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Geomagnetic fluctuations during a polarity transition

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Abstract. The extensive Roza Member of the Columbia River Basalt Group (Washington State) has intermediate paleomagnetic directions, bracketed by underlying normal and overlying reverse polarity flows. A consistent paleomagnetic direction was measured at 11 widely distributed outcrops; the average direction has a declination of 189° and an inclination of –5°, with greater variation in the inclination [*Rietman*, 1966]. In this study the Roza Member was sampled in two Pasco Basin drillcores, where it is a single cooling unit and its thickness exceeds 50 m. Excellent core recovery allowed uniform and dense sampling of the drillcores. During its protracted cooling, the Roza flow in the drillcores recorded part of a 15.5 Ma geomagnetic polarity transition. The inclination has symmetric, quasi-cyclic intraflow variation, while the declination is nearly constant, consistent with the results from the outcrops. Thermal models of the cooling flow provide the timing for remanence acquisition. The inclination is inferred to have progressed from 0° to –15° and back to –3°over a period of 15 to 60 years, at rates of 1.6° to 0.5°/yr. Because the geomagnetic intensity was probably weak during the transition, these apparently high rates of change are not significantly different from present-day secular variation. These results agree with the hypothesis that normal secular variation persists through geomagnetic transitions. The low-amplitude quasi-cyclical fluctuations of the field over tens of years, recorded by Roza, suggest that the geomagnetic field reverses in discrete steps, and that more than 15–60 years were required to complete this reversal.

Introduction

The *Earth's* magnetic field is usually in one of two stable polarity states, superimposed by modest secular fluctuations. During polarity transitions the geodynamo appears to be unstable, possibly exposing more of its underlying dynamics. Therefore analyzing the field's characteristic timescales during transitions may aid in constraining mechanisms for geomagnetic field generation and causes of reversals. Studies of fundamental geomagnetic rates of change are complementary to analyzing the morphology and intensity fluctuations of the field during transitions.

The present understanding of geomagnetic transitions is incomplete; only a coarse description of first-order features is known, and many details appear inconsistent between records, even of the same transition. Details of geomagnetic transitions come primarily from lava sequences, rapidly deposited sediments and intrusives, each expressing different details of the paleofield. Sediments and slowly cooled magmatic bodies typically represent an integrated and relatively continuous time series of the field. However, these records often miss higher frequency geomagnetic fluctuations, due to inherent smoothing during remanence acquisiton, potential complexities in the recording material, as well as post-deposition and postacquisition alteration. Lava successions often reliably record the paleomagnetic vector at discrete times, but lavas typically erupt at irregular and unknown time intervals. In this paper we report results from a partial polarity transition recorded in a single thick lava flow with a protracted cooling history.

Geology and Paleomagnetism of the Roza Member

The Columbia River Basalt Group in the northwest United States is an extensive succession of basaltic lavas (Figure 1), spanning 17 to 6 Ma (million years before present) and several magnetic polarity chrons [e.g., *Swanson et al.*, 1979; *Hooper*, 1982]. The Roza Member of the Wanapum Basalt erupted about 15.5 Ma [*Baksi*, 1988] and recorded intermediate magnetic polarity; it is underlain by the normal polarity Frenchman Springs units and overlain by the reverse polarity Priest Rapids flows [e.g., *Beeson et al.*, 1985]. The Roza Member originally extended over about 40,000 km^2 and had a volume in excess of 1500 km^3 [*Swanson et al.*, 1975]. In the western part of the plateau the Roza Member is present as one flow, but in the eastern part two flows are common [*Mackin*, 1961; *Bingham and Walters*, 1965; *Bingham and Grolier*, 1966]. *Shaw and Swanson* [1970] suggested that the main flow of the Roza Member was extruded in a matter of days.

Rietman [1966] sampled the Roza Member for paleomagnetism at 11 widely separated sites and measured approximately the same transitional directions, declination D = 189.0° and inclination I = –4.8°, with α_{95} = 7.0° for N = 9 sites. Rietman's results show that the range of the site-mean inclinations (–21° to +8°) is approximately twice the variation of the declinations (180° to 196°).

The thickness of the Roza Member often exceeds 50 m in the Pasco Basin and 30 m over a large area of the western plateau. *Audunsson and Levi* [1988] calculated that cooling of the flow everywhere to below about 300°C would require tens of years. Therefore, a continuous record of the geomagnetic field is expected to have been recorded in the cooling Roza flow, as the blocking temperature isotherms traversed the flow.

The consistent intermediate paleomagnetic direction of the Roza Member, its stratigraphic position between underlying normal and overlying reverse polarity units and its extended cooling history suggest that the Roza Member recorded part of a

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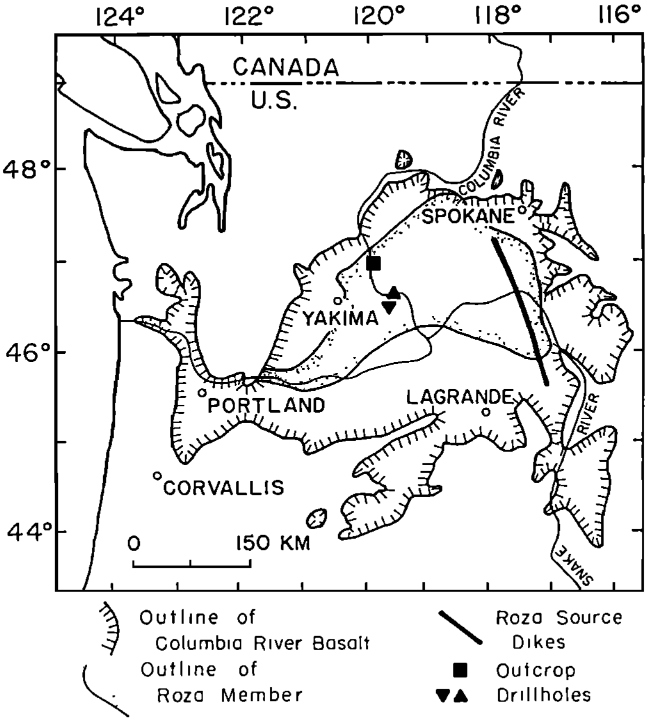

Figure 1. Map showing the extent of Columbia River Basalt and the Roza Member, as well as the sampling sites. Drillcore DC2, triangle; drillcore DC12, inverted triangle; outcrop near Vantage, rectangle. Map is modified from *Swanson et al.* [1975]. Drillcores in Pasco Basin, Hanford reservation: Drillcore DC2 (46°34'N, 119°31'W); depth of the Roza flow 349.2–410.8 m below surface. Drillcore DC12 (46°28'N, 119°33'W); depth of the Roza flow 409.0–463.3 m below surface. Vantage outcrops: Wanapum Dam (46°54'N, 119°57'W) is a 30-m hill east of Wanapum Dam and just east of Washington State Highway 243 (along the east bank of the Columbia River), 5 km south of the Interstate 90 bridge across the Columbia River. Frenchman Coulee (47°2'N, 119°58'W) is a roadcut in the south wall of the north alcove of Frenchman Coulee; sampled outcrop is about 35 m long and centered around a spiracle in the Roza flow.

geomagnetic polarity transition. Calculations of the lava's thermal history together with paleomagnetic measurements throughout the flow would provide an estimate of the rates of change of the recorded geomagnetic parameters. Our results show that as the Roza flow cooled through its blocking temperatures, the inclination fluctuated by about 15°, with a characteristic time of 15 to 60 years, while showing no discernible variations in the declination.

Sampling and Laboratory Procedures

Sampling

When the Roza Member extruded, the Pasco Basin was a topographical low and the flow ponded to thicknesses exceeding 50 m. We sampled two Pasco Basin drillcores (DC12 and DC2), separated by about 11 km, where the Roza flow is now at a depth of about 0.4 km [*Moak*, 1981]. We also sampled two outcrops about 70 km northwest of the drill sites, where the flow is approximately 30 m thick (see Figure 1 for site locations).

The subsurface geology in the Pasco Basin has been defined by extensive drilling, and the Roza flow is easily recognized and correlated between drill holes [*Reidel and Fecht*, 1981]. In cores DC12 and DC2 the Roza Member is a single cooling unit, massive through most of its thickness, and its top and base are easily distinguished. The nearly 100% core recovery permitted uniform and dense sampling through the entire flow. Horizontal minicores 25 mm in diameter were drilled from the drillcores using a drill press (Figure 2). Vertical orientation of samples was comparatively accurate, but the drillcores were azimuthally unoriented. The high rate of core recovery made it possible to jigsaw fit several segments from drillcore DC12 to obtain continuous relative declinations for these sections. *Audunsson and Levi* [1989] analyzed the drilling induced remanent magnetization (DIRM) in these drillcores and showed that it is concentrated at the surface of the drillcores and that it can usually be removed by alternating fields (AF) demagnetization. Consequently, only the central 22–24 mm specimen from each minicore was used for this paleomagnetic study.

Analysis of Remanence

A single axis AF demagnetizer was used, progressively increasing the peak AF to a maximum of 100 mT. Heatings for thermal demagnetization were done in low magnetic fields, ≤ 10 nT, and pressures $\leq 10^{-4}$ torr.

In this study we compare small differences in the characteristic remanence of adjacent samples. The orientation of the apparently stable remanence in each specimen was analyzed using two different assumptions [*Audunsson*, 1989]. First, it was assumed that the higher coercivity remanence is a single primary component. The characteristic direction was estimated by fitting a line through a subset of consecutive points of the demagnetized remanence, constrained through the origin and denoted as D_0 (declination), I_0 (inclination). This approach reduces the weight of the typically more scattered data near the origin. Second, instead of the a priori assumption of a single, primary component of remanence, the fitted vector was not constrained through the origin, and the orientation was denoted D_f and I_f, which repre-

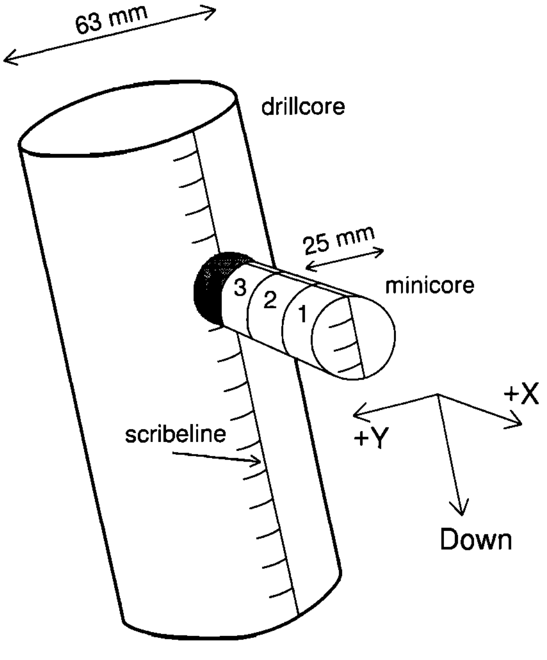

Figure 2. Minicore sampling and the orientation convention. Only the center specimen was used for this study to minimize the effects of the drilling induced remanence, which is concentrated at the drillcore's surface.

sents the direction of a segment of the demagnetization path, equivalent to the direction of the removed remanence over that interval. When the angle Δ_f between these two estimates exceeds the inherent scatter in the sample's remanence direction, it is concluded that the primary remanence was not isolated and the sample was rejected from further study. As a measure of the inherent scatter in directions we used the "the maximum angular deviation" (MAD) [*Kirschvink*, 1980; *Audunsson*, 1989], which is the angle spanned by the standard deviation of the data perpendicular to and parallel to the best fitting line. Furthermore, all vector projection diagrams (VPD) were inspected visually, and significant scatter or nonlinear trends in the demagnetization paths not detected by the above method might lead to the rejection of additional samples.

Paleomagnetic Results

Results From Drillcore DC12

NRM properties. The Roza in drillcore DC12 is about 54 m thick, and 83 minicores were sampled at 0.5- to 1-m intervals. The intensity of the natural remanent magnetization (NRM) and its value after AF demagnetization to 10 mT (Figure 3a) indicate that the remanence is more stable in the top 25% of the flow. This is supported by the magnetic stability of laboratory induced anhysteretic remanent magnetization (ARM), shown in Figure 3b.

The NRM inclinations are generally steep and scattered, and they usually deviate significantly from the near horizontal primary directions of the Roza flow. Most of the overprint appears to be DIRM [*Audunsson and Levi*, 1989] and present-day viscous remanence. The two topmost specimens in Roza (depth ≤ 1.5 m) have stable NRM inclinations of −65° in good agreement with the primary inclination of the overlying 33-m Priest Rapids flow [*Packer and Petty*, 1979], suggesting that these specimens were thermally remagnetized during the emplacement of the overlying flow.

Demagnetization. Specimens from 64 minicores were AF demagnetized, ten were thermally demagnetized, and an additional 9 specimens were first AF demagnetized in low fields (≤ 15 mT) prior to thermal demagnetization. Alternating fields demagnetization was usually successful at isolating a stable primary remanence. Twelve of the 64 AF demagnetized specimens were rejected; eight had high Δ_f and four had poor VPD, as outlined above. However, the remanence direction from most of the rejected samples is consistent with those of adjacent samples, and their exclusion does not alter the intraflow inclination pattern. The two topmost specimens were omitted from further consideration because they were thermally overprinted. Representative VPDs of AF demagnetized specimens from DC12 are shown in Figure 4.

Ten specimens, evenly distributed through the flow, were thermally demagnetized. Of these, only the two uppermost specimens (4.1 and 9.1 m below the top of Roza), in the upper 25% of the flow, produced reliable directions with I_0 of −6° and −7° (Figure 5), nearly identical to values from adjacent AF demagnetized specimens. The primary remanence in the deeper specimens (≥ 13.1 m below the top of the flow) was masked by a steep overprint, and thermal demagnetization was not successful at its selective removal.

The hybrid of AF followed by thermal demagnetization of nine additional specimens led to vector orientations similar to those of adjacent AF demagnetized specimens; however, the results were excluded from further consideration because the inherent scatter exceeded the criteria outlined above.

The results from the Roza and the underlying Frenchman Springs flows indicate that for these units AF demagnetization is more efficient than thermal demagnetization at removing drilling induced and/or viscous overprints. In most of the DC12 Roza specimens (43 of 50), demagnetization in peak AF of 30 mT was sufficient to isolate the primary remanence, and these directions were calculated using AF levels ≥30 mT. In seven specimens a minimum AF of 40 or 50 mT was needed to isolate the primary remanence; however, including the 30 and 40 mT AF levels caused only 1° to 3° change in the stable directions.

Profiles of the primary remanence. Figure 6a shows the intraflow stable inclinations in drillcore DC12; I_0, assuming a single remanence component, and I_f, the removed remanence, calculated for the same AF interval as I_0. It is evident from Figure 6a that both analyses produce nearly identical intraflow variation of the inclination, supporting the conclusion that there is only one high coercivity component, and that it is unlikely that the

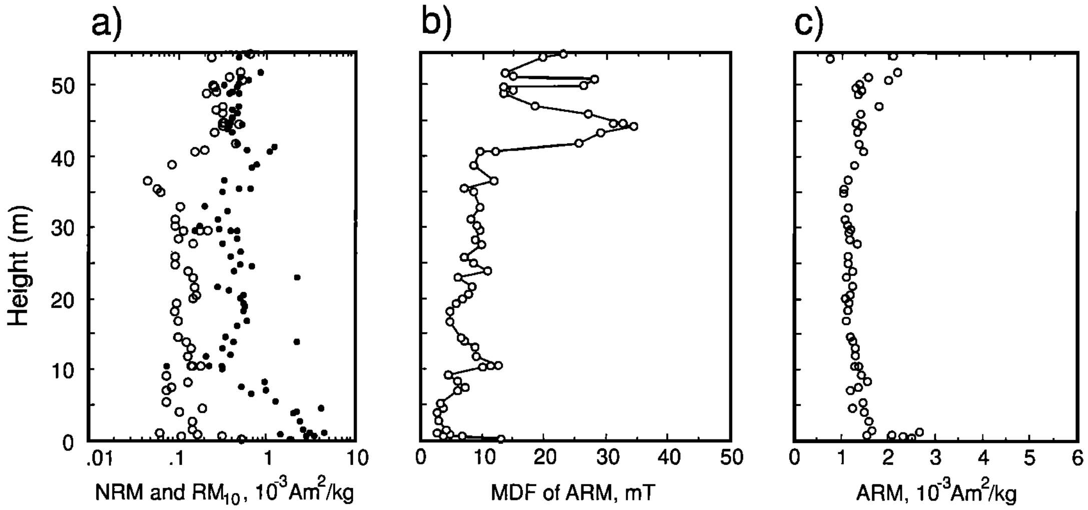

Figure 3. Depth profiles of magnetic properties of the Roza flow in DC12: (a) intensity of NRM and after demagnetization in peak alternating fields of 10 mT, closed and open symbols, respectively; (b) ARM stability as measured by the median demagnetizing field (MDF); (c) ARM intensity (induced in a peak AF of 100 mT and DC field of 0.05 mT).

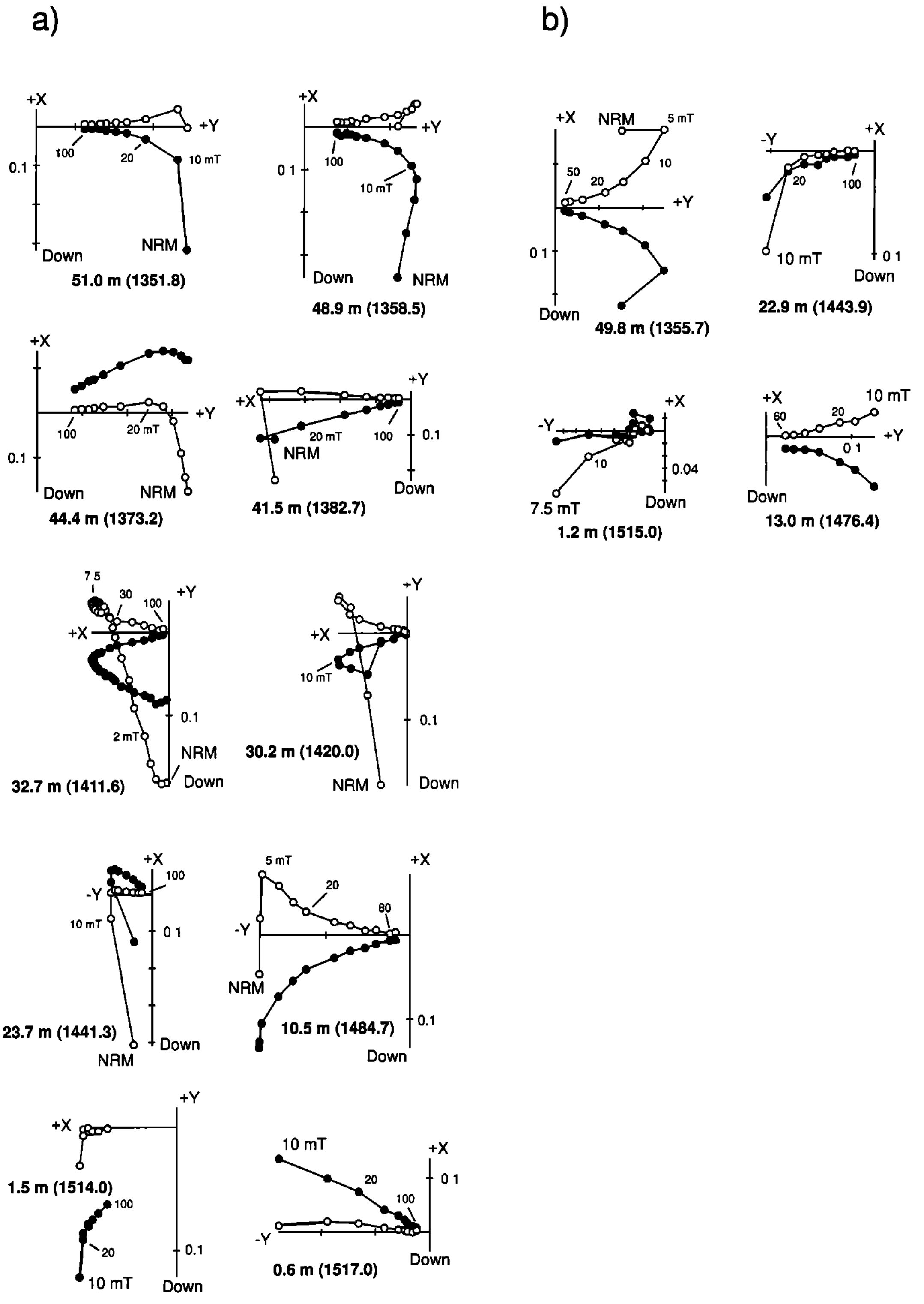

Figure 4. Vector projection diagrams for AF demagnetized specimens from the Roza flow in DC12. The closed (open) symbols refer to remanence projections on to the horizontal (vertical) plane. The intensity units are 10^{-3} Am^2/kg. (a) Examples of specimens considered reliable. (b) Examples of specimens rejected for failing the remanence reliability criteria. Samples 1355.7 and 1476.4 were rejected as Δ_f were significantly greater than the inherent scatter in the orientation (MAD). Samples 1443.9 and 1515.0 were rejected due to poor VPD (trend and high scatter, respectively). Numbers (e.g., 48.9 m) indicate height from the base of the Roza flow; numbers in brackets (e.g., 1443.9) are depths in the drillcore measured in feet (1 ft × 0.3048 = m).

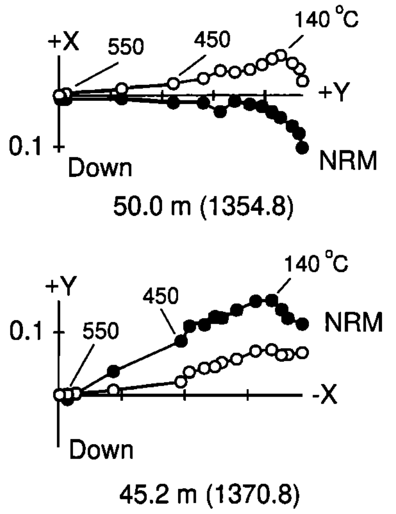

Figure 5. Vector projection diagrams of thermally demagnetized specimens from the Roza flow in DC12. Symbol convention is the same as in Figure 4.

inclination profile in DC12 is due to bias in the method for estimating the orientation of the stable remanence.

The angle Δ_f between the two mean directions D_0, I_0 and D_f, I_f is shown in Figure 6b. Higher values of Δ_f are caused by greater scatter in the measurements of the demagnetized remanence, especially the removed remanence (D_f, I_f), and incomplete demagnetization of secondary components. The values of Δ_f show that the error in determining the orientation of the stable remanence in each specimen is typically less than about 5°, significantly less than the overall intraflow variation of the stable inclination (I_0). Many of the rejected data have mean directions that coincide with the adjacent reliable specimens, although the remanence fails the reliability criteria (i.e., Δ_f is too high).

The high rate of core recovery enabled jigsaw fitting of drillcore segments of up to 19 m for azimuthal realignment and relative declination measurements. The average declination of each reconstituted segment was adjusted to 190°, the mean value for the outcrops. There is no significant change in stable declination within any contiguous drillcore segment, and the overall standard deviation is about 4° (Figure 7). The apparent uniformity of the observed intraflow declination in DC12 is consistent with the results from the outcrops (Table 1).

Results From Drillcore DC2

The Roza flow in DC2 has generally lower magnetic stability, and produces a lower quality paleomagnetic record than Roza in DC12. Below the more stable upper part of the flow in both drillcores, the median demagnetizing field of ARM is typically between 4 and 6 mT for DC2 as compared to 3 to 13 mT in DC12 (Figure 3b; also Figure 1 in *Audunsson et al.* [1992]). The stable remanence directions in DC2 were analyzed as before, and the same selection criteria were applied as for DC12. Finally, 19 of 34 AF demagnetized specimens were retained. Although the profile of stable inclinations (I_0) in DC2 is more scattered and not as well resolved, it has a similar general pattern as the profile of DC12, that is, indistinguishable means (Table 1), and the most positive inclinations are at the margins of the flow [*Audunsson*, 1989].

Results From the Outcrop

The Roza Member was sampled at two outcrops near Vantage in Washington State (Figure 1), separated by about 15 km. The flow is approximately 35 m thick at both locations. *Myers* [1973] described the local geology and a general discussion is given by *Mackin* [1961].

Only results from the base of the Roza outcrops are used in this study. The remanence at both outcrops is inherently unstable, and most specimens higher in the flow have significant overprints,

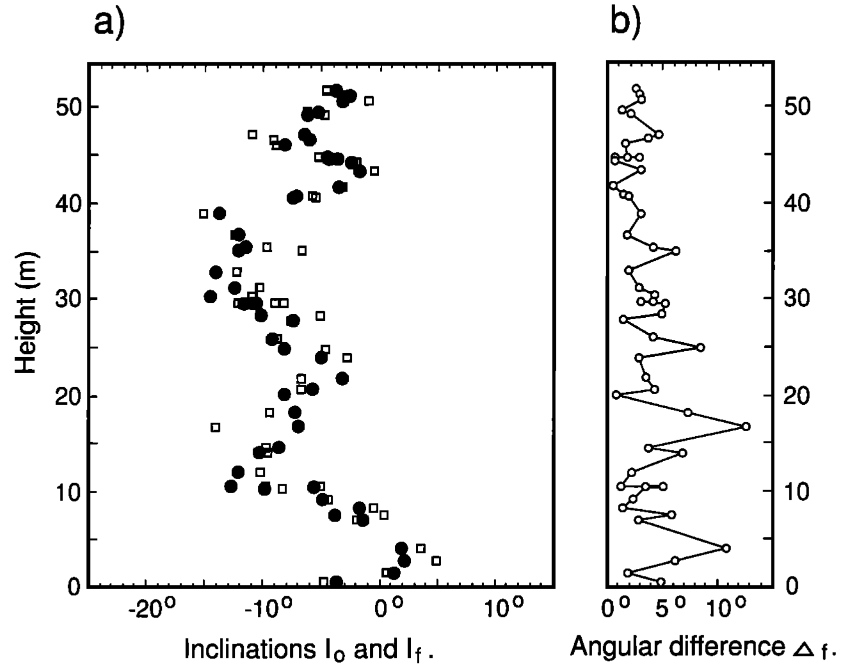

Figure 6. Depth variations in the Roza flow of DC12: (a) inclinations I_0 and I_f, circles and squares, respectively (see text for discussion); (b) angular differences (Δ_f) between the characteristic (D_0, I_0) and the removed remanences (D_f, I_f).

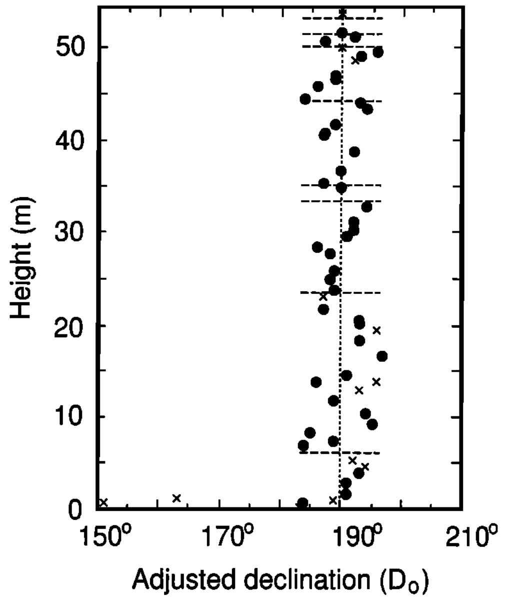

Figure 7. Profile of stable declination (D_0) of the Roza flow in DC12. Pieces of rock were jigsaw fit into contiguous segments of core of known relative orientation. Horizontal dash lines indicate unreconciled breaks in the core alignment. Rejected specimens are shown as crosses. The mean declination of each aligned core segment is adjusted to 190°, the value of the outcrops.

probably viscous remanent magnetization (VRM) acquired during the normal Brunhes field [*Audunsson*, 1989]. The stable remanence at the two outcrops are indistinguishable, and the mean direction is: $I = -3.5°$ and $D = 187.7°$ (Table 1).

Discussion

Possible Nongeomagnetic Origin for the Drillcore Intraflow Inclination Variation

Massive igneous bodies with protracted cooling histories often contain large, magnetically less stable, particles. In addition, during polarity transitions the geomagnetic field intensity is generally weak, and secondary overprints may therefore be relatively more prominent, requiring thorough demagnetization to recover the primary remanence. These factors may cause difficulties for paleomagnetic interpretations. Below, we discuss and reject four nongeomagnetic mechanisms that may be responsible for the inclination profile in Roza in DC12.

Heating by the overlying flow. Overlying the Roza flow in DC12 is a 33-m-thick flow with reverse polarity ($I = -65°$). The potential thermal overprint by the overlying flow might have had a significant effect on the remanence of Roza, because it would have been produced in a stronger geomagnetic field than the transitional field during Roza extrusion. Only the two uppermost specimens, at depths 0.3 and 0.8 m, which were AF demagnetized, were apparently completely remagnetized; the next specimen at 2.7 m below the top of Roza shows no evidence of an overprint. The VPDs for the two uppermost thermally demagnetized specimens from the Roza flow in DC12 at depths of 4.1 and 9.1 m are shown in Figure 5. There is no indication of a steep reverse polarity overprint. In addition, the overprint due to reheating by the overlying flow would be expected to produce progressively steeper negative inclinations (up to −65°) on approaching the upper margin of the Roza flow. This is not observed, and the most negative inclinations are in the interior of the flow, near 11 m and between 30–40 m above the base of the Roza flow (Figure 8a). Similar results were obtained for Roza in DC2, but there the overlying flow is only 15 m thick. Any significant reheating of Roza appears to have been confined to the top few meters of the flow. This is in agreement with the observations of limited reheating by the Roza of the underlying Frenchman Springs flow [*Audunsson and Levi*, 1988]. We therefore conclude that there is no evidence for significant thermal overprinting by the overlying unit, below the top 2–3 m of the Roza flow.

Percolation of hot water. Percolation of hot water into the Roza flow in DC12, associated with the cooling overlying unit, might have caused localized partial remagnetization, which would likely result in a more negative inclination. The most negative inclinations occur near 43 and 21 m below the top of Roza. Significant hydrothermal reheating would be expected to cause rock magnetic alterations; however, there are no significant variations in the magnetic properties of the drillcores in the vicinity of 21 m below the top (Figures 3 and 8b) [*Audunsson et al.*, 1992]. In addition, it seems contrived to suggest that the percolation would cause symmetric and nearly identical peaks in the inclination only at these two levels in DC12, as well as a similar overall trend of the inclination in both DC12 and DC2. Therefore percolating hot water appears to be an unlikely cause for the intraflow inclination variation in the Roza flow in the drillcores.

Viscous remanent magnetization. Variable VRM acquisition in the present field is rejected as a possible explanation for the inclination pattern in DC12, because the inclination is more negative ($I \approx -15°$) in the magnetically less stable flow interior (Figure 3b) [*Audunsson et al.*, 1992] than in the more stable flow top ($I \approx -3°$). This is opposite to the expected VRM acquisition in the present normal field ($I \approx +70°$), which should be more pronounced in the magnetically less stable flow interior.

Flow deformation and tilting. It is highly unlikely that the intraflow inclination pattern in DC12 was caused by deformation and tilting. First, the close agreement of the average paleomagnetic directions at numerous and widely separated sites of the Roza flow by *Rietman* [1966] and by us (Table 1) suggest that the sites have been largely undisturbed since remanence acquisition. Second, DC12 and DC2 are in the Pasco Basin, which was a topographical depression when the Roza flow extruded and ponded, and the massive textures in the Roza flow in the drillcores suggest a quiescent cooling environment. Third, the Curie temperatures of the magnetic minerals in the interior of the

Table 1. Statistics of Characteristic Remanence

Site	*n/N*	*D*	*I*	asd	α_{95}
DC12	50/64	na	−6.9	5.9	1.5
DC2	19/34	na	−4.5	5.0	2.1
Vantage*	11/18	187.7	−3.5	5.7	3.2
Wanapum Dam	5/10	186.8	−4.6	6.7	6.4
Frenchman Coulee	6/8	188.5	−2.8	4.7	3.9
Roza Member†	9 sites	189.0	−4.8		7.0

Directions are best vector estimates (D_0,I_0), determined from AF demagnetization. *N*, number of measured samples; n, samples used in the analysis; na, not available. Variables α_{95} and asd in the drillcores are computed following *Briden and Ward* [1966] and *Kono* [1980].

* Only specimens from the lowest sample clusters at Wanapum Dam and Frenchman Coulee are used in the analysis; Vantage represents the mean from Wanapum Dam and Frenchman Coulee. Bedding corrections: Vantage outcrops dip 1° to SSE [*Myers*, 1973]. The dip of Roza flow in the Pasco Basin drillcores DC2 and DC12 is assumed to be negligible.

† Values reported by *Rietman* [1966].

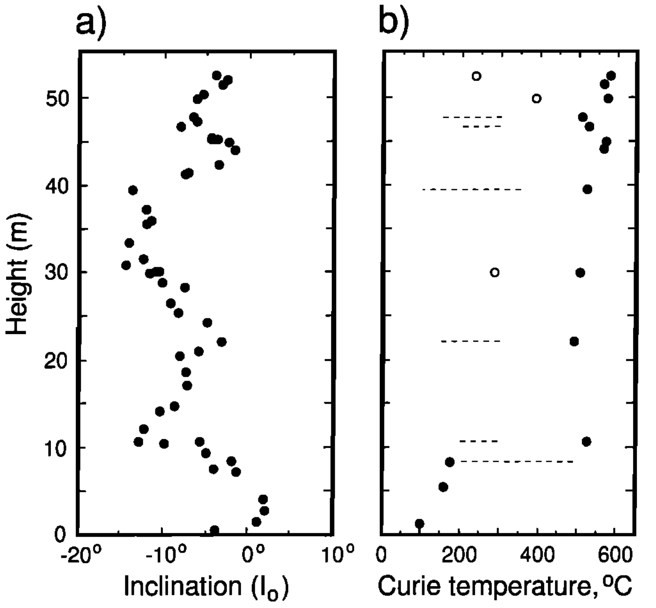

Figure 8. (a) Stable inclinations (I_0) from the Roza flow in DC12 showing symmetric pattern centered near 22 m. (b) Curie temparatures (T_c) of 14 samples from the Roza flow in DC12. Solid circles represent the predominant higher temperature T_c; open circles denote the lower T_c when two phases were present; the dashed lines indicate the range of T_c when a continuous distribution was observed. T_c values of four samples from Roza in DC2 are in good agreement with the profile of DC12. Figure 8b is slightly modified from *Audunsson et al.* [1992].

Roza flow are between 200° and 500°C (Figure 8b). Hence the remanence blocking temperatures are at least 500°C below the solidification temperatures (Table 2). Fourth, DC12 and DC2, which are separated by 11 km, have similar inclination profiles with the most positive values near the flow boundaries and the most negative inclinations in the interior. It is therefore highly unlikely that the intraflow inclination variation in DC12 was caused by deformation and tilting.

Paleomagnetic Record

Alternating fields demagnetization was successful at isolating the primary remanence in most specimens of the 54-m-thick Roza flow in DC12, uncovering intraflow fluctuations of the stable inclination, from about 3° to –15°. Recovery and analysis of the primary paleomagnetic record from the Roza flow was complicated by the relatively low magnetic stability, which resulted in significant overprints that were primarily produced by drilling and VRM acquisition in the present geomagnetic field, which is probably stronger than during the transition.

The average stable inclinations (I_0) and the dispersions in drillcores DC12 and DC2, which are 11 km apart, are very similar (Table 1). While the Roza flow in DC2 is magnetically less stable and the inclinations are more scattered than in DC12, the results from DC2 support those from DC12, showing the same range of inclinations and indistinguishable means. Although the inclination profile of DC2 is insufficient to resolve detailed fluctuations, the gross agreement in the profiles of the two drillcores reinforces our interpretation that the inclination fluctuations in DC12 are of geomagnetic origin. Furthermore, the intraflow range of inclinations observed in the drillcores (–15° to +3°) is similar to the range of *Rietman*'s [1966] site-mean inclinations (–21° to +8°) at nine outcrops. The observed intraflow uniformity of the declination in drillcore DC12 is consistent with measurements from the outcrops, where the site-mean declinations vary from 180° to 196° [*Rietman*, 1966] (see Table 1).

The remanence direction from the base of Roza at Frenchman Coulee and Wanapum Dam (I = –4° and D = 188°) has a very similar inclination as those measured at the boundaries of the Roza flow in the drillcores (Figure 6a and Table 1). These values represent the field direction immediately after the emplacement of the Roza flow.

As lower-temperature isotherms penetrated the interior of the flow during cooling, a thermal remanent magnetization was acquired parallel to the ambient field. This forms the basis for relating the observed intraflow variation of the primary remanence with a cooling model to deduce the time sequence of the geomagnetic fluctuations. It was not possible to determine blocking temperatures (T_b) from the thermal demagnetization experiments, largely due to the significant secondary overprints, but the measured Curie temperatures (T_c) provide upper limits to T_b (Figure 8b).

Record in Time

Cooling history of the Roza flow. The cooling history of the Roza flow was examined through a detailed paleomagnetic analysis of the underlying Frenchman Springs lava. The conclusion was that simple conductive thermal models are not adequate to describe its thermal history. *Audunsson and Levi* [1988] observed only limited (≤ 5 m) basement heating caused by Roza in drillcores DC12, DC2 and in the outcrop in Frenchman Coulee. It was inferred that groundwater effectively maintained low temperatures (~100°C) within a few meters below the base of Roza. Therefore, initial cooling of the Roza flow appears to have been approximately symmetrical, governed by comparable cooling rates from the base and top, with the isotherms migrating inward at nearly equal rates. This contrasts with simple conductive cooling models of lavas [e.g., *Audunsson and Levi*, 1988] where isotherms below 400°C are predicted to migrate predominantly downward from the top surface, producing asymmetrical cooling. The temperature distributions for these distinct cooling models are shown in Figure 9, and the thermal parameters are given in Table 2 (see also *Audunsson* [1989]). The distributions of opaque grains, plagioclase and pyroxene phenocrysts [*Audunsson et al.*, 1992; E. Verplanck and M. Fisk, unpublished manuscript, 1988] have maximum particle sizes near the flow's center, in agreement with quasi-symmetrical crystallization temperatures. Also, the measured primary inclinations are approximately symmetrical with respect to the center of the flow in the drillcores, compatible with the thermal history constrained by limited basement heating. Therefore, based on the limited base-

Table 2. Thermal Parameters

Symbol	Value	Definition
T_m	1140°C	initial (melting) temperature of lava
T_0	10°C	surface and initial basement temperatures
ΔT	100°C	temperature range of crystallization (1140° to 1040°C)
C	3×10^6 J/m^3°C	heat capacity
L	1.1×10^9 J/m^3	latent heat of crystallization (released between 1140 and 1040°C)
k	1.5 J/sm°C	thermal conductivity

Values based on *Peck et al.* [1977] and *Murase and McBirney* [1973].

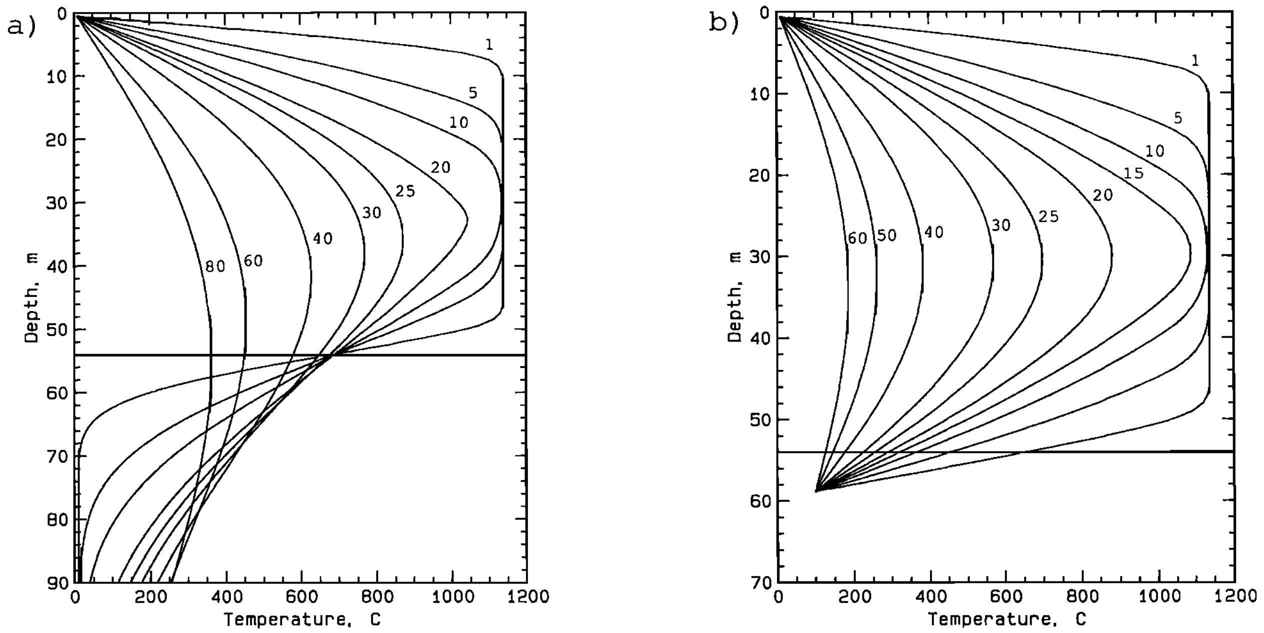

Figure 9. Computed thermal models (finite difference) for the cooling of a 54-m-thick lava flow. (a) Asymmetric cooling by simple conduction, and (b) symmetric cooling with 100°C isotherm at 5 m below the base of the flow. Isochrons are labeled in years. Thermal parameters are given in Table 2.

ment heating, symmetric grain size distributions, and intraflow stable inclinations, we conclude that cooling of the Roza flow was predominantly symmetrical at the two drillcore sites during remanence acquisition.

Paleomagnetic record from the Roza flow in drillcore DC12. The magnetic properties are uniform through most of the flow interior, between heights of approximately 5 m to 42 m (Figures 3 and 8b) [*Audunsson et al.*, 1992], and the remanence blocking temperatures are therefore likely to be similar over this interval. The observed inclination profile is nearly symmetrical over this depth range, centered at height 22 m above the base of the flow (Figure 6a). According to the symmetrical cooling model, there is one cycle in the evolution of the inclination with initial values about 0° near the base and top (heights 5 m and 44 m) to –15° at heights 11 m and 33 m, and a return to –3° near the center (height 22 m).

The measured Curie temperatures are between 200° and 500°C in the flow interior (Figure 8b) [*Audunsson et al.*, 1992]. The predicted time for the blocking isotherms, between 200° and 500°C, to traverse from heights 5 m and 44 m toward the center of the flow is about 15 years (see Figure 9b). Hence there is an apparent 15-year period for the inclination fluctuation, and the rate of change of the directions is therefore 12° in 15/2 years (1.6°/yr). These values may be uncertain by up to a factor of 2, due to uncertainties in the blocking temperatures and thermal history. (This rate is unchanged if the record is interpreted according to the asymmetric cooling model. Then the inclination record would be inferred to represent two cycles, but in about twice the time due to the slower cooling, hence similar rate and period.)

Another plausible interpretation is to include inclination variations of the entire flow, assuming that the variations near the top and base are undulations due to inhomogeneity of the blocking temperatures. Then the complete record is again one cycle in inclination, and it would take the 500° and 200°C isotherms approximately 30 and 60 years, respectively, to sweep through the whole flow. The corresponding rate of change for the directions would be 1° and 0.5°/yr (15° in 15 and 30 years), respectively.

These interpretations predict field fluctuations with characteristic times of 15 to 60 years and rates of change of 1.6° to 0.5° per year. Figure 10 shows a sketch of the inclination in time. The virtual geomagnetic poles calculated from the transitional Roza directions (approximately 45°S and 230°E) are near-sided [e.g., *Hoffman*, 1977] and they fluctuate in a latitude band of about 7°. In the 15–60 years of remanence acquisition in the Roza flow, during a polarity transition, the field underwent low-amplitude undulations in the inclination, with no clear progress toward the reverse polarity state of the overlying Priest Rapids flows. This behavior is consistent with the notion that the field reverses in discrete impulses separated by more quiescent periods during which the field might linger at intermediate directions for finite time intervals (e.g., *Prévot et al.*, 1985; *Laj et al.*, 1987; *Hoffman*, 1991). The Roza may be unique, to date, in providing a lower limit estimate on the time required to complete a geomagnetic reversal, showing that it took longer than the 15–60 years to complete this polarity transition, circa 15.5 Ma in the Columbia Plateau.

Secular Variation During a Transition

The record from the Roza flow contains information about part of a polarity reversal. The record can be regarded as secular variation during the transition and can be compared with typical secular variation of the stable field. Assuming that the angular rate of change of the total field is due to fluctuating nondipole field (f) superimposed on a quasi-stationary and much stronger dipole field (F), then an estimate of the angular rate of change (degrees/year) is the ratio time-change-of f/F. Typical rates of change of the present geomagnetic field are up to 0.15°/yr [*Barraclough*, 1987] and 0.15 μT/yr [*Langel*, 1987]. Therefore the estimates for angular change of 0.5° to 1.6°/yr from the Roza flow appear at first to be significantly greater than those of the present field. However, paleointensities might be quite low during transitions, possibly 5 to 10 μT; hence rates of change of 0.5° to 1.6°/yr would correspond to intensity fluctuations of 0.04 to 0.3 μT/yr, in agreement with present-day variations. Thus secular

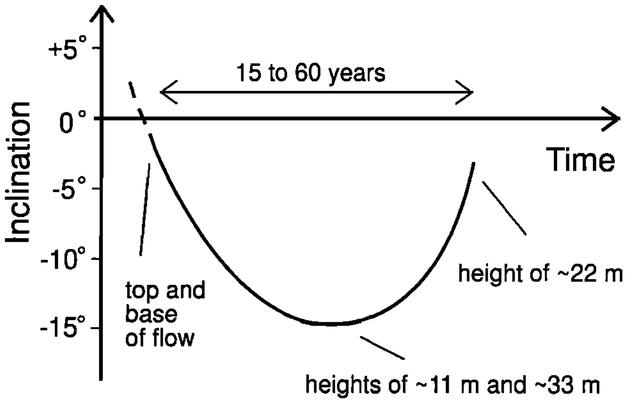

Figure 10. Sketch of the inclination versus time, interpreted from the record in the Roza flow in drillcore DC12 (Figure 6a) and its thermal history (Figure 9).

variation of the geomagnetic intensity, akin to the present day, may persist through geomagnetic transitions, while the main part of the geomagnetic field has significantly lower intensity [e.g., *Williams et al.*, 1988].

In addition to these modest variations, there may be extraordinary rates of ~3°–6°/day, as has been inferred from directional changes in two Steens Mountain lavas, which recorded a geomagnetic transition [*Coe and Prévot*, 1989; *Coe et al.*, 1995]. If these rapid rates are of internal geomagnetic origin and due to normal secular variations, the accompanying geomagnetic intensity would have had to be unusually weak.

Conclusions

Magmatic bodies with cooling histories of 10^1 to 10^3 years may contain high-resolution information on the geomagnetic field and its behavior during transitions, including secular variation, intensity fluctuations, and the associated rates of change of these properties. The higher resolution often comes at the expense of having shorter records, which may, however, provide unique information not otherwise available.

The 15.5 Ma Roza flow extruded while the geomagnetic field was in transition from normal to reverse polarity. In the drillcore DC12, where Roza's thickness is 54 m, the inclination fluctuates between –15° and +3°. The intraflow pattern of the inclination is interpreted as a record of geomagnetic fluctuations, acquired progressively as the lava cooled below its blocking temperatures. The inclination profile from the Roza flow in drillcore DC12 suggests that for this transition the inclination did not reverse monotonically, but rather underwent quasi-cyclical fluctuations, similar to secular variation. Thermal modeling of the flow's cooling history suggests that the remanence of the Roza flow was acquired over 15 to 60 years, with geomagnetic fluctuations of 1.6° to 0.5° per year.

The relatively modest amplitude inclination fluctuation in the Roza flow provides a rare lower limit for the duration of a polarity reversal, showing that a longer period than 15 to 60 years was required to complete this polarity transition. Moreover, these results support the idea that the field occupies intermediate configurations for finite periods and that it reverses in steps, in contrast with more uniform progress between the stable polarity states.

The estimated rates of directional change, 0.5° to 1.6° per year, is faster than present-day secular variation of up to ~0.15°/yr. Because the strength of the transitional field might have been considerably lower, of the order of 1/5 of its present value, the inferred rate of change in intensity appears consistent with present-day variations (up to ~0.15 μT/yr). Hence the measured rates of change for the intermediate-polarity field are compatible with the hypothesis that during reversals the main field is predominantly nondipole with secular variation similar to the present field.

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