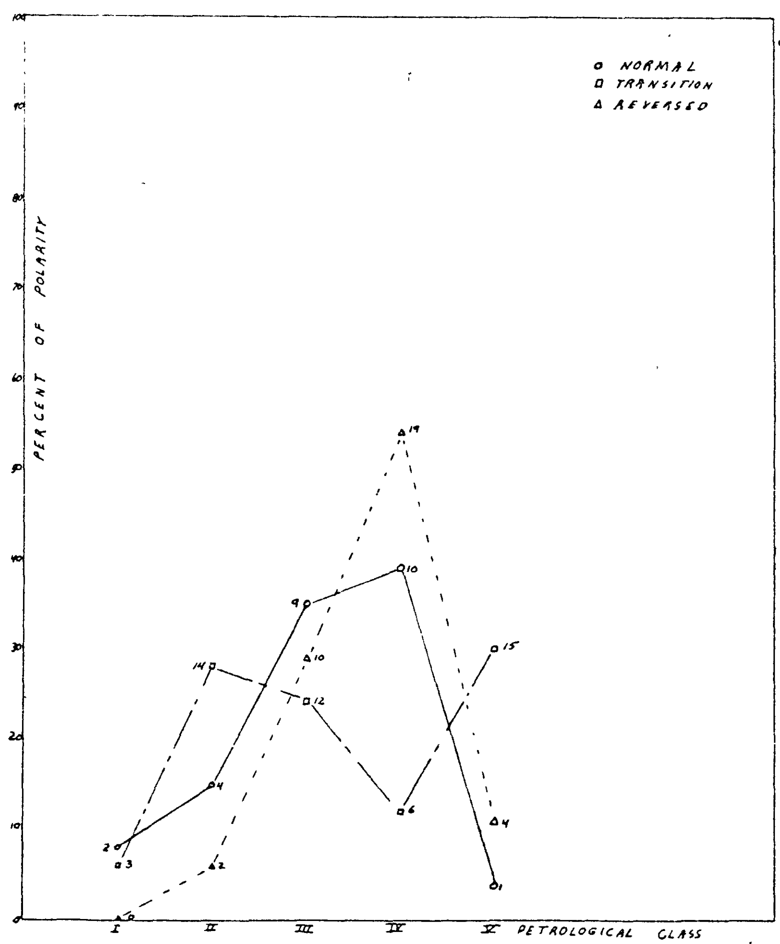


Figure 4-24

Percent of the total number of samples of one polarity versus petrologic class
Wilson and Watkins, 1967

as that phase of the reversal where the virtual magnetic dipoles fell between 60° north and south latitudes. Other workers have used similar definitions for the transition zone.

If there are any anomalies in the states of oxidation versus flow number, it occurs in the transition zone and is shown by three successive flows with class V oxidation states. It is not obvious, as opposed to Wilson and Watkins conclusions, that the reversed samples are of a higher oxidation state.

From this present study, particularly the Steens Mountain section, an obvious correlation between oxidation and polarity is non-existant. Highly oxidized samples are found in all three zones and relatively unaltered samples are found only in the normal and transitional phases. However, there are only two samples from the reversed section. Although only 27 samples were studied, it is felt that the more obvious correlation is between oxidation and stability not oxidation and polarity.

In another recent paper by Watkins (1967), he studied a transition zone in the Steens Basalt found in Guano Valley. This is approximately 70 miles southwest of Steens Mountain and about 55 miles southeast of Poker Jim

Ridge. He identified maghemite in some of the samples and showed that the presence of this mineral correlates with the transition zone. He concluded, that upon reheating, the maghemite could oxidize to hematite and form a very stable NRM. This would be a low temperature phenomena and the magnetization acquired would not represent the original field. By super-imposing two stable but nearly opposite magnetic components, the stable non-typical directions of the transition zone could result. Hence, he felt that the transition zone was a function of the mineralogy and not a true representation of a transition zone. Watkins also noted that some critical samples were very unstable; the samples that marked or identified critical parts of the transition.

This reversal went from reversed to normal polarity with an apparent intermediate position similar to that of the present study. This reversal is also in the Steens Basalt near the top of the section. This is demonstrated by the presence of a yellow tuff layer, probably the Plush Tuff as described by Larson (1965). Larson (1965) describes only one reversal in the Steens from reversed to normal and it is relatively close to the top of the section. Therefore, there is a good possibility that the reversal at

Guano Valley is the same reversal as found at Poker Jim Ridge and Steens Mountain.

In the present study, no maghemite was identified in any of the samples. But, some of the unstable samples did correspond to the critical parts of the transition, similar to Watkins. By combining the results from both of these studies, it is concluded that the same reversal was sampled in three widely separated places and that the reversal is independent of the mineralogy.

Chapter V - Conclusions and Recommendations

The results of this study are very interesting and contribute to the ever expanding knowledge of the history of the ancient magnetic field. Of principal significance is that the same general sequence of events, as the magnetic polarity switched from reversed to normal, was found in three separated places. These are Steens Mountain, Poker Jim Ridge and Guano Valley (Watkins, 1967).

Larson (1965) has shown that the Steens Basalt found at Poker Jim Ridge is the same age as that found at Steens Mountain. Larson also concluded that the reversals found at these sites mark the same event. From Watkins' (1967) description of the Guano Valley site and also from Larson's work, the reversal at Guano Valley is probably this same event.

The reversal seems to take place in stages or phases, and all three locations show these. The first phase is shown by a rapid change in the inclination and only a minor change in the declination. The second phase is shown by a somewhat stable non-typical direction. This is very unusual and is good evidence that the earth's field reversed. All the mechanisms which have been proposed for these intermediate directions include the reversing of the earth's field. The third and final stage is shown by a rapid change in the declination and only a minor change in the inclination. Steens Mountain - section one is the best example of these phases.

The fact that the intermediate directions persisted over several flows and that the most dynamic changes generally took place over one flow suggests that the reversal may have proceeded in spurts. That is, the field may have had periods of very rapid change followed by periods of little or no change. Maybe, as some mechanisms for reversals suggest, the stable intermediate period is when the dipolar field had collapsed and only the non-dipolar components were present.

The time involved in all of the phases of the reversal is not very definite. There is no direct evidence that indicates that each flow represents the same time span. The many flows which contain the large plagioclase crystals suggest periods of quiescense. Hence, a time scale based on field evidence is very difficult to devise. However, it seems quite reasonable to assume that the time involved in the intermediate stage is longer than that for the periods of rapid change.

The mineralogy was studied in detail at Guano Valley and at Steens Mountain. At Guano Valley, Watkins (1967) found a correlation between the presence of the mineral maghemite and the transition zone. He concluded that the non-typical directions, the evidence of the transition, were a result of the presence of this mineral and not a result of intermediate directions of the magnetic field. In the Steens Mountain section, no maghemite was identified, yet the same non-typical directions were found in both places.

Therefore, it is believed that the apparent transition zone found in the Steens Basalt is a valid transition and represents the ancient magnetic field. The presence of maghemite in the transition could be strictly fortuitous.

Further, it is believed that the reversing of the earth's magnetic field is the cause of the reversed polarities found in the Steens basalt. This conclusion is based on the preceding discussion. In summary, the same reversal and the same sequence of events are found in three widely separated areas. A valid transition zone with non-typical directions is present. And, there are mineralogical variations between the areas.

The conclusion that the earth's field reverses certainly is not new. Cox, Doell and Dalrymple (1965) have correlated reversals on a world-wide scale based on age dates and showed that they are world-wide events. This present data supports this, but eliminates the problems of age dating, at least on a regional scale.

The results of this study suggest some other conclusions. A possible rotational pattern for the direction changes is suggested. The motion in the initial change seems to take place in a counter-clockwise manner; the north seeking pole seems to move in a counter-clockwise manner. The evidence during the second major change is not very definite, but a counter-clockwise motion is again suggested. More of this type of information is necessary to construct models for the source of the earth's field.

This study did not produce very much positive information concerning the history of the intensity of the field during a reversal. The Q_{200} data suggests that the intensity decreased during the reversal. The nature and relevance of this data must be kept in mind, however. An extensive study of the intensities would be necessary before any positive conclusions could be made.

Typical of most field investigations of this nature, it seems more questions are left unanswered than are answered. This certainly seems true in this case. Of primary importance and interest are the questions of: 1) how did the intensity of the field vary during the transition, and 2) how long does it take to reverse the field? Also of great significance would be to find this same transition in some other part of the world.

It is felt that the Steens Mountain basalt is a prime candidate for these extended studies. Many of the samples show high degrees of oxidation, and, hence, there is a good chance of finding a substantial number of "stable" samples. This is very necessary for a successful study of the intensities. This problem and recommended approaches have been discussed in Chapter VI. It is hoped that this study continues.

As far as the question of time, samples from Poker Jim Ridge are now in the process of being dated using K-Ar techniques. Hopefully, these results will soon be available and will help to determine the time involved in this transition.

In light of Watkins' work at Guano Valley, it may prove very interesting to continue the mineralogical studies. So far, only microscopic identification has been done. Maybe chemical analysis or X-ray techniques would be helpful by showing further likenesses and differences between the three areas.

On a world-wide basis, a reversal dated at 14.3 million years to 13.1 million years was reported by Kawai and Hirooka at the Review Meeting on Paleomagnetic Study od the Circam-Pacific Area (1966). One immediately wonders if this is not the same transition as found in the Steens basalt. It may prove very interesting to take samples from both places and date them in exactly the same manner. It would be a significant find and man's knowledge of the ancient field would take great strides forward if they proved to be the same age.

Somewhat along these same lines, Glass and Heezen (1967) report that some tektites from Czechoslovakia have been dated at 15 million years. They had found that some reversals of the magnetic field correlated in time with some large tektite deposits. They concluded that large meteorites crashing into the earth may be the cause of or the impetus for the field reversing. It would be very interesting to find out if the reversal of the present study is the same age as these tektites.

Chapter VI - Paleo-intensity

Introduction

Most of the work on paleo-intensities has been done using archeological objects. Very little has been done on volcanic rocks. Hence, the history of the field's intensity does not extend very far back.

A very unique but time consuming technique for finding paleo-intensities was devised by Thellier in 1937 (Thellier and Thellier, 1959). This method basically uses the principles of additive partial thermoremanence (PTRM) and the fact that the acquired TRM is proportional to the field. PTRM is that TRM which is gained or lost in any particular temperature range. PTRM is assumed to be unique for each temperature, and the sum of all PTRM's should equal the total TRM.

Briefly, the procedure is as follows. After the NRM is measured, which is assumed to be all TRM, the sample is heated to a certain temperature, say 100°C, and cooled in the absence of a field. The intensity is again measured. Then the sample is heated to 100°C and this time is cooled in the presence of a known field. The intensity is again measured. By knowing the directions and magnitudes of all of the resultant magnetic vectors, it is now possible to calculate, for the interval of room temperature to $100^{o}C$, the original PTRM, the laboratory PTRM and the ratio of the original PTRM/lab PTRM. This ratio is found for many temperature intervals up to the Curie temperature of the sample. By using extreme care and by being very critical of the data, this ratio should be the ratio of the ancient field to the present.

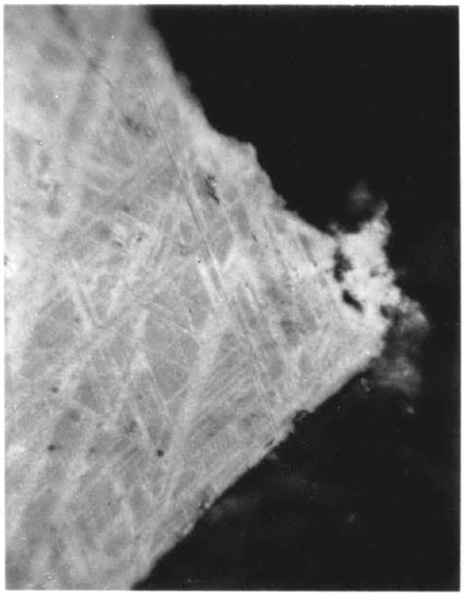
As stated above, this is a very good technique because there are many "built-in" checks to insure that all the assumptions are supported. However, it is very difficult to use with volcanics (Coe, 1966). The main difficulties seem to arise from the repeated heating of the samples. It was hoped that criteria could be found for pre-selecting "good" samples. This is, samples which would not change with heating and meet all the standards of Thellier's method. This would be a great time saver.

Results and Recommendations

It is necessary to find relatively simple fast experiments or tests upon which acceptance or rejection of a sample can be based. The first test, and probably one of the most critical, is a microscopic petrological examination before and possibly after heating. This should be done at very high magnification. Based on the work of Coe (1966), Smith (1967b) and Strangway, Larson and Goldstein (in press) it is preferable to select only those samples which show a very high degree of high temperature oxidation. Much hematite, ilmenite, pseudobrookite and other highly oxidized forms of titanium iron oxides should be evident. No fresh unaltered magnetite should be present. Samples which show extreme stages of oxidation appear to be the most resistant to changes due to heating in air. This is evident in the few experiments done in this study (see Figure 6-1 and Table III). The initially high oxidized samples show minor visible changes by heating. Whereas, the more un-oxidized samples show drastic changes.

These changes, or the effects of these changes were demonstrated in another way (see Figure 6-2). The sequence of events for this experiment is as follows:

1. Heated samples to 650°C; cooled in 1.2 gauss field; A.C. demagnetization spectra.
2. Heated to 800°C; cooled in 0.06 gauss field; A.C. demagnetization spectra.
3. Heated to 650°C; cooled in 0.35 gauss field; A.C. demagnetization spectra.



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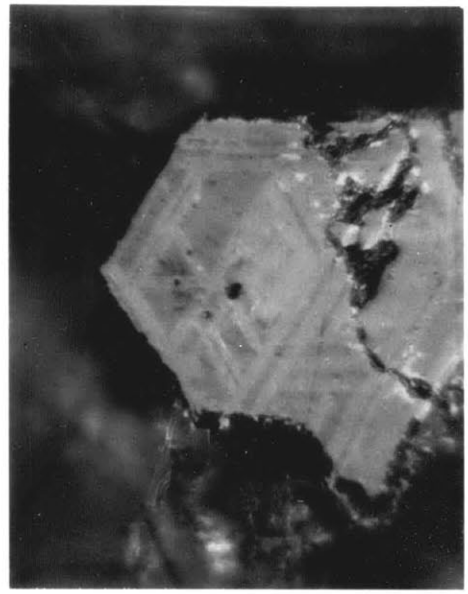

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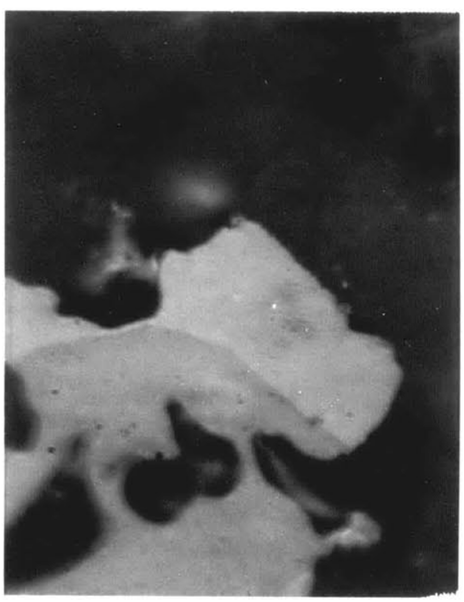

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Figure 6-1

Table III

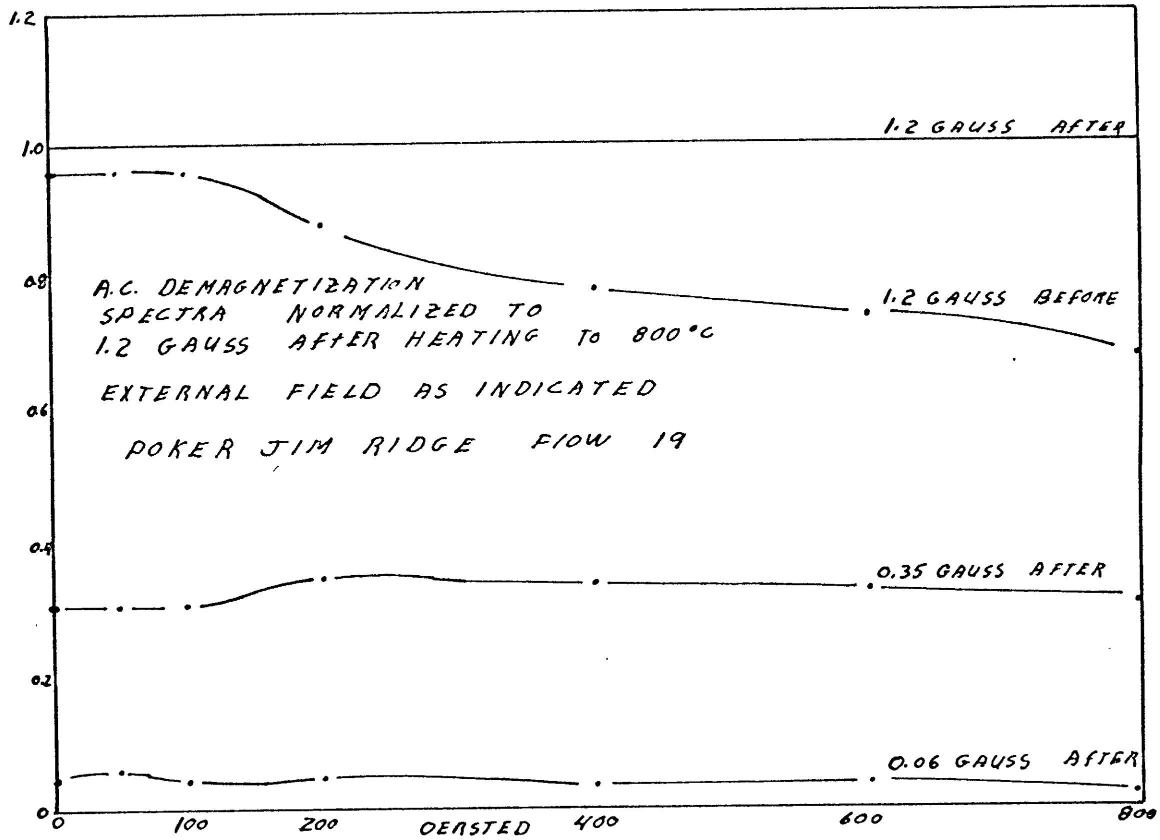
Description of Photographs

1. Poker Jim Ridge flow 19 before heating.
Mostly maghemite-ilmenite and hematite, some pseudobrookite, minor amounts of relatively unaltered magnetite with what appears tobe traces of ilmenite.
Picture shows magnetite-ilmenite with some hematite.

2. Poker Jim Ridge flow 19 after heating.
Mostly magnetite-ilmenite with hematite. Maybe slightly more hematite than before heating. No unaltered magnetite now present. However, large magnetite grains show the development of broad ilmenite lamella. This was not found before heating.
Picture shows the broad ilmenite lamella developed.

3. White River sample 3-4 before heating.
Mostly unaltered magnetite and magnetite-ilmenite grains. No lamella development.
Picture shows magnetite-ilmenite grain. Ilmenite is the dark portion.

4. White River sample 3-4 after heating.
Slight amounts of hematite present in the magnetite grains. Magnetite no longera chocolate brown, rather, it is slightly gray. Appears that some lamella are starting to develop. Magnetite-ilmenite grains present.
Picture shows the development of lamella and hematite.


1.2
1.0
0.8
0.6
0.4
0.2
0
1.2 GAUSS AFTER
1.2 GAUSS BEFORE
A.C. DEMAGNETIZATION SPECTRA NORMALIZED TO 1.2 GAUSS AFTER HEATING TO 800°C
EXTERNAL FIELD AS INDICATED
POKER JIM RIDGE FLOW 19
0.35 GAUSS AFTER
0.06 GAUSS AFTER
0
100
200
OERSTED
400
600
800

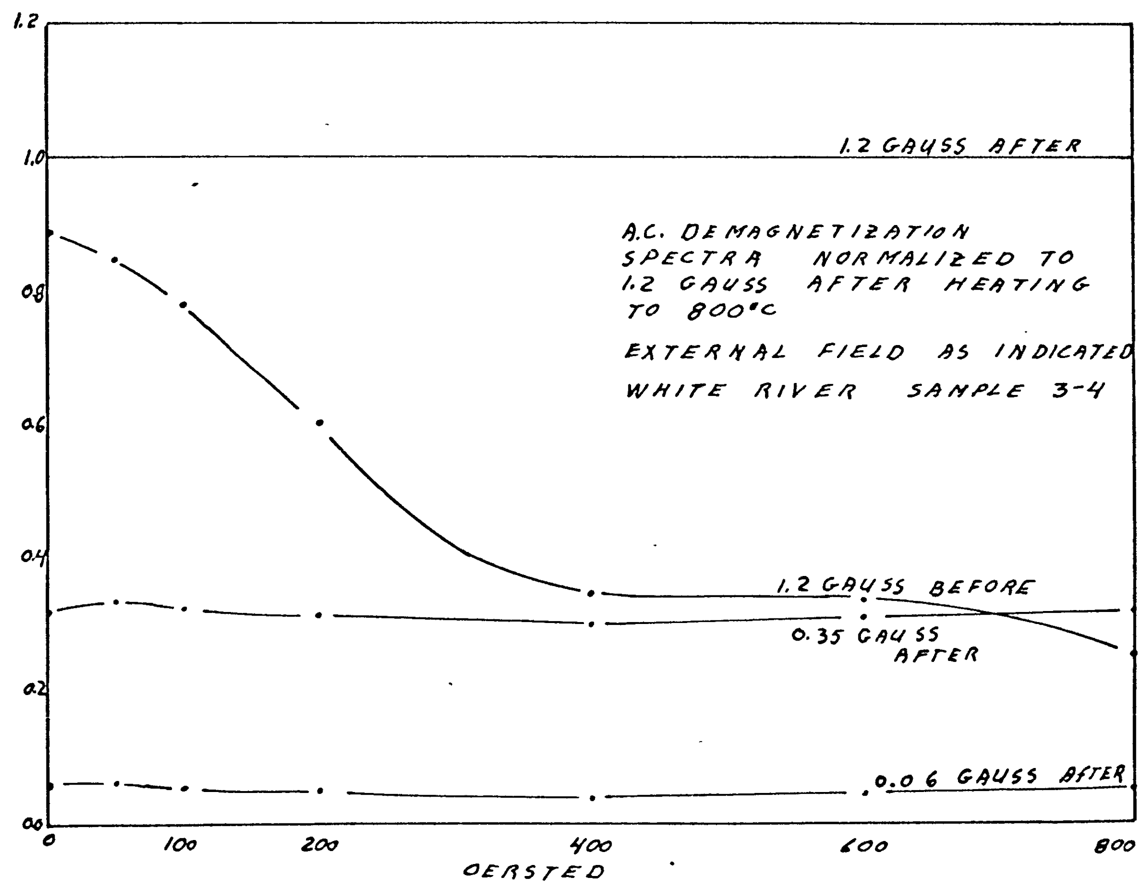

1.2
1.0
0.8
0.6
0.4
0.2
0.0
1.2 GAUSS AFTER
A.C. DEMAGNETIZATION SPECTRA NORMALIZED TO 1.2 GAUSS AFTER HEATING TO 800°C
EXTERNAL FIELD AS INDICATED
WHITE RIVER SAMPLE 3-4
1.2 GAUSS BEFORE
0.35 GAUSS AFTER
0.06 GAUSS AFTER
0
100
200
400
600
800
OERSTED

Figure 6-2

4. Heated to 650°C; cooled in 1.2 gauss field;

A.C. demagnetization spectra

The intensity values for each A.C. demagnetization field strength have been normalized to that value of the intensity found after the last heating.

If there were no changes of the sample of any kind due to heating; then it was predicted that all of the normalized curves would be flat lines. That is, the distribution of magnetization would remain the same. This is based on the idea that TRM is proportional to the field. In particular, the TRM that is affected by A.C. fields of less than 1000 oe.

In the few samples studied, this was not true. Specifically, the curves for 1.2 gauss before heating to 800°C are not flat. The plot for White River 3-4 shows the most drastic change which was predicted from the microscopic examination. The curves for 0.06 and 0.35 gauss seem relatively flat. This indicates that most of the changes took place while heating the samples to 800°C and that the samples become stabilized at that time.

These plots suggest that there is a basic relationship between stability and intensity of magnetization. Looking at the curves for 1.2 gauss before and after heating, it is seen that the total TRM's are equal or nearly so, but upon

A.C. demagnetization, these curves start to deviate. This shows that the distribution of magnetization has changed That is, the ratio of magnetization to field has changed for each interval or range of stability. Specifically, this shows that the ratio has increased for the more stable fractions, and has probably decreased for the less stable portion. This phenomena may be the effects of a two or more phase system. By heating, the low stability phases have been converted to higher stability phases. Just how this happens is unknown, but it may have something to do with the development of hematite and ilmenite as shown in the photographs.

It would be very interesting to investigate the distribution of magnetization within each temperature range. This could easily be done by repeating these experiments but use PTRM's rather than the total TRM. This would demonstrate the stability distribution of TRM in each temperature interval and the relationship of each stability fraction with intensity of magnetization.

These conclusions maybe somewhat pre-mature, but the results of the initial experiments are very interesting and could lead to some basic conclusions for paleo-intensity studies.

Many phenomena could cause the observed effects. As shown by Figure 6-1, oxidation appears to have taken place. Ilmenite and hematite were formed; both of which could account for the observed changes. Smith (1967b) mentioned other reactions due to heating in air. These are reduction, ionic ordering, annealing and phase homogenization. All of which could effect the magnetic character of the sample.

Although more work is necessary to determine the cause, prevention, and detection of sample changes due to heating, the fact that some of the changes are observable under a microscope is of immediate interest. This experiment demonstrated the relative ease by which these samples can be changed and also shows the importance of a microscopic study. Such an examination will not guarantee the pre-selection of "good" samples, however, many samples that would fail Thellier's criterial will be eliminated.

The next simple experiment that could be done would be to get J versus T curves at very low field strengths (Smith, 1967a). Some idea of expected degree of change due to heating might be derived from comparing the heating and cooling curves. Maybe this will have to be done on samples before and after heating. This experiment can easily be done on a Curie balance equipped with a non-inductive furnace. This is not the same as measuring the total remanence of the sample in a spinner magnetometer, but it should show some of the samples low field strength characteristics. Criteria for allowable before and after heating changes will have to be determined. Many laboratory tests will be necessary to establish these criteria; but, once set, J versus T curves should be very useful in accepting or rejecting samples.

Smith (1967a) suggested comparing J_s versus T curves before and after heating. This reveals some of the high field strength properties of the sample and, hence, it is not a direct indication of its low field characteristics. However, it should be somewhat sensitive to mineralogical changes in the specimen. Again, criteria for tolerable changes would have to be determined.

The remanent coercivity could also be measured before and after heating. This would indicate changes in the "hardness" of the remanent magnetization. As before, criteria for acceptance or rejection need to be determined.

A.C. demagnetization spectrum could be done on the NRM and TRM of the sample. These curves should have very similar shapes, suggesting that the NRM may be TRM and that the distribution of the magnetic energy is the same.

The hysteresis curves could be made for the samples before and after heating. This would show some of the bulk properties of the sample, but may not be very sensitive to minor changes. However, experiments should be done to see just how sensitive this test is, and if it would be helpful in pre-selecting samples.

Of these suggested experiments, probably the most useful will be the microscope study, J versus T at low fields, the remanent coercivity and the NRM versus TRM demagnetization curves. Criteria for acceptance or rejection need to be determined for all of these tests.

To further save time and effort, it is suggested that Thellier's method for intensity determination be slightly modified. It is suggested that only certain temperature intervals be investigated. It was noticed in works of Coe (1966) and Kono and Nagata (1966) that the middle temperature intervals gave close to the correct answer for samples that met Thellier's criteria. Ranges like $150^{\circ}C$ - $250^{\circ}C$, $250^{\circ}C$ - $350^{\circ}C$, and $350^{\circ}C$ - $450^{\circ}C$ seemed to be the best. For the low temperature NRM/TRM ratio, the NRM probably contains some remanence other than TRM. At high temperatures, the chances of altering the sample increases. Hence, it is felt that by looking only at the middle temperature range of pre-selected samples, sufficient data will be available to make an accurate determination of the ancient field.

Prior to doing this, however, it is necessary to determine the temperature ranges which generally show the most stable or "hardest" TRM. This can easily be done by by creating a PTRM in a specific temperature range and then perform an A.C. demagnetization spectrum. By comparing the spectrum from many temperature intervals, the "hardest" ranges can be selected.

Although only the very beginnings of this work have been done, the ideas and directions of the experiments are very important to the over-all problem. Hence, they have been included in this thesis. The history of the directional changes during a transition is only half the picture. Before an adequate understanding of the history of the field during a reversal can be gained, it is very necessary to study the changes in the field's intensity. It is felt that the Steens Mountain basalt is a good choice for these studies.

Appendix A

Typical NRM and A.C. demagnetization data

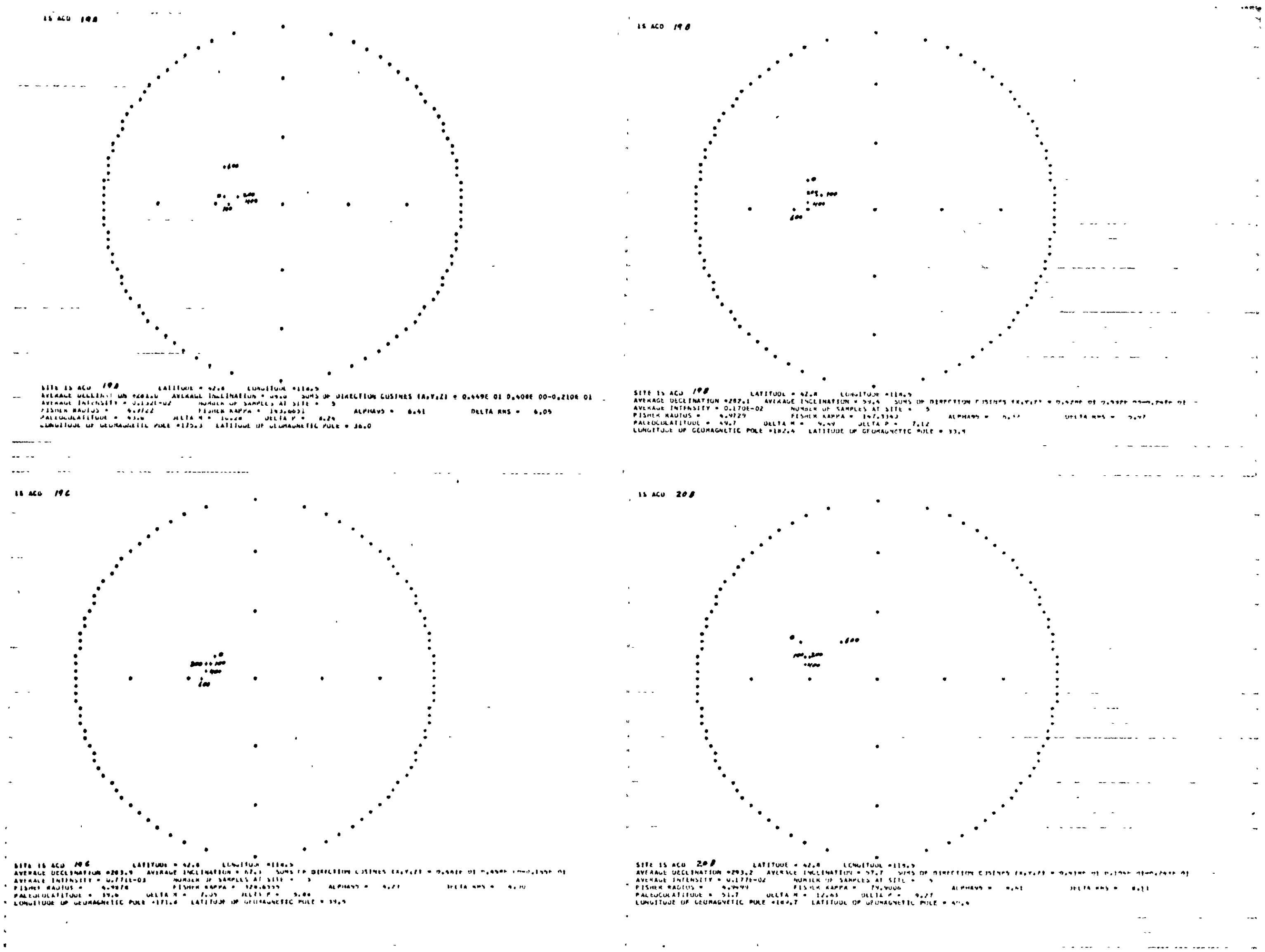


Figure A-1

A.C. Demagnetization Steens Mountain flows 19 and 20

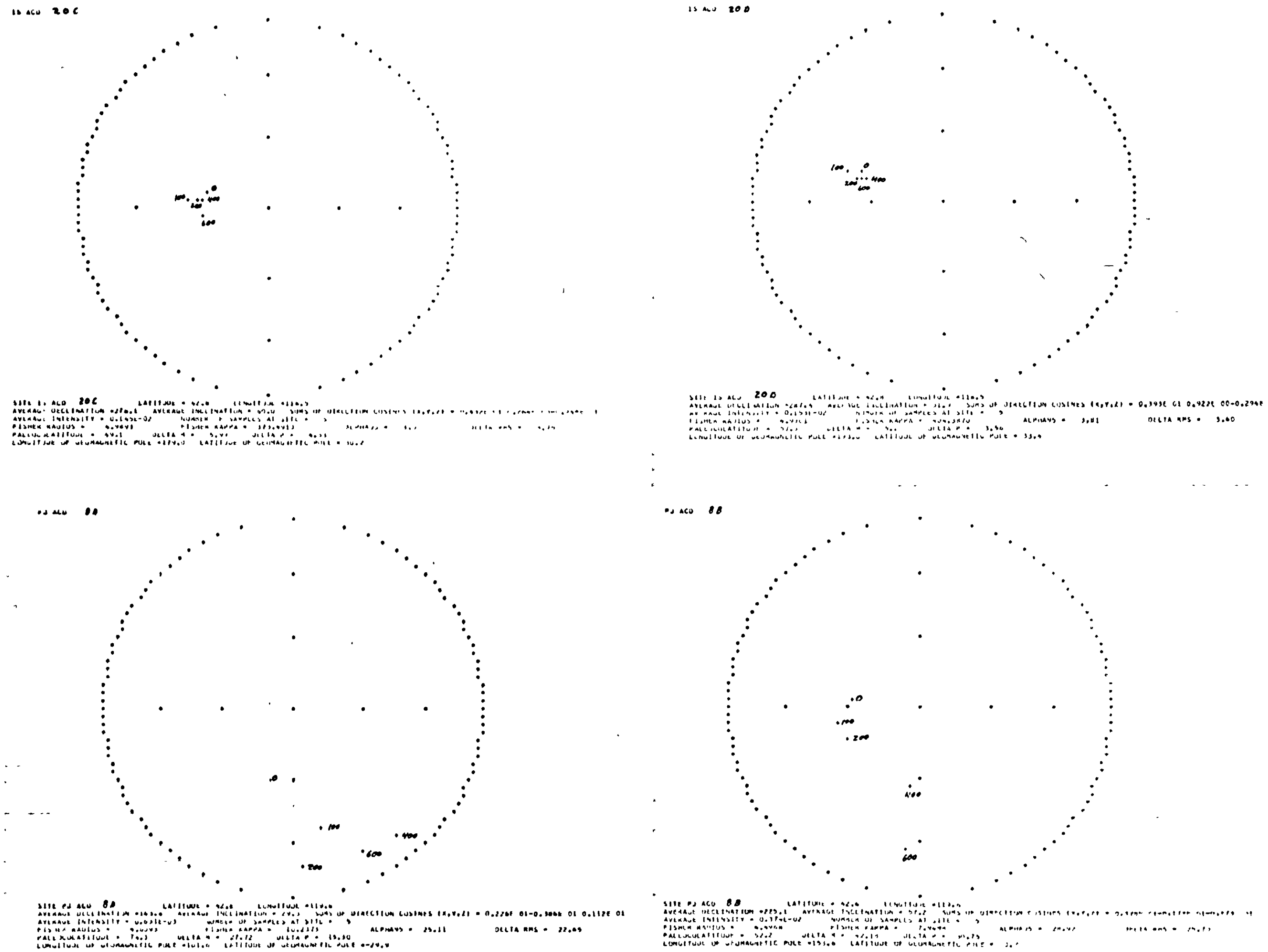


Figure A-2

A.C. demagnetization Steens Mountain 20 and Poker Jim 8

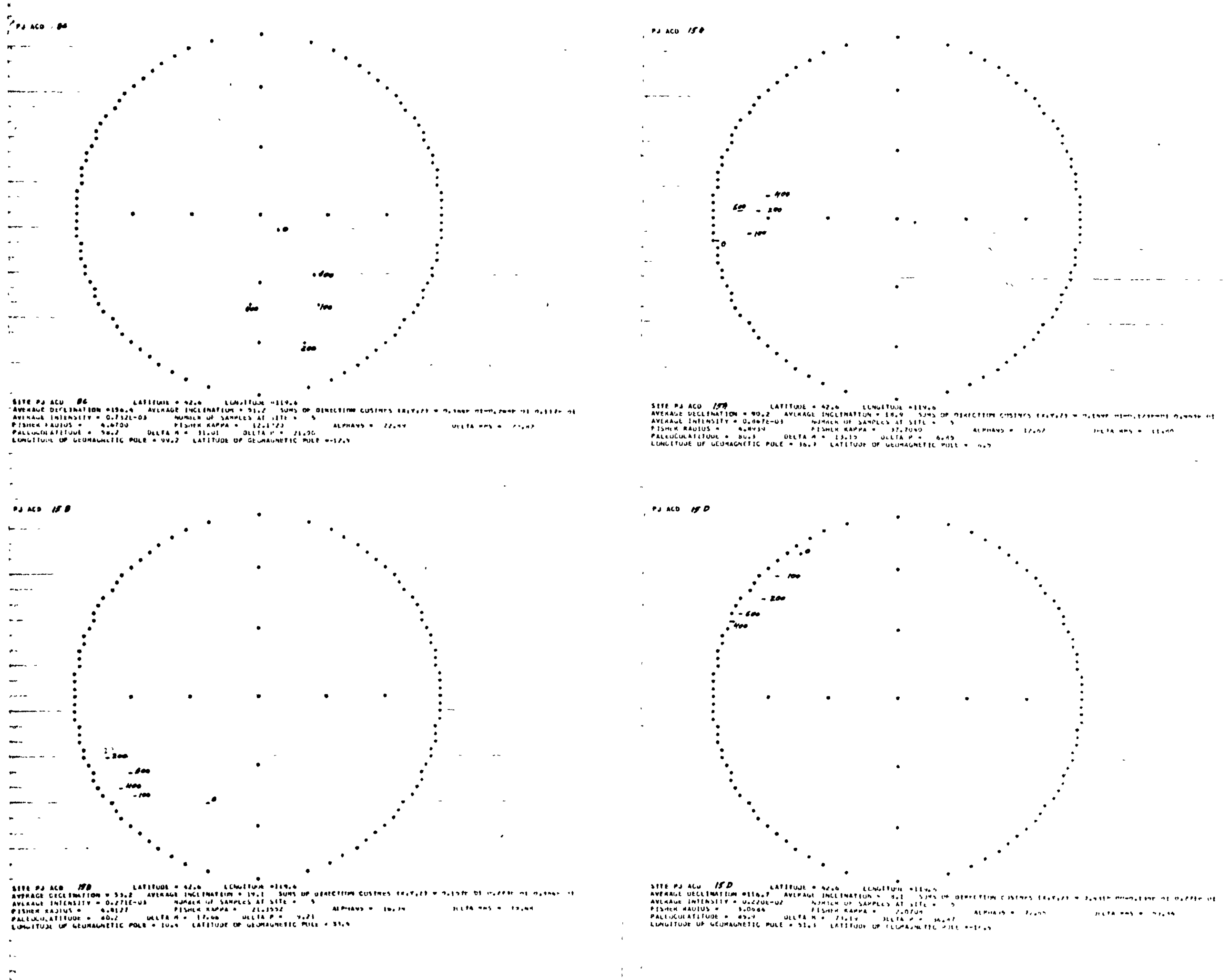


Figure A-3

A.C. demagnetization Poker Jim flow 8 and 15

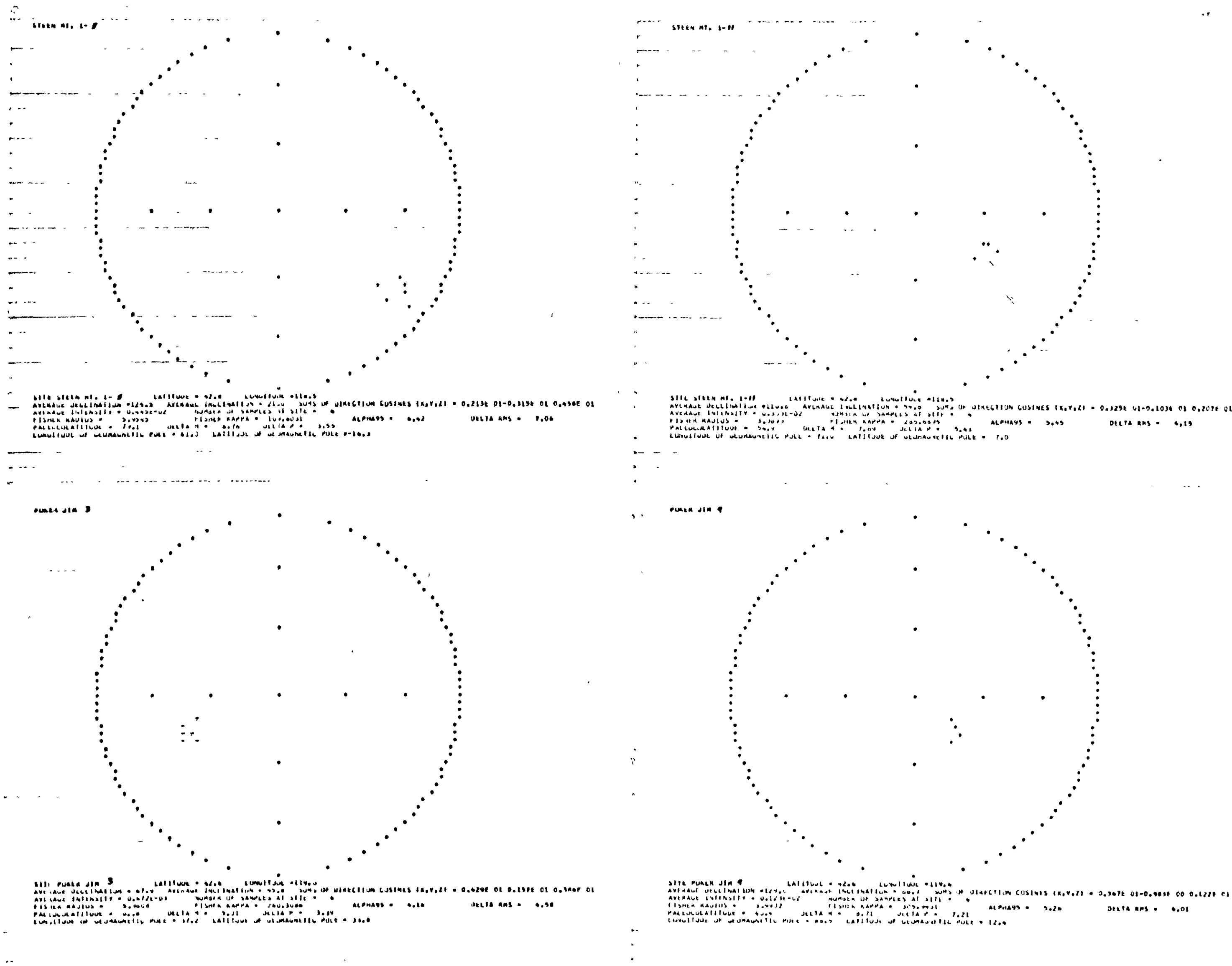


Figure A-4

Examples of tight grouping NRM data

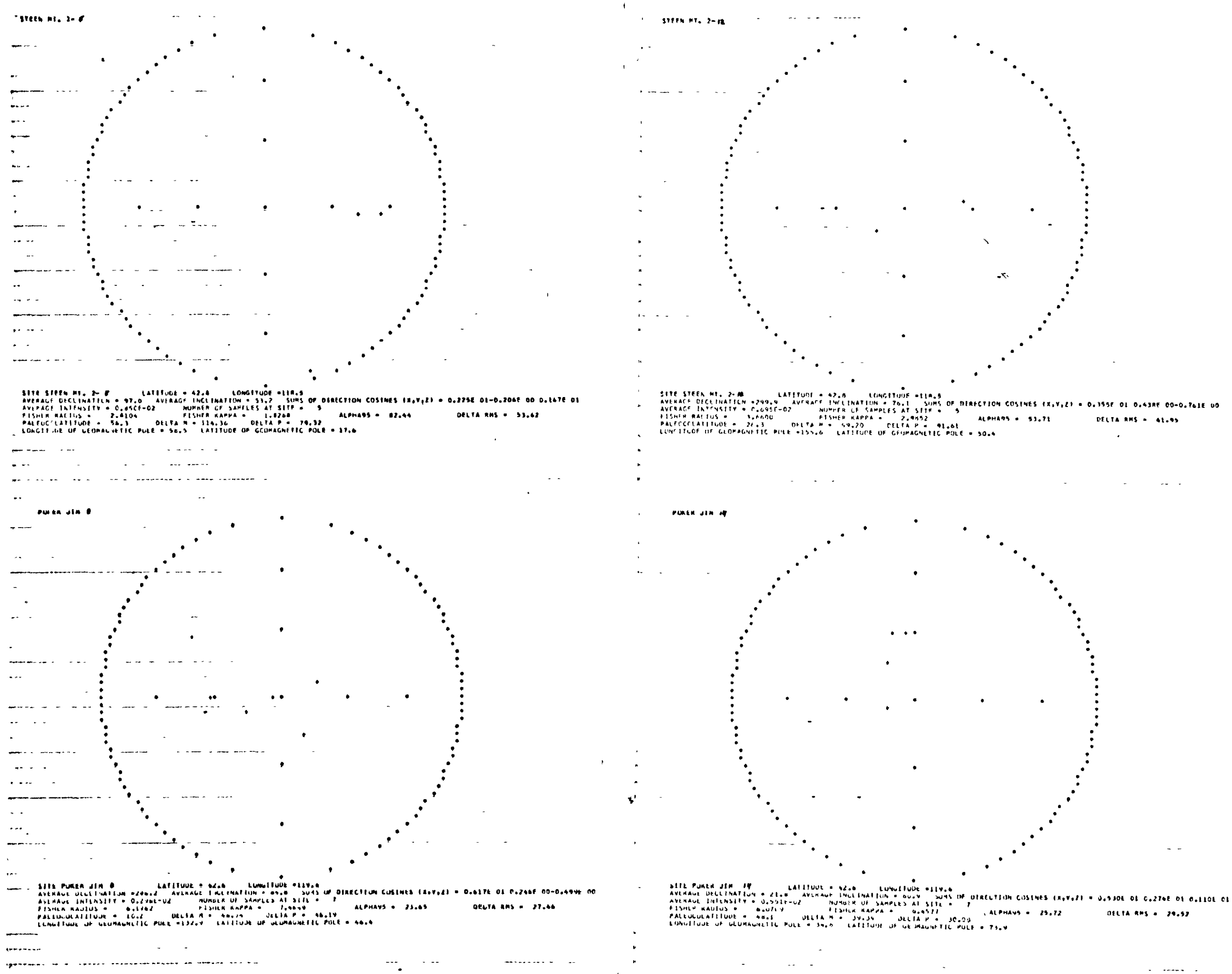


Figure 4-5

Examples of poor grouping NRM data

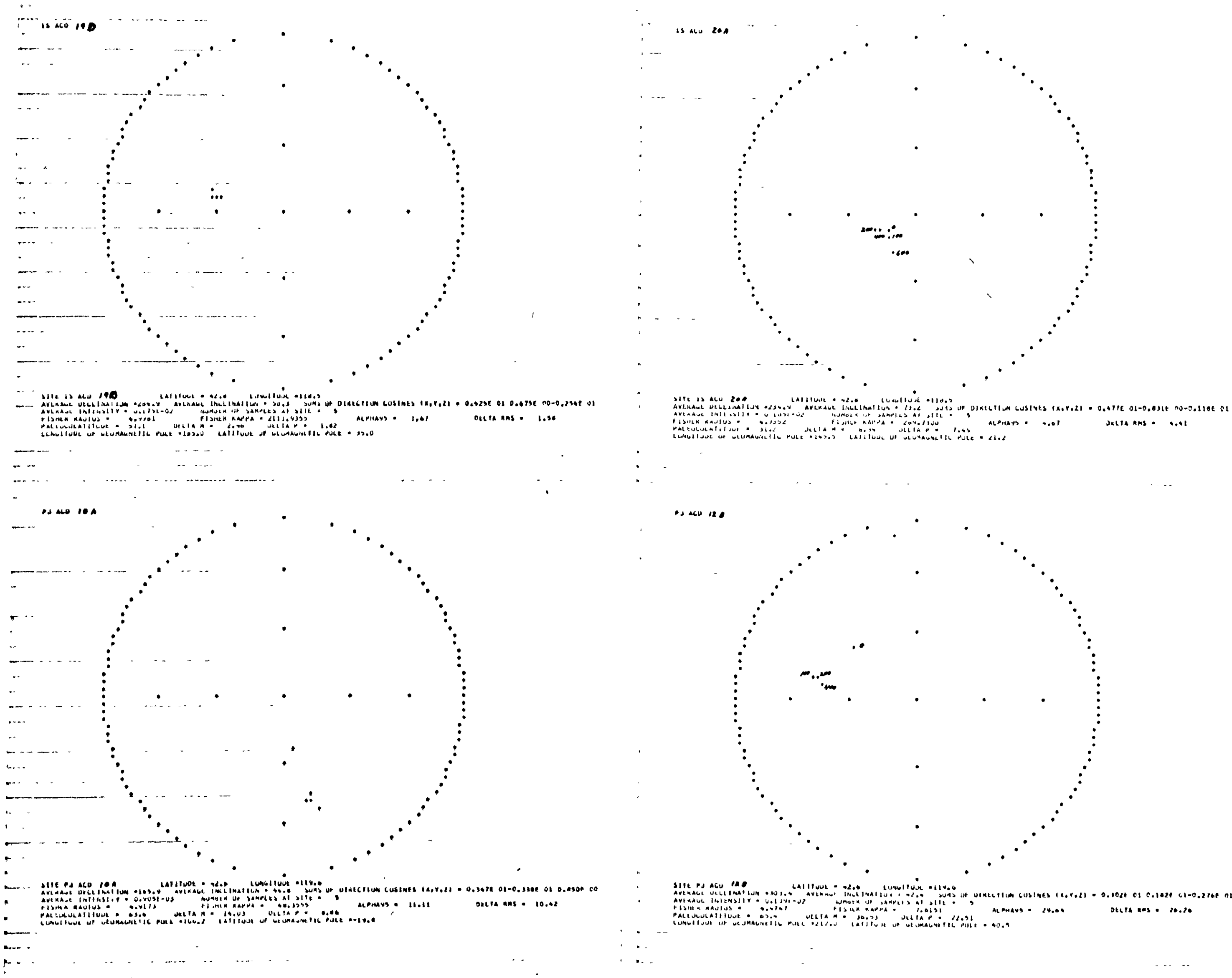


Figure A-6

Examples of tight grouping A.C. demagnetization data

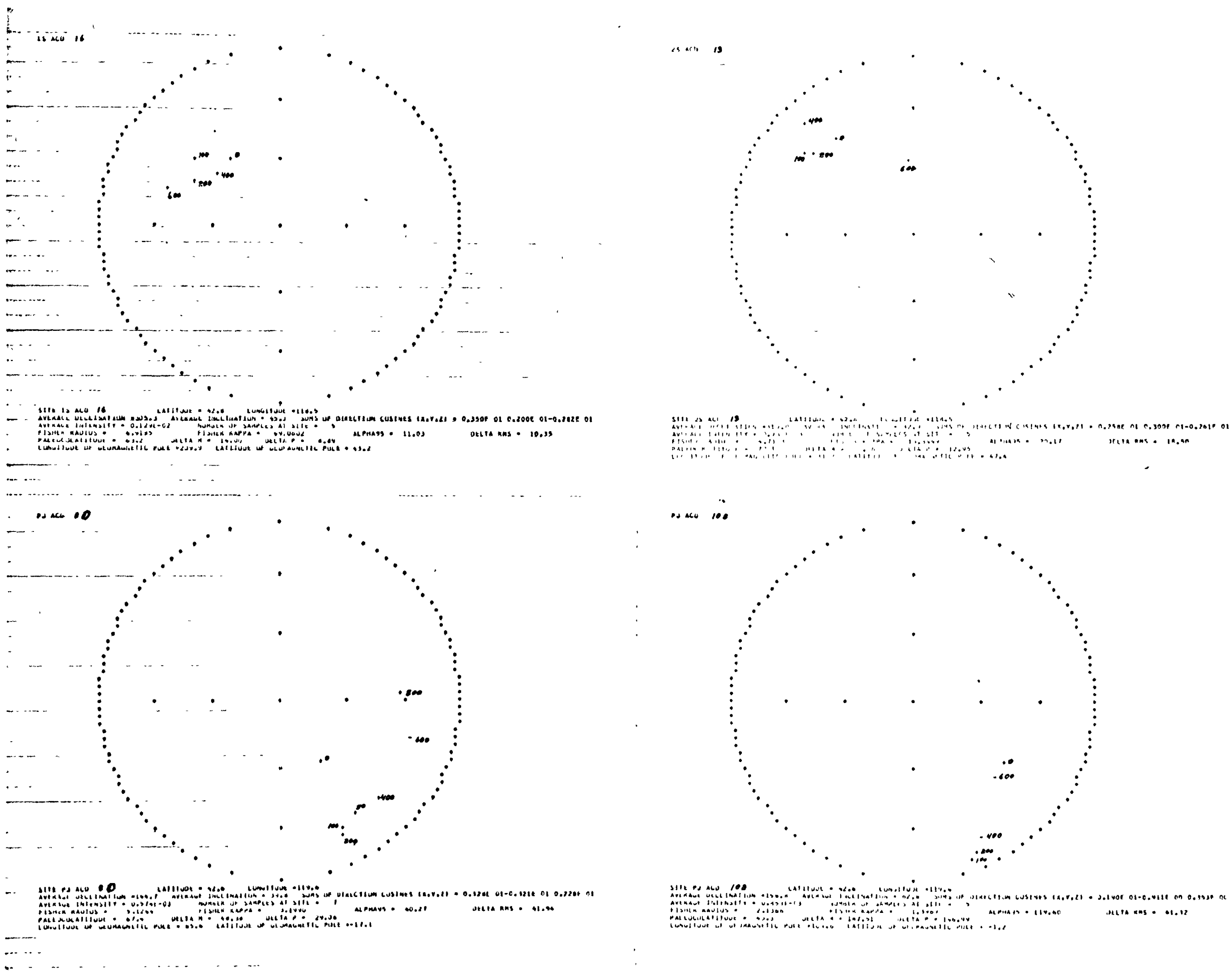


Figure A-7

Examples of loose grouping and the proximity of 100 and 200 oe.

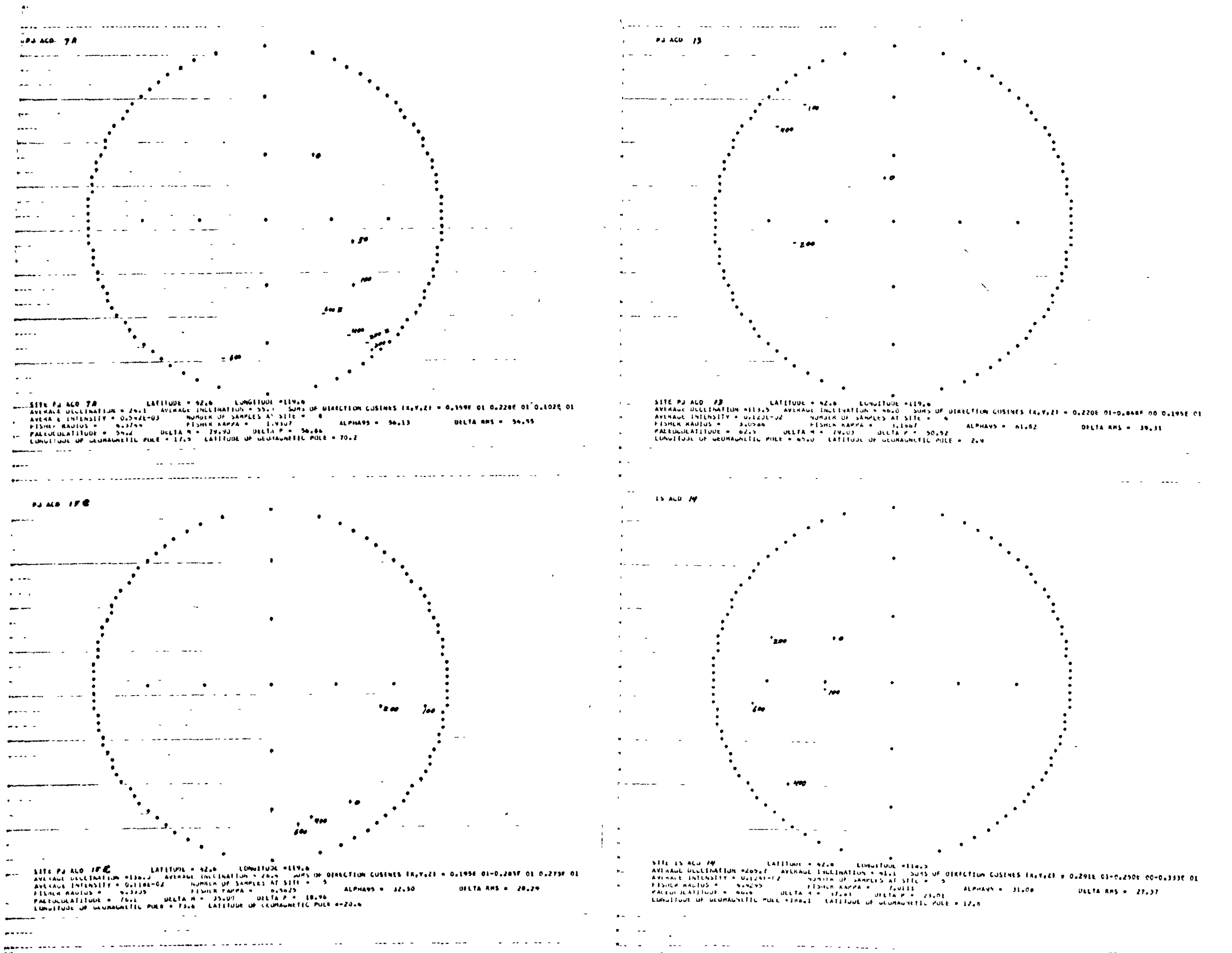


Figure A-8

Examples of poor groupings A.C. demagnetization data

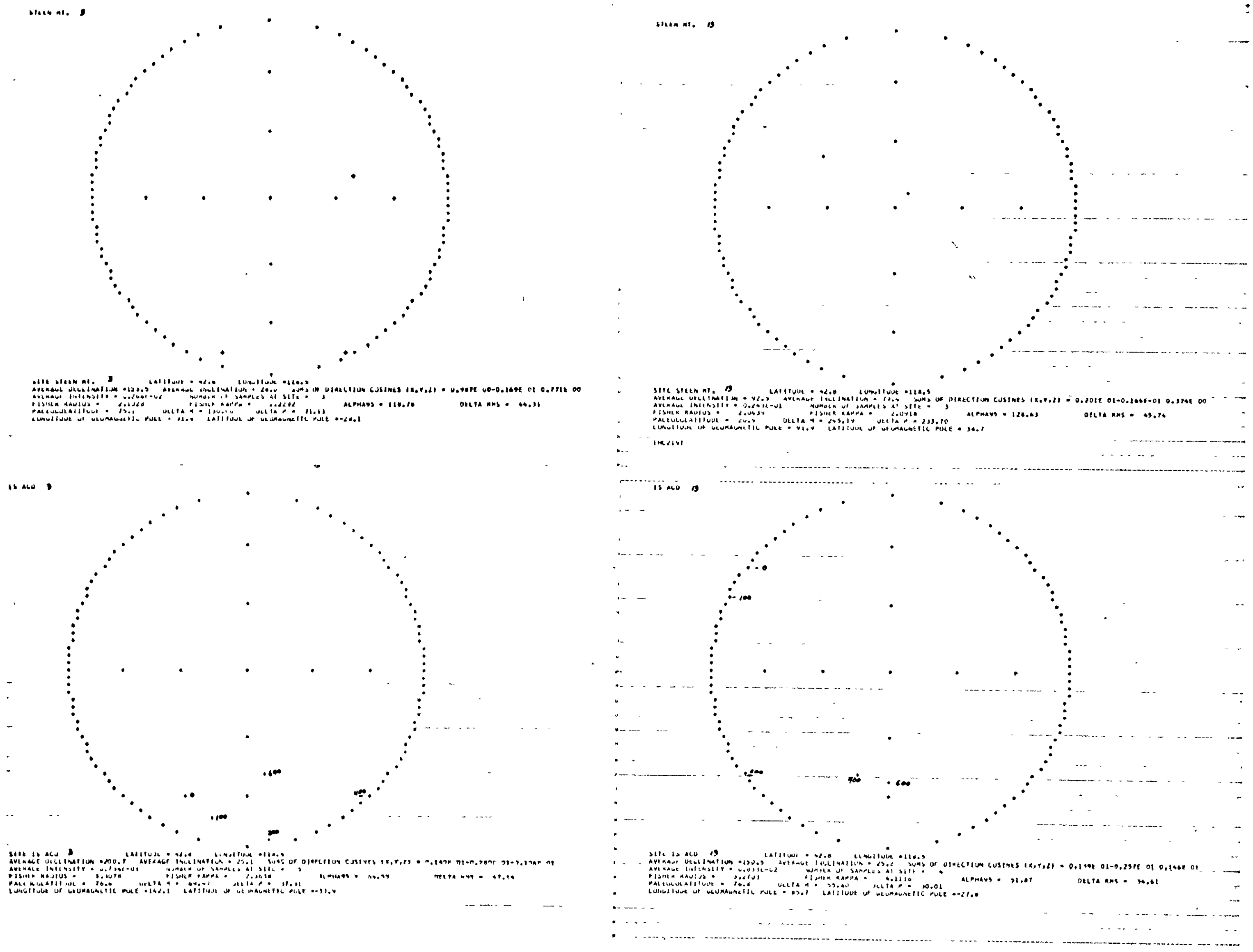


Figure A-9

Steens Mountain - section one flows 3 and 13

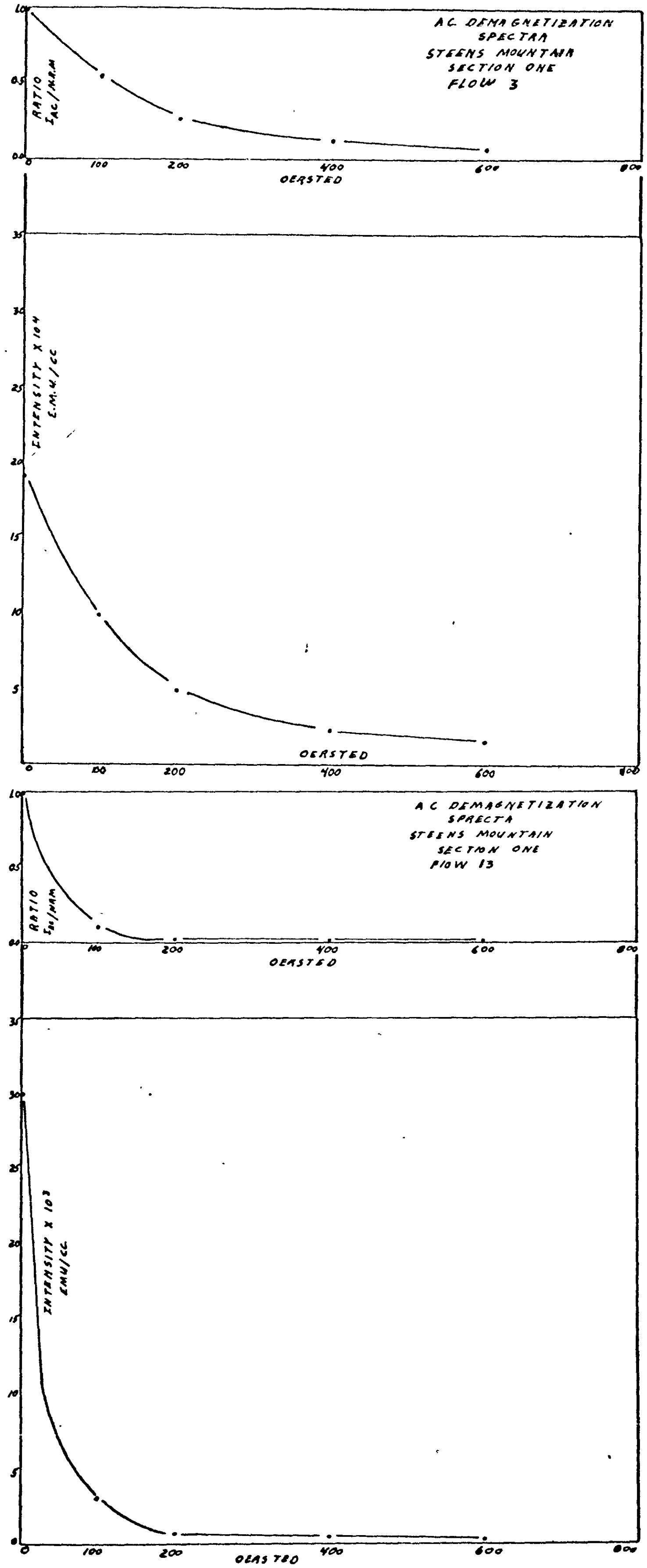

AC DEMAGNETIZATION SPECTRA
STEENS MOUNTAIN
SECTION ONE
FLOW 3
RATIO
OERSTED
INTENSITY X 10^4
E.M.U/CC
OERSTED
A C DEMAGNETIZATION SPRECTA
STEENS MOUNTAIN
SECTION ONE
FLOW 13
RATIO
OERSTED
INTENSITY X 10^3
EMU/CC
OERSTED

Figure A-10

Appendix B

Supplementary Data

Steens Mountain - section one

Intensity at 200 oe. versus flow number

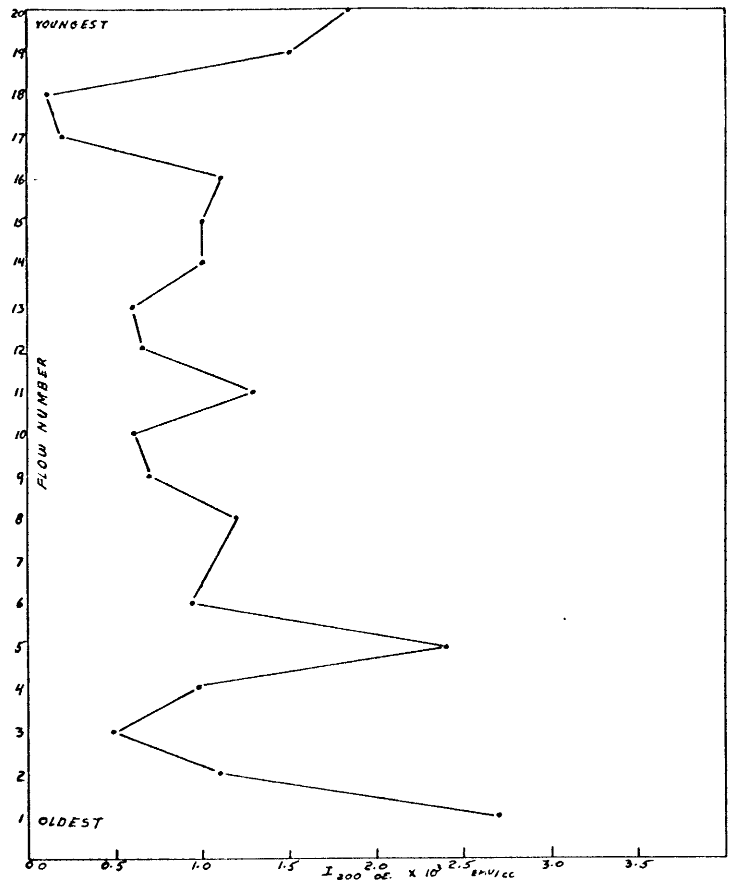


Figure B-1

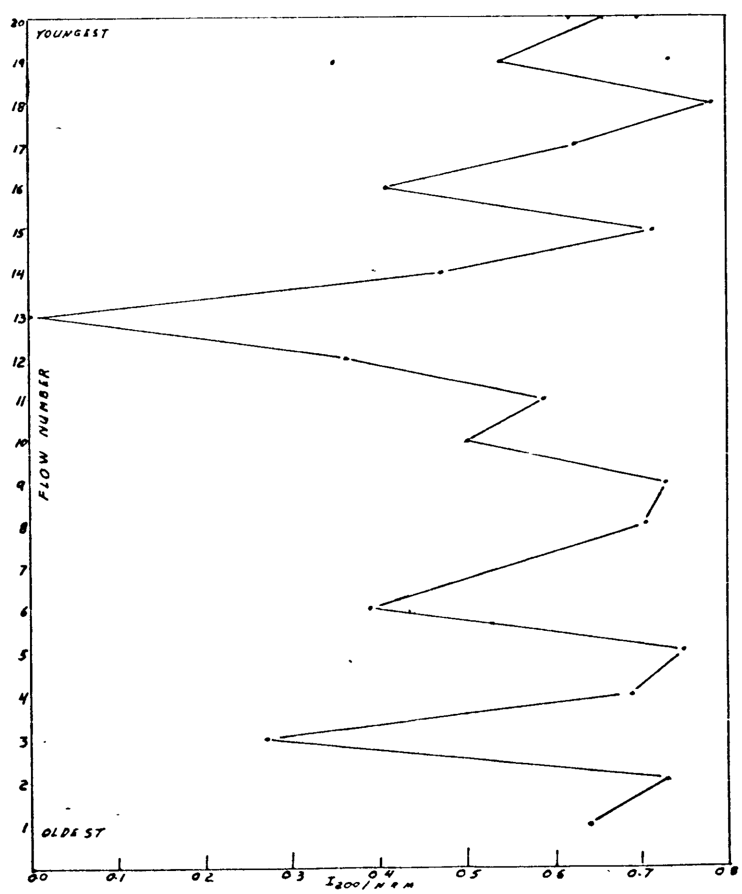


Figure B-2

Steens Mountain - section one

Ratio I_{200}/NRM versus flow number

Steens Mountain - section one

Susceptibility versus flow number

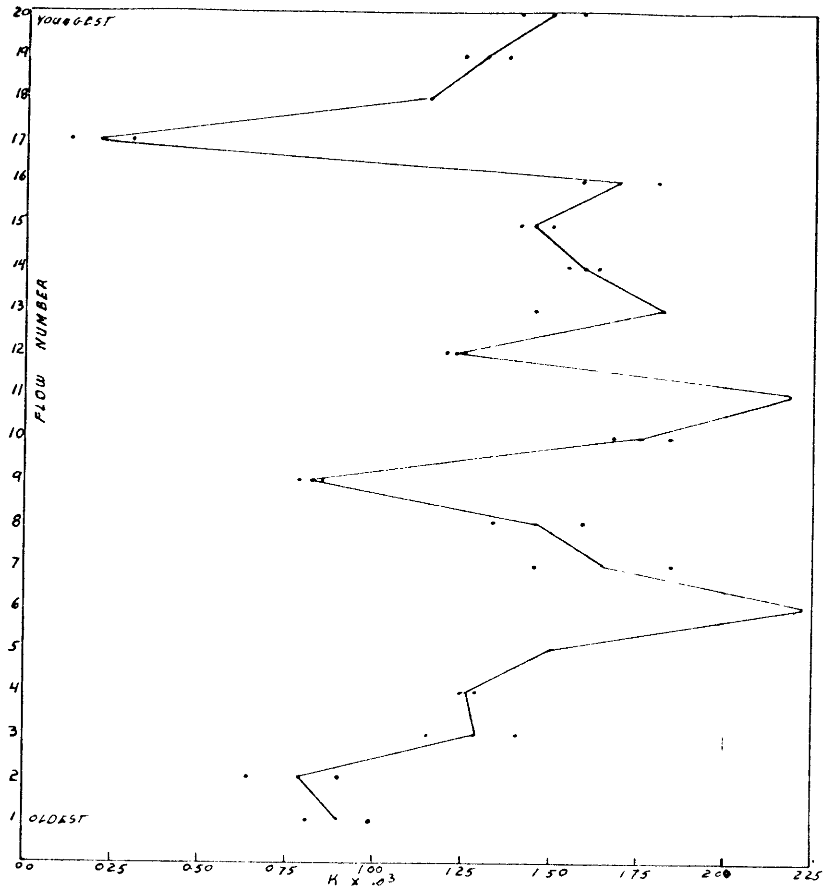


Figure B-3

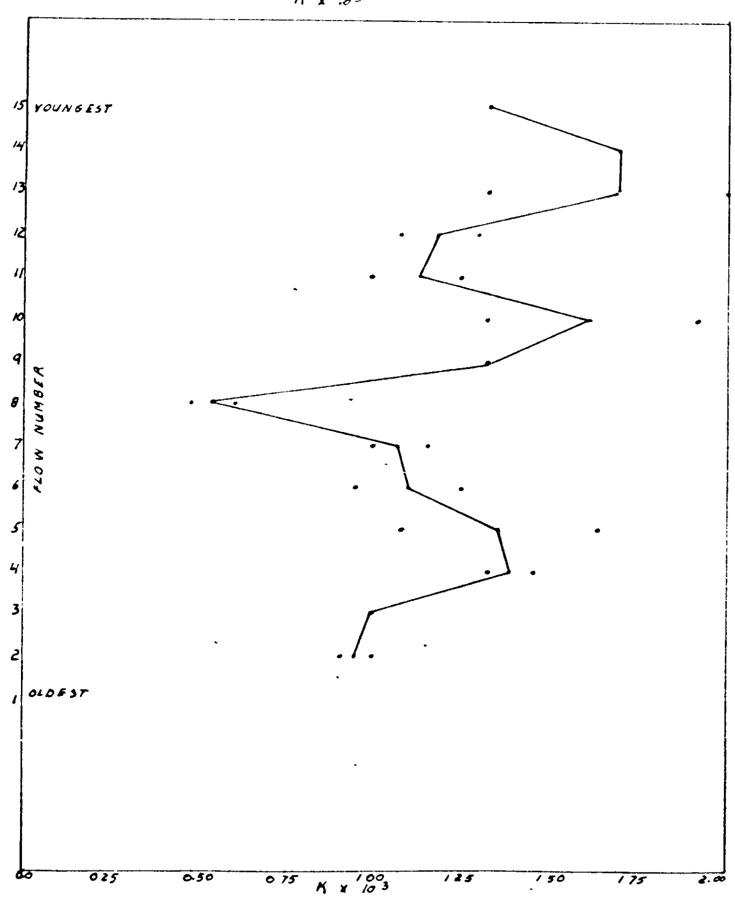


Figure B-4

Steens Mountain - section two

susceptibility versus flow number

Steens Mountain - section two

Intensity at 200 oe. versus flow number

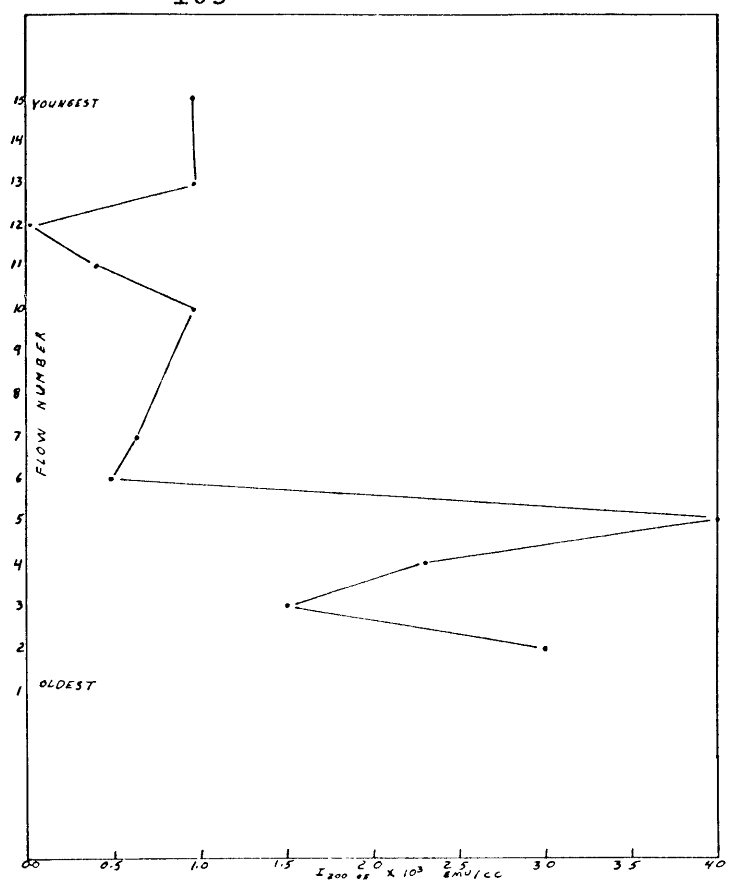


Figure B-5

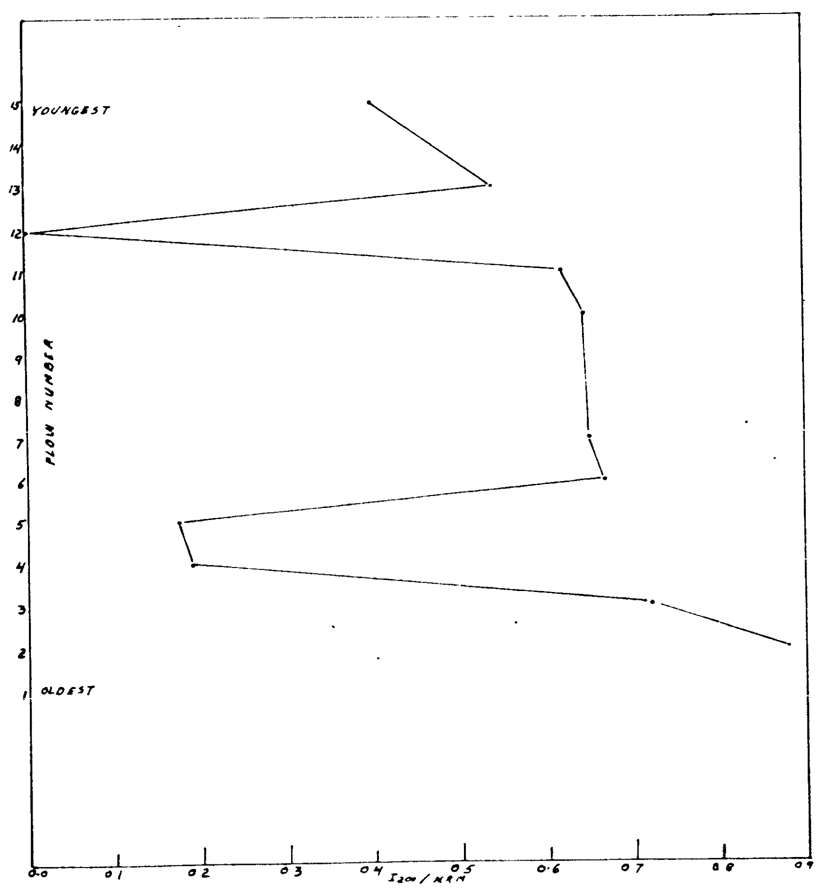


Figure B-6

Steens Mountain - section two

Ratio I_{200}/NRM versus flow number

Poker Jim Ridge

Intensity at 200 oe versus flow number

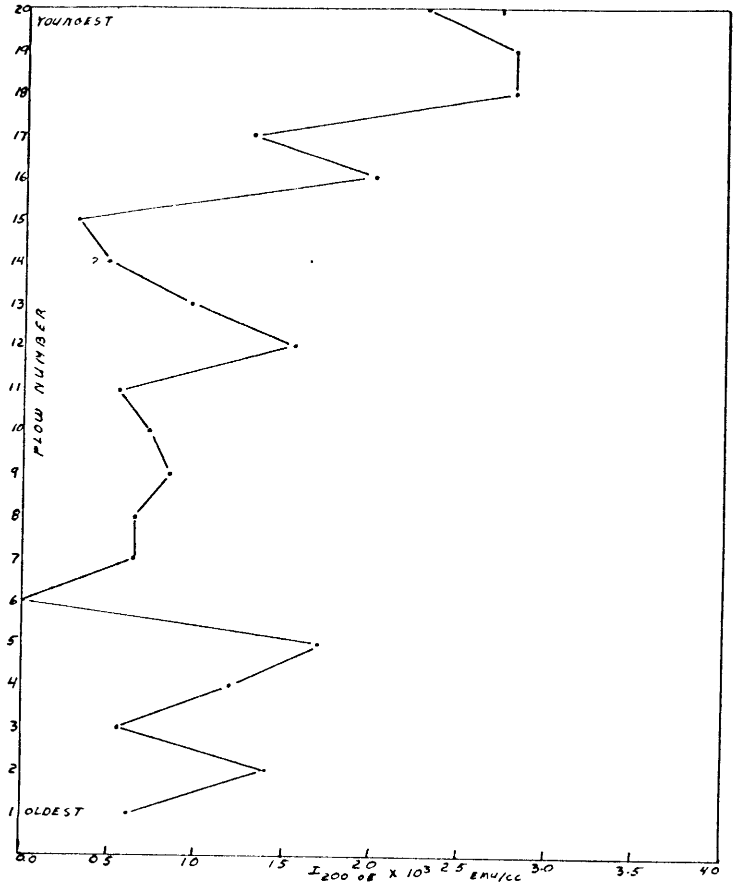


Figure B-7

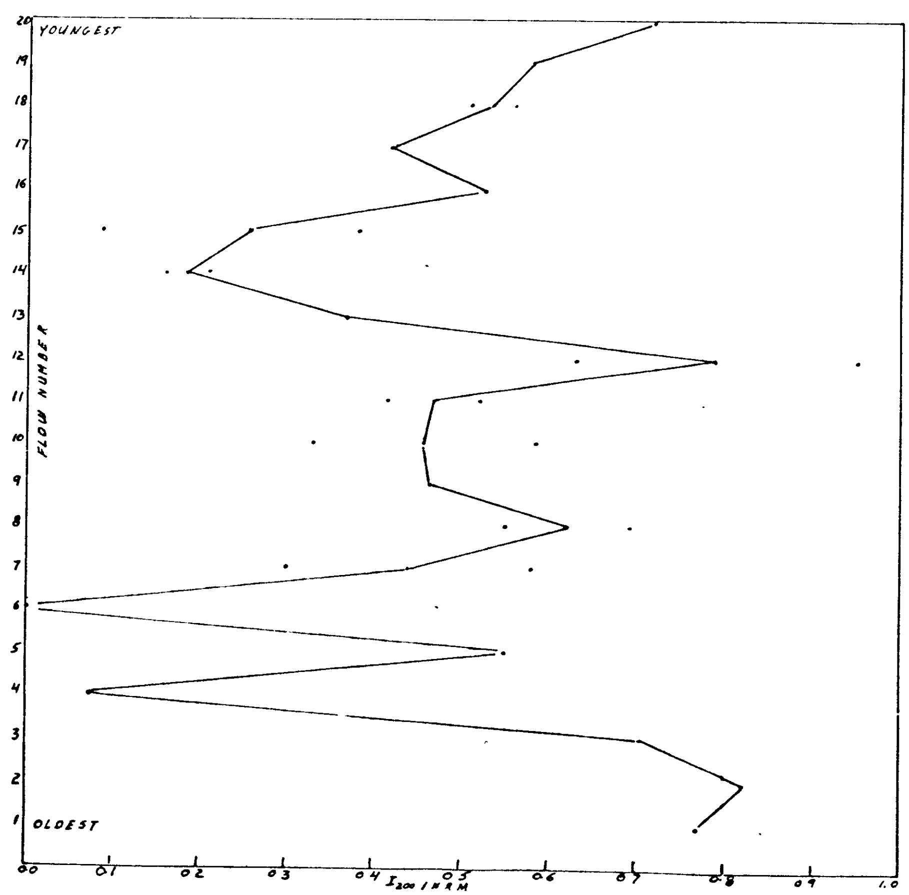


Figure B-8

Poker Jim Ridge
Ratio I_{200}/NRM versus flow number

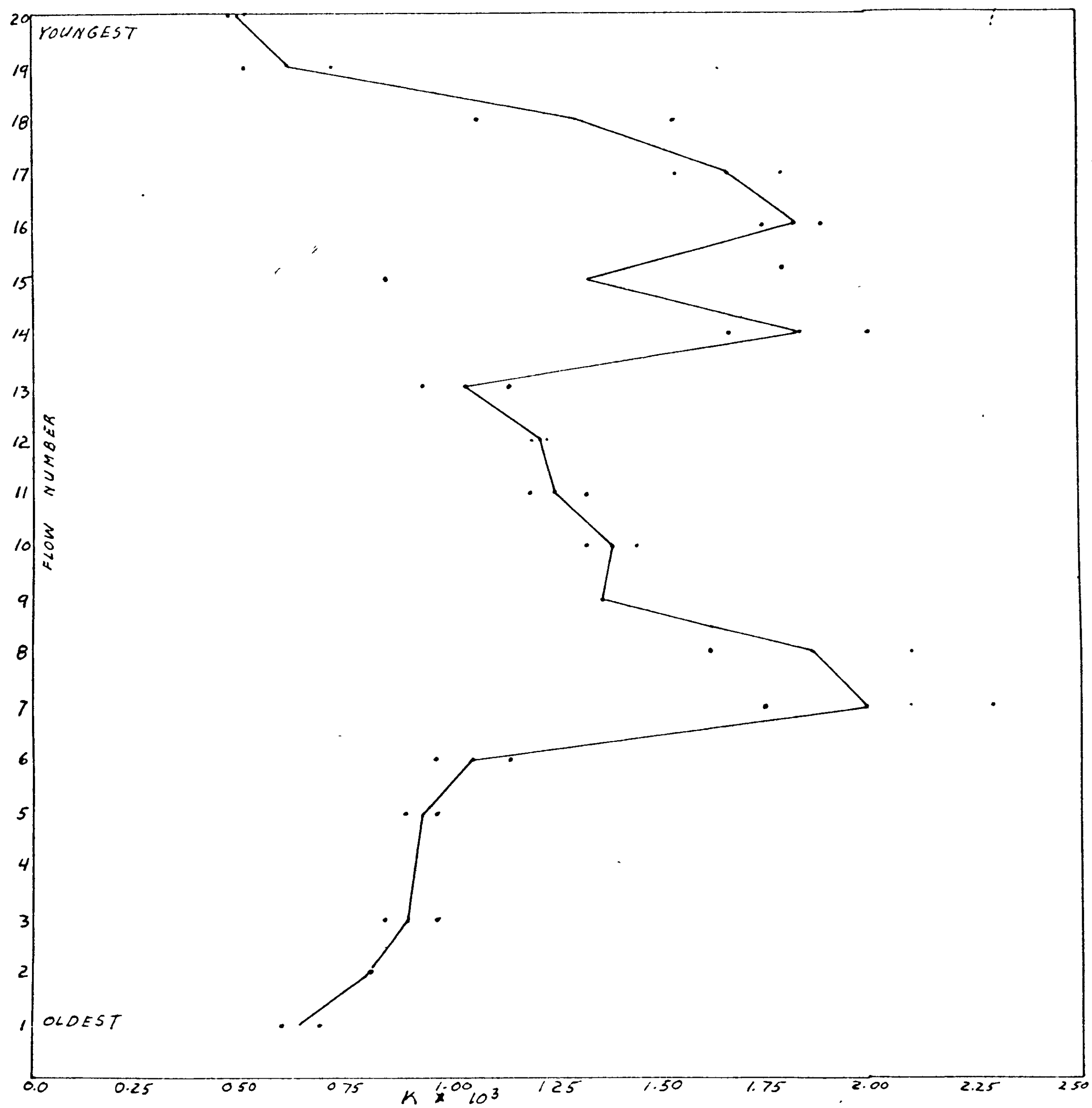


Figure B-9

Poker Jim Ridge susceptibility versus flow number

Table IV

Summary of original NRM data Steens Mountain - section one

Flow Number	Ave. Dec.	Ave. Inc.	Ave. Intensity	Number of Samples	Fisher Radius	Fisher Kappa	Alpha 95	Longitude of Pole	Latitude of Pole
youngest									
20	287	56.1	$.255\times10^{-2}$	7	6.93	87.4	6.49	188	35.0
19	307	63.9	$.207\times10^{-2}$	8	7.56	16.1	14.2	186	52.8
18	264	66.0	$.126\times10^{-3}$	1	1.00	0.0	0.0	167	27.4
17	288	66.7	$.286\times10^{-3}$	3	2.92	25.2	25.1	174	41.8
16	325	46.7	$.240\times10^{-2}$	3	2.98	106	12.1	224	57.9
15	319	47.5	$.146\times10^{-2}$	3	2.97	70.2	14.8	218	54.3
14	323	43.3	$.270\times10^{-2}$	3	2.95	40.4	19.6	226	55.0
13	300	15							
12	99.0	50.9	$.348\times10^{-2}$	3	2.91	23.2	26.2	57.9	14.9
11	117	54.6	$.303\times10^{-2}$	4	3.99	286	5.45	71.0	7.0
10	129	49.0	$.230\times10^{-2}$	5	4.95	76.9	8.78	75.8	3.4 south
9	116	51.7	$.150\times10^{-2}$	5	4.96	97.0	7.81	69.1	5.0
8	128	46							
7	112	46.4	$.411\times10^{-2}$	4	3.97	91.0	9.69	62.9	4.3
6	134	60.6	$.395\times10^{-2}$	6	5.33	7.49	26.2	85.6	4.1
5	124	21.0	$.445\times10^{-2}$	6	5.95	109	6.42	61.0	16.3 south
4	122	17.6	$.282\times10^{-2}$	3	2.97	72.6	14.6	58.1	16.4 south
3	156	28.0	$.266\times10^{-2}$	3	2.10	2.22	119	91.4	28.1 south
2	182	-23.0	$.796\times10^{-2}$	2	1.99	109	24.2	122	59.2 south
1	191	-19.8	$.368\times10^{-2}$	4	3.96	12.7	26.9	138	56.0 south
oldest									

Table V

Summary of A.C. demagnetization data, Steens Mountain - section one

Flow Number	Ave. Dec.	Ave. Inc.	Number of Samples	Fisher Radius	Fisher Kappa	Alpha 95
youngest						
20a	235	73.2	5	4.98	270	4.67
20d	287	51.9	5	4.99	404	3.81
19a	281	64.6	5	4.97	144	6.41
19d	285	58.3	5	4.99	2111	1.67
18	271	61.3	5	4.99	810	2.69
17	287	55.2	5	4.94	72.6	9.04
16	305	45.3	5	4.92	49.1	11.0
15	311	50.1	5	4.97	130	6.73
14	266	41.1	5	4.43	7.01	31.1
13 ?	150	25.2	4	3.27	4.11	51.9
12	120	43.8	5	4.85	27.2	14.9
11	110	47.8	5	4.79	19.3	17.9
10	122	35.2	5	4.73	15.2	20.3
9	137	37.8	5	4.97	124	6.89
8	124	50.3	5	4.96	93.0	7.97
7						
6	122	35.7	5	3.17	2.18	69.1
5	132	13.0	5	4.98	255	4.80
4	119	30.7	5	4.49	7.87	29.1
3	185	20				

Table V - continued

Flow Number	Ave. Dec.	Ave. Inc.	Number of Samples	Fisher Radius	Fisher Kappa	Alpha 95
2	184	-17.6	5	4.98	250	4.85
1	199	-23.8	5	4.89	35.8	13.0

Table VI

Summary of data Steens Mountain - section two original NRM data

Flow Number	Ave. Dec.	Ave. Inc.	Ave. Intensity	Number of Samples	Fisher Radius	Fisher Kappa	Alpha 95	Longitude of pole	Latitude of pole
youngest 15	311	41.3	$.144 \times 10^{-2}$	3	2.98	171	9.45	217	45.3
14	316	43.1	$.153 \times 10^{-2}$	7	6.73	21.9	13.2	220	49.7
13	337	54.5	$.148 \times 10^{-2}$	7	6.89	53.9	8.3	224	70.3
12 ?	161	5							
11	111	47.6	$.556 \times 10^{-3}$	3	2.98	122	11.2	63.1	5.5
10	135	46.7	$.958 \times 10^{-3}$	6	5.98	207	4.67	79.5	8.2 south
9	145.2	36.7	$.272 \times 10^{-2}$	6	5.65	14.4	18.3	84.0	19.2 south
8	134	35.8	$.579 \times 10^{-3}$	3	2.99	942	4.02	74.0	14.4 south
7	116	46.7	$.938 \times 10^{-3}$	6	5.73	18.5	16.0	66.1	1.8
6	123	42.2	$.507 \times 10^{-3}$	6	5.94	79.8	7.55	68.6	4.9 south
5 ?	305	-64							
4	160	50.4	$.391 \times 10^{-2}$	4	2.80	2.51	74.4	101	14.0 south
3 ?	227	5							
2	194	-33.1	$.301 \times 10^{-2}$	5	4.99	683	2.93	149	62.5 south
1 oldest	198	-35.6	$.220 \times 10^{-2}$	2	1.99	1194	7.23	158	62.3 south

Table VII

Summary of Data, Steens Mountain - Section two, A.C. demagnetization data

Flow Number		Ave. Dec.	Ave. Inc.	Number of Samples	Fisher Radius	Fisher Kappa	Alpha 95
15		306	30.9	5	4.78	18.0	18.5
14		no data					
13		319	32.9	5	4.74	15.3	20.2
12	?	308	42				
11		134	30.4	5	4.86	27.9	14.7
10		137	32.8	5	4.92	49.5	11.0
9		no data					
8		no data					
7		141	26.5	5	4.94	67.7	9.36
6		128	25.2	6	5.84	30.8	12.3
5	?	183	-45				
4	?	191	2				
3		193	-29.7	5	4.99	531	3.32
2		196	-36.2	5	4.99	2563	1.51

Table VIII

Summary of Original NRM Data, Poker Jim Ridge

Flow Number	Ave. Dec.	Ave. Inc.	Ave. Intensity	Number of Samples	Fisher Radius	Fisher Kappa	Alpha 95	Longitude of Pole	Latitude of Pole
youngest									
20	34.9	73.9	$.211 \times 10^{-2}$	5	4.91	42.8	11.8	81.1	62.6
19	52	64							
18	153	72.2	$.523 \times 10^{-2}$	4	3.86	22.1	20.0	105	12.4
17	153	72							
16	? 78	48							
15	223	16							
14	? 319	65							
13	? 20	36							
12	319	65.6	$.132 \times 10^{-2}$	7	6.80	29.7	11.26	185	61
11	340	58.7	$.784 \times 10^{-3}$	5	4.73	14.8	20.56	214	74.6
10	156	62.7	$.101 \times 10^{-2}$	7	6.88	50.0	8.62	103	0.6 south
9	129	66.9	$.123 \times 10^{-2}$	4	3.99	305	5.26	88	12.4
8	? 216	67							
7	? 29	52							
6	? 244	39							
5	163	-30.9	$.104 \times 10^{-1}$	4	3.67	9.17	32.1	265	60.4
4	254	31.7	$.101 \times 10^{-1}$	3	2.66	5.98	55.6	186	0.7
3	247	-45.8	$.672 \times 10^{-3}$	6	5.98	260	4.16	217	33.8 south
2	237	-61.5	$.115 \times 10^{-2}$	5	4.97	165	5.97	229	48.8 south
1	215	-48.0	$.781 \times 10^{-3}$	5	4.87	32.6	13.6	195	58.5 south
oldest									

Table IX

Summary of the A.C. demagnetization data, Poker Jim Ridge

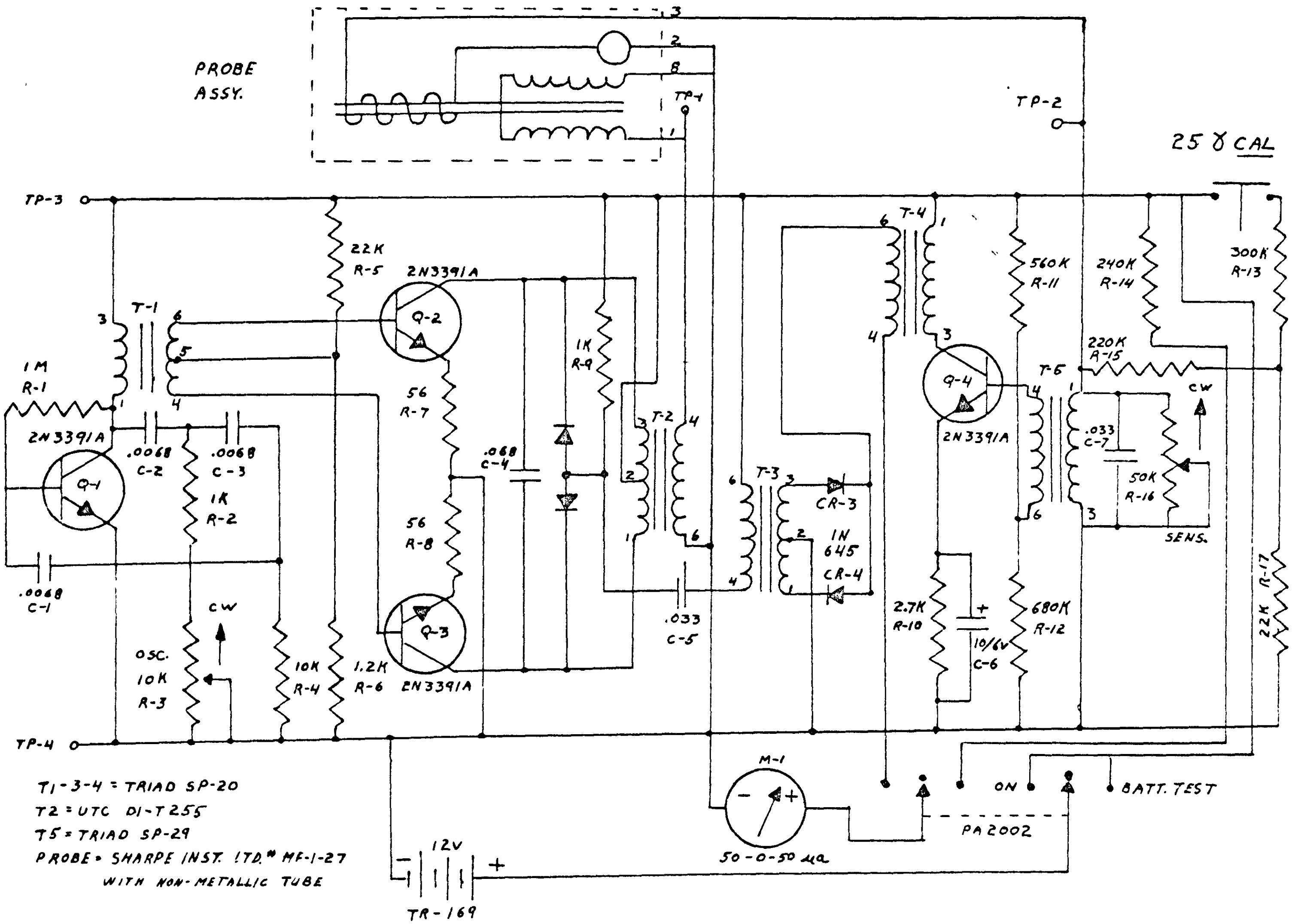
Flow Number	Ave. Dec.	Ave. Inc.	Number of Samples	Fisher Radius	Fisher Kappa	Alpha 95
20	15.5	80.6	5	4.99	949	2.48
19	41.7	76.9	7	6.92	73.8	7.07
18a	153	80.8	5	4.99	724	2.84
18b	166	59.2	3	2.95	40.7	19.6
17a	251	73.3	5	4.95	87.6	8.2
17b	344	86.0	2	1.99	245	16.0
16	66.4	74.9	5	4.99	409	3.79
15b	233	-19.0	4	3.82	16.8	23.1
15c	136	26.4	5	4.39	6.56	32.3
14a	328	69.7	3	2.98	123	11.2
14b	255	37	8	5.29	2.59	43.3
13 ?	309	2				
12a	305	34.5	4	3.40	5.02	45.7
12b	303	42.4	5	4.47	7.61	29.6
11a	106	85.1	8	7.06	7.48	21.7
11b	292	54.9	5	4.64	11.2	23.8
10a	166	44.8	5	4.92	48.4	11.1
10b ?	145	0				
9	124	54.1	5	4.72	14.4	20.9

Table IX - continued

Flow Number		Ave. Dec.	Ave. Inc.	Number of Samples	Fisher Radius	Fisher Kappa	Alpha 95
8a		164	29.3	5	4.61	10.2	25.1
8d	?	136	30				
7a	?	127	8				
7b	?	91	41				
6		no useable data					
5		205	-27.9	7	6.79	28.6	11.5
4		233	26.1	4	3.50	6.03	40.8
3		235	-65.2	5	4.73	15.1	20.3
2		260	-59.3	5	4.99	871	2.59
1		247	-53.5	5	4.99	460	3.57

Appendix C

Fluxgate Magnetometer



PORTABLE FLUXGATE MAGNETOMETER

Figure C-1

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