RICE UNIVERSITY

The Relationship of Cooling History and Stability in Two Suites of Igneous Rocks

by

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Thesis Director's Signature

H.C. Clark

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INTRODUCTION

In field sampling for paleomagnetic study, one always hopes to choose the most stable samples available in order to obtain reliable information about the earth's ancient magnetic field. If the remanence is unstable, of course, the direction and intensity of the magnetization may have changed through time, thus diminishing the value of the field effort, its time and expense. It was our hope in this study to find reliable methods to choose samples in the field by studying the position of a sample in the sill or flow versus its cooling history, and then the relationship of cooling history to stability. AC demagnetization was used to evaluate the stability of the samples. Petrographic examination under reflected light determined the composition and oxidation state of the opaque minerals. Recent work has indicated that oxidation states and stability are closely related (Watkins and Haggerty, 1967, Ade-Hall et al., 1968). We hoped to extend the generality of that relationship and examine its connection to cooling history.

METHODS USED

Sample Collection: Two igneous bodies with different cooling histories were examined, a basalt flow in Mexico City and a differentiated gabbroic sill from western Oregon. The flow is Holocene in age, and the sill is

Tertiary (Oligocene) in age. Each was sampled in at least one vertical traverse, using a gasoline powered core drill. The Mexico City samples come from two full traverses and one supplementary traverse where the flow has broken apart and each side rotated about 40 degrees (fig. 1).

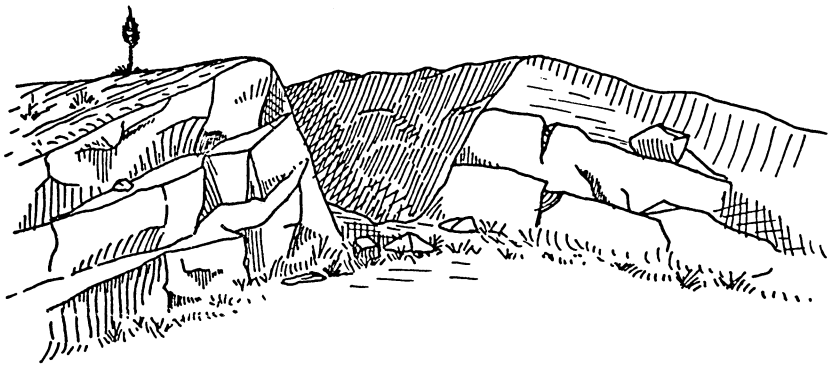
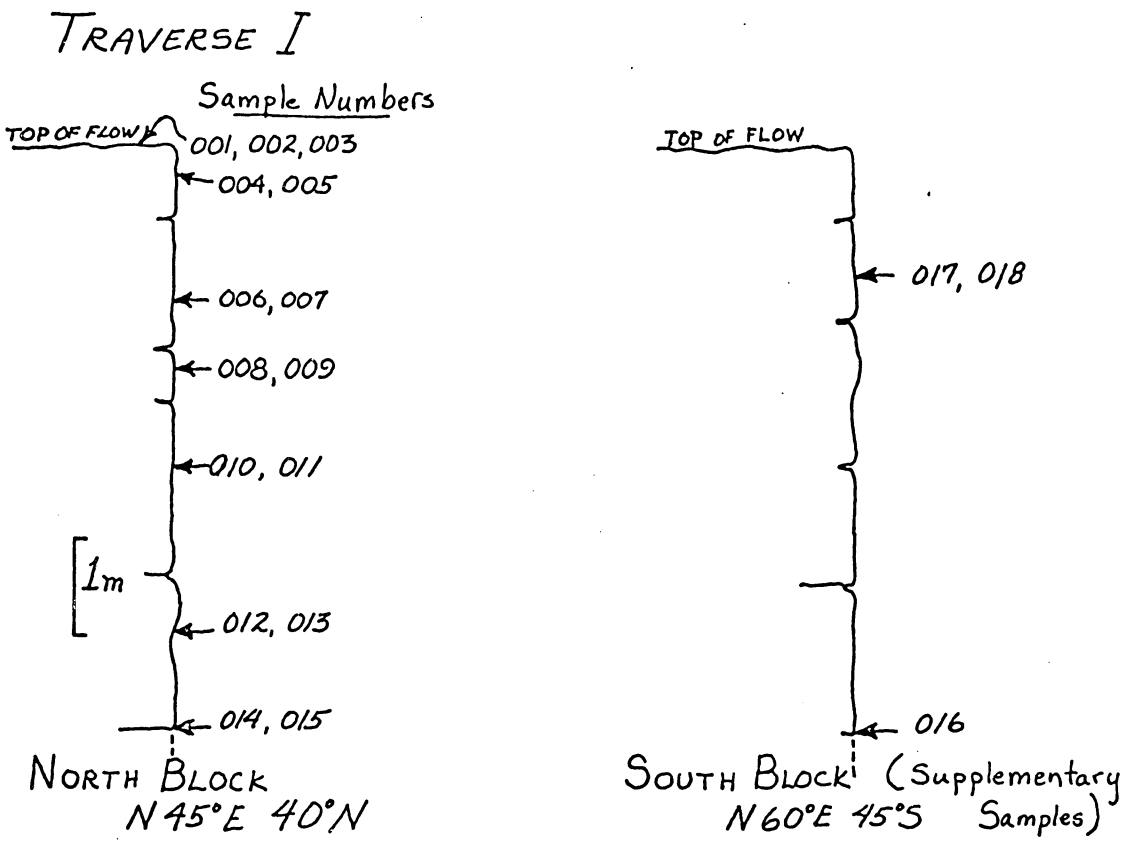


Figure 1. Mexico City. Artist's representation of the broken flow of traverse I.

The sample site spacing varied from 30 cm to 3 meters. The flow varies from 6 to 8 meters in thickness. The Cedar Creek sill in Oregon was sampled at intervals of 5 to 15 meters. The sill was sampled through 32 meters



(a)

Figure 2. a,b. Position of samples in flow, Mexico City. The samples from the south block of Traverse I are the supplementary samples.

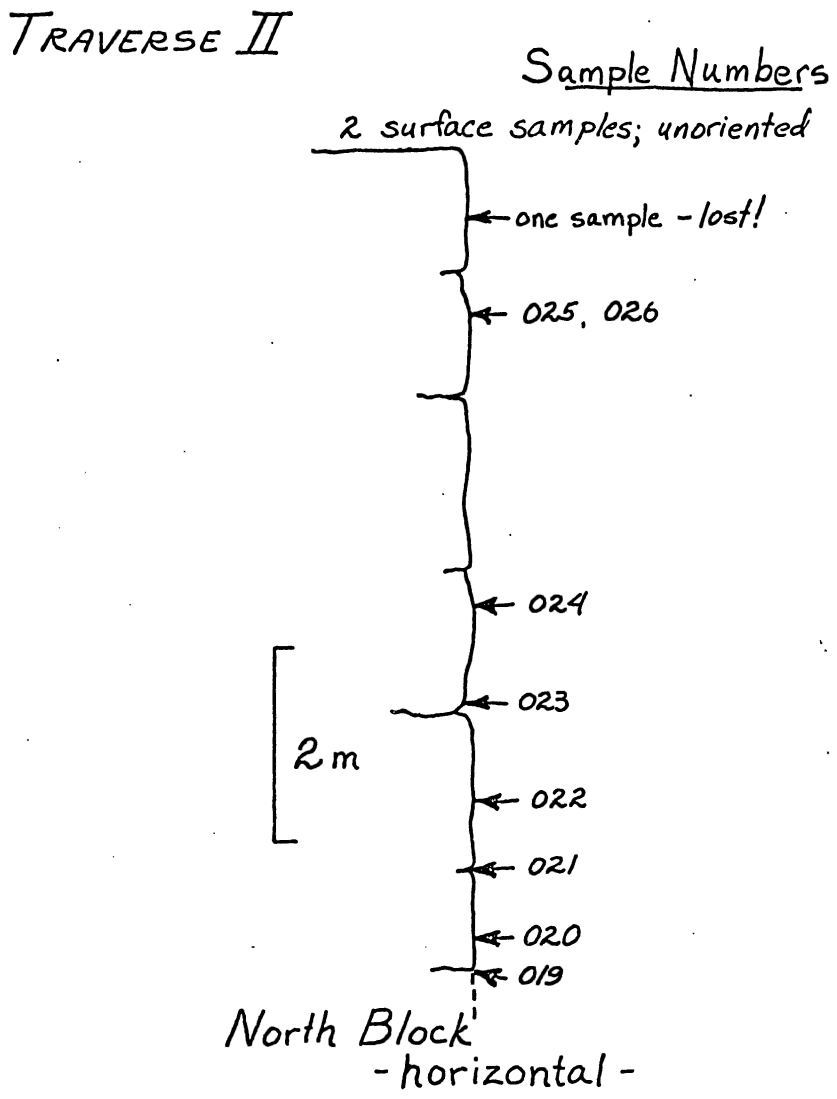

TRAVERSE II
Sample Numbers
2 surface samples; unoriented
one sample - lost!
025, 026
024
023
2 m
022
021
020
019
North Block
- horizontal -

Figure 2b.

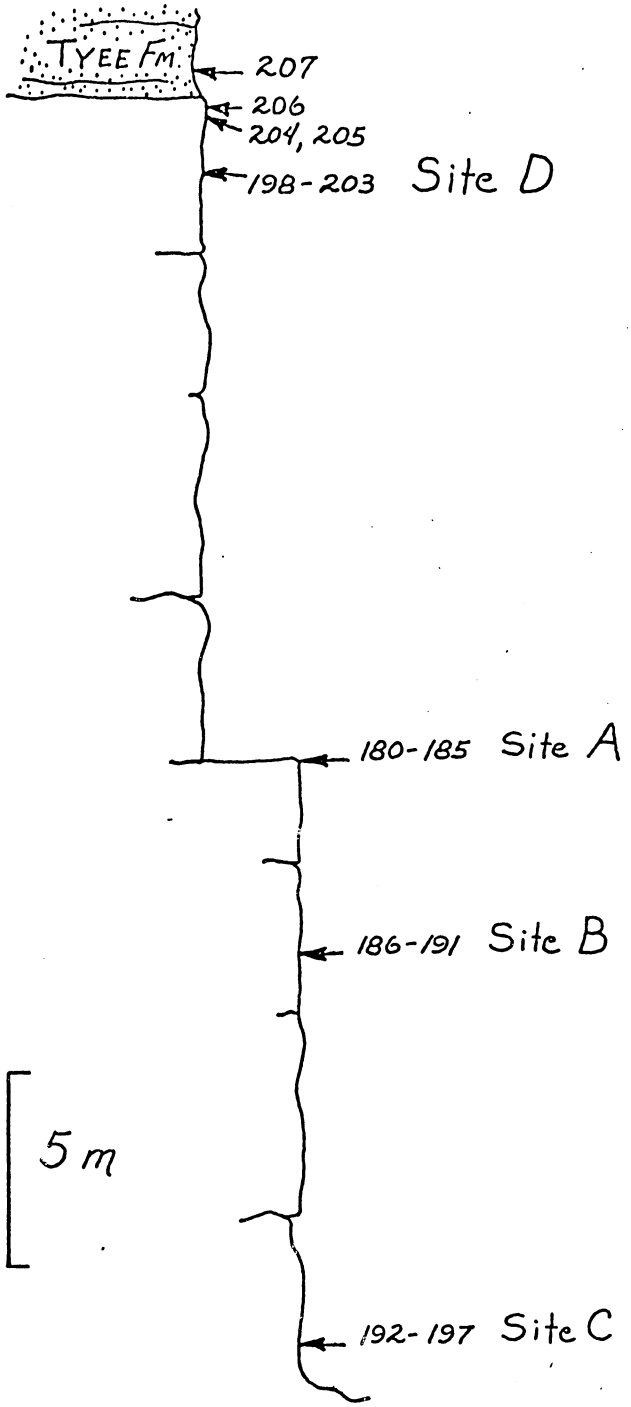


Figure 3. Position of samples in sill, Cedar Creek, Oregon.

but its entire thickness is probably 75 meters (Snavely, unpublished manuscript).

Laboratory Analysis: Each core was cut into 2.28 cm lengths for analysis in an 11-cycle fluxgate spinner magnetometer. Selected samples were progressively demagnetized in a 4 axis tumbler in AC fields up to 100 oe produced by a 400-cycle AC power supply. Other samples were cut and polished for examination under reflected light at 1000X magnification in oil with a Zeiss photomicroscope.

Demagnetization: The stability of a sample is determined by the "hardness" of its remanent magnetization. If a sample has a large number of low coercivity domains, then its magnetization is easily removed or changed by the application of magnetic fields; the intensity of magnetization required to remove the remanence is a measure of the sample stability. By spinning the sample randomly in an alternating magnetic field which decreases from some peak value to zero, it is hoped that the directions of all domains with a coercivity below that peak will become randomly distributed, removing the direction of magnetization that was present before. If this process produces some bias or spurious direction, called anhysteretic magnetization (ARM), then it is not entirely successful (see Appendix B).

An arbitrary number, the S number (Ade-Hall, 1969), was used to compare the stability of the samples. The formula

$$S = \frac{R}{R+r}$$

where R is the intensity after the last demagnetization and r is the sum of the differences of the resultant vectors from the previous demagnetization (fig. 4). If a sample is completely stable, that is, there is no change in its direction or intensity, then r = 0 and S = 1.

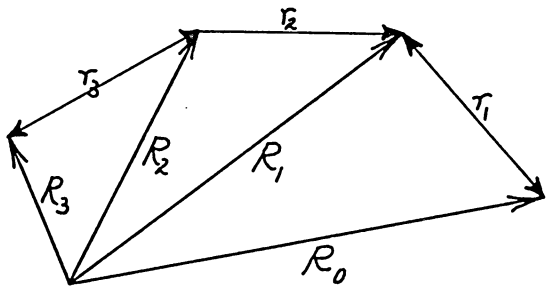


Figure 4. Vector representation of the stability number (S number) calculation. R_0 is the original direction, R_1, after the first demagnetization, etc.; $r_1 = R_0 - R_1$. The non-vector sum of the r_i's gives the r of the equation. The vector sum would be $R_0 - R_i$, which represents only the change from R_0 to R_i, not the intermediate changes.

Petrographic Examination: The relationship of stability and magnetite oxidation is generally well established; high oxidation correlates with high stability, low oxidation with lower stability (Watkins and Haggerty, 1965, 1967, Wilson and Haggerty, 1966, Wilson and Watkins, 1967, and Ade-Hall et al., 1968). High oxidation states are not necessary to produce high stability, but rather the determining factor is effective grain size. The oxidation process reduces the size of the magnetic domains by the exsolution of ilmenite lamellae, which serve as grain "boundaries" for the magnetic domains. If the grains are small enough, a single domain per "grain" state, which is extremely stable, may be reached. These single domain grains are small enough to be beyond the limits of microscope resolution (Larsen et al., 1969).

Under reflected light the sequence of oxidation of titanomagnetite can clearly be seen. The classification of the oxidation states is according to the appearance of certain index minerals (Watkins and Haggerty, 1967, Ade-Hall et al., 1968).

Class I - Unaltered titanomagnetite.

Class II - Containing a few lamellae of exsolved ilmenite.

Class III - More than 50% of the grain contains exsolved ilmenite.

Class IV - The ilmenite alters to "metailmenite", a white alteration product too fine to be identified. Magnetite alters to hematite.

Class V - Rutile appears in a hematite host in both ilmenite and titanomagnetite. Relict areas of magnetite may contain exsolved alumino-spinel rods.

Class VI - The highest state of oxidation, characterized by pseudobrookite, a high temperature (585° C) index mineral.

In order to evaluate the oxidation state of the sample, a grain count of each polished section was made, counting at least 100 magnetite grains. Ilmenite grains were also counted in passing, and the presence or absence of sulfides noted. The oxidation state (M number) of the sample is determined by the formula

$$M = \sum_{n=1}^{6} \frac{\text{number of grains with oxidation state n}}{\text{total number of grains counted}}$$

RESULTS

Mexico City

NRM: All the samples from this flow are normally magnetized, as one might expect. The directions are not badly scattered, as shown in figure 5, and are similar to that of the present field but shallower in inclination.

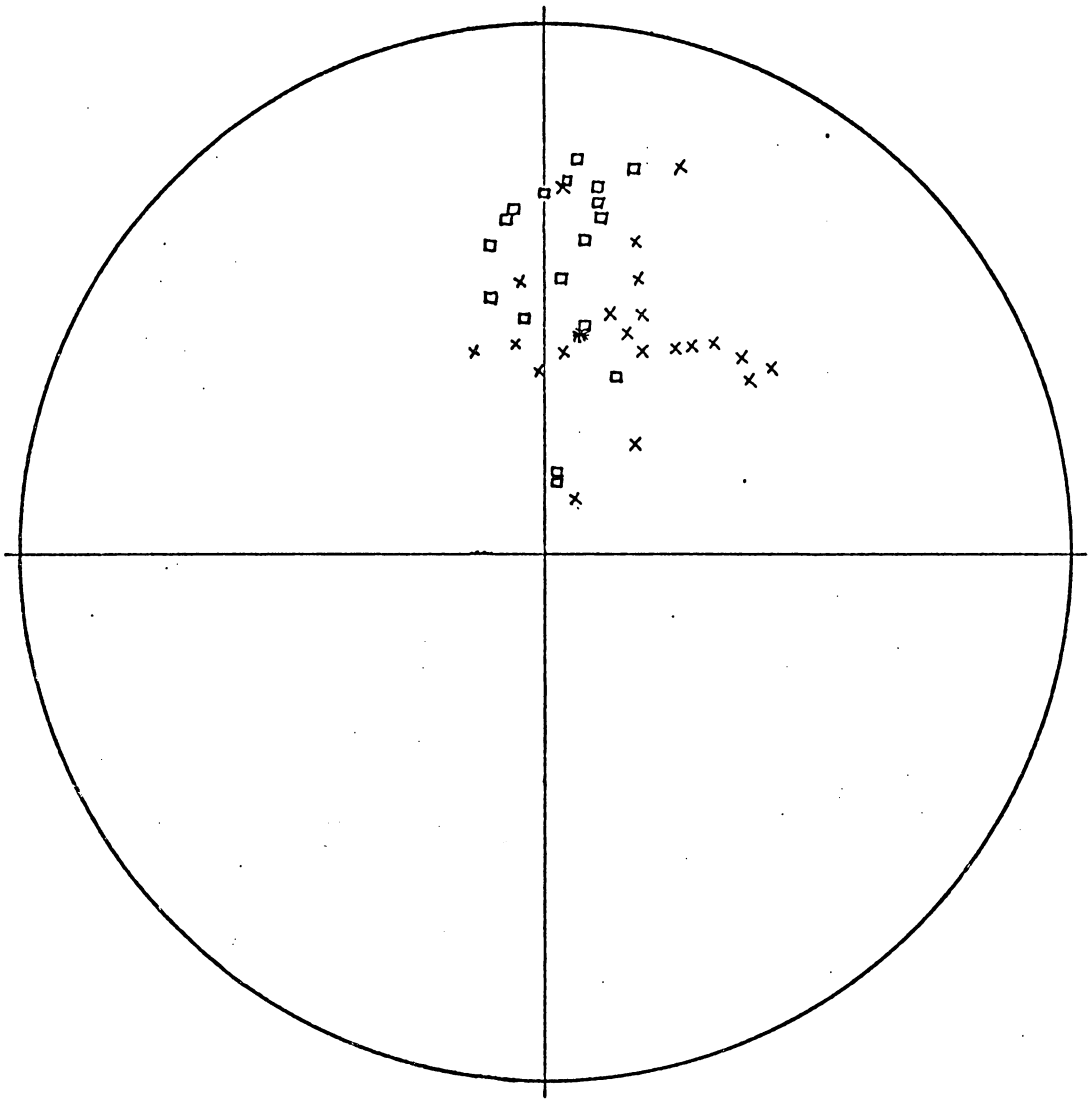


Figure 5. Directions (plotted on an equal area stereonet) for natural remanent magnetization (NRM) of the Mexico City samples.

x= Traverse I, □ = Traverse II, ✱ = present direction of magnetic field.

The general separation of the samples from the two traverses is clear.

The variation of inclination with depth, for traverses I and II (fig. 6) shows that the range of values generally decreases downward for traverse I (the tilted block), suggesting that the rotation may have occurred as the block was cooling. No definite conclusion may be drawn, however, since the inclinations of traverse II show such a wide variation. Thus the question of the source of scattering remains - a result of rotation during cooling or sample instability?

Demagnetization: AC demagnetization of samples of traverse I up to 100 oe generally moves these directions toward the present field, and toward traverse II directions, but not conclusively into traverse II (see fig. 7). Samples demagnetized at 100 oe show the same decrease in inclination with depth that the NRM samples show (fig. 6).

Oxidation States: The oxidation states in these samples are uniformly low. The larger grains generally never pass the stage of ilmenite exsolution (Class II or III in Watkins and Haggerty, 1967, and Ade-Hall et al., 1968). Only the smallest grains show any higher oxidation. Discrete ilmenite is abundant in some samples and nearly absent in others. In a few samples from traverse II there is alteration of the discrete ilmenite to hematite, but this may be a secondary change, not necessarily produced at high temperatures. There appears to be no significant

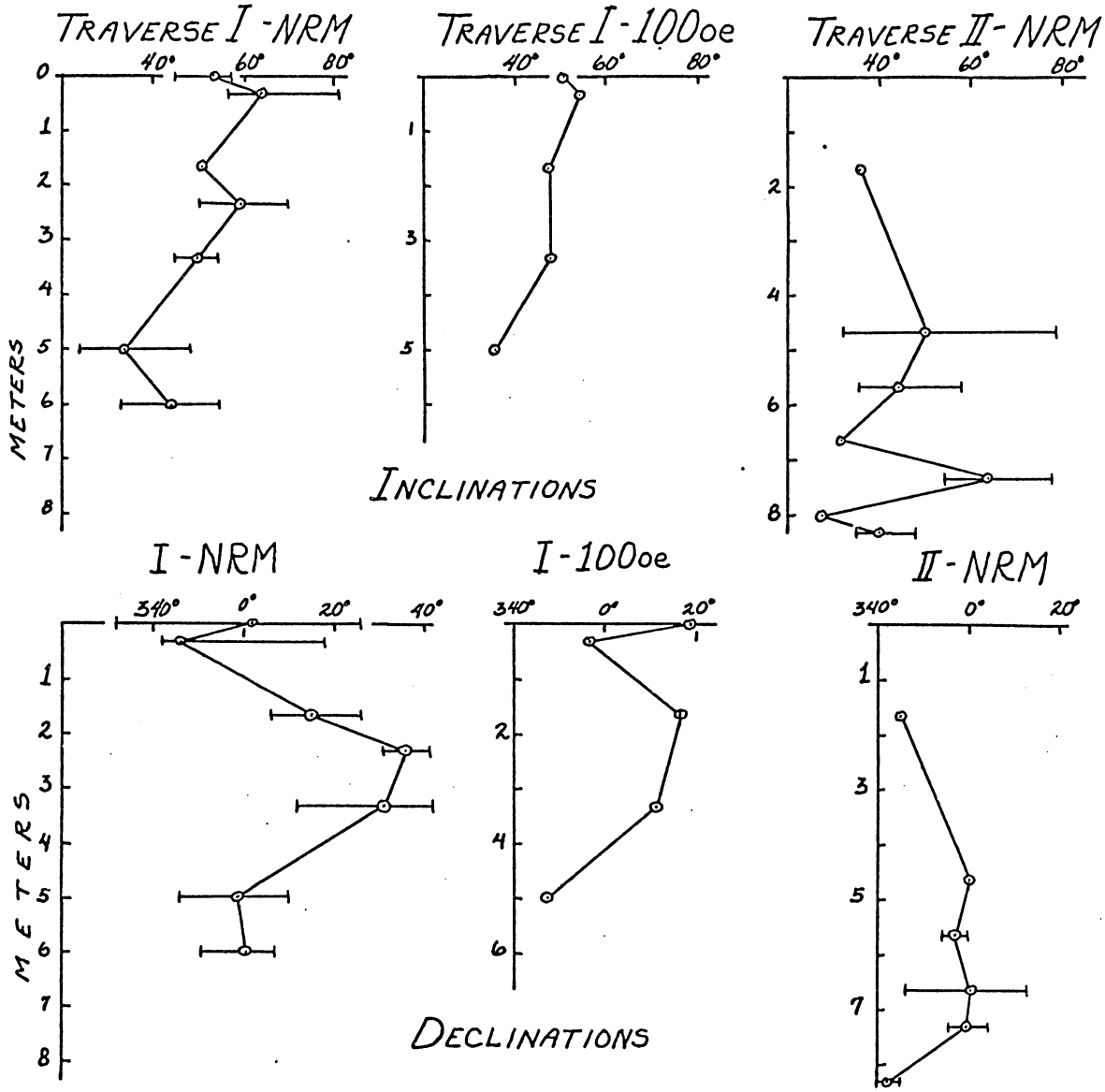


Figure 6. Inclination and declination versus position in the flow, traverse I and II, Mexico City. Bars on the original magnetization lines represent the range of values, points represent the averages.

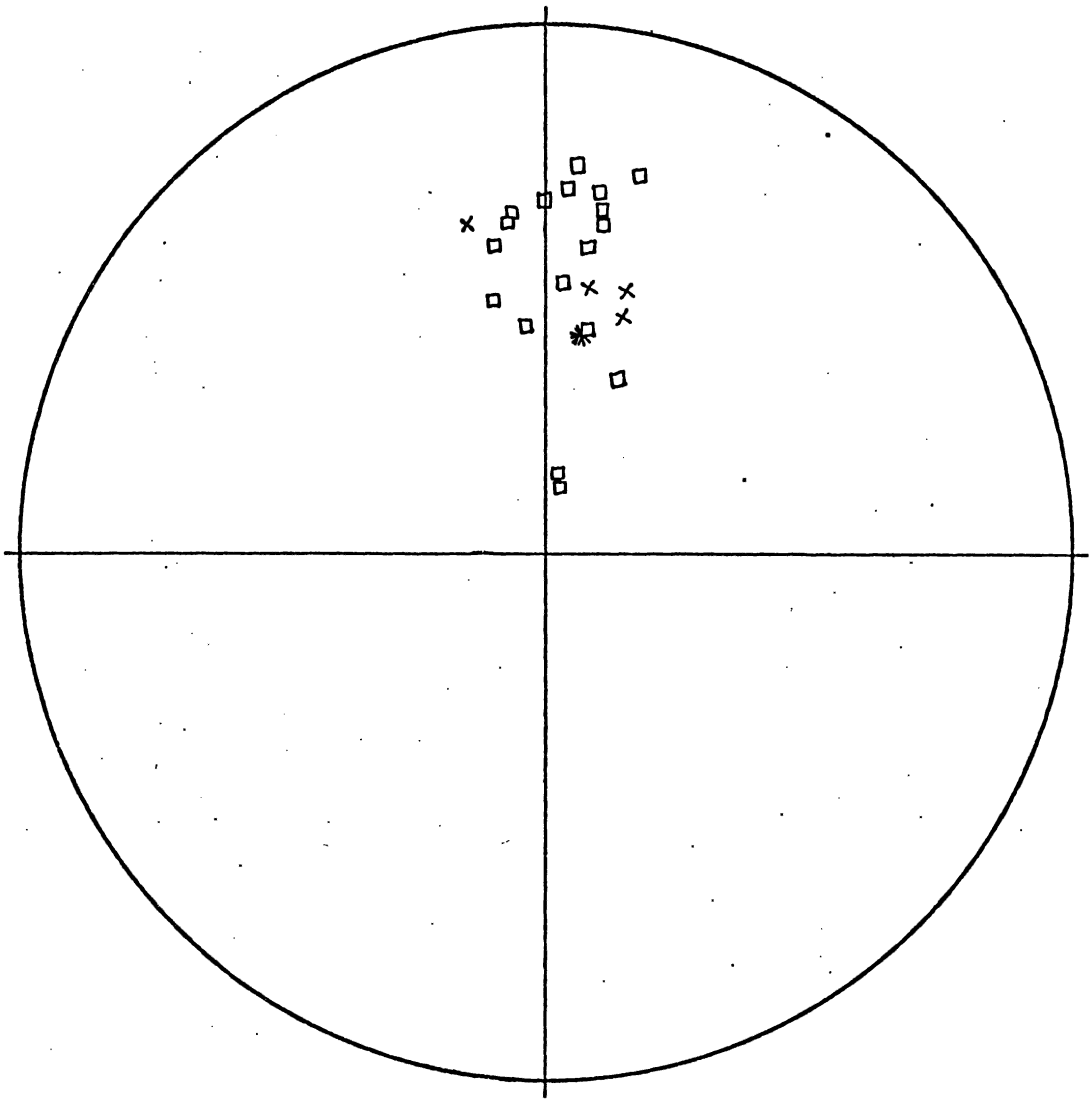


Figure 7. Demagnetized directions (100 oe) for traverse I (×), and original magnetization for traverse II (□), showing the rotation of the traverse I directions toward those of traverse II. Present field (✱).

difference in directions for these samples. Plots of oxidation states, stability, and inclination versus position in the flow show no direct correlation (fig. 8).

Cedar Creek, Oregon

NRM: The original magnetization directions of the Cedar Creek sill are normally magnetized in the lower part of the sill sampled (Sites A, B, and C, figs. 3 and 9), but those of the upper part are reversely magnetized, and badly scattered (fig. 10). The Tyee Sandstone sample also shows a normal magnetization (fig. 11). The cause of the reversal is purely conjectural, but self reversal is a distinct possibility.

Demagnetization: AC demagnetization results show that the reversed samples are quite unstable (fig. 12), and that the normally magnetized samples are reasonably stable, with one exception in the lower part of the sill (fig. 13). Demagnetization does nothing to resolve the problem of the reversal in the upper portion of the sill. It must be noted that because of limitation of time and equipment more samples were not demagnetized at higher fields. This might give a clearer picture of reversal trends in the upper part of the sill.

Opaque Petrology: Ilmenite and magnetite are the major opaque constituents, but there is a considerable

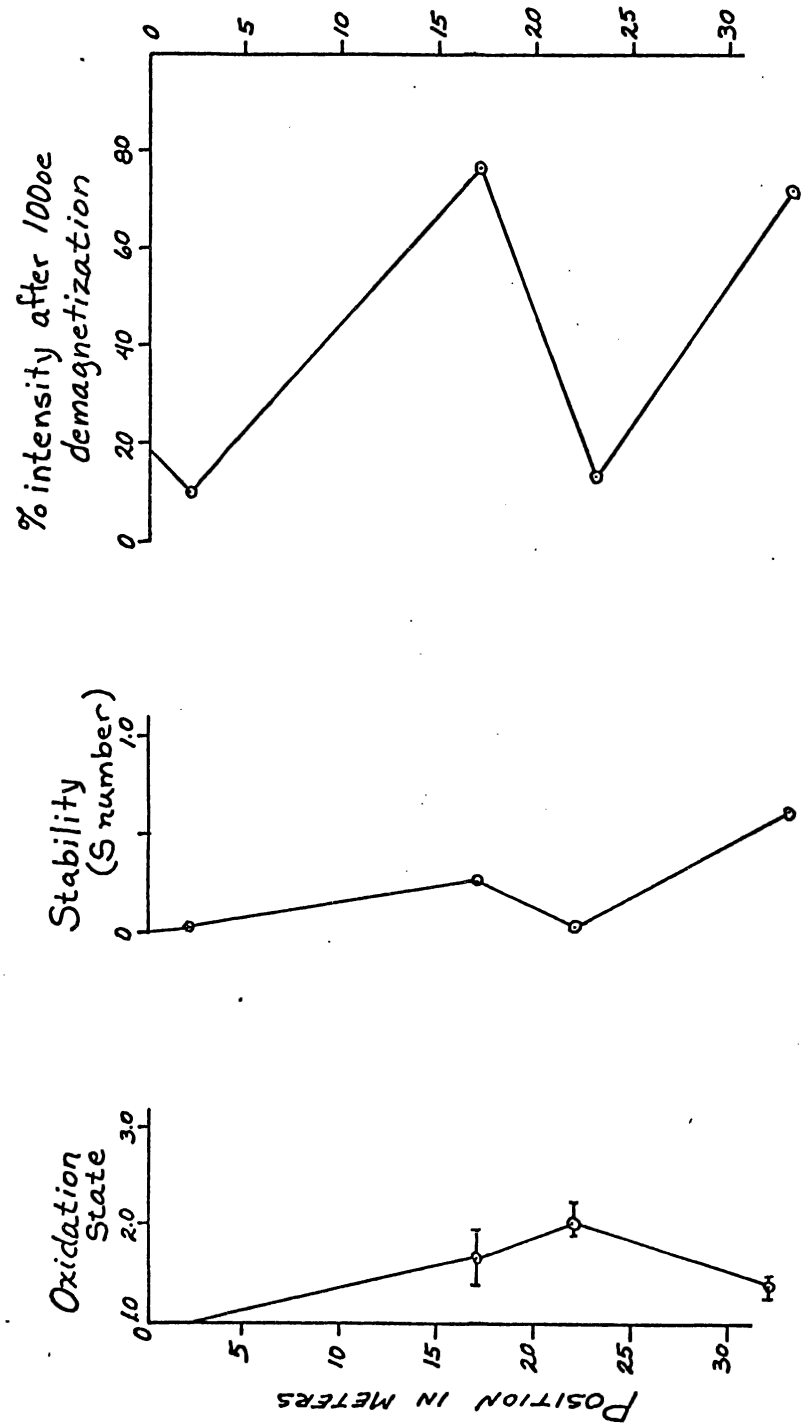


Figure 8a. Stability number, magnetite oxidation number and inclination versus position in the flow, Mexico City.

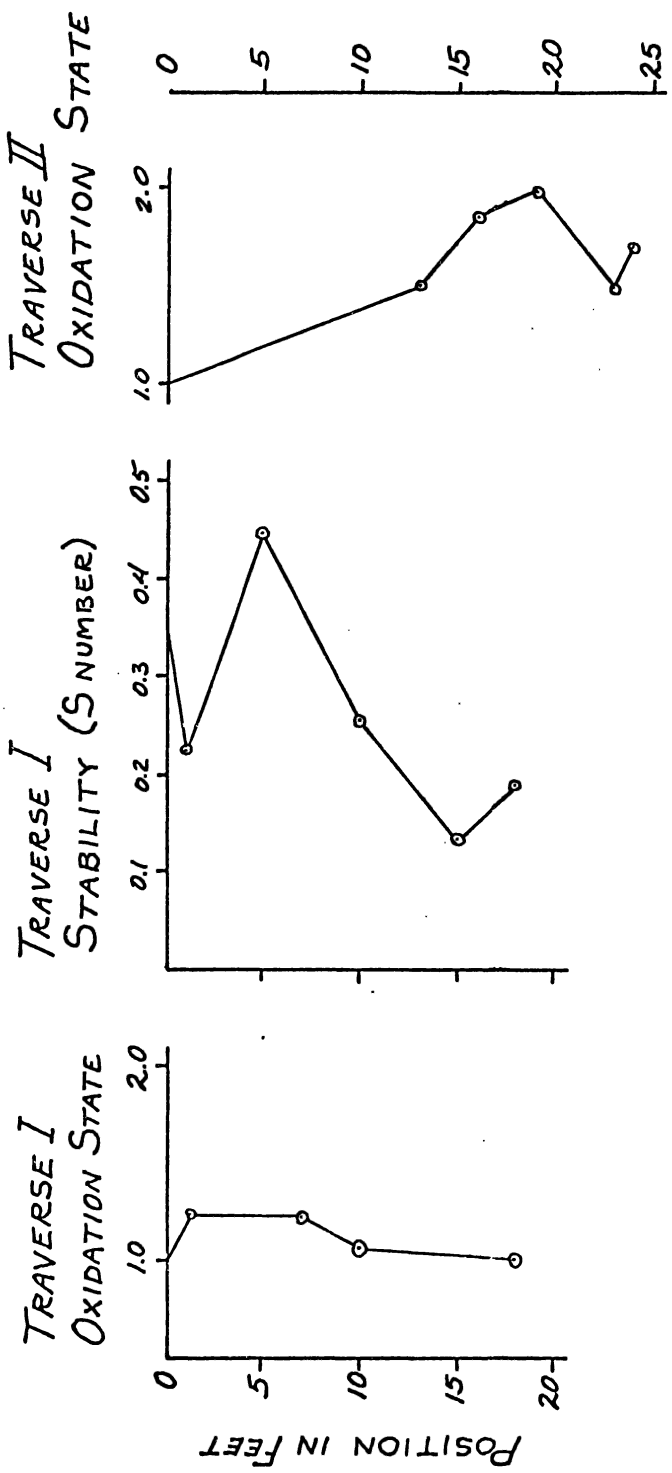


Figure 8b. Stability number, magnetite oxidation number, and % intensity remaining after 100 oe demagnetization versus position in the sill, Cedar Creek.

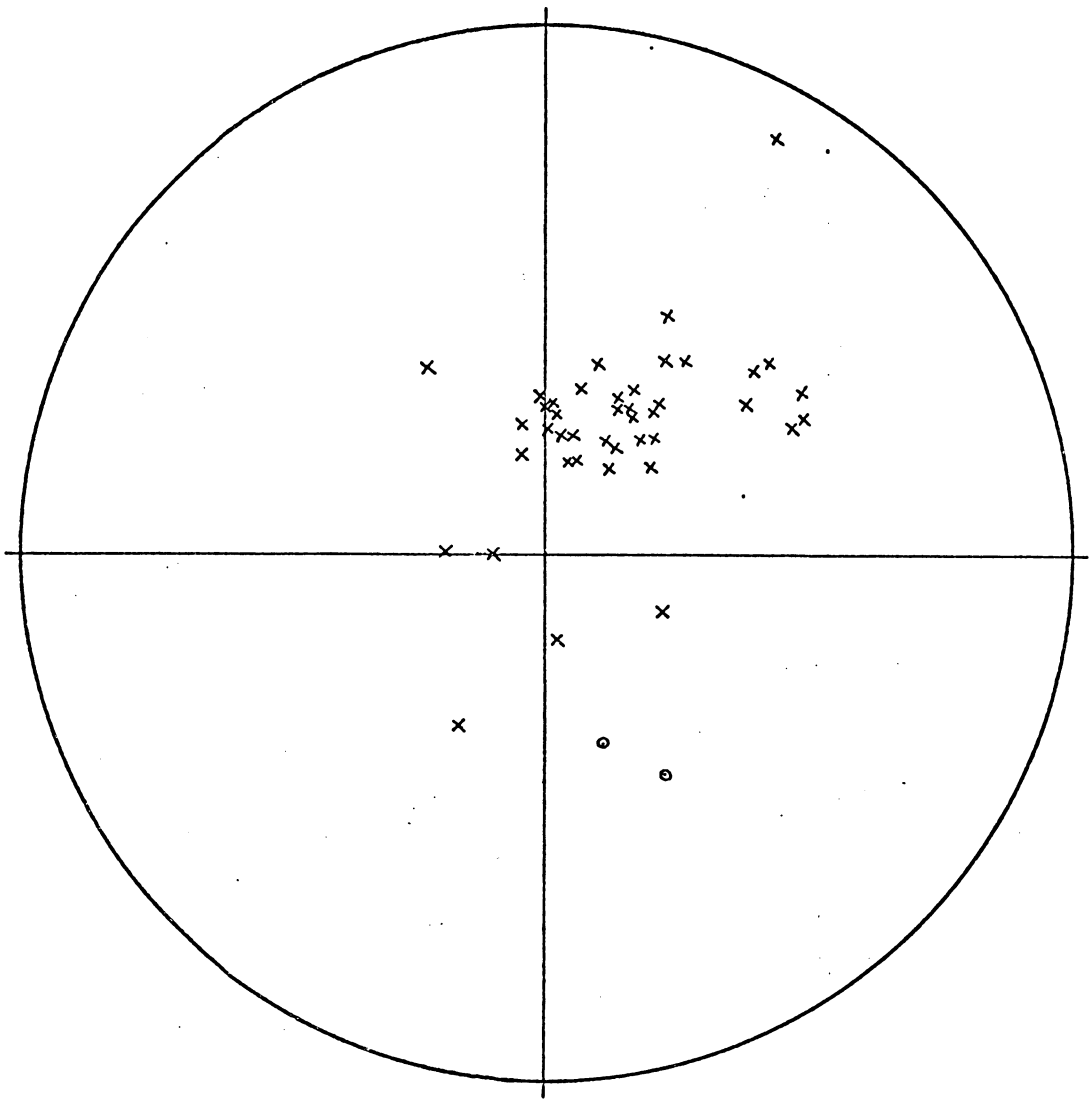


Figure 9. Directions of original magnetization for sites A, B, C (see fig. 3), Cedar Creek sill.
× = normal magnetization (lower hemisphere)
⊙ = reversed magnetization (upper hemisphere)

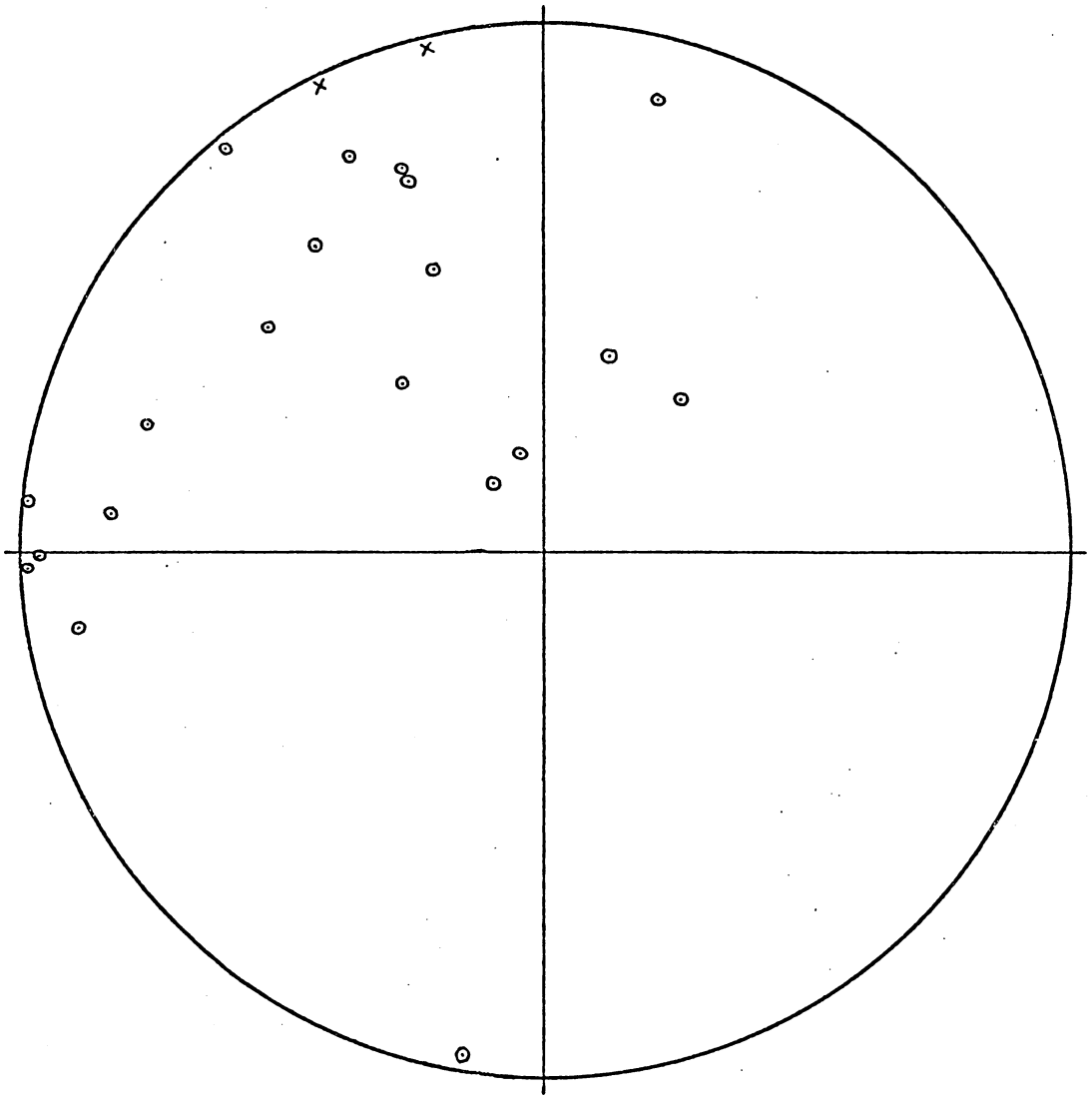


Figure 10. Original magnetization, site D.

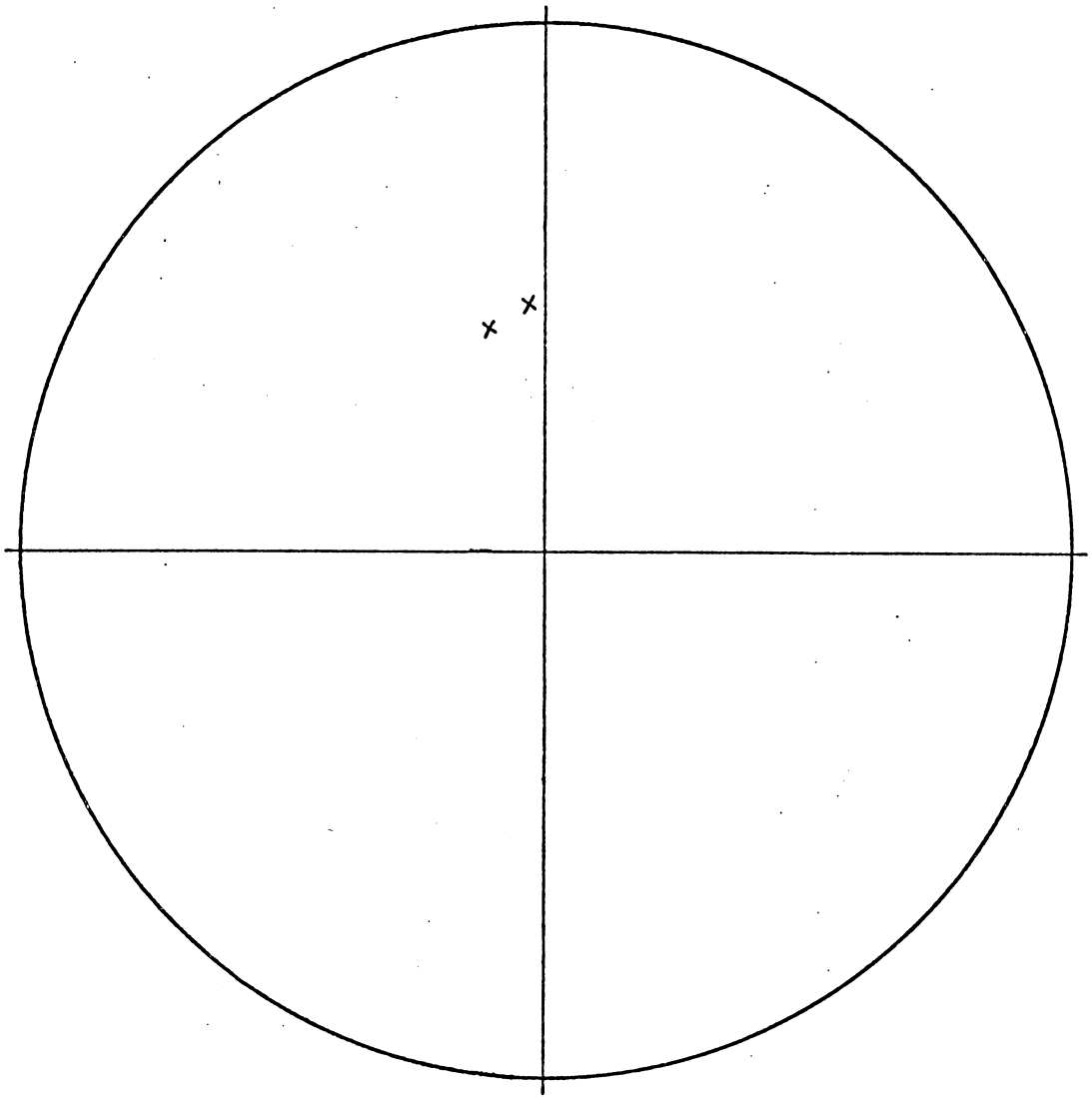


Figure 11. Original magnetization, Tyee sandstone.

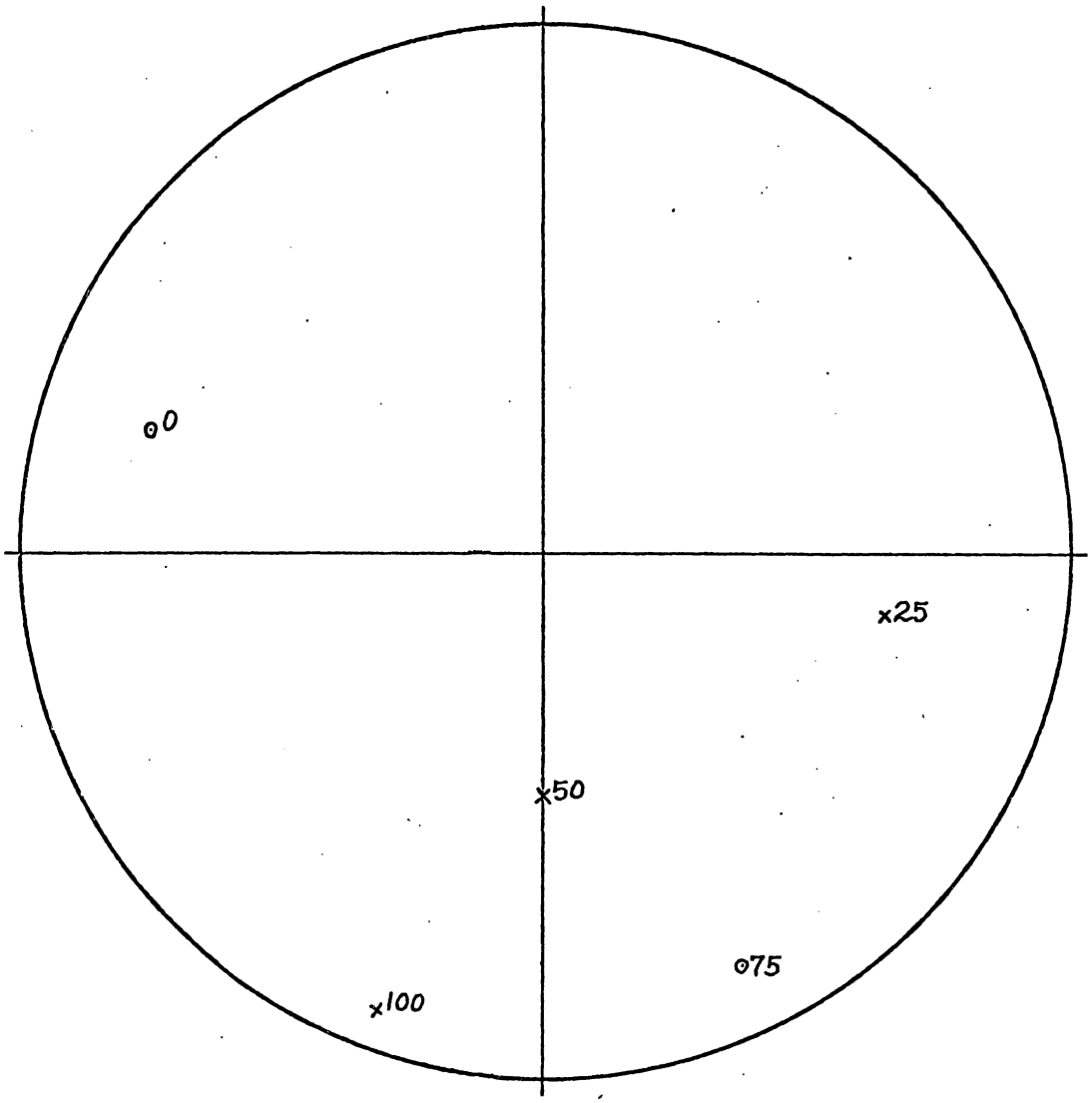


Figure 12, a,b. Demagnetization paths for two samples from site D, Cedar Creek. The number beside the symbol represents the demagnetizing field in oersteds. Symbols as for fig. 9.

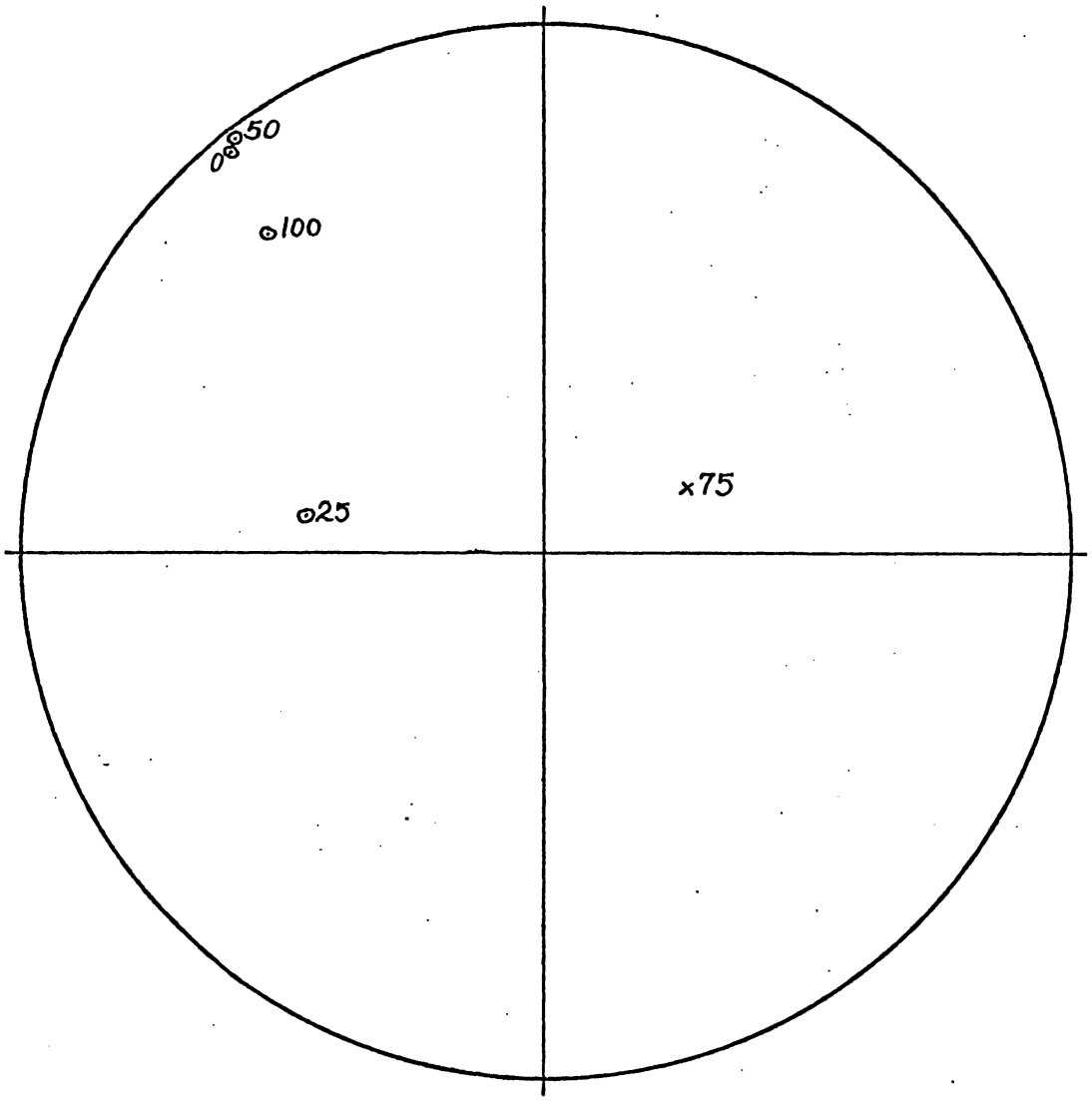


Figure 12b.

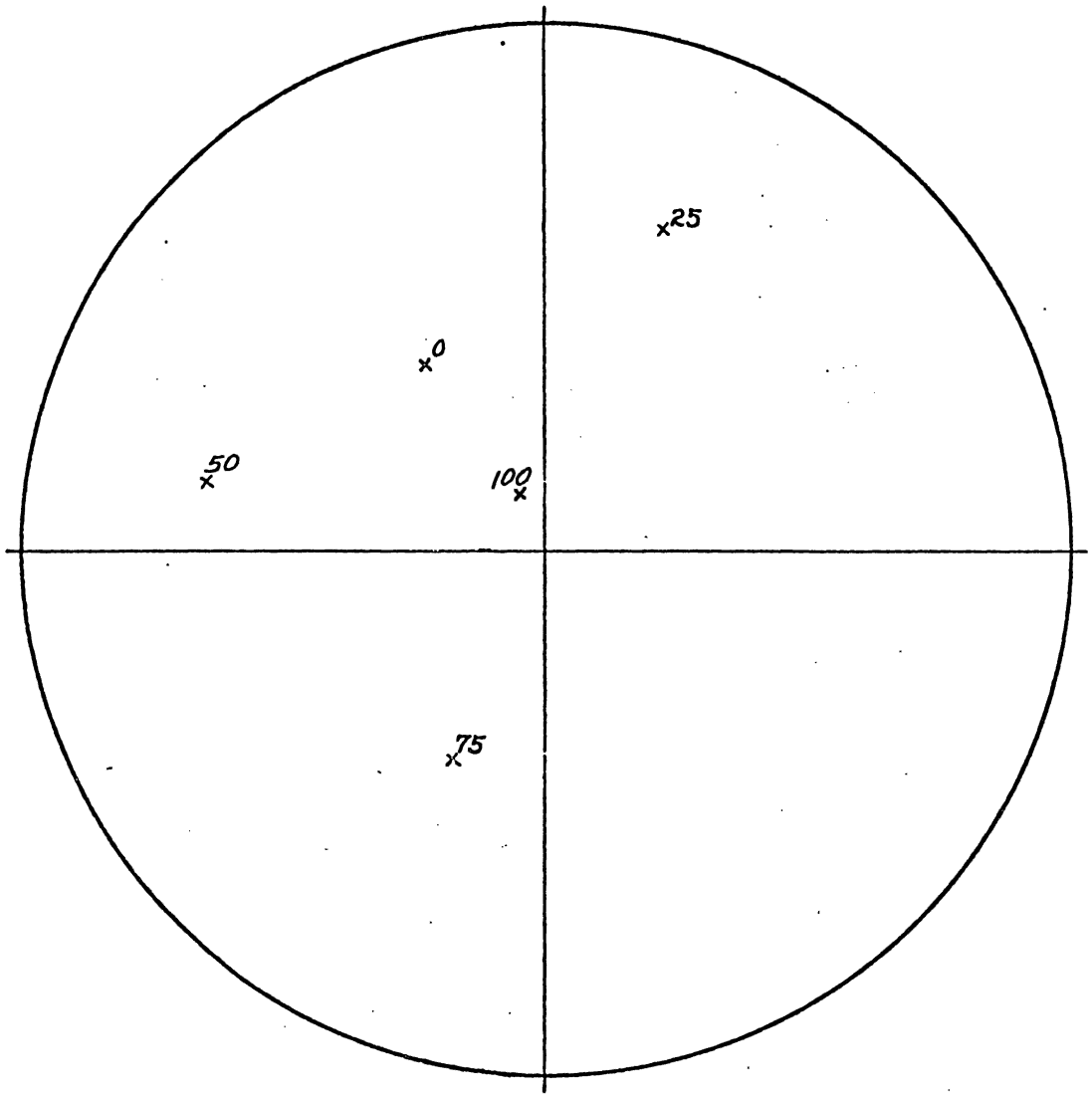


Figure 13. Demagnetization path for sample from site A, Cedar Creek.

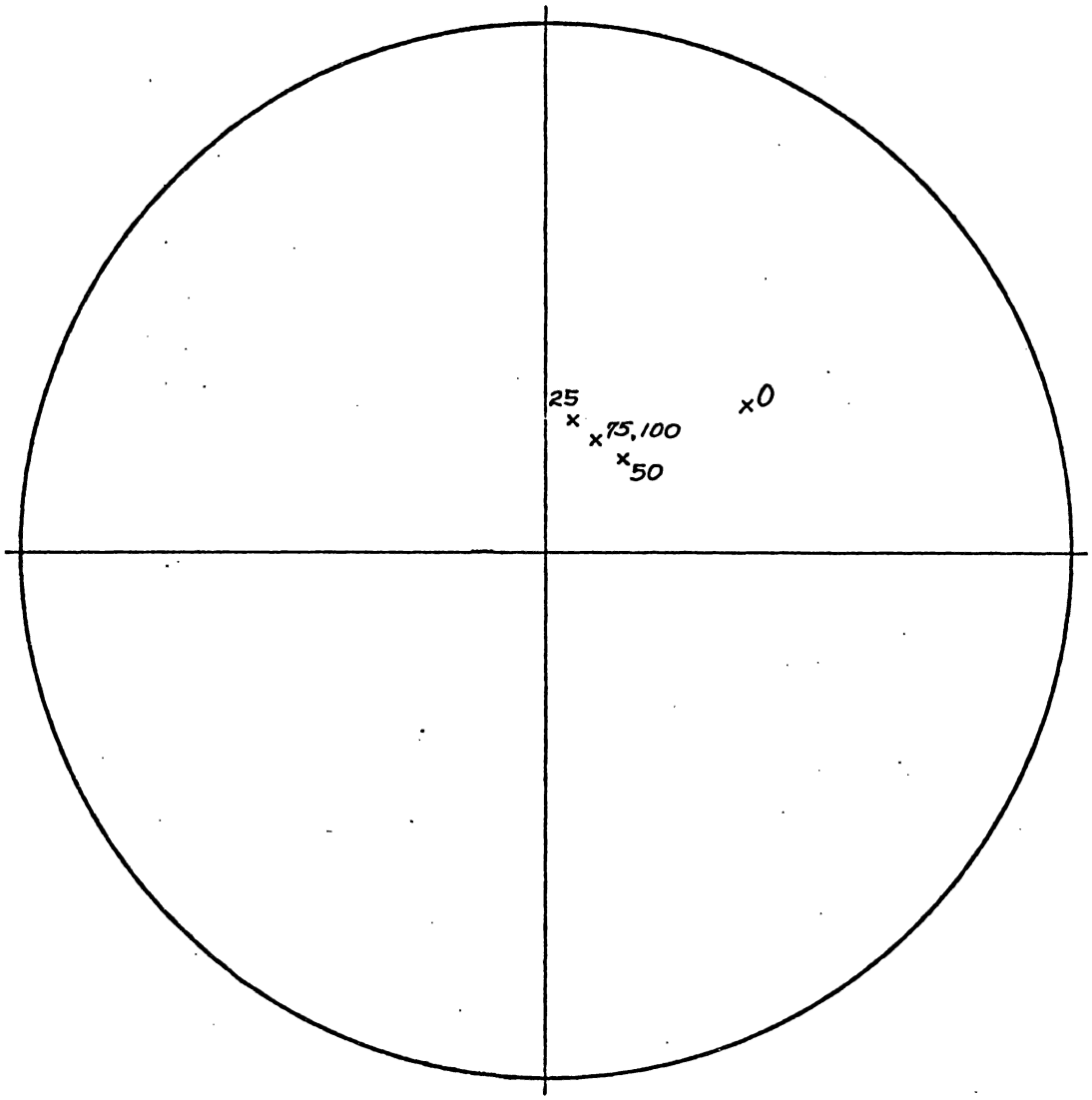


Figure 13b. Demagnetization path for sample from site B, Cedar Creek.

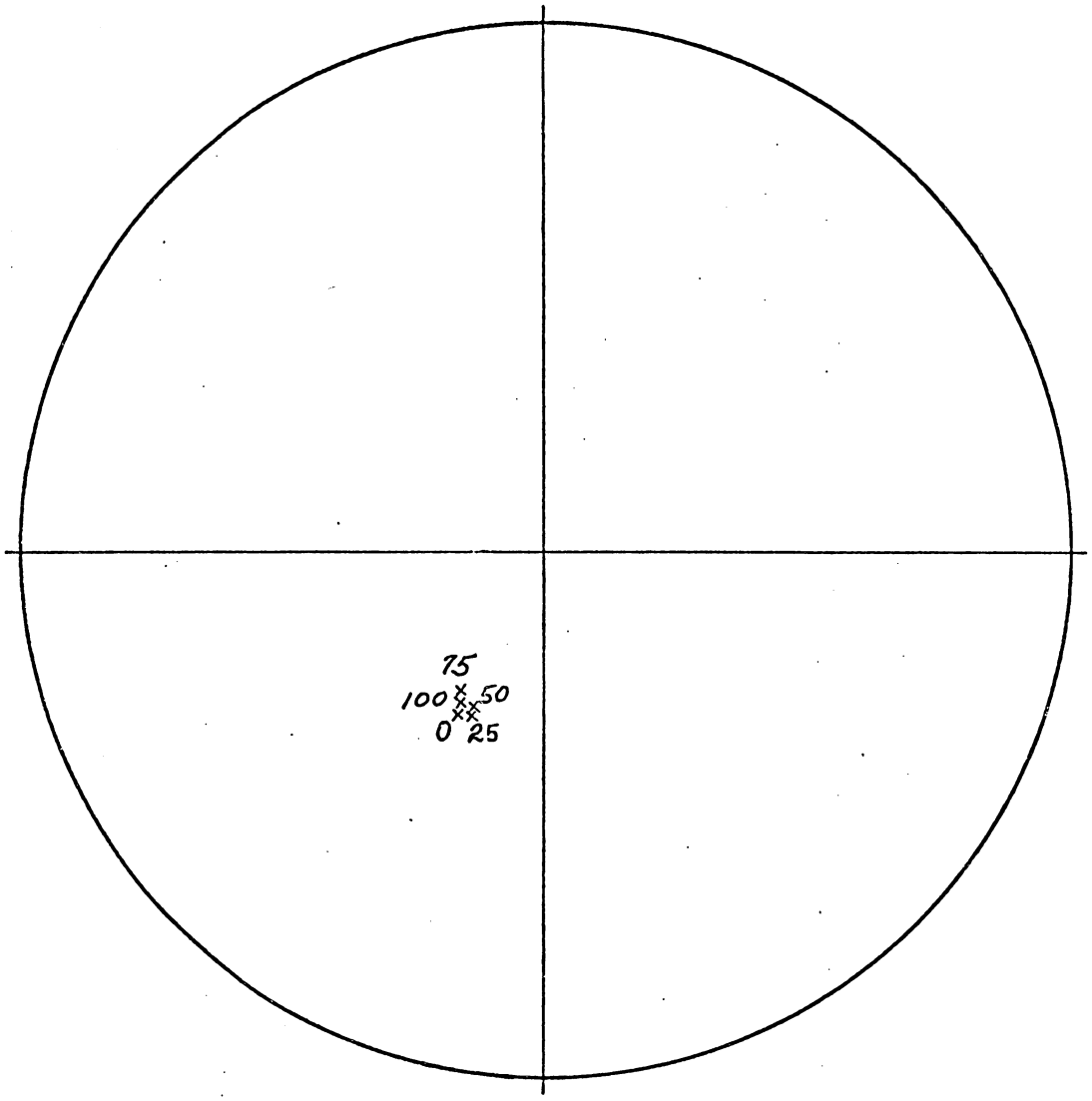


Figure 13c. Demagnetization path for sample from site C, Cedar Creek.

amount of sulfide minerals present (e.g., pyrite, marcasite, chalcopyrite). These sulfides occur as discrete grains, generally small, less than 1 mm in diameter, and are also associated with the ilmenite and magnetite as enclosed, adjoining, or "nearby" grains. The presence of these sulfide minerals is particularly important in light of the low oxidation states found throughout the sill. The alteration of magnetite reaches the ilmenite exsolution stage (Classes II and III) but seldom goes beyond that. There is a textural indication that the ilmenite in some cases was originally exsolved as ulvospinel, which is also a high temperature alteration product of magnetite (Verhoogen, 1961, Ramdohr, 1970). Maghemite may be present as an alteration of the titanomagnetite; this could be confirmed by Curie temperature analysis.

Another feature which appears in the lower portion of the sill is an alteration of the magnetite which may be the titanomagnetite "granulation" of Ade-Hall et al., 1968. In that case the magnetite was altered to what was identified as a type of ferri-rutile. This is probably a low temperature (200 to 300° C) alteration, which occurred much later than the original crystallization and oxidation. Ade-Hall et al., 1968, feel that this granulation is the result of burial and re-heating to the proper temperature.

THEORETICAL COOLING HISTORIES

The cooling history curves contain certain assumptions and approximations which may have some effect on the results obtained, but hopefully these approximations yield "ballpark" figures for the length of cooling and shape of the temperature curve. For the flow, "instant" extrusion was assumed, and the top surface was held at 0° C, certainally an approximation in air, but not for underwater extrusion. The error introduced has been shown to be small (Lovering, 1935) - only a few percent. The lower surface is allowed to heat up through conduction. A diffusivity,

$$h^2 = \frac{k}{c_p \rho}$$

where k = conductivity, c_p = specific heat, and ρ = density, of 0.008, an average thickness of 7 meters and an extrusion temperature of 1200° C were assumed (Lovering, 1936). Curves based on calculations from Lovering (1935) (fig. 14) show that the flow cooled rapidly, passing through the magnetite Curie temperature in less than 20 days and, according to these calculations, based on equations and graphs in Lovering (1935) the entire flow had cooled past 70° C in about six months.

The sill, on the other hand (fig. 15), took approximately 1000 years, according to these calculations, to pass the Curie temperature at its center. The

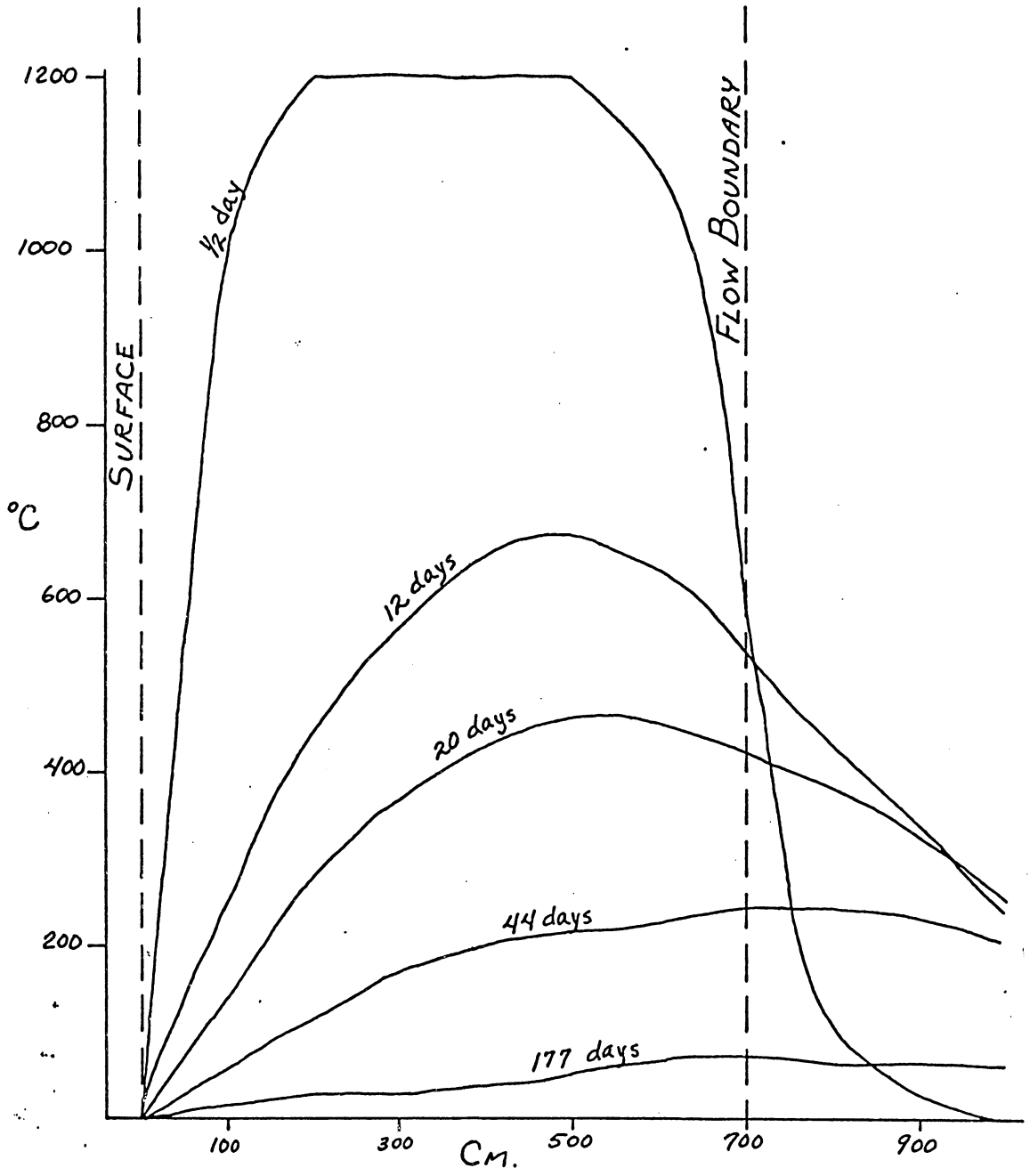


Figure 14. Theoretical cooling curve for the Mexico City flow. Dashed lines represent the flow boundaries, and solid lines isotherms at each time.

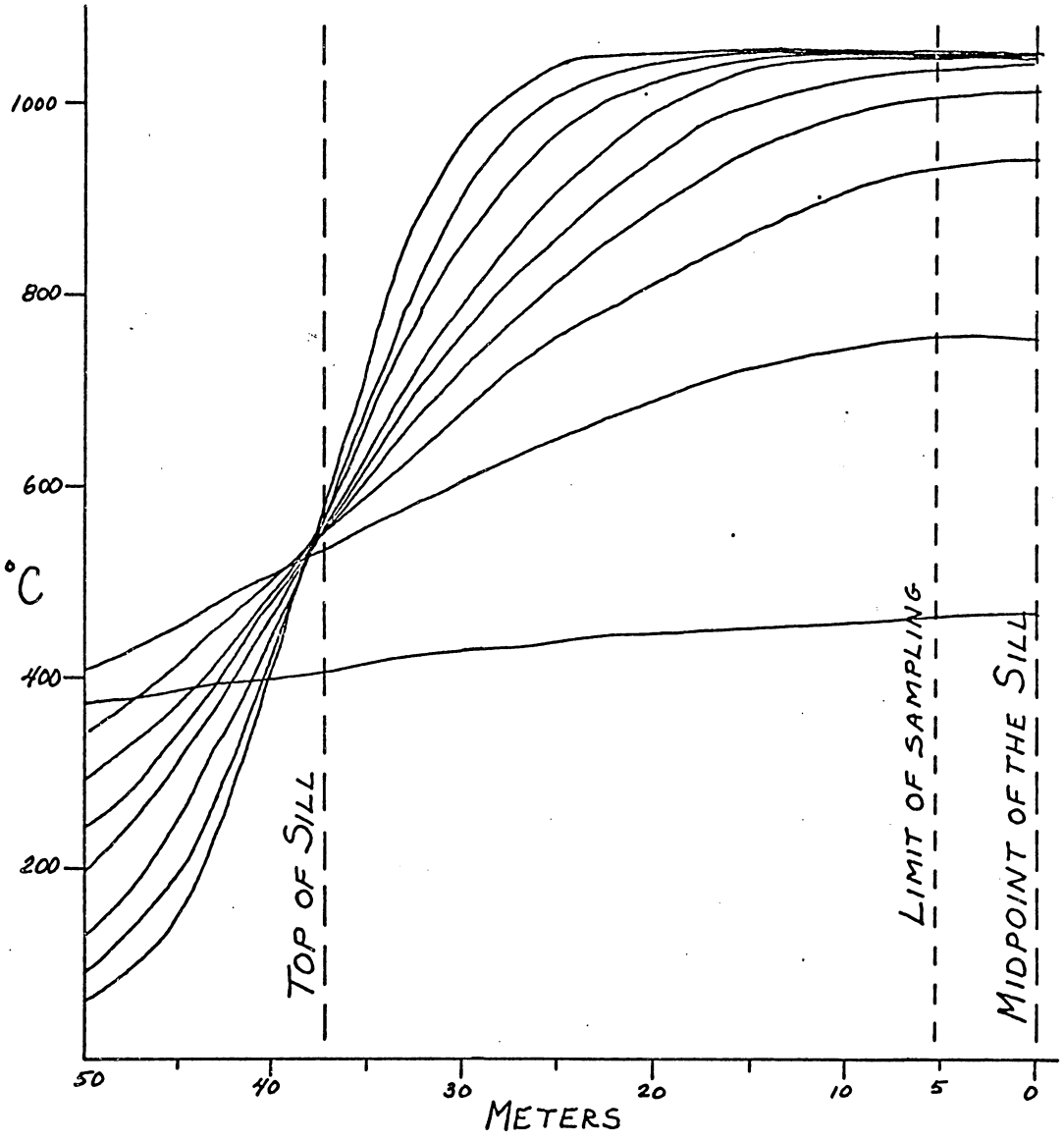


Figure 15. Theoretical cooling curve for Cedar Creek sill. Solid lines represent isotherms, dashed lines represent sill boundary and limit of sampling. Only half the sill is represented, the other (lower) half being theoretically symmetrical.

assumptions made in this case certainly produce inaccuracies. Temperature of the wall rock was assumed to be 50° C at a depth of 3.3 km (Snavely, unpublished manuscript), and instant intrusion of the sill at a temperature of 1050° C (h^2= 0.011) were also assumed. The largest approximation, however, is the assumption of heat flow by conduction only, leading to the symmetrical distribution of heat shown in fig. 15. This was almost certainly not so, as the sill has been observed to be well differentiated (Snavely, unpublished manuscript), a situation which would probably lead to an asymmetric distribution of heat because of convection and crystal settling. Unfortunately this method of heat flow is not easily calculated by these equations.

SUMMARY OF RESULTS

Mexico City Flow

In the Mexico City flow, cooling has been shown to be rapid, probably one reason for the low oxidation state of the grains throughout the sampling area. Stability, perhaps as a result of this low oxidation, is also moderately low, although the directions, even considering the ambiguity of the rotation, are consistent. The cooling curve (fig. 14) shows that, theoretically, the entire sill should have passed the Curie point of magnetite in less than 20 days. Since the full rotation back to the

horizontal of the blocks of traverse I produces badly scattered results and reversed inclinations, it must be assumed that most of the rotation of the blocks occurred before the Curie point had been reached, at least within a few days after extrusion.

Cedar Creek Sill

The samples with reversed inclinations at the top of the sill certainly raise the question of the origin of the reversal. There are at least two possibilities - an actual reversal of the earth's magnetic field, or self reversal. Of the two, self reversal seems the more likely, because of the low stability of the samples and the normal inclinations of the overlying Tyee Sandstone and the rest of the sampled portion of the sill. Further study of the samples by demagnetization at higher peak fields, thermal demagnetization and Curie point studies would give a clearer picture of the origin of this phenomenon. The rest of the sill (at least that portion sampled) shows normal inclinations and moderately good stability in spite of the low oxidation state of the samples. This lack of oxidation is probably attributable to the lack of available oxygen, as shown by the presence of the sulfides.

The possibility that the cooling history has recorded a reversal in inclination of the earth's magnetic field, although an alluring idea, is not well supported because the data are so scattered. Also, the presence of

normally magnetized samples in the overlying Tyee Sandstone does not encourage this hypothesis.

Self reversal can occur in two different forms (Verhoogen, 1961) - reproducible and non-reproducible. Reproducible self reversals may be documented in the laboratory by heating the sample and cooling it in a controlled magnetic field, providing the minerals producing the reversal are not destroyed by heating. Destruction of these minerals by heating might be detected in the Curie temperature curve. Non-reproducible reversals may occur through a combination of oxidation and cooling history. Verhoogen (1961) gives several possibilities for self reversal, especially for certain bulk compositions or mineral phases (particularly ulvospinel). Chemical analysis would reveal whether or not these samples would lie in a compositional field that would allow self reversal to occur.

CONCLUSIONS

The first and most inevitable conclusion of this thesis is that we did not accomplish what we set out to, as stated in the introduction. Igneous bodies vary widely in their oxidation characteristics, and length of cooling history will not contribute to sample stability if other factors for oxidation are not favorable. We studied two bodies with cooling histories different by orders of

magnitude, and found the oxidation states to be similar in each. The search for stable samples in the field cannot rely solely on theoretical cooling curves, for as we found, sample stability is not always dependent on oxidation state, nor is oxidation solely dependent on the cooling period.

Even though the original aims of the study were not completely fulfilled, or perhaps shown to be impractical, other interesting questions have been raised. The origin of the reversal in the Cedar Creek sill could be determined by further research. The nature and implications of the titanomagnetite alterations could be determined. Additional tests, such as Curie temperature analysis, thermal demagnetization, further alternating field demagnetization could be made to confirm and further define the nature of the remanence, especially its stability.

Appendix A - Preparation of Polished Samples

Either chips or whole samples, when chips were not available, were polished for petrographic examination. Chips were set in epoxy, then sawed and polished. The whole samples were cut in half (to accomodate the working distance of the microscope) and polished. Polishing was accomplished on a series of laps, first in the Rock Preparation Laboratory in the Geology department and then on the more refined laps in the Materials Science department, which has laps for polishing with grits as fine as 0.05μ. Since 0.3μ is often fine enough for this microscope work, the new facilities in the Rock Preparation Lab should be sufficient.

Appendix B - Test of AC Demagnetization

The alternating current demagnetization equipment was tested to determine if any systematic anhysteretic bias would be acquired by a sample. The test was designed along the lines of that described by Doell and Cox (1967). Briefly, the sample holder of the tumbler was assigned three orthogonal axes (I, II, and III), coinciding with the arbitrary sample axes (x, y, or z). The sample was placed in the holder, subjected to peak field demagnetization, and measured with the spinner magnetometer, in each of 12 possible orientations. The tests were conducted without nulling the earth's vertical field. The resulting directions were resolved into the x, y, and z components of the sample, and the corresponding I, II, and III components of the sample holder (fig. B-1).

The results of the tests, for these samples, show no systematic bias. In actual situations, if a sample has a widely different post-demagnetization direction, it is usually reversed in the sample holder and subjected to the same peak field. The two results are averaged.

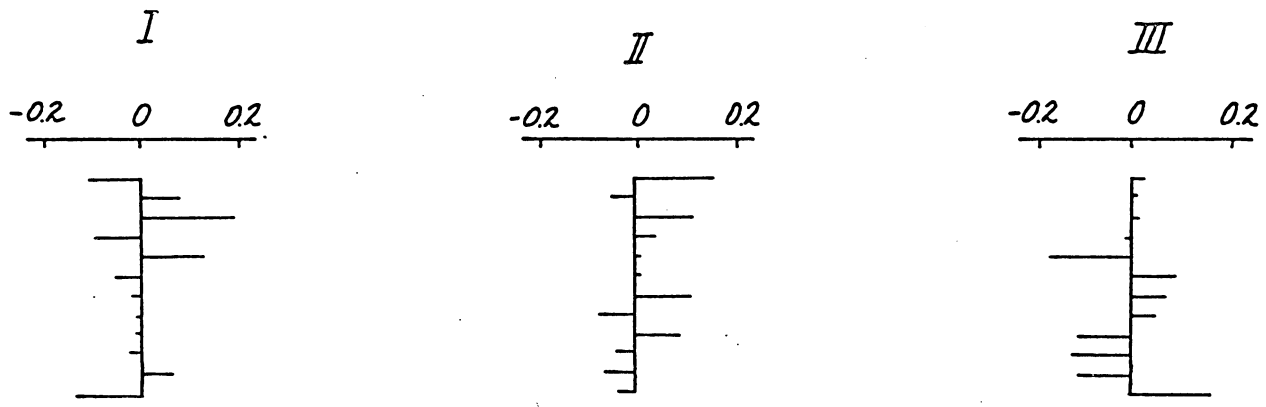


Figure B-1. Variation in directions for data referred to sample holder axes I, II, III. Scale is arbitrary but proportional to the magnetic intensity in emu/cc.

(a). At 100 oe, vertical field = Earth's field.

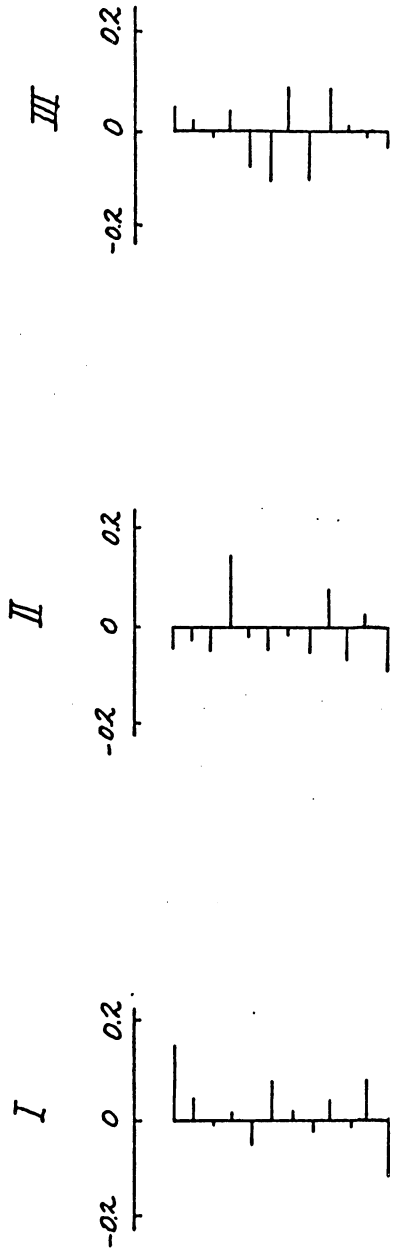


Figure B-1 (b). At 200 oe, vertical field = Earth's field.

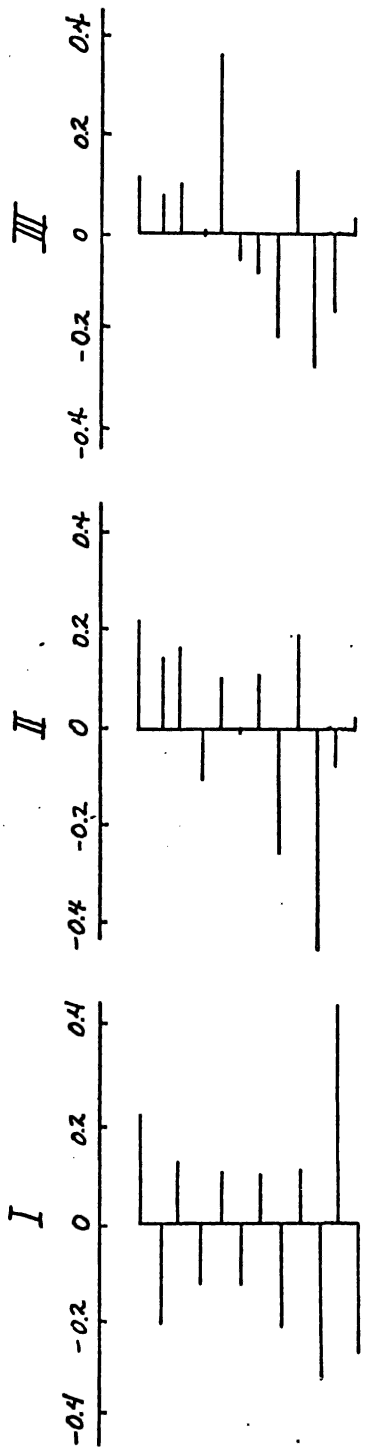


Figure B-1 (c). At 200 oe, vertical field = 0.

ACKNOWLEDGMENTS

Financial support for this research was provided by the Geology department of Rice University. Special thanks must be given to Dr. H.C. Clark who guided the study from its conception to its present state. Dr. Louis L. Nettleton provided encouragement and a job source when departmental financial aid was not available. Dr. Clark collected the samples for this study, with the assistance in Mexico of Dr. Edward A. Johnson. Highest credit, however, goes to my husband, Woody. Without his encouragement and unfailing good humor, as well as his typing and draftsmanship, this thesis would never have been completed.

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