

PALEOMAGNETIC DATING OF HOLOCENE VOLCANISM
IN NORTHWESTERN UNITED STATES
A PRELIMINARY REPORT

by

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Abstract

A fairly good record of the variation in direction of the geomagnetic field in northwestern United States from 1500 BP to 3000 BP and from 5800 BP to 6900 BP has been obtained by measurement of dated volcanic rocks. A less complete record has been obtained for the variation in intensity of the field. Preliminary ages are given for 6 previously undated lava flows on the Snake River Plain, Idaho by comparing their directions of magnetization with the known record. Possible age assignments are suggested for another 5 flows. A major pulse of volcanism occurred on the Snake River Plain between 2000 BP and about 2600 BP. Several tens of cubic kilometers of basalt erupted along the Great Rift in this time period.

Introduction

Some of the most promising known geothermal areas in the western United States are directly associated with volcanoes which have erupted within the last 5,000 to 10,000 years. The presence of very young or currently active volcanoes, therefore, provides an important guide in the exploration for undiscovered geothermal resources. Knowledge of local patterns of volcanic eruptions in time and in space, moreover, provides clues about the evolution, state, and position of magma reservoirs at shallow levels in the crust and can help guide detailed exploration and development of hydrothermal systems or hot rocks associated with these reservoirs. Thus a technique for identifying and dating very young volcanoes as well as individual lava flows and domes is of practical importance in the development of geothermal energy.

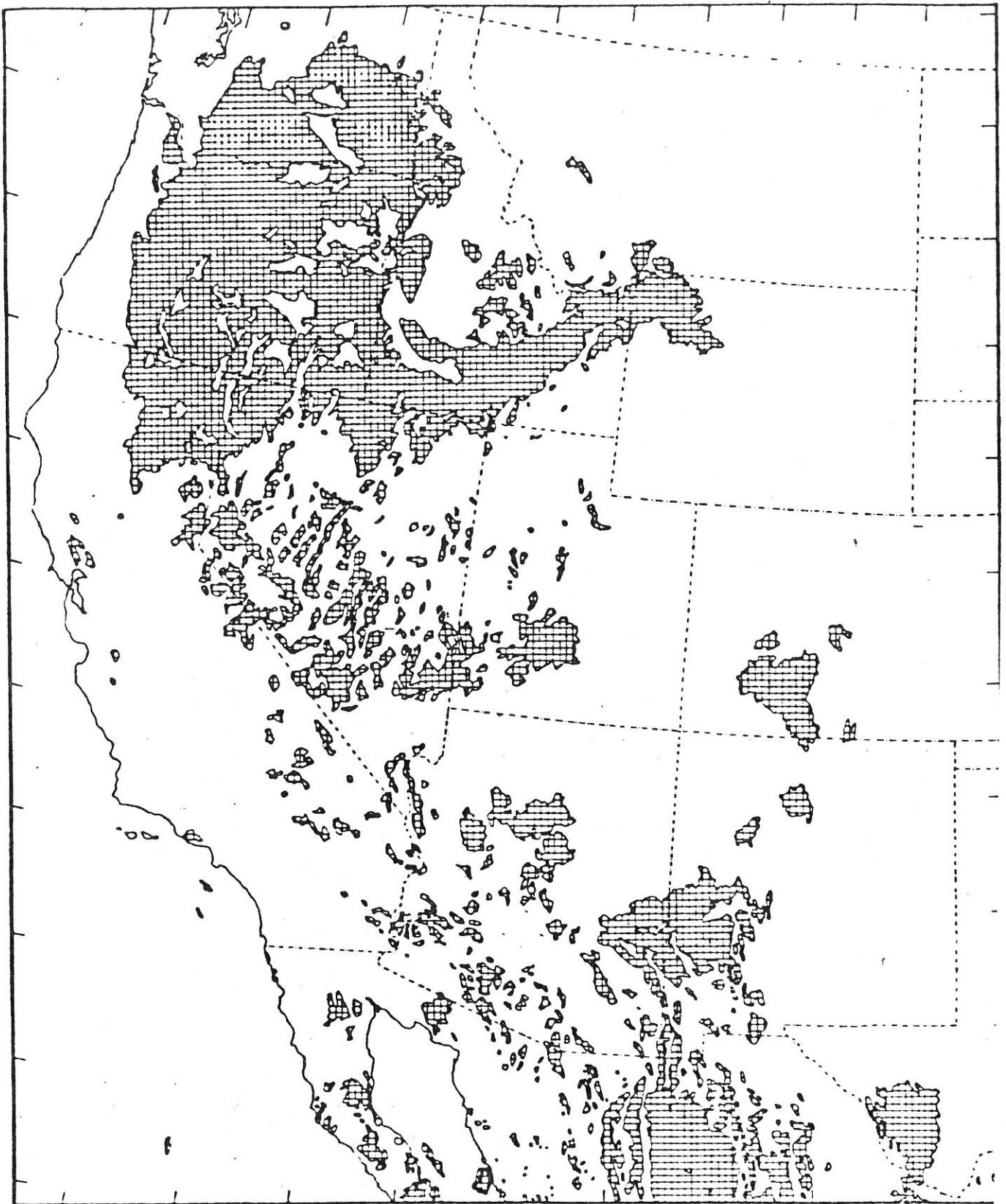
Very young volcanic rocks can be dated by means of paleomagnetism on the basis of relatively large secular variations which have occurred in the geomagnetic field. Both the direction and intensity of the field at many places on the earth have varied with a frequency of the order of one cycle per 10^3 years. By combined measurement of paleodirections and paleointensities, lavas ranging in age from the present back to about 10,000 years can be dated, provided that the local history of geomagnetic secular variation is sufficiently well known.

Our first step in applying the paleomagnetic dating technique has been to determine the record of geomagnetic secular variation in western United States, for the last 7000 years, by measurement of paleodirections and paleointensities from 24 dated lava flows. This work was in progress at the time this report was prepared. Thus the results given here should be regarded as strictly preliminary. Even at this early stage of the work, however, some interesting applications of the results can be made in dating lava flows on the Snake River Plain, Idaho. The pattern of volcanism found on the Snake River Plain suggests that at least one area appears to warrant further study from the standpoint of geothermal resources.

Distribution of Holocene Volcanic Rocks in Western United States

Holocene volcanic activity has been widely distributed in the western United States through the region occupied by Cenozoic volcanic rocks (fig. 1). Accurately dated Holocene lava flows and ash deposits occur in the Cascade Range, extending from California to Washington, the Newberry Crater area, Oregon, the Medicine Lake Highlands, California and on the Colorado Plateau, the Snake River Plain, Idaho and scattered localities along the border of the Basin and Range Province.

Figure 1.



Several dozen lava flows and other types of volcanic deposits of Holocene age have now been fairly accurately dated, primarily by the ^{14}C method. Among these are 23 lava flows and one ash flow (fig. 2) for which ages have been published and which have been sampled and measured in the initial part of this investigation. Reliable directions of magnetization were obtained from 22 of these volcanic units, which range in age from about 300 years BP to nearly 7000 years BP (table 1). Gaps in the time distribution of the measured units occur between 3000 and 3850 BP, and between 4150 and 5800 BP. Holocene volcanic rocks are sufficiently abundant, however, that, with further work, a fairly complete record of the geomagnetic field for the last 7000 years probably can be obtained.

Most flows were dated from charcoal in tree molds within the flows or from carbonized wood overridden by the flows. Precision of the available ^{14}C dates ranges from ± 60 to ± 400 years. Bounds on the ages of some of the flows studied have been determined from ^{14}C ages of overlying and underlying deposits. Dates for all units are listed in ^{14}C years BP, with the exception of the date for the Bonito Flow, Arizona which was determined by dendrochronology and which is given in absolute years BP.

Field Methods

Samples taken for paleomagnetic measurement are 1-inch diameter cores, which are, generally, 4 to 5 inches long; they are cut with a hand-held gasoline-powered drill. Orientation of the cores is measured to a precision of about 1° by means of spirit level and sun compass, prior to removal from the outcrop. Samples of dated flows are taken as close as possible to the ^{14}C sample localities to ensure that the mag-

Figure 2.

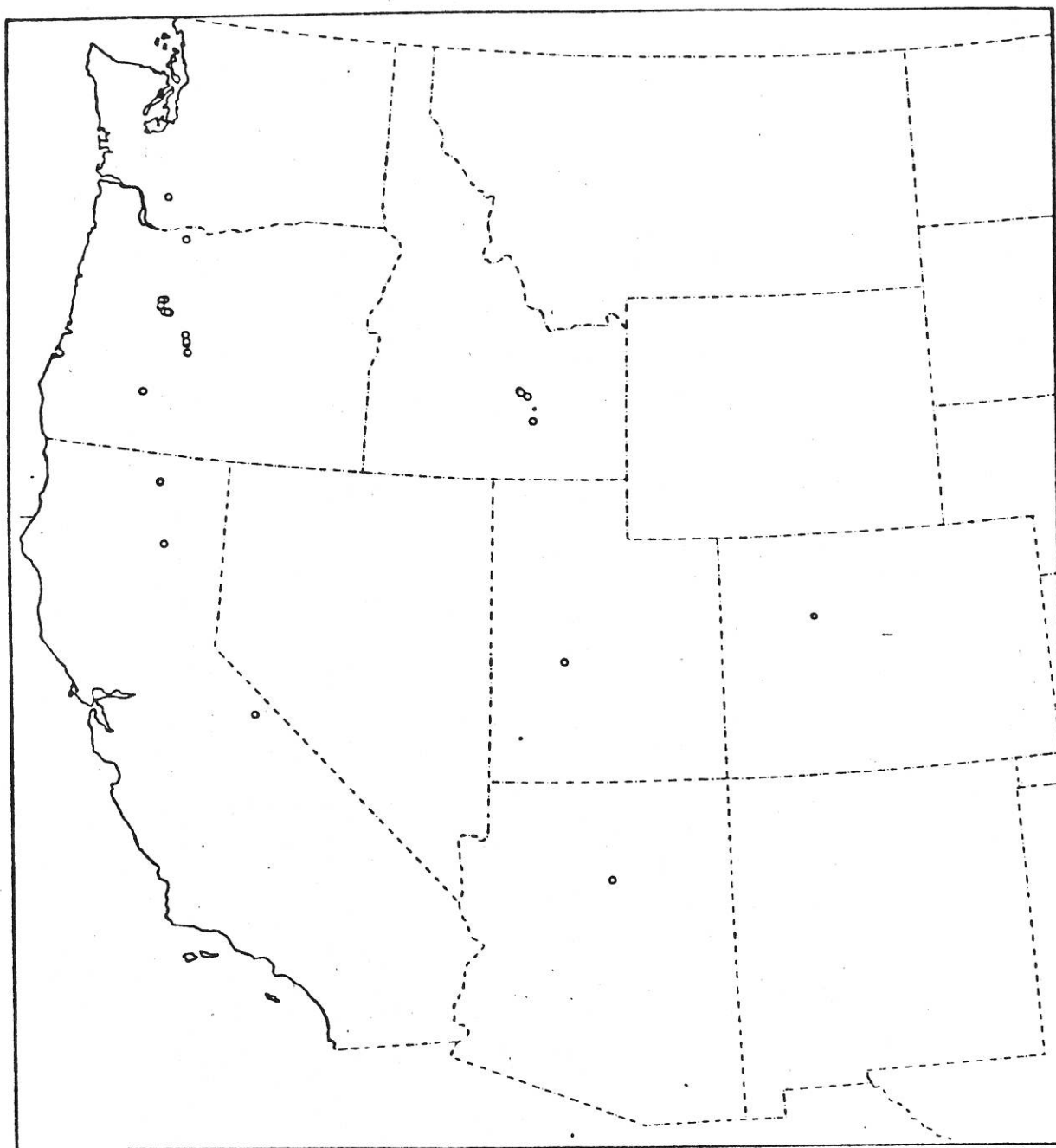


Table 1. Dated Holocene lava flows and ash flow deposit for which reliable directions of magnetization have been obtained.

Volcanic Unit	Age ^{1/}	Reference
Burnt Lava Flow, Medicine Lake Highlands, California	320±200	1
Ice Spring Field, Black Rock Desert, Utah	660±170	2
Bonito Flow, San Francisco Volcanic Field, Arizona	886±2	3
West Belknap Flow, McKenzie Pass, Oregon	{ 1420±100 1590±160	4 4
South Belknap Cone Flow, McKenzie Pass, Oregon	1775±400	5
Cave Basalt Flow, Mt. St. Helens, Washington	1925±95	6
Rattlesnake Butte Flow, Snake River Plain, Idaho	2080±85	2
Watchman Flow, Snake River Plain, Idaho	2140±60	2
Trenchmortar Flat Flow, Snake River Plain, Idaho	2255±60	2
Kings Bowl Flow, Snake River Plain, Idaho	2360±150	2
Yapoah Flow, McKenzie Pass, Oregon	{ 2550±165 ^{2/} to 2883±175 ^{2/}	4 4
Little Belknap Flow, McKenzie Pass, Oregon	2883±175	4
Clear Lake Flow, McKenzie Pass, Oregon	{ 2705±200 2990±300 3200±220	7 5 7
Hackleman Creek Flow, McKenzie Pass, Oregon	3850±215	4
Dotsero Flow, Dotsero, Colorado	4150±300	1
Gas-Line Flow, Newberry Crater, Oregon	5800±150	8
Lava Cascade Flow, Newberry Crater, Oregon	5800±100	8
Forest Road Flow, Newberry Crater, Oregon	5960±100	8
Surveyor Flow, Newberry Crater, Oregon	6080±100	8
Lava Cast Forest Flow, Newberry Crater, Oregon	{ 6150±210 6380±130	8 8
Crater Lake ash flow deposit, Crater Lake, Oregon	6640±250	9
Parkdale Flow, Mt. Hood, Oregon	6890±130	10

^{1/} Two or more ages are listed where more than one age has been reported in the literature and no clear cut criteria exist for selecting one reported age over another.

^{2/} Ages of volcanic units which overlie and underlie Yapoah Flow.

netic measurements pertain to the dated units.

Holocene lava flows present a special problem for paleomagnetic sampling because they are almost never dissected by erosion. Thus samples must be taken from original surface parts of the flows. Nearly all of the flows studied to date are basalt or basaltic andesite. Samples were taken from parts of these flows where the surface is structurally coherent and where there appears to be no evidence of deformation or rotation of the surface of the flow after cooling. For instance, we have found lava gutters to be structurally stable localities for sampling aa flows. On some flows the only structurally stable parts of the surface are constructional features such as spatter ramparts.

As a check on the structural stability of the sample sites, 6 samples are taken from two separate sites on each flow. The dispersion of directions of magnetization must be small at both sites and the mean direction must be sensibly the same at both sites before we accept the results. Field measurements are made of the local directional anomaly of the magnetic field at each site to determine whether a correction must be applied in the interpretation of the measured paleodirection.

Considerable care must be exercised in the field in the identification of the lava flows to which measured ages properly apply. For each flow sampled, observations are made on the stratigraphic relations to other flows and to sediments, on the development or absence of soil profiles, and on the extent and type of vegetation.

Secular Variation of Direction of Magnetization

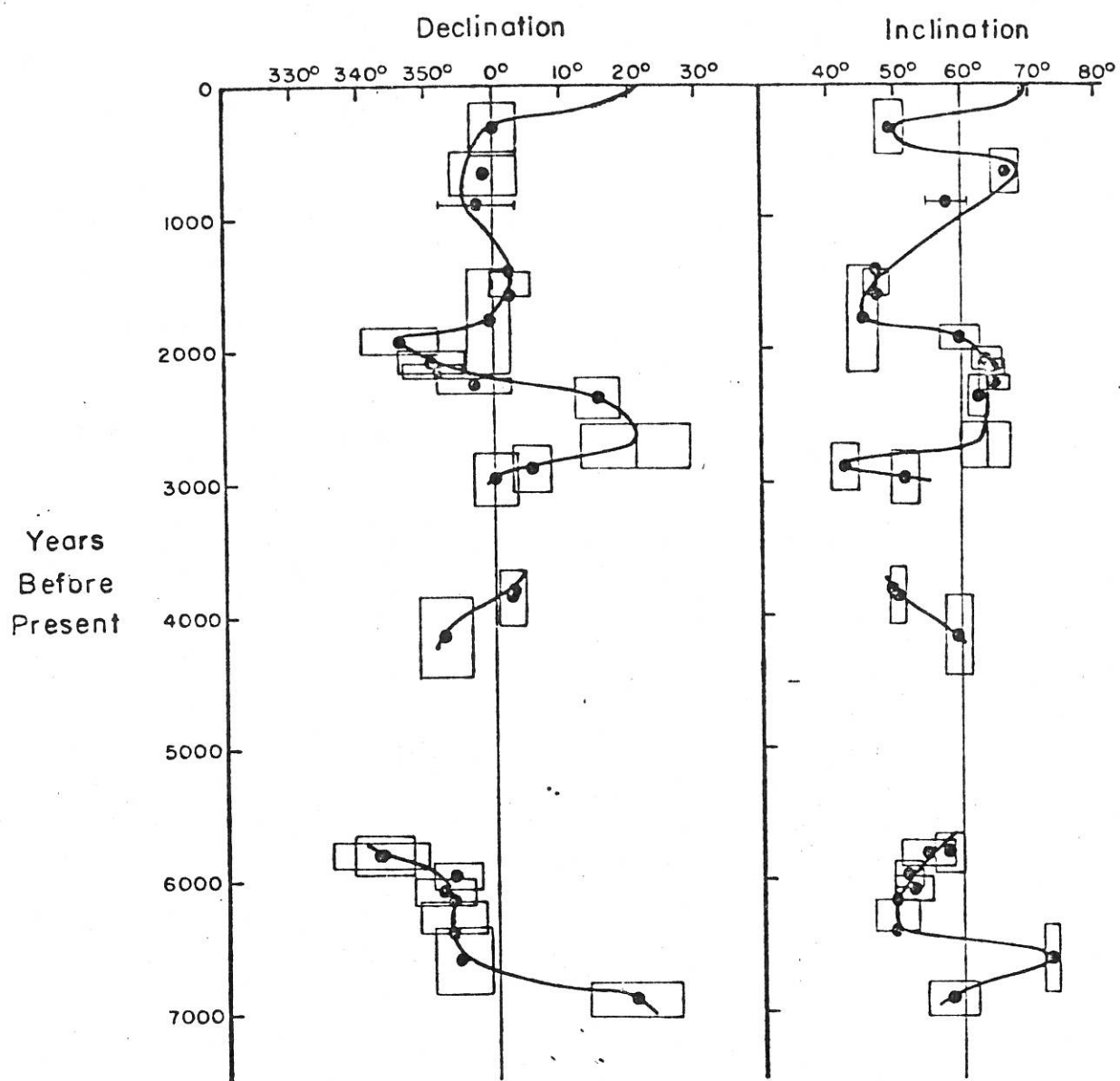
In the laboratory, the cores are cut into 1-inch cylinders and the natural remanent magnetization (NRM) is measured with a spinner magnetometer (11). One sample from each site is chosen for stepwise alternating

field demagnetization up to a peak field of 1000 Oersted. This is done to determine whether isothermal remanent magnetization (IRM) is present and, if so, to determine what demagnetization fields are required to remove it. Removal of IRM from the samples we have studied is rarely required. The magnetization remaining after the IRM has been removed is thermoremanent magnetization (TRM) acquired by the rock when it originally cooled. The mean TRM direction of the samples taken from a given lava flow is used as an estimate of the direction of the local geomagnetic field at the time the lava cooled. The mean direction and the confidence interval for the mean are computed by standard statistical methods (12).

As determined from 22 dated volcanic units, the direction of the geomagnetic field in the western United States has varied from 343° to -21° in declination and from 43° to 73° in inclination during the last 7000 years (fig. 3). All but 3 of the measured directions are for localities in northwestern United States. For this region, we have a fairly good record of the direction of the geomagnetic field from about 1500 BP to 3000 BP and from about 5800 BP to 6900 BP. The largest sources of uncertainty in reconstructing the record of secular variation lie in the errors of ^{14}C dating of the units sampled. Changes of 30° in declination and more than 20° in inclination have occurred within intervals of time as short as 500 years. Thus errors of 100 to 200 years in age determination can lead to large errors in the estimated rate of change in directions of the geomagnetic field.

The volcanic units sampled in the northwestern United States are separated by as much as 10° in longitude and 6° in latitude. At any one time there must have been significant differences in direction of the

Figure 3.



geomagnetic field across this region. These differences, however, probably lie within the 95 % confidence limits for the mean declination and mean inclination shown for each unit in figure 3. Therefore we have drawn declination and inclination curves through the mean points for each unit, which are intended to represent the approximate history of declination and inclination in northwestern United States. In drawing the curve for inclination, account has been taken of the low latitudes of sampled units in Utah and Arizona.

Secular Variation of Intensity of the Geomagnetic Field

The intensity of TRM of a volcanic rock is related to the intensity of the local geomagnetic field at the time that the rock cooled. A method originally developed by E. Thellier in 1938 (13) and refined and applied to volcanic rocks by E. Thellier and O. Thellier (14) can be used to estimate the ancient field intensity, provided that certain conditions are fulfilled. Basically, this method consists of heating a sample and removing the NRM in progressive temperature steps up to the Curie temperature. The sample is also heated and then cooled in a stepwise fashion in a field of known intensity in which it acquires a new TRM. Under ideal conditions, the ratio of NRM lost to new TRM gained, at progressive increments of temperature, multiplied by the field applied in the laboratory gives the intensity of the field in which the rock originally cooled. A recent discussion and evaluation of the method has been given by Coe (15).

A difficulty in applying Thellier's method to volcanic rocks arises from their tendency to oxidize during heating in the laboratory. Coe (15), Khodair and Coe (16), and Grommé and Coe (17) have found that, by heating volcanic rocks in nitrogen of high purity or in a vacuum,

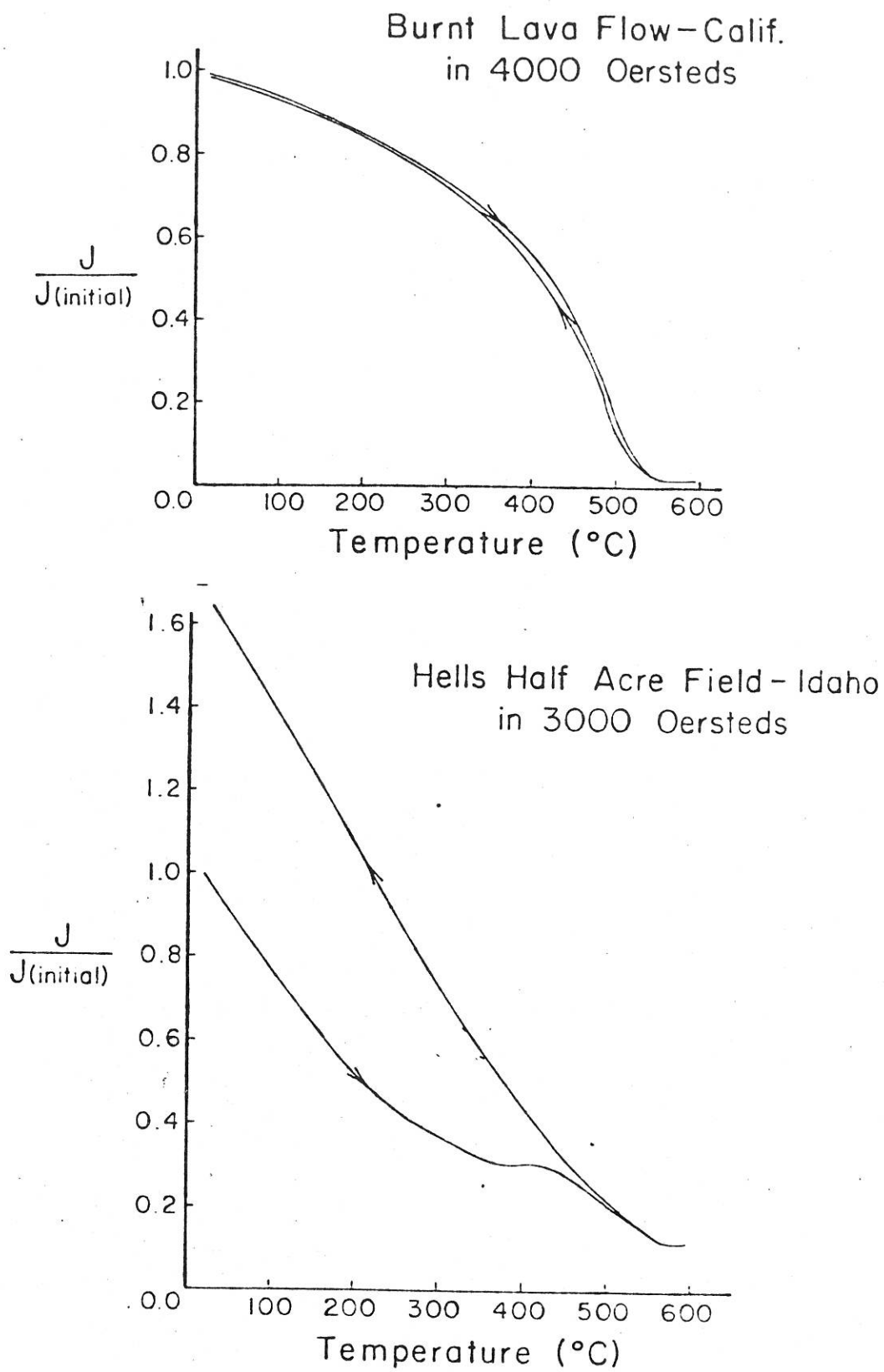
apparently reliable paleointensities can be obtained by Thellier's method. Equipment built especially by Grommé for paleointensity determination by heating in vacuum was used in this study.

A reliable determination of paleointensity by Thellier's method requires that the NRM of a sample is entirely TRM or that all other components of magnetization can be successfully identified and removed. The magnetic phases of the sample must not have changed during initial cooling of the rock or after cooling. Furthermore, they must not change during repeated heating and cooling in the laboratory.

Stability of the magnetic phases of a rock during heating and cooling can be evaluated by cycling a rock from room temperature to temperatures above the Curie temperature in vacuum on a magnetic balance. Saturation magnetization is measured as a function of temperature on the balance. If the magnetic phases are stable, the saturation magnetization at given temperatures on the cooling part of the thermal cycle will be the same as the saturation magnetization observed during heating. A reversible saturation magnetization versus temperature curve for a sample from the Burnt Lava Flow, California (fig. 4) is typical for rocks with relatively stable magnetic phases. In contrast, an irreversible curve was found for a sample from the Hell's Half Acre lava field, Idaho (fig. 4). A phase change which occurred near 400°C during heating of the Hell's Half Acre sample renders this specimen unsuitable for paleointensity determination.

Samples which had little or no IRM were selected from each volcanic unit for analysis by Thellier's method. A small specimen from each sample selected was tested on the magnetic balance, and demonstrably unstable samples were rejected. The saturation magnetization versus

Figure 4.

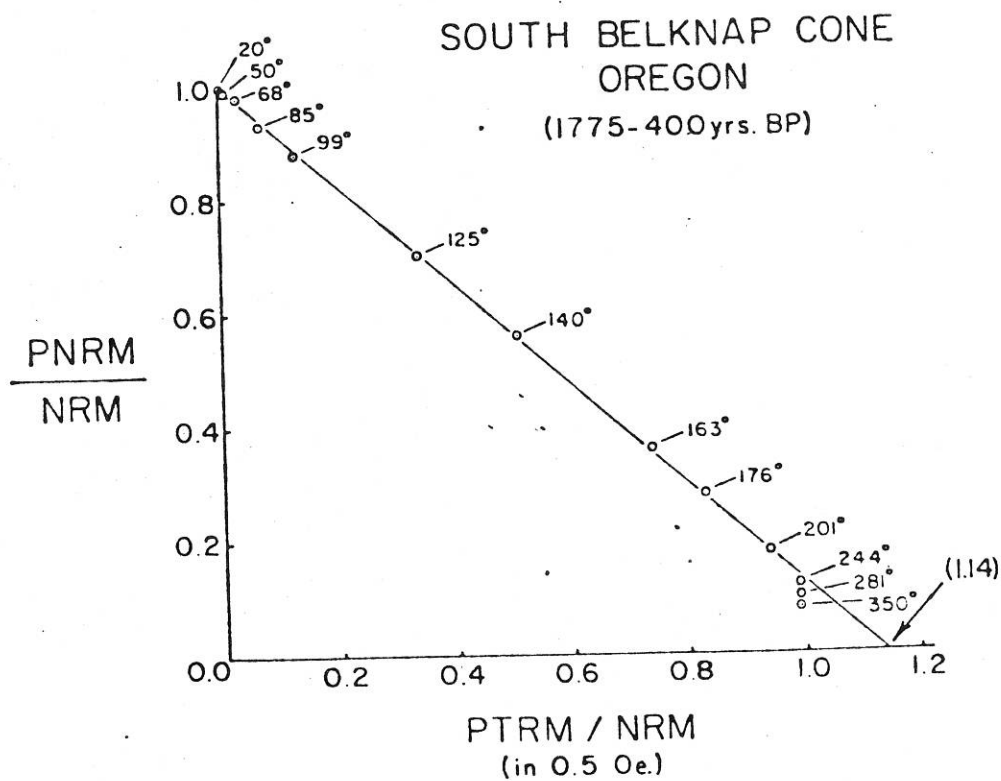
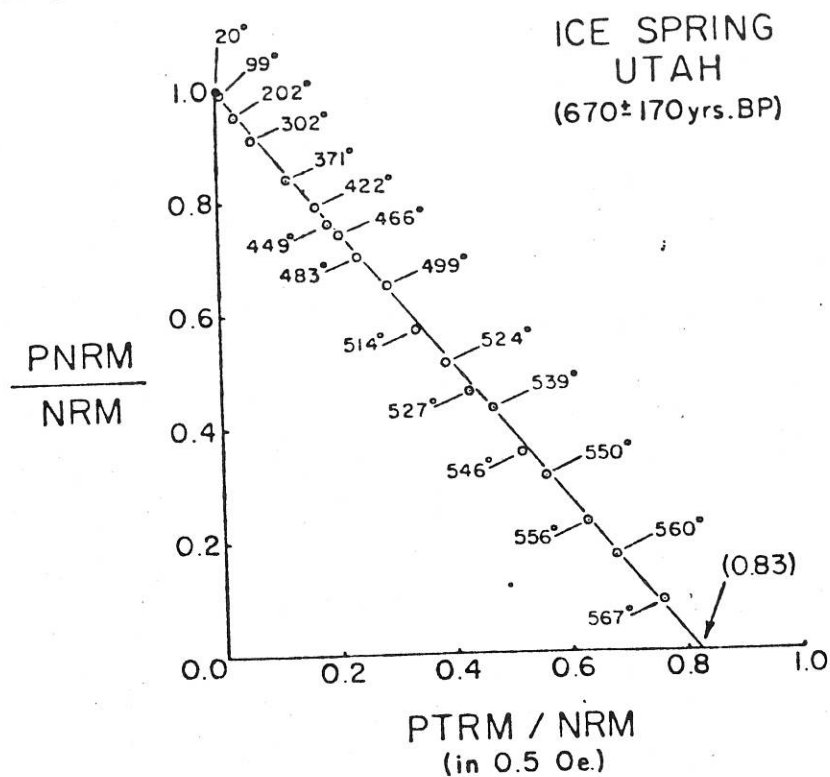


temperature curves of the accepted samples were then used to plan the temperature steps to which each sample would be heated for paleointensity determination. The loss of NRM as a function of temperature varies greatly from specimen to specimen, and it is desirable to remove roughly comparable small fractions of the NRM at each progressive temperature step.

In Thellier's method, first the intensity and direction of the initial NRM of the sample is measured. Then the sample is heated in zero applied field to a known temperature, T_1 , at which some fraction of the NRM is removed, and the specimen is cooled in zero field. The intensity and direction of the remaining NRM, designated PNRM, is measured. Then the sample is reheated to temperature T_1 and cooled in the presence of a known applied field (0.50 Oe). The sample is again measured and the component of TRM acquired by the sample during cooling in the applied field, designated PTRM, is found by vector subtraction. Next, the procedure is repeated, by heating the sample in zero applied field to a higher temperature, T_2 , cooling and measuring it, and heating it again to T_2 and cooling it in 0.50 Oe applied field and measuring it. By this means, a series of measurements of PNRM and PTRM are obtained at successive temperatures up to or close to the Curie temperature.

If the ratio of the PNRM decrement to the PTRM increment at each heating step is constant, then PNRM will be a linear function of PTRM (fig. 5). The slope of this function, in Thellier's theory, is the ratio of the paleointensity of the geomagnetic field to the field applied in the laboratory. Two samples which exhibit satisfactory linear relationships between PNRM and PTRM are illustrated in figure 5, one with a high Curie temperature, from Ice Spring, Utah, and one with a low Curie

Figure 5.

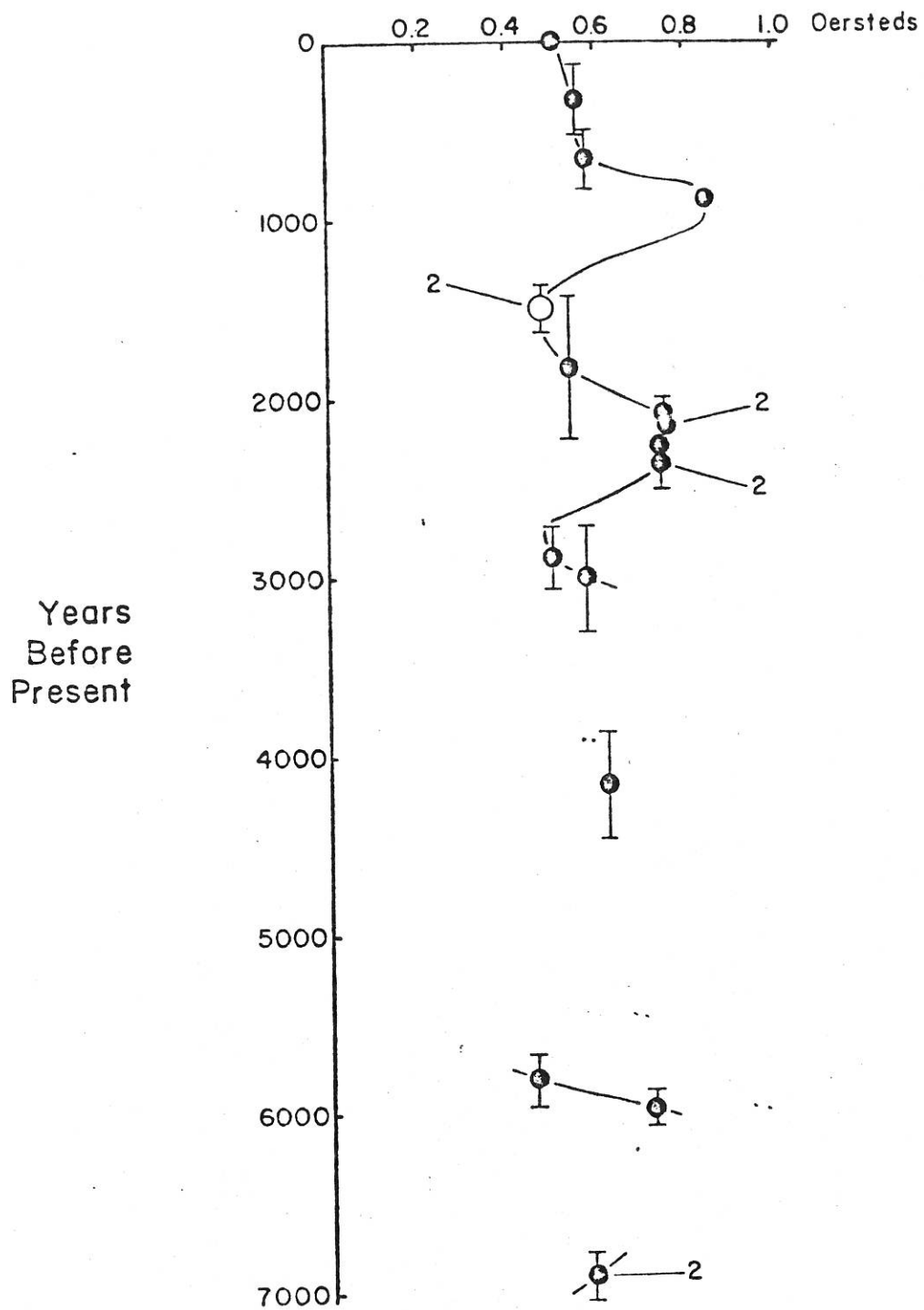


temperature, from South Belknap Cone, Oregon. In figure 5, the PNRM and PTRM measured at each heating step are normalized to the initial NPM; the intercept on the normalized PTRM axis of the straight line fitted to the measurements is the inverse of the paleointensity/laboratory intensity ratio. Thus the paleointensity at 670 ± 170 years BP, derived from the Ice Spring sample, is $0.50 \text{ Oe} / 0.83 = 0.60 \text{ Oe}$, and the paleointensity at 1775 ± 400 years BP, derived from the South Belknap Cone sample, is $0.50 \text{ Oe} / 1.14 = 0.44 \text{ Oe}$.

As illustrated by the South Belknap Cone sample, the ratio of PNRM decrement to PTRM increment commonly does not remain constant at temperature steps very close to the Curie temperature. In such cases, the measurements obtained close to the Curie temperature are neglected in fitting a straight line. Many samples, moreover, do not exhibit as high a linear correlation between PNRM and PTRM as the Ice Spring and South Belknap Cone samples. A certain degree of judgement, in some instances, is involved in deciding how best to fit the line.

At the time of writing, paleointensity determinations had been completed on samples from 15 dated lava flows (fig. 6). Duplicate samples had been run for 4 of these flows. Triplicate paleointensity determinations are planned for each flow studied. Duplicate determinations of the paleointensity for 3 lava flows fall well within the diameters of the solid circles plotted on figure 6. The difference between duplicate determinations of paleointensity for a flow at approximately 1500 years BP is equal to the diameter of the open circle plotted. Just as in the case of variation in direction of the geomagnetic field, the principle source of uncertainty in reconstructing the record of variation of intensity appears to lie in errors of ^{14}C dating.

Equivalent Intensity at 62° Inclination



In order that the paleointensity determined from lava flows at different paleomagnetic latitudes can be intercompared, the paleointensity obtained from each flow has been reduced in figure 6 to an equivalent intensity of the geomagnetic field for the 62° isocline. For a dipole field, 62° inclination corresponds to a magnetic latitude of 43° . On the basis of 15 flows studied, the 62° isocline equivalent intensity of the geomagnetic field has ranged from 0.46 to 0.85 Oe during the last 7000 years. The variation in intensity appears to have occurred with a frequency comparable to that observed in the variation in direction of the field. Indeed, there appears to be a rough correlation between intensity and inclination.

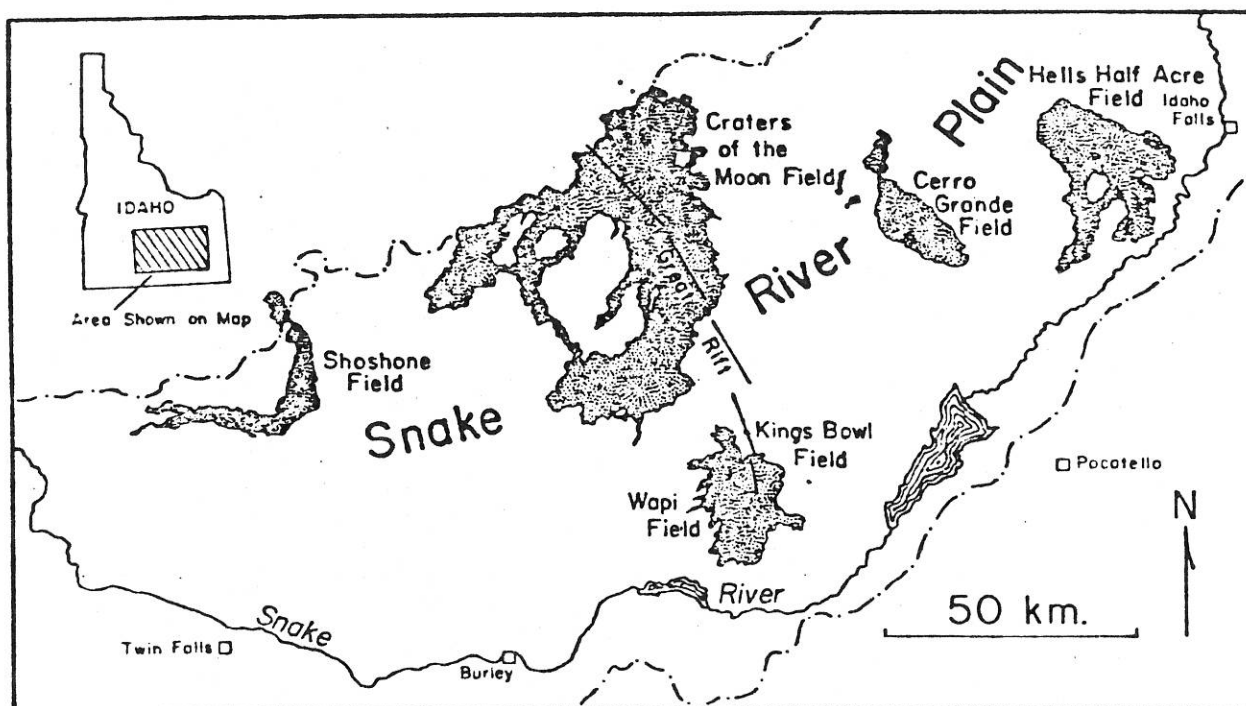
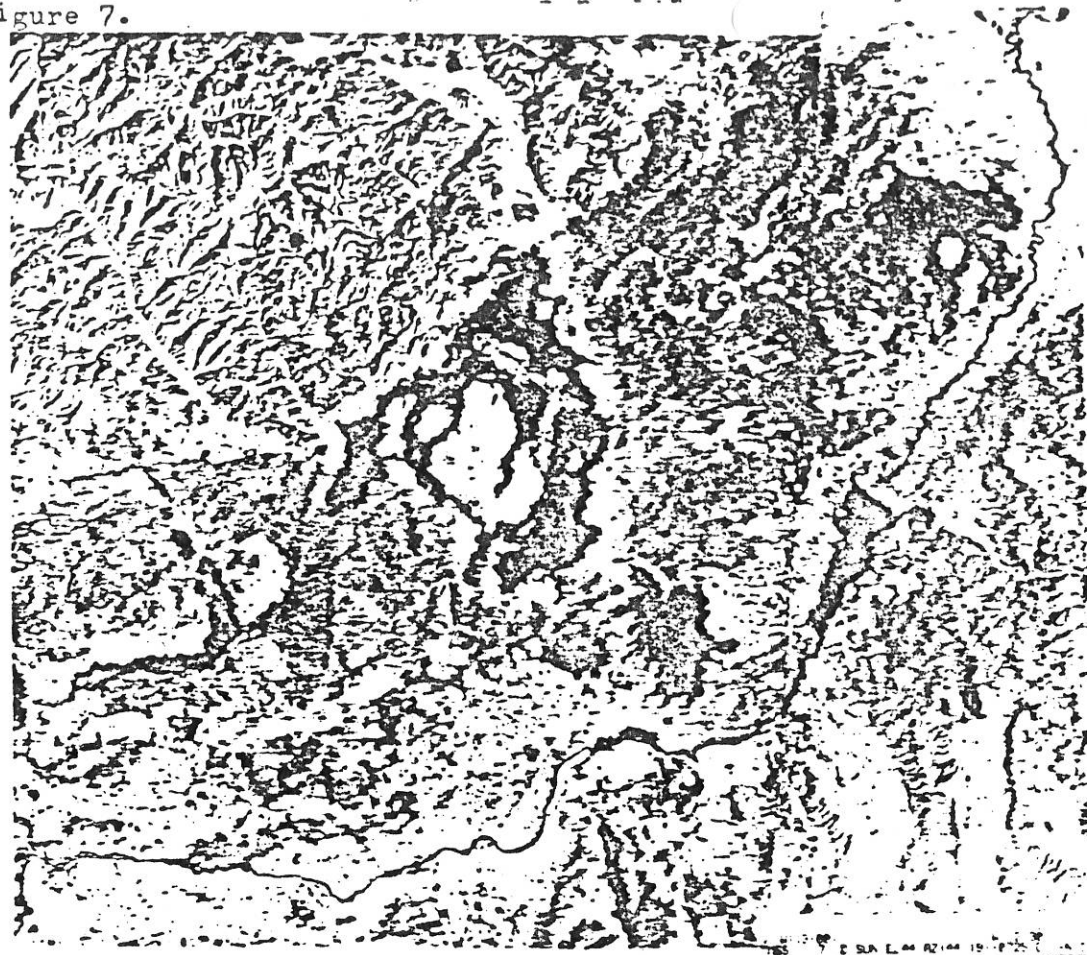
Application of Paleomagnetic Dating to Holocene Lavas of the Snake River Plain, Idaho

Extensive basaltic lava flows of Holocene age occur on the Snake River Plain, Idaho, distributed in 6 widely separated fields (fig. 7). These young lavas are easily recognized as dark, unvegetated areas on LANDSAT (ERTS) pictures (fig. 7). Three of the Holocene fields are located along the Great Rift, which bisects the eastern Snake River Plain.

Preliminary investigation of the directions of magnetization of the young Snake River Plain lavas suggests that the ages of many of them fall within the range of time for which we have fairly good information on the secular variation of the geomagnetic field. Thus preliminary age assignments can be given to some of the lavas by means of paleomagnetic measurements.

For purposes of paleomagnetic dating it is useful to compare directions of the magnetic field rather than compare the declination

Figure 7.



and inclination components of direction separately. The stereographic equal area projection is a convenient method of portraying the direction of the magnetic field (fig. 8). In the projection adopted in figure 8, declination becomes the azimuthal coordinate and inclination is the radial coordinate. The magnetic field direction may be thought of as a unit vector whose origin is at the center of a sphere of unit radius; the stereographic projection represents the lower half of this sphere.

Mean directions of magnetization for 10 dated lava flows ranging in age from 1495 ± 130 BP to 2990 ± 300 BP are shown in figure 8a. Around each mean is a circle which represents the 95% confidence limit of the mean. A generalized path of the magnetic vector for northwestern United States from 3000 BP to 1500 BP, which is inferred from the data shown, is indicated by the curved line with arrows. Four of the 10 control points on this path, shown by underlined ages, are from the Snake River Plain. The arrows indicate the forward direction of time. It may be seen that the magnetic vector traced out a closed loop in 1500 years, moving clockwise with time.

In figure 8b, approximate points in time along the path of the magnetic vector are indicated with tick marks, spaced at intervals of 100 ^{14}C years. The position of these points has been estimated from the control shown in figure 8a. Mean directions of magnetization for 6 undated lava flows from the Snake River Plain which lie close to the inferred path of the magnetic vector are also shown in figure 8b. Localities of samples from which these directions have been obtained are shown in figure 9. Four of the directions, those for the North Crater Flow, Hells Half Acre Field, Wapi Field, and the Carey Tongue, lie precisely on the segment of the magnetic vector path between 2500

Figure 8.

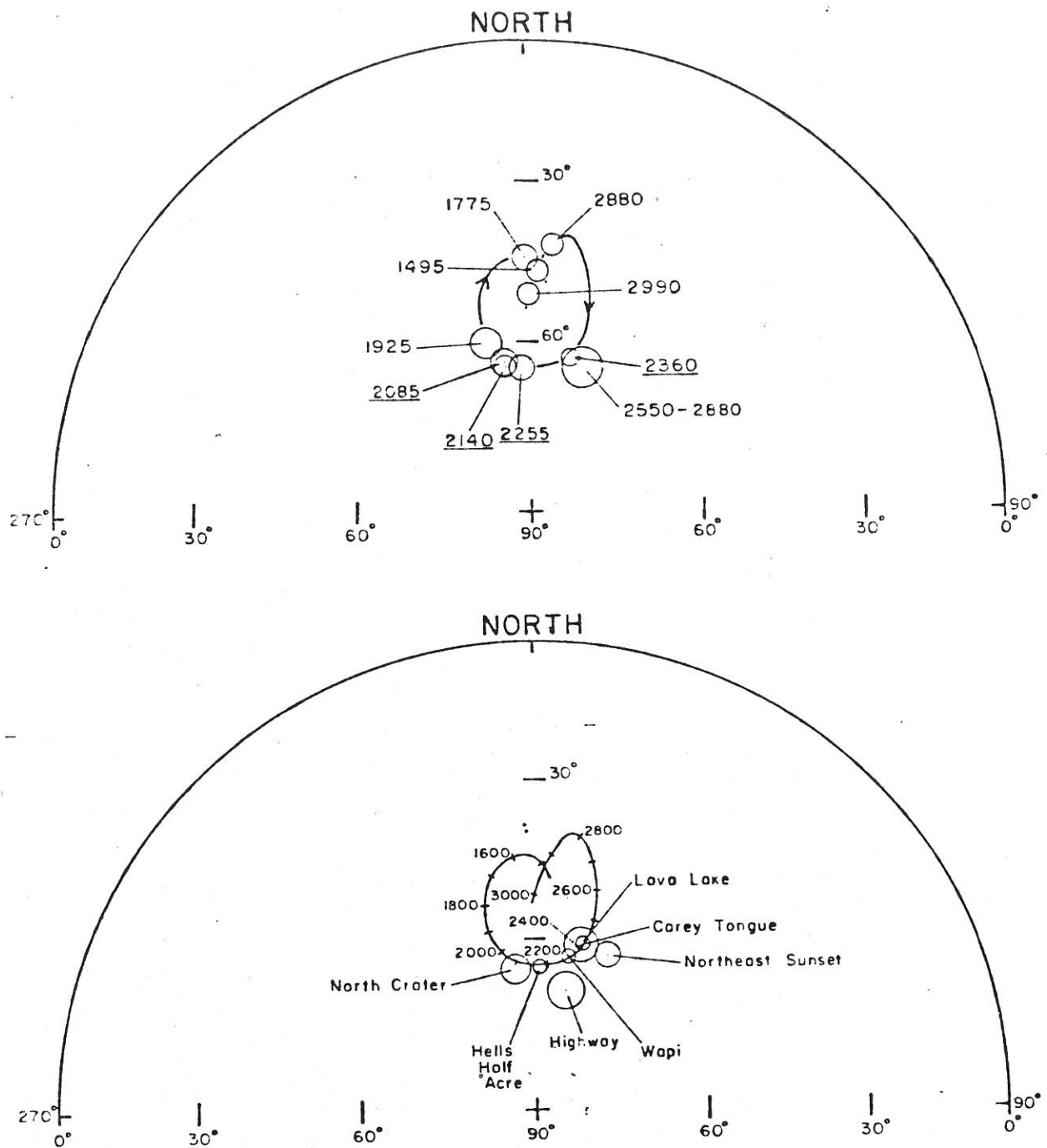
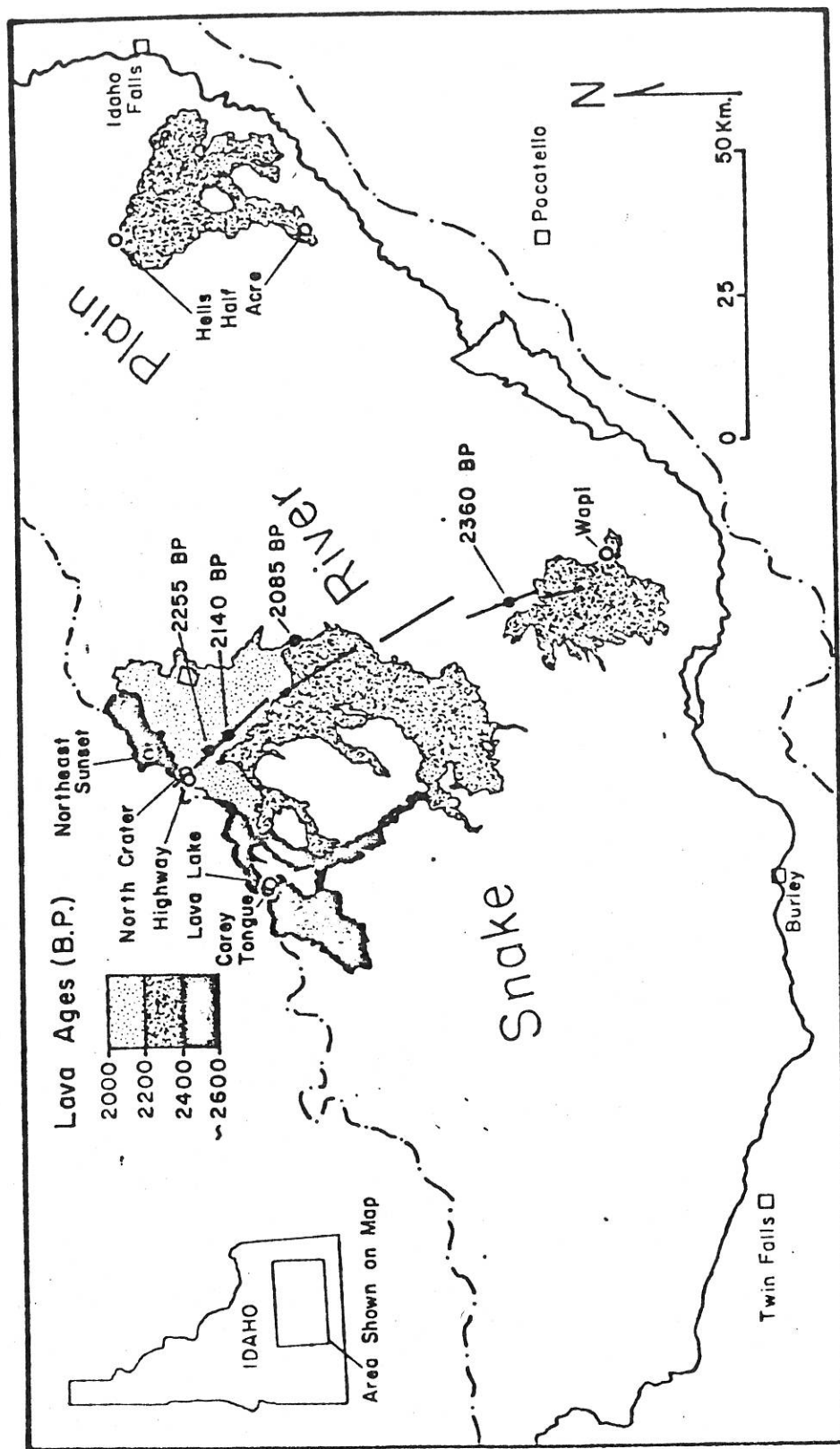


Figure 9.



BP and 2100 BP. Directions for 2 of the flows, Highway and Northeast Sunset are close to this segment but are separated from it by more than their 95% confidence limits.

North Crater Flow is one of the highest stratigraphic units in the northern part of the Craters of the Moon volcanic field (18,19). Its direction of magnetization is close to the 2100 BP point on the magnetic vector path: this indicated age is comparable to the 2080 ± 85 ^{14}C are found for the Rattlesnake Butte Flow, the youngest dated flow in the Craters of the Moon Field. A 62° isocline paleointensity of 0.71 Oe determined from the North Crater Flow is close to but slightly lower than the paleointensity determined from the Rattlesnake Butte Flow (fig. 6). We suggest that the age of the North Crater Flow is close to 2100 BP or, perhaps, slightly younger, to account for its slightly lower paleointensity.

The mean direction of magnetization of lava from the Hells Half Acre Field lies between the 2200 and 2300 BP points on the magnetic vector path. The mean for the Wapi Field lies between the 2300 and 2400 BP points. As these mean directions have very high precision and lie exactly on the magnetic vector path, we regard the ages indicated as very probably the true ages, even though paleointensities have not yet been determined for these lavas. The direction of magnetization of the Wapi lava is very close to the direction of a lava flow in the nearby Kings Bowl Field, dated at 2360 ± 150 BP. Probably the eruption of lava in these two fields was nearly simultaneous (20).

Mean directions of magnetization have been obtained for 2 localities on the Carey Tongue, in the Craters of the Moon Field. These localities are identified as Carey Tongue and Lava Lake in figure 9.

Directions from these localities are virtually identical and lie on the magnetic vector path between points estimated for 2400 and 2500 BP. The time points, however, have been derived by interpolation between the positions of two dated lavas which are separated by at least 200 years and more likely by about 500 years in age. Neither the directions of the magnetic field nor time are tightly controlled for this segment of the path. A single 62° isocline paleointensity of 0.48 Oe, determined from a Lava Lake sample, is closer to the paleointensity from a lava near 2900 years in age than to that from a lava near 2400 BP (fig. 6). The Carey Tongue, therefore, may be substantially older than 2400 years, even though its position on the magnetic vector path is close to the estimated 2400 BP point. Provisionally we adopt an age between 2500 and 2600 BP for this flow.

The Highway Flow, in the Craters of the Moon Field, has a mean direction of magnetization which is significantly steeper in inclination than the nearest part of the magnetic vector path shown in figure 8. Because the surface of this flow is large block aa, the samples were taken along an ENE trending fault scarp, where the massive interior of the flow is exposed. The throw on this fault is more than 100 feet; the outcrop sampled could be rotated down, perhaps as much as 5° to the NNW, an amount that would be difficult to recognize in the field. Correction for such a rotation would place the magnetic direction of the Highway Flow on the magnetic vector path in the 2300 to 2400 BP time interval. We plan to search for a place on the Highway Flow remote from faults, where it can be resampled to obtain an unequivocal magnetic direction. Determination of the paleointensity will also provide a check on this suggested age.

A fairly precise mean direction of magnetization has been obtained for the Northeast Sunset Flow in the Craters of the Moon Field. This direction is close to the segment of the magnetic vector path derived by interpolation between directions at 2883 ± 175 and 2360 ± 165 BP, but the Northeast Sunset direction is significantly higher in declination than any part of the interpolated segment. It is entirely possible that this segment of the path, as shown, is in error and that it should be redrawn to pass the Northeast Sunset direction. The mean direction for the Northeast Sunset Flow is on the 95% confidence circle for the Yapoah Flow in McKenzie Pass, Oregon, which lies between volcanic units dated at 2883 ± 175 and 2550 ± 165 BP. For the present, this age range appears to be the best age assignment that can be made from the paleomagnetic data for the Northeast Sunset Flow. Because its direction of magnetization is fairly close to the direction of the Kings Bowl Field at about 2400 BP and far from directions at about 2900 BP, we would guess that the true age of the Northeast Sunset Flow is in the neighborhood of 2600 years.

A preliminary map of the distribution of 2000 to ~2600 year old lavas on the Snake River Plain is shown in figure 9. Previously published ^{14}C ages, our preliminary paleomagnetic ages, and stratigraphic relationships of flows in the Craters of the Moon Field observed by Lefebvre (21) have been utilized to construct this map. Lavas in the 2000 to ~2600 BP age group occur in all 3 lava fields along the Great Rift and in the Hells Half Acre Field. The exposed Holocene lava in the Wapi Field essentially constitutes one large flow (20). The same is true, so far as we know, of the Hells Half Acre Field. A complex sequence of flows is present, however, in the

Craters of the Moon Field.

The lowest stratigraphic units now recognized in the 2000 to 2600 year old lava sequence in the Craters of the Moon Field are the Carey Tongue, which extends to the southwest of the Great Rift, and the Northeast Sunset Flow, which flowed northeast from the Rift. Younger flows, for which no ages are yet available, locally overlie the Carey Tongue. The largest of these, the Minidoka Tongue, is a great sheet of lava in the southern part of the Craters of the Moon Field, which is comparable in area to the Wapi and to the Hells Half Acre Fields. These undated lavas are overlain, in turn, by the Rattlesnake Butte Flow, dated at 2080 ± 85 BP, and probably by the Watchman Flow, dated at 2140 ± 60 BP. In figure 9, we have tentatively placed the undated flows of intermediate stratigraphic position into the 2200 to 2400 year age category, which includes the lavas of the Wapi, Kings Bowl and Hells Half Acre Fields. Paleomagnetic and other studies are needed to test this suggestion. Lavas assigned to the age range 2200 to 2000 BP occur along the northern part of the Great Rift. They overlie both the Northeast Sunset Flow and the undated flows of intermediate stratigraphic position.

In addition to the lavas assigned to the 2000 to ~2600 year age group, 8 other Holocene lava flows on the Snake River Plain have been sampled and their directions of magnetization measured. Mean directions for 5 of these flows form a remarkably tight cluster (fig. 10), which suggests that they may be closely related in age. Thus another, earlier episode or pulse of volcanism on the Snake River Plain may be represented by these lavas. Although the control from dated lavas for the secular variation of the geomagnetic field

in the Holocene is not yet adequate to date these 5 flows with any confidence, one possible time interval within which some or all of these flows may fit is suggested by the available data. Their magnetic directions are bracketed by the directions of the Dotsero Flow, Colorado, dated at 4150 ± 300 BP, and the Hackleman Creek Flow, Oregon, dated at 3850 ± 215 BP. Among the 5 undated flows, the Grassy Cone Flow, which has a magnetic direction close to that of the Dotsero Flow (fig. 10), yields a 62° isocline paleointensity of 0.70 Oe, somewhat higher than that obtained from Dotsero (fig. 6). A fair determination of paleointensity from the "Fingers Butte" Flow of 0.44 Oe is far below that from Dotsero. Until further work is done, the possibility remains that the clustering of observed magnetic directions is a coincidence.

The 5 lava flows with tightly clustered directions are in widely separated areas of the Snake River Plain (fig. 11). Three of these flows, Grassy Cone, "Fingers Butte", and Kimama, are pahoehoe flow units in the Craters of the Moon Field which lie stratigraphically below the 2000 to ~ 2600 year old lavas (21). Inferred paths of flow and source areas for these 3 flow units are shown in figure 11. Two of the 5 lava flows are thought to constitute the bulk of the Cerro Grande and Shoshone Fields.

At least one fairly well defined pulse of volcanism occurred in the eastern Snake River Plain during the Holocene; it may have been preceded by other major pulses. Lavas erupted during the time interval from ~ 2600 BP to 2000 BP covered about 2000 square kilometers on the Snake River Plain. Several tens of cubic kilometers of basalt erupted along the Great Rift in this time period, the bulk of it along

Figure 10.

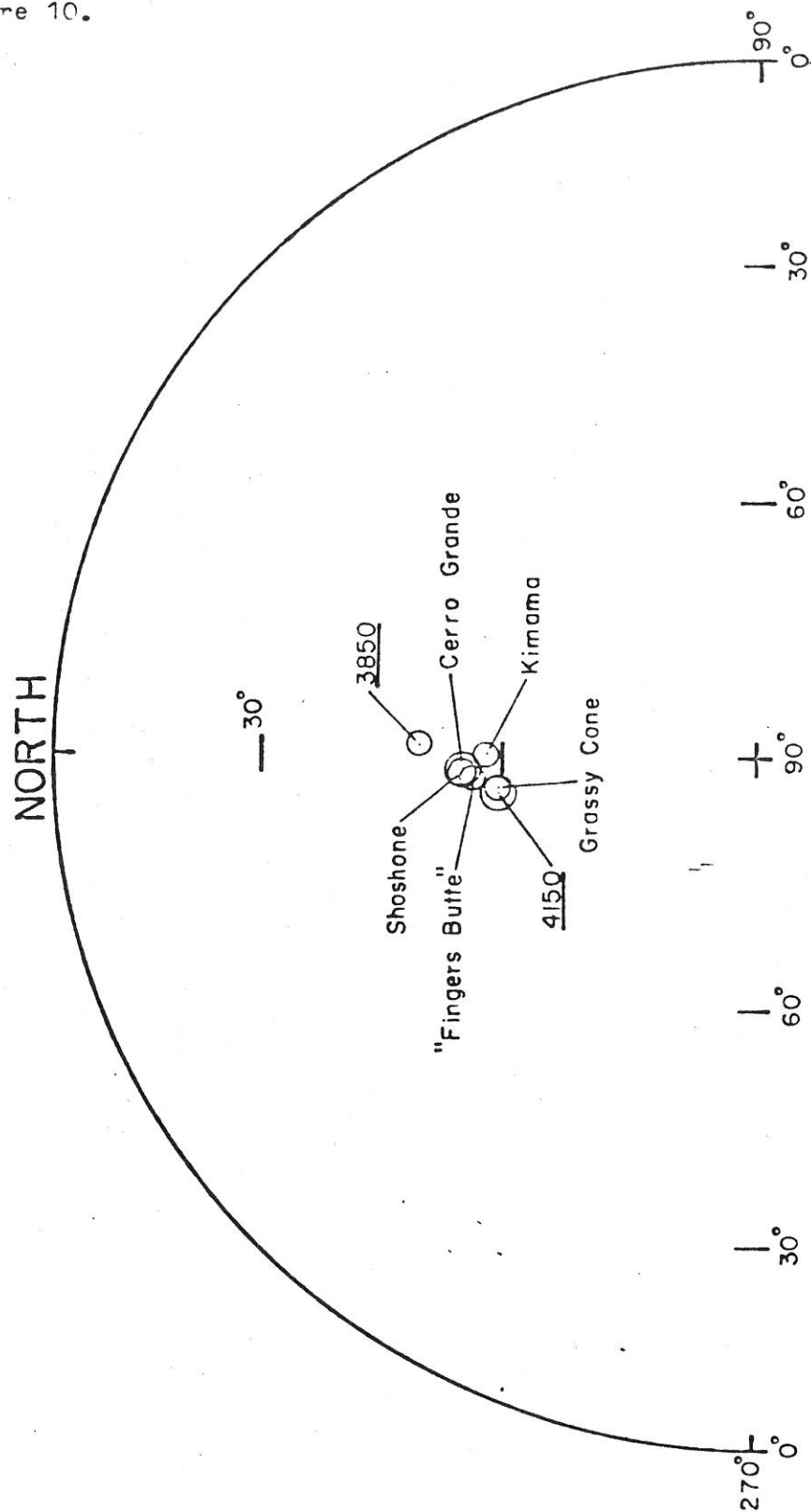
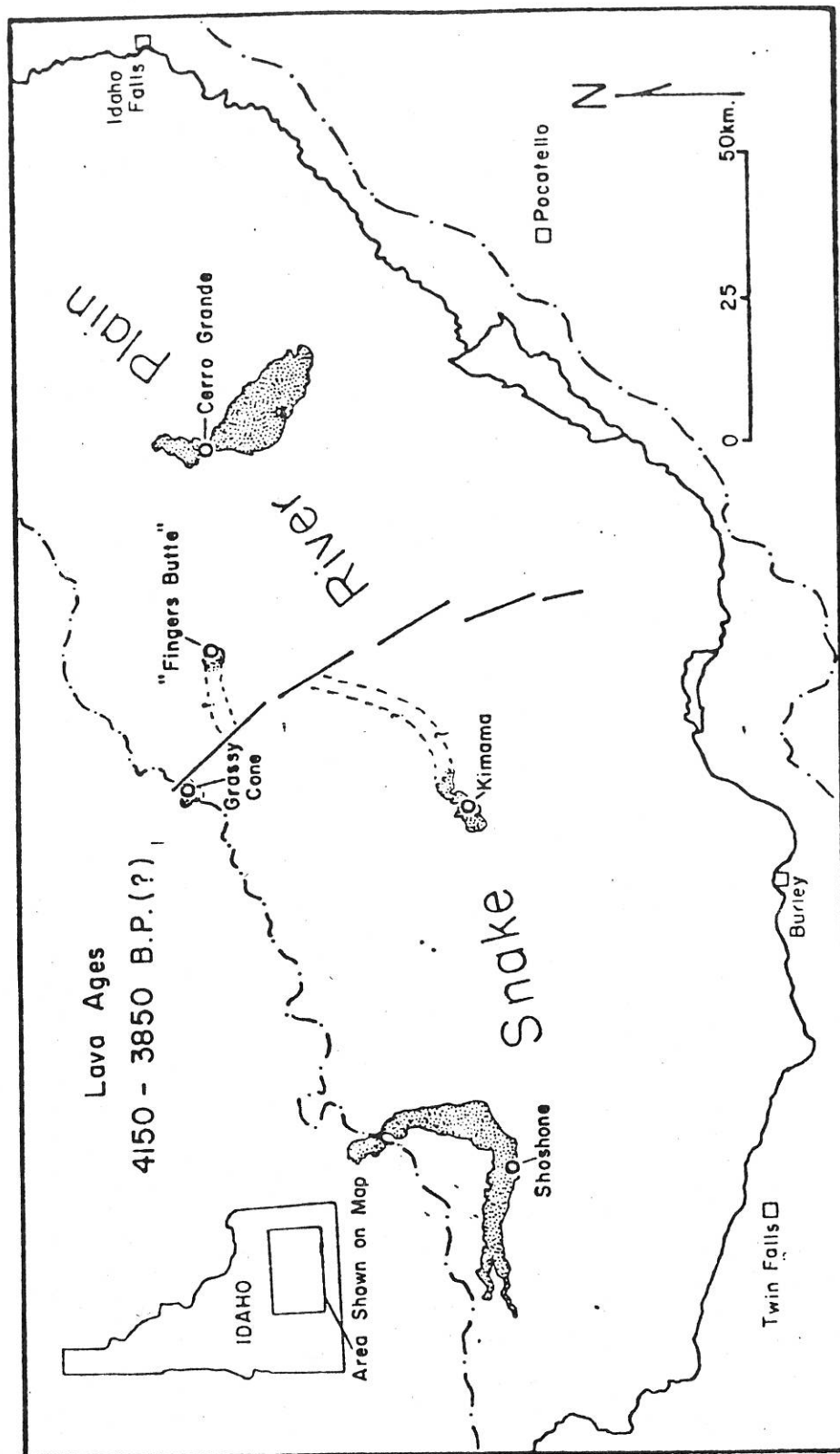


Figure 11.



the northern part of the Rift, in the Craters of the Moon Field.

An unpublished aeromagnetic anomaly map prepared by the U.S. Geological Survey shows a magnetic high localized over the northern part of the Great Rift. A small number of available gravity measurements suggests that a moderate negative gravity anomaly also occurs along this part of the Rift. These anomalies may simply reflect magnetic and density contrasts in rocks that underlie the lavas of the Snake River Plain. On the other hand, the aeromagnetic anomaly might also be caused, in part, by intrusions of basalt associated with the voluminous late eruptions. A swarm of dikes along the Rift, the upper parts of which had cooled below the Curie temperature, could contribute to the observed aeromagnetic anomaly. A negative gravity anomaly, if it is related at all to the volcanism, could be produced by a substantial body of magma at greater depth. In view of the evidence for extrusion of large volumes of lava within the last few thousand years, study of the northern part of the Great Rift from the standpoint of potential geothermal resources seems warranted.

Acknowledgments

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Captions for Illustrations

- Figure 1. Map of western United States showing distribution of Cenozoic volcanic rocks.
- Figure 2. Map of western United States showing distribution of dated Holocene volcanic units which were sampled in this investigation.
- Figure 3. Secular variation of the direction of the geomagnetic field in western United States, 7000 years BP to the present. Ages are in radiocarbon years, except for dendrochronological age at 886 BP. Boxes around data points represent estimated errors. Widths of boxes are 95% confidence limits for declination and inclination; heights of boxes are stated errors of ^{14}C determinations.
- Figure 4. Saturation magnetization versus temperature curves for 2 samples of Holocene basalt. Ordinates are saturation magnetization normalized to initial saturation magnetization at room temperature.
- Figure 5. Thellier diagrams for 2 samples of Holocene basalt. Ordinates are partial natural remanent magnetization normalized to initial natural remanent magnetization; abscissas are partial thermoremanent magnetization acquired in laboratory field of 0.50 oersted, normalized to initial natural remanent magnetization. Temperatures, in degrees C, at which partial demagnetization and partial remagnetization have been done are shown by leaders.
- Figure 6. Secular variation of the intensity of the geomagnetic field, 7000 years BP to the present. Ages are in radiocarbon years, except for dendrochronological age at 886 BP. Vertical error bars are stated errors of ^{14}C determinations. Data points based on duplicate determinations of paleointensity are indicated by a 2 with a leader.
- Figure 7a. (above) Mosaic of LANDSAT images of eastern Snake River Plain. Holocene volcanic rocks can be recognized as irregular dark patches.
- 7b. (below) Map of eastern Snake River Plain showing Holocene volcanic fields, and the Great Rift.
- Figure 8. Stereographic equal area projections showing direction of the geomagnetic field in northwestern United States between 2990 $\pm$ 300 and 1495 $\pm$ 130 BP. In figure 8a (above), mean directions for 10 ^{14}C dated lava flows are shown by points, surrounded by circles which indicate the 95% confidence limits for each mean. The number by each direction is the central value for the ^{14}C age; underlined numbers are for dated flows on the Snake River Plain. Curve with arrow is inferred path of the magnetic vector for northwestern United States. In

figure 8b, estimated radiocarbon time points on the magnetic vector path are shown by tick marks for each 100 years. Mean directions with 95% confidence circles are shown for undated lava flows on the Snake River whose ages are inferred to lie in the range 2600 to 2000 BP.

Figure 9. Preliminary map of eastern Snake River Plain showing distribution of lava flows with ages between 2000 and about 2600 years BP. Paleomagnetic sample localities are shown with solid circles, for ^{14}C dated flows, and with open circles for flows dated by paleomagnetism. Central values of the ^{14}C ages are shown for each of the ^{14}C dated flows.

Figure 10. Stereographic equal area projection showing tightly clustered directions of magnetization of 5 undated lava flows on the Snake River Plain and the directions of 2 ^{14}C dated lava flows. Underlined numbers are the central values of the ^{14}C ages of the Dotsero Flow, Colorado (4150) and the Hackleman Creek Flow, Oregon (3850), which may bracket the ages of some of the undated flows.

Figure 11. Map of eastern Snake River Plain showing distribution of undated lava flows with tightly clustered directions of magnetization. Paleomagnetic sample localities are shown as open circles. Ages of some of these lava flows may fall in the approximate interval 4150 to 3850 BP.