number $Z = 112$) in an accelerator target (*26*).

8) Searches for extinct ^{244}Pu in lunar rocks should continue. The oldest lunar rocks encountered thus far are essentially threshold objects for the observation of xenon from lunar plutonium (*27*). Slightly older rocks can be expected to give positive results.

9) Detailed predictions based on theories of both r-process and s-process nucleosynthesis have recently met rather stringent experimental tests. The presence of ^{244}Pu in the early solar system confirms the r-process as ongoing in the galaxy. And predictions from s-process theory of the relative values of cross sections of certain fast neutrons in samarium and tellurium have been strikingly confirmed (*28*). Scientists at Oak Ridge played a major role in both tests. The success of the present work depended greatly upon the superb sample of ^{244}Pu which was prepared by the Electromagnetic Isotope Separator Group at the Oak Ridge National Laboratory.

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22 March 1971

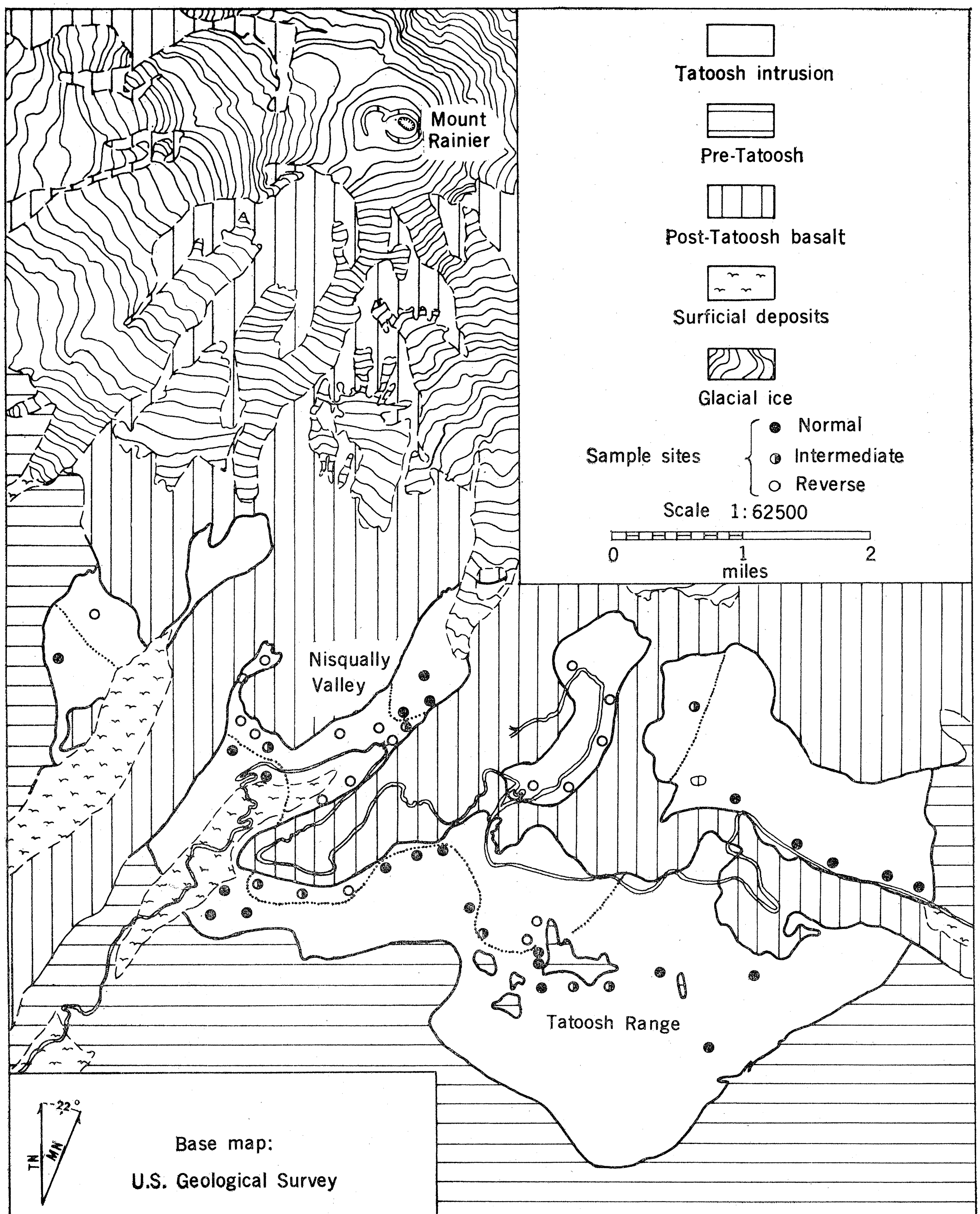
Paleomagnetic Study of a Reversal of the Earth's Magnetic Field

Abstract. *A detailed record of a field reversal has been obtained from the natural remanent magnetization of the Tatoosh intrusion in Mount Rainier National Park, Washington. The reversal took place at 14.7 ± 1 million years and is interpreted to be from reverse to normal. A decrease in the intensity of the field of about an order of magnitude occurs immediately before the reversal, while its orientation remains substantially unchanged. The onset of the reversal is marked by abrupt swinging of the virtual geomagnetic pole along an arc of a great circle. During the reversal the pole traces a path across the Pacific. In the last stage of the process recorded in the sections, the succession of virtual geomagnetic poles is very similar to those generated by secular variation in the recent past. Although the cooling rate of the intrusion is not sufficiently well known to permit a useful calculation of the duration of the reversal process, an estimate based on the length of the supposed secular variation cycles gives 1 to 4 × 10^3 years for the reversal of field direction and approximately 1 × 10^4 years for the time scale of the intensity changes.*

With the demonstration of the reality of geomagnetic field reversals (*1*) the phenomenon has assumed a position of importance in a number of areas within the earth sciences. In addition to being a critical aspect of the earth's field, which must be explained by any successful model (*2, 3*), reversals bear on sea-floor spreading (*4*), on the stratigraphy of ocean cores (*5*), and even possibly on the evolution of life (*6*). Yet, a high-resolution continuous record of a reversal has not been obtained. The natural remanent magnetization (NRM) of lavas has, however, revealed that the reversal of the field takes of the order of thousands of years (*7*), that during the reversal the field intensity diminishes by as much as an order of magnitude (*8*), and that the local field vector exhibits erratic fluctuations which appear to be superimposed upon a more gradual change in orientation (*9, 10*). In contrast to lavas, which give instantaneous readings of the field with little indication of absolute age on the time scale of a single reversal, sediments give continuous records, so that chronology is more straightforward. Paleomagnetic studies of field reversals recorded in ocean sediments have given estimates of the duration of the reversal of less than 5000 years and of approximately 10^4 years (*11*). Ancient sediments (*12, 13*) have revealed considerable detail of the reversal process (for example, the swinging of the field), but it is extremely difficult to get high resolution because of the slow accumulation rate of sedimentary material.

Fig. 1. Map of Tatoosh intrusion. The dotted lines indicate the boundaries between normal and reverse magnetized regions (1 mile is 1.6 km). *TN*, true north; *MN*, magnetic north.

We have studied reversals recorded by the NRM of intrusives because, as the cooling front traverses a small body or the margin of a larger body, a high-resolution continuous record of the field changes should be produced. After sampling about a dozen intrusions in the Pacific Northwest, we have obtained two records of reversals. The first was found in the Pliocene Laurel Hill intrusion of the Mount Hood region (*14*). The reversal is reverse to normal (R → N) and its age is 8.2 ± 0.5 million years according to K/Ar determination (*15*). The record



is noisy, for reasons that are not yet completely clear but appear to be related to the prominent multidomain magnetite in these rocks. The second reversal is from the Tatoosh intrusion in Mount Rainier National Park. The age of this body in the region that carries the reversal is 14.7 ± 1 million years (*16*).

The geology of the Tatoosh intrusion has been described by T. L. Wright (*17*). The body is exposed to the south of Mount Rainier both in glacial valleys, where overlying lavas from Rainier have been eroded, and in the main mass of the Tatoosh range which was not covered by the flows. The intrusion continues beneath Mount Rainier and has an overall diameter of many miles. Our work has been confined to the southern portion (Fig. 1), which was intruded at shallow depth and contains a substantial fine-grain marginal phase. The NRM of the body has recorded at least two reversals. The first is normal to reverse (N → R) and is close to the contact. The second is in the upper Nisqually Valley region where the rock is a medium-grain granodiorite that shows very little variation in petrology or in magnetic properties.

There are basically three reasons which, considered in conjunction, convince us that the Nisqually Valley section records a true reversal and that neither complicated mineralogical changes nor reheating with the superposition of a later magnetization of opposite polarity can explain the observations. First, the distribution of normal, reverse, and intermediate rocks within the body is not random but gives a relatively simple pattern, which can be explained by the motion of the cooling front proposed by Wright (*17*). Second, the low intensity of NRM of intermediate samples is due to acquisition of remanence in a weak field of intermediate direction throughout the whole range of blocking temperatures; it is not due to the superposition of normal and reverse components acquired in different blocking ranges. Third, the stable NRM of normal, reverse, and intermediate rocks is predominantly carried by fine-grain magnetite, for which no intrinsic self-reversal mechanism is known.

The reversal is interpreted to be reverse to normal (R → N) because intermediate samples close to the reverse region tend to give a more reversed orientation on thermal demagnetization; the remanence blocked in the highest temperature range is more nearly reversed than that in lower blocking ranges. Evidently, the field was changing during the cooling of these samples from reverse to intermediate. An R → N transition is consistent with the occurrence of reverse samples vertically above intermediate samples in Nisqually Valley and the proposed motion of the cooling front (*17*).

A section located approximately half a mile (0.9 km) south of the main outcrop in which the reversal was studied was investigated to see if any evidence of secular variation could be observed prior to the reversal. The NRM's of samples from this section, and indeed the NRM of all samples used in this work, were exposed to alternating-field demagnetization to 100 oersteds. As the section was traversed into the intrusion, an increase in intensity of remanence of approximately a factor of 5 was found. There is some indication of rotation of the local vector similar to the rotations seen in secular variation records (*18*).

Figure 2 illustrates the NRM immediately before and during the reversal. The values given are for individual drill samples along the section. The results are presented in the form of intensity, declination, and inclination plots of NRM (Fig. 2a) and as virtual geomagnetic poles (VGP) (Fig. 2b). The VGP is the pole of the dipole field that accounts for the local field vector recorded by the magnetization of the rock. It is a very convenient representation of the local vector (*19*) but *must not* be regarded as indicating that the field was necessarily dipolar.

The section consists of an almost continuous outcrop of low bluffs on the east side of Nisqually Valley. In the first part of the section, over a distance of some 400 feet (131 m), the intensity of NRM decreases by a factor comparable to the increase observed in the previous section. During the major part of the intensity decrease, the direction of magnetization does not change significantly, although there is a slight increase in the scatter of VGP's (Fig. 2b, parts 1 and 2). This increase

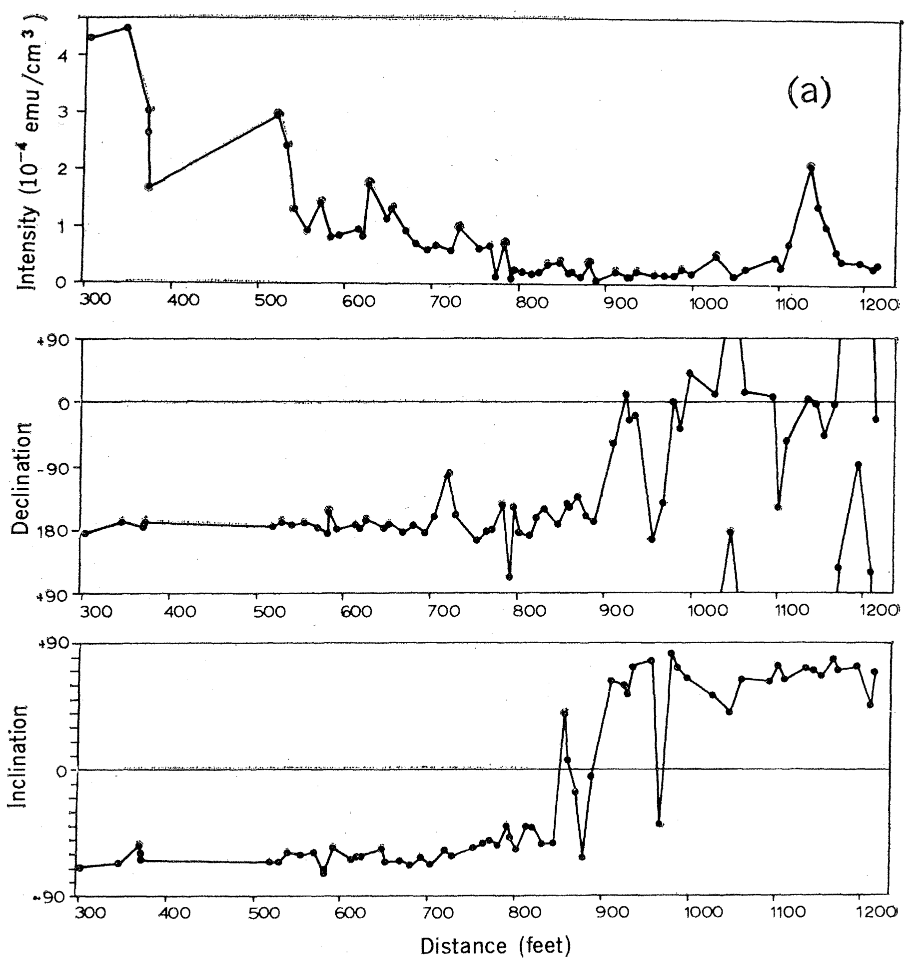


Fig. 2a. East side of Nisqually Valley: intensity, declination, and inclination of NRM as a function of distance along the outcrop (1 foot = 0.3 m).

in scatter gives way, during the final stage of the decrease in intensity, to systematic swings of the VGP along a great circle (Fig. 2b, part 3). There is some indication of rotation about a point 10° from the South Pole. The anticlockwise rotation becomes clearly apparent in part 4 of Fig. 2b, and two cycles are completed. The centers of rotation move progressively away from the South Pole. A mixture of rotation and swings of the VGP ensues. In part 6 of Fig. 2b, evidence of clockwise rotation is seen. The cycle involving the first seven VGP's in part 6 of Fig. 2b coincides with a transitory recovery of NRM intensity.

Results from a section on the west side of Nisqually Valley record the field soon after the normal VGP is seen (Fig. 3). Major fluctuations in intensity are again evident. The VGP is confined to some 30° of the present rotation pole throughout most of the section. The latter half of the section reveals a succession of VGP's, which is remarkably similar to those found in the archeomagnetic records of recent secular variation (*18*). The cusps and excursions of the VGP path are larger, however, than in the archeomagnetic data. The VGP moves relatively rapidly between the centers of minor rotation.

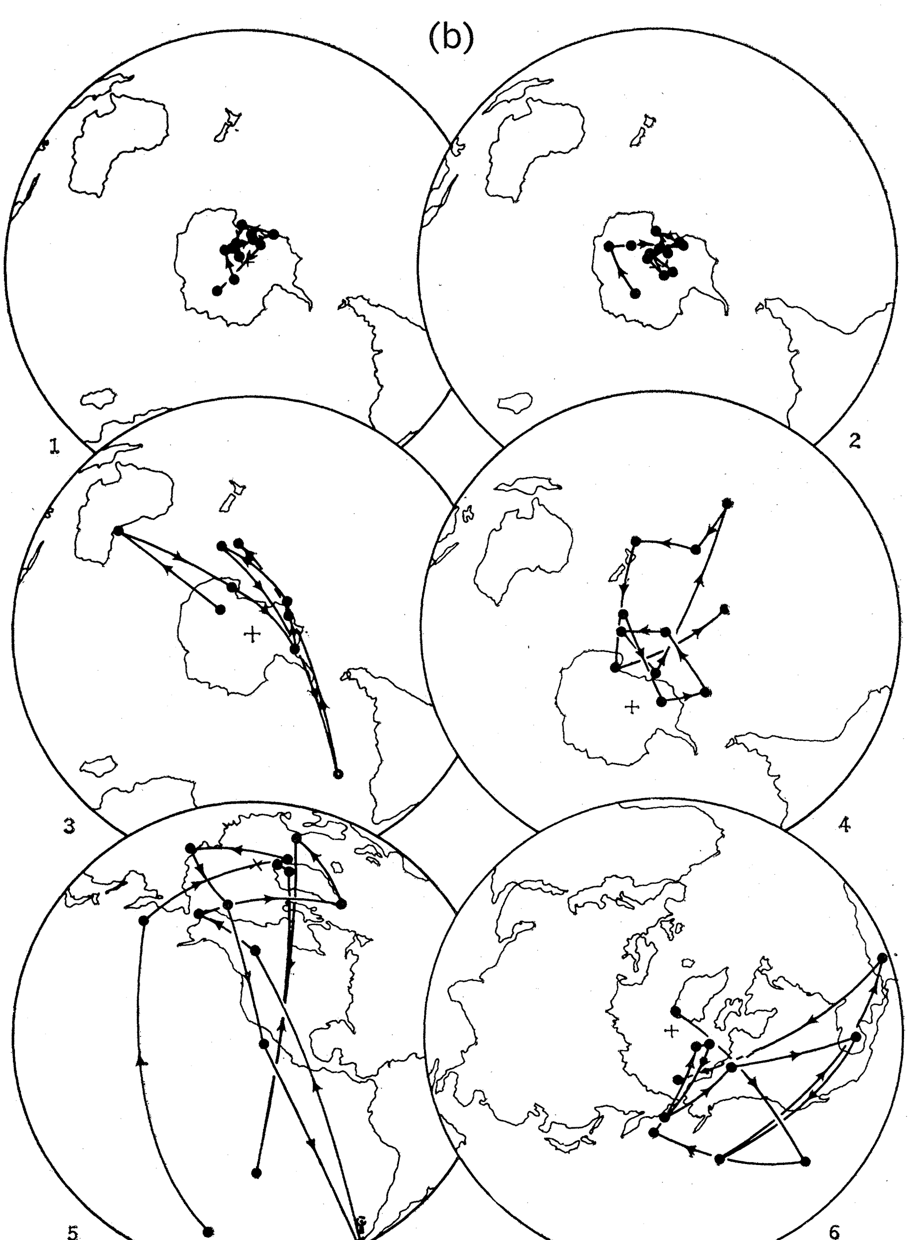


Fig. 2b. East side of Nisqually Valley: plots of VGP along outcrop. Part 1, 300 to 580 feet; part 2, 580 to 700 feet; part 3, 700 to 800 feet; part 4, 800 to 900 feet; part 5, 900 to 1100 feet; and part 6, 1100 to 1250 feet (1 foot = 0.3 m).

The pattern of changes in direction and intensity of the NRM is comparable with the pattern reported in earlier work. For example, the whole succession of directions has strong affinities with both the Pliocene Laurel Hill intrusion reversal (*14*) and the reversal found in the Pliocene sediments of Turkmenia and Azerbaidzhan (*12, 13*). The intensity variation gives high values immediately before and after the actual transition that are somewhat similar to those noted by Van Zijl *et al.* (*10*) and by Kaporovich *et al.* (*12*).

Before considering the interpretation of the paleomagnetic record, it is important to discuss certain aspects of the magnetic properties of these rocks. A variety of techniques (*20*) have been used to determine the nature of the NRM and its carrier. They suggest that the stable part of NRM is predominantly carried by fine-grain magnetite with a blocking temperature range of 580° to 560°C. Some of this magnetite is found enclosed by later felspar crystals, so that it was probably formed above its Curie point and, during subsequent cooling, acquired thermoremanent magnetization (TRM).

Two remarkable results have been obtained, which complicate the interpretation of the NRM. First, the ratio of NRM to laboratory TRM, after both have been demagnetized to 100 oersteds, is itself a function of the laboratory TRM [that is, $NRM_{100} : TRM_{100} = f(TRM_{100})$]. Thus, the linear relationship between NRM and TRM, which is the usual basis of field intensity determinations, is lost. Second, in both NRM and TRM the range of blocking temperatures is a function of the inducing field. Although an understanding of these phenomena may have important consequences, it is unlikely the results reported here will be critically altered. We have carried out field intensity determinations (*21*) in a weak field of 0.02 oersted for specimens at distances of 625, 652, 791, 861, and 1209 feet (204, 214, 260, 282, and 397 m) in the section exhibiting the reversal (Fig. 2). We obtained values of 0.14, 0.12, 0.02, 0.05 and 0.06 oersted, respectively, for the ancient field intensity. Hence, the general form of the variation of NRM intensity with distance may be taken as a preliminary indication of the variation of field intensity during the transition.

For a description of the reversal process, knowledge of the cooling rate of the intrusion becomes critical. For a given range of blocking temperatures, it is the cooling rate that controls the degree of averaging of the field during the acquisition of remanence. Moreover, estimates of the cooling rate also control estimates of the time taken for the reversal. Now, if the geometry and the necessary thermal parameters of a body are known, cooling models give its thermal evolution (*22*). Despite difficulties in assigning these parameters, Lovering's analysis (*23*) for a laccolith has been applied with the assumption that the Nisqually rocks were 10^3 feet ($\sim$ 330 m) from the contact. The estimated cooling rates then suggest that averaging should take place over periods of at least 10^3 years for the known range of blocking temperatures. Yet, throughout the sections we see convincing evidence of secular variation, which asserts that such long-period averaging has not taken place and that therefore the cooling rate must have been much faster. It seems possible that the extremely shallow intrusion depth of the body may give rise to a geological situation that departs significantly from the assumptions of the standard cooling models.

If we assume that the cyclic motions of the VGP are manifestations of secular variation and that the secular variation had similar periodicities then to those observed in the immediate past, we can speculate on the duration of the reversal. The time taken for nondipole anomalies to pass the site and give rise to the cycles and minor loops, such as those completed in about 100 feet (33 m) of section, should be approximately 500 years. The sections on the east and west sides of Niqually Valley represent some 10^4 years. The transition in direction from R $\rightarrow$ N therefore takes place in 1000 to 4000 years, an estimate that is in agreement with earlier paleomagnetic results (*7, 11*). The time scale of the intensity changes is more like 10^4 years. Naturally all these estimates of absolute lapsed time are highly speculative. In contrast, it is securely established that the reversal in direction is on a considerably shorter time scale than are the intensity changes.

It is clear that at present we cannot place critical constraints on the various geomagnetic dynamo models (*2, 3*), which are still for the most part kinematic. Nevertheless, the record we obtained is reminiscent of the behavior of coupled homopolar dynamos (*24*). Moreover, the possibility of distinguishing between hypotheses in the future is promising. For example, low-latitude records of reversal would test the Parker cyclone approach (*25*), according to which the absence of low-latitude cyclones is a necessary condition for a reversal. The most promising kinematic model, which is that due to Bullard, Gellman, and Lilley (*3*), can give rise to reversals without fundamental changes in the $T^2T_2^{2c}T_2^{2s}$ harmonics that play the main role in the regenerative process. However, the predicted fluctuations of the poloidal field are essentially erratic and unlike our impression of the geomagnetic field. Nagata's reversal model based on this dynamo scheme (*26*) suggests that there is intermittent loss of the Braginskii criterion (*27*) for regenerative motion. Nagata's model predicts infrequent substantial fluctuations of field intensity accompanied by reversals on half of the occasions. Cox's (*28*) discussion of reversals gives a very different prediction, since he asserts that some measure of the nondipole field triggers a reversal in polarity on a small number of the many occasions on which the dipole harmonic oscillator is close to a minimum. It appears that careful studies of the field intensity in continuous records, such as can be obtained from suitable intrusions, should therefore eventually provide critical geomagnetic data.

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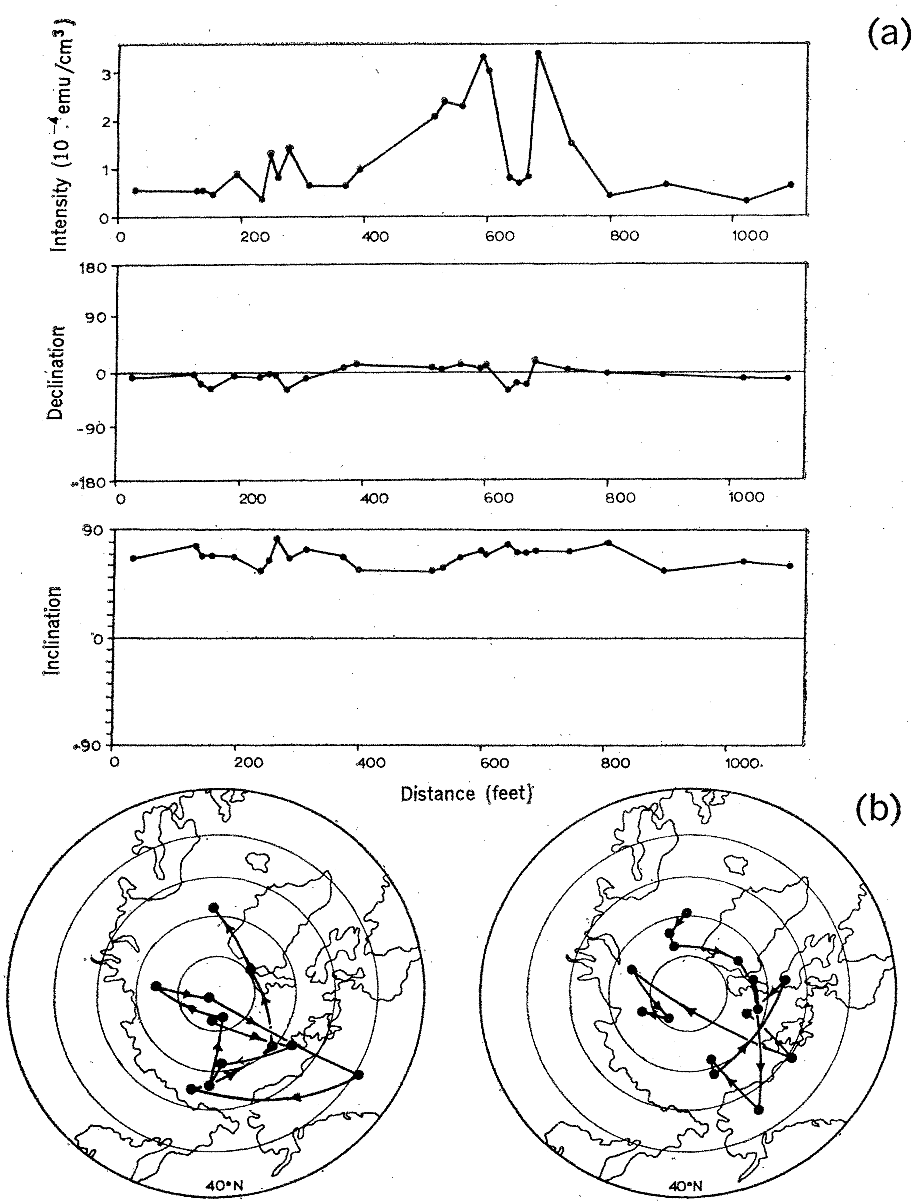

Fig. 3. West side of Nisqually Valley. (a) Intensity, declination, and inclination of NRM as a function of distance along the outcrop. (b) Plots of VGP along outcrop: (left) 0 to 400 feet; (right) 400 to 1100 feet (1 foot = 0.3 m).

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Solar Radiation: Absence of Air Pollution Trends at Mauna Loa

Abstract. *Measurements of solar radiation made at Mauna Loa, Hawaii, over a period of 13 years give no evidence that human activities affect atmospheric turbidity on a global scale. Short-term fluctuations in insolation appear to be associated with naturally produced tropospheric aerosols. The intrusion of volcanic dust into the stratosphere results in prolonged increases in atmospheric opacity due to the extended residence times of aerosols in the stratosphere.*

Concern over the earth's energy balance has been expressed in discussions about the diminution of solar radiation and the associated variations in world climate, consequent on the continuing and increased emission into the atmosphere of particulate matter by industrial processes. Observations of an increase in atmospheric turbidity, which is a measure of the extinction of solar radiation in excess of that to be expected from a clean atmosphere, in Washington, D.C., and Davos, Switzerland, led McCormick and Ludwig (*1*) to hypothesize the long-term effects of pollutant aerosols. Flowers *et al.* (*2*) have examined the data from a network of stations designed to measure turbidity and have established a pattern for the continental United States which clearly shows a correlation between high turbidity concentrations and geographic locations with heavy industrialization.

The occurrence of air pollution, however, to which these turbidity increases can be attributed, is a property of the lower troposphere and thus subject to temporal and spatial variations within short intervals. In each of the documented episodes of acute pollution in the past (for example, the Meuse Valley, 1930; Donora, Pennsylvania, 1948; London, 1952 and 1962; and the U.S. East Coast, 1970) a prolonged period (several weeks) of unusual weather conditions accompanied the air pollution incidence, which resulted in a failure of the usual natural processes to dilute and dissipate air pollutants.

In order to detect secular trends in turbidity on a global scale, it is necessary to subdue by experimental design the short-term existence of airborne particulate matter in the lowest portions of the atmosphere in the proximity of pollution sources. Fischer (*3*) carried out measurements of atmospheric turbidity in Antarctica in 1966–1967. A comparison of these data with earlier data on Antarctica led him to conclude that no pronounced change in Antarctic turbidity had occurred in the 16-year period prior to 1966. Mauna Loa Geophysical Observatory (19°32′N, 155°35′W) at an altitude of 3400 m qualifies as a bench-mark station for probing the trace constituents of the atmosphere in virtue of its great distance from continents, the absence of potential pollution sources on the island of Hawaii, and the protection of the measurement site from local emissions, including water vapor, afforded frequently by a persistent trade wind inversion. The monitoring of solar radiation at Mauna Loa is part of a bench-mark program initiated at the beginning of the International Geophysical Year (*4*). Eight pyrheliometers have been used in a continuing program to monitor the normal component of the solar beam. Peterson and Bryson (*5*) concluded, from the evaluation of radiation data taken at Mauna Loa Observatory, that a steady increase in turbidity has taken place between 1958 and 1963.

We have carefully evaluated the data presented in this report (collected over a 13-year period) in order to eliminate as much as possible all contributions to turbidity from random variations of the optical density of the atmosphere, including those caused by locally produced tropospheric aerosols such as sea spray and volcanic effluents. Control days, distinguished from the