



Transitional geomagnetic impulse hypothesis: Geomagnetic fact or rock-magnetic artifact?

Pierre Camps, Robert Coe, Michel Prévot

► To cite this version:

Pierre Camps, Robert Coe, Michel Prévot. Transitional geomagnetic impulse hypothesis: Geomagnetic fact or rock-magnetic artifact?. *Journal of Geophysical Research: Solid Earth*, 1999, 104 (B8), pp.17747-17758. <10.1029/1999JB900164>. <hal-03839452>

HAL Id: hal-03839452

<https://hal.science/hal-03839452v1>

Submitted on 4 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

Transitional geomagnetic impulse hypothesis: Geomagnetic fact or rock-magnetic artifact?

Pierre Camps

Laboratoire Géophysique, Tectonique et Sédimentologie, ISTEEM, Université Montpellier 2
France

Robert S. Coe

Earth Science Department, University of California Santa Cruz

Michel Prévot

Laboratoire Géophysique, Tectonique et Sédimentologie, ISTEEM, Université Montpellier 2
France

Abstract. A striking feature of the Steens Mountain (Oregon) geomagnetic polarity reversal is the two (maybe three) extremely rapid field directional changes (6 degrees per day) proposed to account for unusual behavior in direction of remanent magnetization in a single lava flow. Each of these very fast field changes, or impulses, is associated with a large directional gap (some 90°) in the record. In order to check the spatial reproducibility of the paleomagnetic signal over distances up to several kilometers, we have carried out a paleomagnetic investigation of two new sections (B and F) in the Steens summit region which cover the second and the third directional gap. The main result is the description of two new directions, which are located between the pre second and post second impulse directions. These findings weigh against the hypothesis that the geomagnetic field cause the unusual intraflow fluctuations, which now appears to be more ad hoc as an explanation of the paleomagnetic data. However, the alternative baking hypothesis remains also ad hoc since we have to assume variable rock magnetic properties that we have not yet been able to detect within the flows at the original section Steens A and D 1.5 km to the north. In addition, new results for 22 transitional and normal lava flows in section B are presented that correlate well with earlier results from section A.

1. Introduction

The question of the temporal nature of transitional geomagnetic field behavior can seldom be addressed in paleomagnetic studies, which usually address its spatial geometry. This more reflects significant experimental limitations of paleomagnetic observations rather than deliberate choices. To get insights into the temporal behavior of the field as it reverses, paleomagnetists have to deal with two difficulties. First, one has to take care in using intermediate directions observed in sedimentary samples because the acquisition process of detrital remanence tends to smooth the geomagnetic signal over an interval of time at least as long as its deposition [Rochette, 1990; Langereis *et al.*, 1992]. Their reliability is thus questionable, particularly when the paleofield is weak [Quidelleur *et al.*, 1995] as it is supposed to be during reversals. Second, one is confronted with the

temporal discontinuities of records from lava sequences due to the intermittence of volcanic eruptions, even though their fidelity of magnetic recording is much more established than that of sedimentary records. Unfortunately, the accuracy of the age determination methods is inadequate to provide significant input on the time elapsed between eruptions because the confidence errors on age estimates are usually much greater than the few thousand years proposed by some as the upper bound for the field to reverse [Kristjansson, 1985].

However, because of the recent advances made in numerical [Glatzmaier and Roberts, 1995; Kuang and Bloxham, 1997; Christensen *et al.*, 1998] and in experimental [Brito *et al.*, 1996] modeling of the geodynamo, establishing constraints on the rate of directional change during a reversal is critical for deciphering properties of the Earth's deep interior and understanding how the geomagnetic field is generated.

This question is a long-standing one. Bogue and Coe [1982] were first to suggest, from a description of two successive reversal records with similar large directional gaps found in several sequences of basaltic lava flows on

Copyright 1999 by the American Geophysical Union.

Paper number 1999JB900164.

0148-0227/99/1998JB900164\$09.00

the island of Kauai (Hawaii), that major changes in direction might have occurred very rapidly during reversals. Hoffman [1992] introduced the so-called idea of "stop-and-go" behavior as a possible general feature of reversals. He inferred that the field alternates between two or more standing transitional configurations with rapid directional bursts from the observation of two virtual geomagnetic pole (VGP) clusters during the Brunhes-Matuyama reversal.

Without any doubt, the most provocative result comes from the Miocene Steens Mountain (Oregon) polarity reversal, during which two (maybe three) astonishingly rapid changes have been suspected [Mankinen *et al.*, 1985; Prévot *et al.*, 1985; Coe and Prévot, 1989]. This interpretation is based on the observations of systematic variations of remanence direction as a function of both demagnetization temperature and vertical position within individual flows, which are more simply explained by a change in field direction as the flows cooled rather than by the alternative explanation involving baking by the overlying flows [Coe *et al.*, 1995]. By means of a conductive model for cooling lava flows, the rate of change was estimated at 6° per day [Camps *et al.*, 1995a]. Because such impulsive changes, if they are true and if they arise internally, have strong implications on how the geodynamo works [Merrill, 1995] and also because some paleomagnetic data [Camps *et al.*, 1995b] do not fit the impulse change hypothesis as well as others [Coe and Prévot, 1989; Coe *et al.*, 1995], we thought it necessary to carry out further stringent tests. A simple one presented in this paper is to check, over distances up to 2 km, the lateral reproducibility of the critical paleomagnetic observations which are at the root of the interpretation in terms of impulsive directional changes. Background and details of the previous results on lava flows suspected to have recorded fast field changes are summarized by Camps *et al.* [1995b].

2. Sampling and Experimental Details

The Steens Mountain record comes from lava at the upper one third of a large, very steep escarpment (about 1000 m high and several tens of kilometers long). Our goal to extend horizontally the paleomagnetic observations of the critical portions ran into difficulties of a topographic nature because not all places can be reached. In addition, there are numerous steeply dipping faults which make difficult stratigraphic correlation from one section to the other independently of magnetic data. Hence our sampling strategy was to look for new paleomagnetic sampling sites by tracing some flows that hold an identifiable magnetostratigraphic signature starting from the original Mankinen *et al.*'s [1985] Steens A and B sections. We failed to find new satisfactory remote sites corresponding to the first directional gap because the outcrops are not easily accessible, nor to the third gap, for which outcrops are unfortunately poor. For

these reasons, the present study is focused on the second impulse for which we found two new remote sections.

One section, herein called Steens F, comprises five volcanic units well exposed 700 m south from the original Steens A section (Figure 1). Some of these units display considerable relief on their boundaries, and they are not laterally continuous. The outcrop is bounded by a fault with significant vertical offset that is only several tens of meters south of the section and by a rubble cover that begins several tens of meters to the north. This makes impossible a one-to-one stratigraphic correlation with units at site A. However, the sampled flows are overlain by a thick flow that is almost certainly A38 (post second jump direction [Mankinen *et al.*, 1985]) which outcrops almost continuously from Steens A, yielding us a known magnetostratigraphic level. We grouped several thin units with confusing geometry of their boundaries, some of them pinching out or thinning northward, into a single unit (F3), considering that they constitute a compound lava flow corresponding to a single volcanic eruption.

The second newly sampled section corresponds to the upward continuation to the Steens summit of Mankinen *et al.*'s [1985] Steens B section (800 m south of

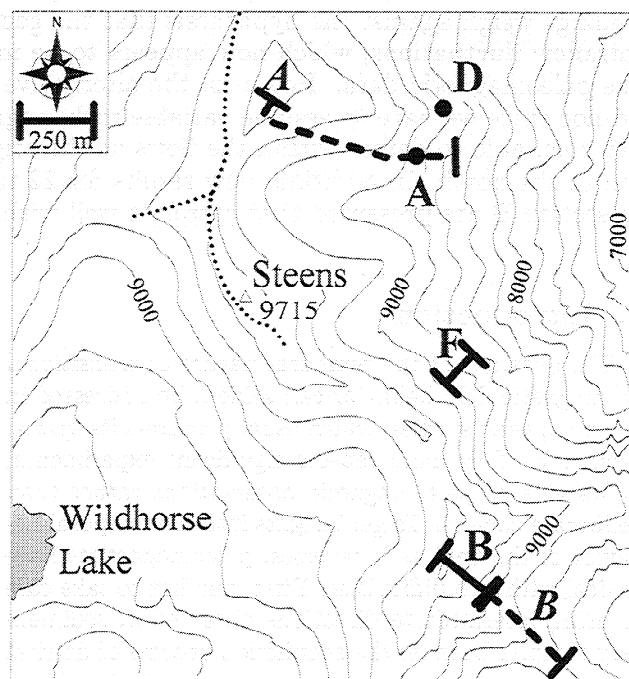


Figure 1. Sketch showing locations of sampled sections. Dashed lines show the positions of Mankinen *et al.*'s [1985] Sections A and B. Solid dots denote the approximate location of the sites where the second geomagnetic impulse has been described at site A [Camps *et al.*, 1995b] and site D [Coe *et al.*, 1995]. Solid lines show locations of the two new sections (B and F) presented in this study. Our section B is the upward continuation to the Steens summit of Mankinen *et al.*'s section B. Note that the contour elevations are in feet.

Steens F), overlapping it by just one flow (B43) (Figure 1). Twenty-five consecutive volcanic units were sampled above B43. By covering the upper part of Steens B, we hoped to sample through and obtain additional information about the second directional gap and maybe the third one too.

We sampled units thought likely to record the second impulse extensively over their entire thickness with a gasoline-powered portable drill and oriented them using a magnetic compass corrected for local anomaly by sighting the sun and known landmarks. Up to 40 samples per flow were collected. As few as four samples were taken from some of the upper flows of lesser importance to the present study. In all, we collected almost 280 oriented cores belonging to 30 units.

While carrying out the paleomagnetic sampling, we examined both sections carefully. The quality of outcrops is generally excellent and contacts between flows are usually visible. The absence of soil horizons or erosion surfaces suggests that there was no significant hiatus between flows. Nor did we find any evidence that any of the volcanic units were sills rather than lava flows. In a few places, we grouped several thin successive flows showing typical pahoehoe boundaries into a single unit. Finally, these simple flow-on-flow sequences appeared undisrupted by faults along both profiles B and F.

In the laboratory, we treated at least one specimen from each core by stepwise thermal (mainly) or alternating field demagnetization in order to remove unstable components of remanence. For each specimen, we used a very detailed experimental procedure involving up to 15 cleaning steps, not only to achieve a good precision in the determination of the initial remanence but also to check for rapid changes in the field direction during the cooling of any of the lava flows. For each sample, we determined the primary direction by means of a least squares method [Kirschvink, 1980], averaged the directions thus obtained for each flow, and calculated the statistical parameters assuming a Fisherian distribution.

3. Results

Interpretation of the demagnetization diagrams was in most cases relatively straightforward. In broad terms, the experimental results can be summarized as follows. A small secondary component close to the axial dipole field direction was sometimes encountered in the low-temperature demagnetization intervals (from room temperature up to a maximum of 300°C). It is likely that this low-temperature component corresponds to a viscous overprint acquired in the recent field. For the highest unblocking temperature interval (from 300°C to a maximum temperature of ≈ 580 –640°C), the magnetization is usually stable and the characteristic component is easily isolated and well determined. These observations remain qualitatively the same for the few cores for

which a second specimen was submitted to a treatment by alternating fields (AF). In addition, none of the samples yields evidence for streaked remanence directions such as was observed in the critical flows at section A [Camps *et al.*, 1995b] and D [Coe *et al.*, 1995] for which the geomagnetic impulse hypothesis was proposed. Neither do any of the flows show the characteristic variation of the remanence direction with vertical position, symmetric about a point a little below the center of the flow, that was found in previous studies of both the first and the second gaps [Coe and Prévot, 1989; Camps *et al.*, 1995b; Coe *et al.*, 1995]. Thus, bearing in mind that relevant flows were sampled vertically throughout their thickness in the present study, if episodes of extraordinarily rapid field change did occur, they were not recorded during cooling of individual flows in sections B and F.

However, it is noteworthy that for several flows, the characteristic components are significantly dependent on the vertical position of each core within the flows. From some point above the bottom toward the top of these flows, the direction of remanence is progressively deflected toward the overlying flow direction (Figure 2).

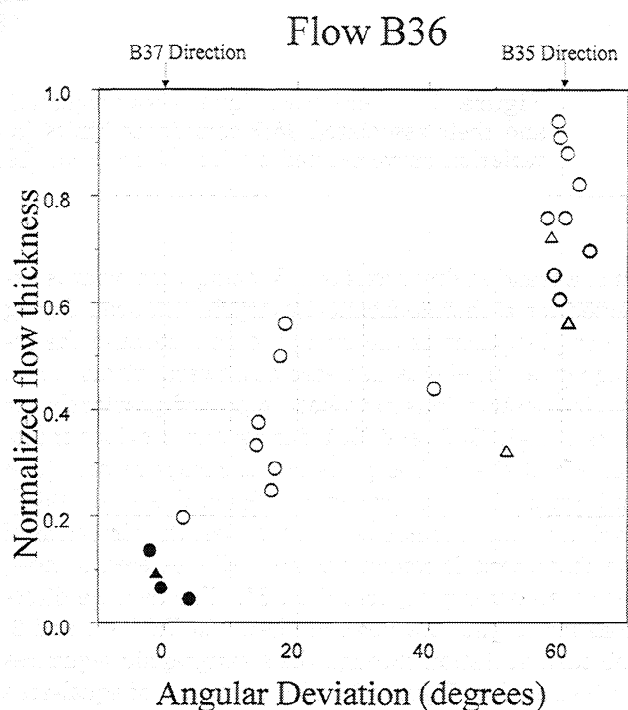


Figure 2. Angular deviation of the characteristic remanence for samples from flow B36 as a function of their vertical position in the flow. Each direction is projected on to the great circle containing the underlying (B37) and overlying (B35) flow directions, the angular deviation being measured along the great circle from the B37 toward the B35 direction. Flow B36 was sampled along two vertical sections (circles and triangles) 20 m from one to the other. Open symbols correspond to samples remagnetized by the overlying flow and thus not included in the statistical analysis. Closed symbols correspond to samples used in the determination of the mean direction of flow B36.

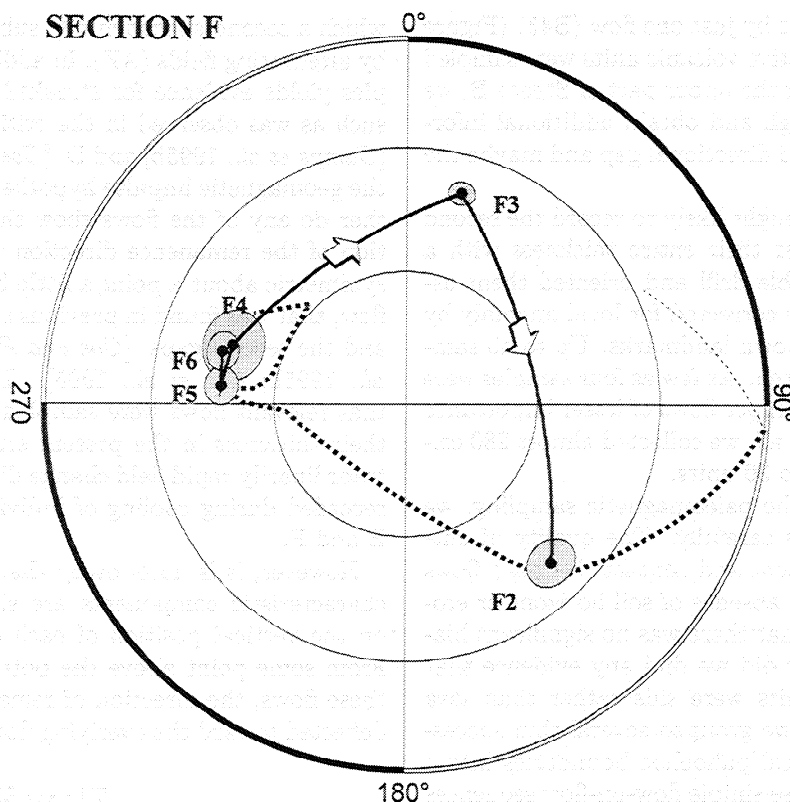


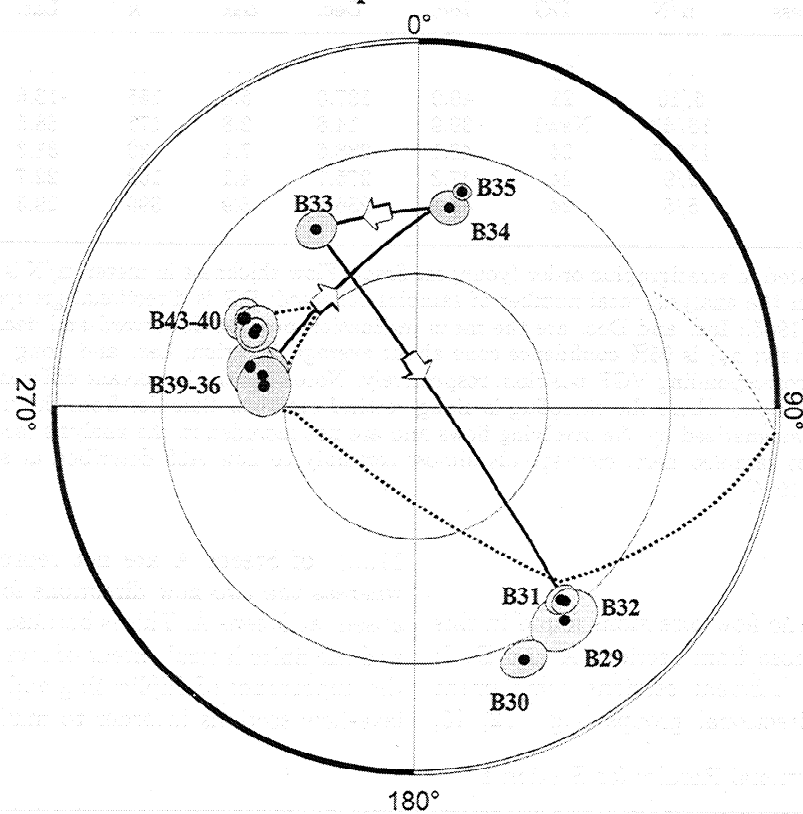
Figure 3. Section F. Equal area projection showing the average direction for each lava flow and their associated 95% confidence limits (α_{95}). The corresponding portion of the directional variation curve defined by Mankinen *et al.* [1985] is represented by the dotted line.

Such a trend in directions is in keeping with what is expected for a thermochemical overprint induced during the emplacement of the overlying flow because the remagnetization effects decrease downward within flows. Similar observations have been reported previously for units A41-1, D40, and B51 during our previous investigation of the critical parts of the Steens record [Coe and Prévot, 1989; Camps *et al.*, 1995b; Coe *et al.*, 1995]. Excluding these remagnetized samples, the directions of the characteristic remanence are well clustered by flow, nearly all having α_{95} less than 8° . The average directions for all the lava flows are listed in Tables 1 and 2, and their variation through the stratigraphic sequences is illustrated in Figures 3 and 4 by means of equal-area azimuthal projections for the F and B sections, respectively.

The directional results corroborate almost exactly the path of field direction changes obtained during the Steens Mountain reversal from the original section A [Mankinen *et al.*, 1985]. All the lava flows can be correlated with the original directional groups (Tables 1 and 2) with three important exceptions that we now discuss. Lava flow F3, located stratigraphically between flows F4 and F2 with pre second and post second gap directions, respectively, yields a direction close to the axial dipole field direction (Figure 3). This is significantly

different from the directional variation curve where the geomagnetic impulse was previously described. A similar but more detailed directional path is observed in section B where the same new direction, recorded here by two flows (B35 and B34), is followed by a northwesterly direction in flow B33 (Figure 4a). As in section F, these two new directions are stratigraphically bracketed by the pre second (B39-36) and post second (B32-29) gap directions. Because these directions have unblocking temperatures ranging up to 600°C , they can not correspond to the viscous overprint impressed by the present normal polarity Brunhes epoch, which is effectively eliminated on Steens basalts after demagnetization at a temperature ranging between 150°C and 300°C . Therefore they correspond to the primary thermoremanence. Thus it appears that the Steens sequence becomes progressively more complete southward at the level of the second directional gap, making the Steens reversal geometry not only more detailed but also more complicated. By contrast, the uppermost part of Steens B (Figure 4b) yields a similar but less detailed directional curve than the initial one of Steens A, with several directional groups not represented (Table 2). Hence the third gap in the directional curve (between flows B29 and B28) remains no better documented than before.

a/ SECTION B: Lower part



b/ SECTION B: Upper Part

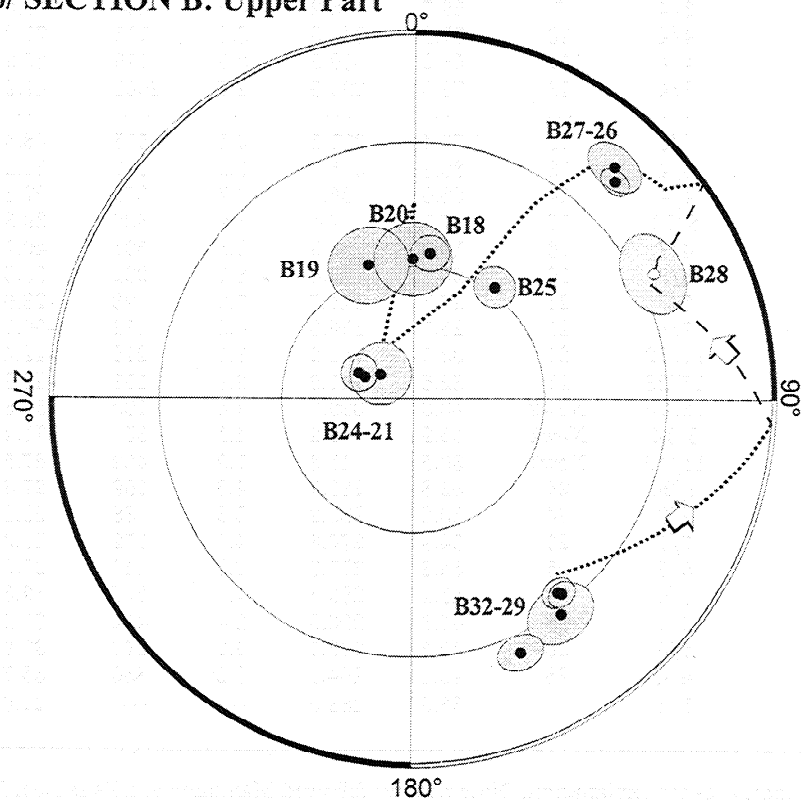


Figure 4. Section B. Same diagram as in Figure 3. The directions are shown on two diagrams for plotting convenience: (a) lower and (b) upper part of our section B.

Table 1. Directional Results for Section F

| Flow | Thickness | n/N | DG | Inc. | Dec. | α_{95} | κ | Lat. | Long. |
|-----------------|-----------|-------|------|------|-------|---------------|----------|-------|-------|
| F1 ^a | | ... | 21 | ... | ... | ... | ... | ... | |
| F2 | 4.5 | 6/10 | 21 | 40.0 | 137.0 | 5.4 | 155 | -13.6 | 281.7 |
| F3 | 5 | 16/40 | New1 | 39.9 | 14.8 | 2.8 | 171 | 68.5 | 36.9 |
| F4 | 2 | 11/12 | 24 | 48.1 | 288.6 | 7.4 | 39 | 31.3 | 161.8 |
| F5 | >4 | 9/9 | 24 | 47.3 | 275.7 | 4.1 | 162 | 22.7 | 169.8 |
| F6 | 1.5 | 5/5 | 24 | 46.1 | 286.0 | 3.9 | 390 | 29.5 | 163.0 |

Flows are listed in stratigraphic order (youngest first). Flow thickness in meter, n/N is the number of samples used in the analysis/total number of samples collected; DG is directional groups defined by *Mankinen et al.* [1985]; Inc. and Dec. are the mean inclination positive downward and declination east of north, respectively; α_{95} is 95% confidence cone about average direction; Lat. and Long. are latitude and longitude of corresponding VGP position, respectively. Note that the important differences between n and N occur for flows where the sampling is along vertical sections. Samples from the upper part of these flows are remagnetized by the overlying flows and are not included in the analysis (see text).

^a This flow, not sampled here, corresponds almost certainly to flow A38 described at section A by *Mankinen et al.* [1985].

4. Discussion

Figure 5 shows how the flow directions found in this study correlate with those from sections A and D. It shows clearly how the different sections complement each other: Several directional groups (e.g. 12, 15,

17,...) of Steens A are not represented at Steens B, whereas the two new directions found at Steens B are absent at Steens A. This is because of the multiple vents and the finite lateral extent of lava flows. It emphasizes the importance of duplicating and stacking overlapping lava-flow sections in order to minimize undersampling

Table 2. Directional Results for Section B

| Flow | Thickness | n/N | DG | Inc. | Dec. | α_{95} | κ | Lat. | Long. |
|------------------|-----------|-------|------|-------|-------|---------------|----------|-------|-------|
| B18 | 6 | 3/4 | 7 | 56.7 | 6.2 | 4.2 | 844 | 82.8 | 17.5 |
| B19 | 14 | 4/4 | 10 | 57.9 | 341.0 | 8.8 | 111 | 75.0 | 142.1 |
| B20 | 12 | 4/4 | 11 | 58.2 | 359.5 | 8.5 | 119 | 86.2 | 67.0 |
| B21 | 8 | 3/4 | 13 | 78.0 | 294.5 | 2.7 | 2061 | 47.9 | 209.3 |
| B22 ^a | 2 | ... | ... | ... | ... | ... | ... | ... | ... |
| B23 | 5 | 4/5 | 13 | 76.4 | 295.5 | 4.1 | 515 | 48.4 | 205.2 |
| B24 | 6 | 4/4 | 13 | 80.8 | 306.7 | 6.9 | 177 | 51.2 | 218.2 |
| B25 | 8 | 4/4 | 14 | 58.6 | 36.0 | 4.7 | 376 | 62.8 | 326.1 |
| B26 | 4 | 8/13 | 16 | 17.1 | 42.4 | 1.9 | 836 | 39.8 | 1.3 |
| B27 | 3 | 4/7 | 16 | 13.9 | 38.9 | 3.8 | 596 | 40.7 | 6.2 |
| B28 | 2 | 3/8 | 19 | -25.7 | 62.4 | 8.1 | 231 | 10.0 | 0.4 |
| B29 | 6 | 6/7 | 21 | 28.7 | 144.7 | 7.0 | 93 | -23.6 | 278.9 |
| B30 | 2.5 | 7/8 | 21 | 25.1 | 156.3 | 4.6 | 172 | -30.1 | 268.3 |
| B31 | 8.5 | 11/12 | 21 | 33.5 | 141.2 | 3.1 | 215 | -19.4 | 280.5 |
| B32 | 3 | 17/23 | 21 | 32.6 | 141.9 | 2.9 | 151 | -20.2 | 280.2 |
| B33 | 10 | 12/15 | New2 | 43.3 | 329.9 | 4.4 | 100 | 59.8 | 125.9 |
| B34 | 5 | 5/14 | New1 | 43.9 | 9.2 | 4.1 | 357 | 71.4 | 34.5 |
| B35 | 6.7 | 15/16 | New1 | 39.5 | 11.8 | 1.9 | 402 | 67.5 | 31.8 |
| B36 | 3.3 | 4/24 | 24 | 52.8 | 280.1 | 4.6 | 399 | 27.8 | 171.8 |
| B37 | 3.1 | 9/9 | 24 | 50.8 | 283.2 | 5.5 | 88 | 29.8 | 168.4 |
| B38 | 4.8 | 7/7 | 25 | 54.9 | 277.8 | 4.6 | 172 | 28.3 | 175.0 |
| B39 | 4 | 5/5 | 25 | 54.8 | 277.3 | 6.3 | 147 | 27.9 | 175.2 |
| B40 | 4 | 6/6 | 28 | 45.1 | 296.3 | 4.3 | 247 | 36.6 | 155.9 |
| B41 | 5 | 9/9 | 28 | 45.6 | 296.9 | 2.4 | 474 | 37.2 | 155.9 |
| B42 | 2.5 | 5/5 | 28 | 49.2 | 295.5 | 4.9 | 240 | 37.9 | 160.0 |
| B43 | 2 | 4/4 | 28 | 49.1 | 294.1 | 3.2 | 830 | 36.7 | 160.7 |
| B43 ^b | 2 | 1/1 | ... | 33.0 | 283.0 | ... | ... | 21.0 | 157.0 |

See Table 1 footnotes for explanation. Note that we followed Mankinen et al.'s system for numbering the Steens B lava flows. Starting with flow B43, the numbers decrease upward until the Steens summit is reached at section B with flow B18.

^aNot sampled here.

^bFrom *Mankinen et al.* [1985].

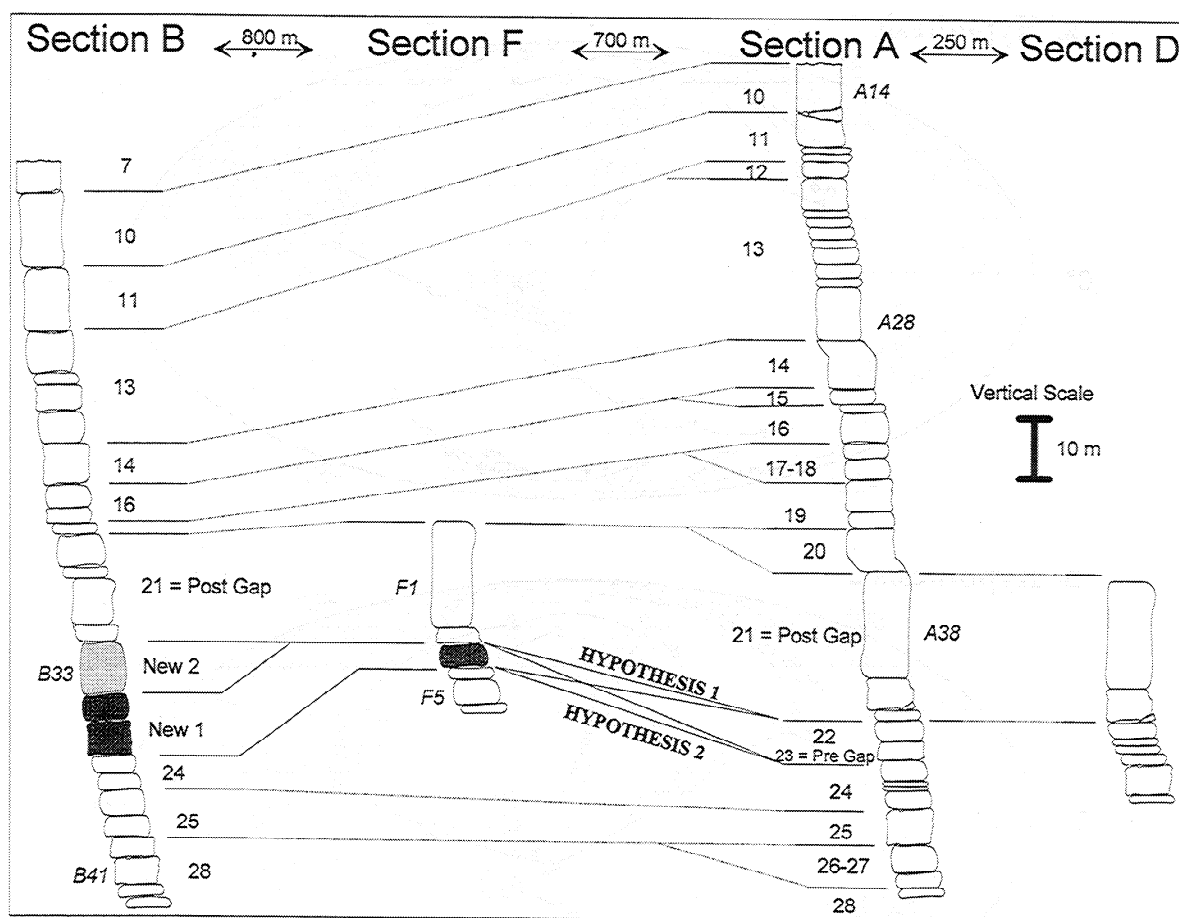


Figure 5. Profiles of the lava sequence in the two new sections B and F with the correlation lines with sections A and D. These correlations are based on the paleomagnetic results and field observations. Numbers indicate the directional groups. Italic font is used for the flow names. The two hypothetical correlations between the new directions found in sections B and F with the original section A are shown. See text for the discussion of these hypotheses.

of the transitional field behavior. We do not agree with Love [1998], who includes in his database only records from stratigraphically consecutive lava flows in order to lessen oversampling of the same field directions from overlapping sections. Given the episodic nature of volcanism, in which the eruption of lava flows is clustered temporally, oversampling of particular field directions cannot be eliminated by restricting consideration to one continuous section, and, for the Steens record and for other cases as well, portions of the transitional field behavior are arbitrarily ignored. It was for these reasons that Mankinen *et al.* [1985] grouped consecutive Steens lava flows with very similar directions into groups and merged records from sections A, B, and C to obtain a more complete record of the progression of the transitional field. In a similar manner, we combine the directions in the two new sections with those from the original section A, and at the end of this paper we present the more detailed compound record in terms of virtual geomagnetic poles in Figure 6 and Table 3.

Because volcanic sequences can only furnish discrete recordings of the geomagnetic field punctuated by gaps

of unknown length between flows, there are alternative positions in the composite reversal record for placing the new directions recorded at Steens sections B and F. The simplest and thus preferred hypothesis is to introduce the new directions between the pre gap and post gap directions, directional groups 21 and 22, as shown in Figure 7a. This choice results in the shortest directional path. Moreover, this position is marked by a baked ash layer at Steens A, and it also corresponds to a change in visual character of lava flows from mildly porphyritic with small plagioclase phenocrysts to highly porphyritic with phenocrysts up to several centimeters in size. Therefore this might be a significant gap in the Steens A record and could have missed an appreciable piece of the transitional record. If this position is correct, then the hypothesis of a very fast directional change recorded during the cooling of individual lava flows in the second directional gap at Steens A and D [Mankinen *et al.*, 1985; Coe and Prévot, 1989; Camps *et al.*, 1995b] is strained because the streaked directions in flows D41, D40, and A41-1 that lie along the dotted line in Figure 7a do not connect to the preceding flow di-

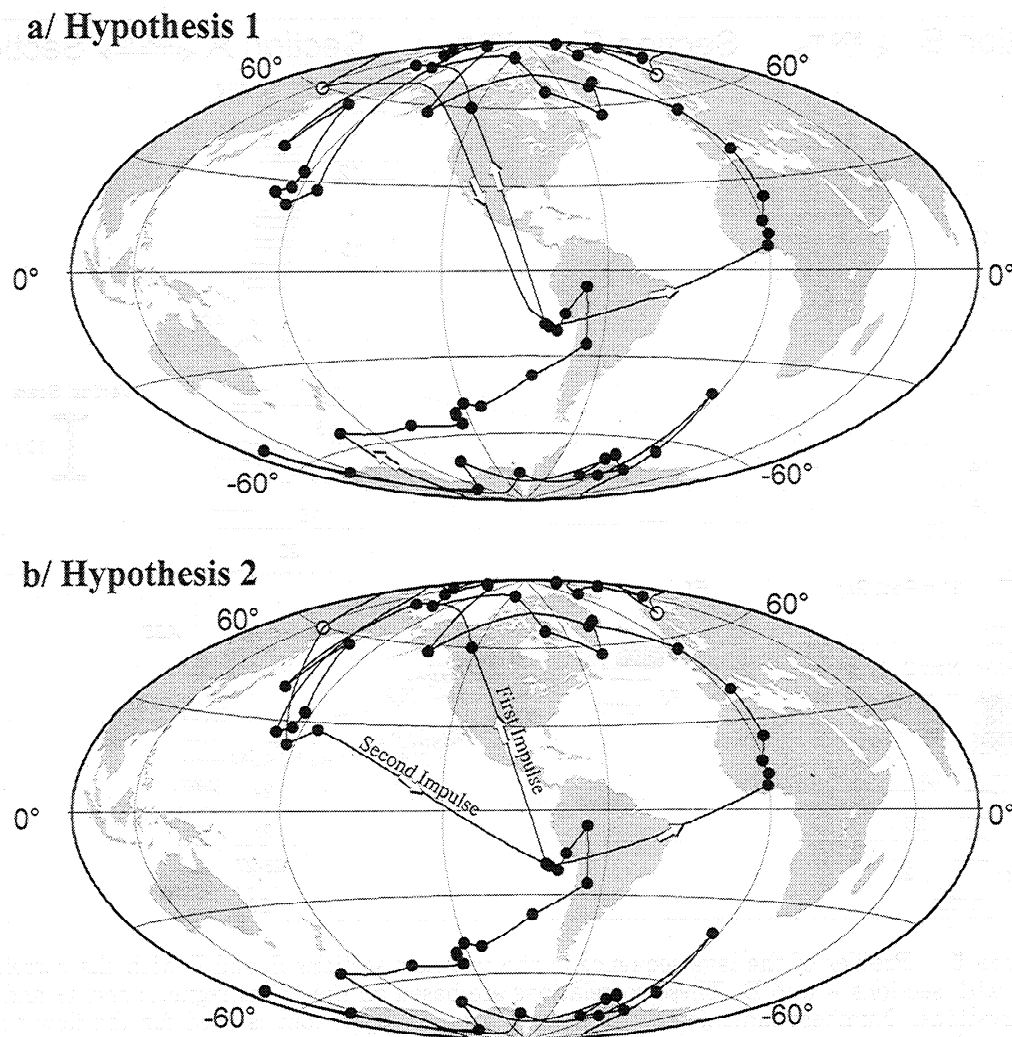


Figure 6. Virtual geomagnetic poles of the Steens Mountain reversal plotted in a Hammer projection. Open symbols correspond to the new directional groups.

rection. The alternative explanation of thermochemical alteration induced by heat from the overlying flow A39, and possibly A38 as well, advanced originally by *Coe et al.* [1995] and proposed again by *Valet et al.* [1998] in their study of a volcanic record from the Canary Islands, would then seem more likely to be correct. A weakness is that we must assume variable rock magnetic properties that we have not succeeded in detecting in order to explain why alteration was most intense in the centers of these flows rather than nearer the tops. In this case, the original remanence of the flows with streaked directions would have had the pre gap direction. However, it is also possible that the new Steens B and F directions occurred lower, between flows that both record the pre gap direction. This alternative correlation is shown two flows down in the pre gap stack in Figure 5 because we think, on the basis of similarities of directions, that both flows B36-37 belong to the directional group 24 and B38-39 correspond to the directional group 25.

The directional path for this alternative hypothesis is shown in Figure 7b. In its support, the second new direction (B33) is halfway between the first new direction (B34, B35, and F3) and the so-called pre gap directions, making plausible the idea that the field may have returned there before proceeding to the post gap direction. This interpretation naturally suggests that the hypothesis of rapid field variation during cooling of a single flow proposed at Steens sections A and D is valid and thus does not require ad hoc assumptions about variable rock magnetic properties.

No matter which hypothesis is correct, the polarity transition is rendered more complex by the new directions. The Steens Mountain reversal was initially described as happening in two phases [Watkins, 1969; Mankinen et al., 1985]. The first phase consisted of a nearly direct change from reversed to normal polarity through a transitional configuration, followed by a second comprising a return to the transitional configura-

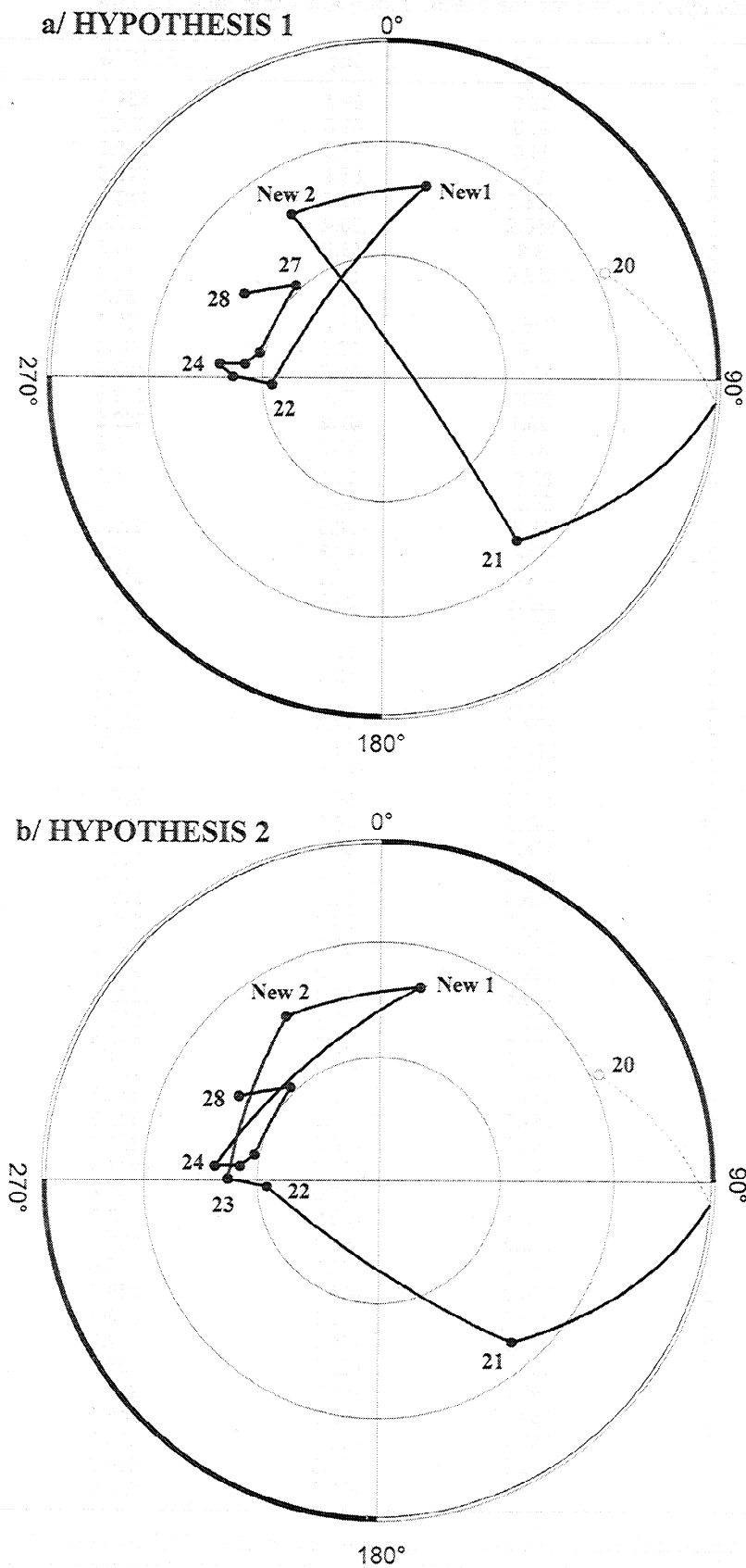


Figure 7. Equal area projections showing the directional groups at the level of the second directional gap and two hypothetical directional variation curves. The new directional groups occurred between (a) DG22 and DG21 or between (b) DG24 and DG23. See text for the discussion of these hypothesis.

Table 3. Paleomagnetic Data for the Steens Mountain Directional Groups

| DG | N | Dec. | Inc. | PLONG | PLAT |
|-----------------|----|-------|-------|-------|-------|
| 01 | 2 | 26.7 | 59.5 | 328.9 | 70.0 |
| 02 | 1 | 46.3 | 61.8 | 314.6 | 56.5 |
| 03 | 1 | 29.5 | 71.6 | 285.2 | 66.8 |
| 04 | 2 | 1.6 | 66.8 | 249.9 | 82.3 |
| 05 | 2 | 338.0 | 62.6 | 163.6 | 74.0 |
| 06 | 1 | 350.2 | 56.4 | 117.4 | 80.5 |
| 07 | 2 | 8.9 | 55.9 | 10.5 | 80.8 |
| 08 | 1 | 358.0 | 52.7 | 71.4 | 80.5 |
| 09 | 1 | 0.1 | 45.0 | 61.3 | 73.9 |
| 10 | 3 | 345.1 | 58.5 | 139.5 | 78.3 |
| 11 | 4 | 0.0 | 57.9 | 61.4 | 85.9 |
| 12 | 1 | 353.8 | 59.7 | 129.3 | 84.9 |
| 13 | 12 | 319.2 | 77.8 | 212.6 | 57.4 |
| 14 | 2 | 29.7 | 61.2 | 322.2 | 68.2 |
| 15 | 1 | 31.6 | 37.5 | 0.8 | 55.9 |
| 16 | 4 | 39.9 | 15.1 | 4.7 | 40.5 |
| 17 | 1 | 50.2 | 10.1 | 4.4 | 24.2 |
| 18 | 1 | 58.7 | -16.5 | 359.8 | 16.2 |
| 19 | 3 | 60.9 | -23.8 | 0.8 | 11.8 |
| 20 | 1 | 64.4 | -27.6 | 359.7 | 7.8 |
| 21 | 8 | 142.6 | 34.0 | 279.1 | -19.7 |
| N2 ^a | 1 | 329.9 | 43.3 | 125.9 | 59.8 |
| N1 ^a | 3 | 12.0 | 41.1 | 30.1 | 68.5 |
| 22 | 1 | 267.0 | 62.4 | 187.0 | 27.3 |
| 23 | 1 | 270.5 | 52.6 | 176.8 | 22.1 |
| 24 | 9 | 279.0 | 49.5 | 169.6 | 26.2 |
| 25 | 3 | 276.9 | 55.1 | 175.6 | 27.8 |
| 26 | 1 | 281.5 | 58.7 | 177.1 | 32.9 |
| 27 | 1 | 315.9 | 58.6 | 160.8 | 56.9 |
| 28 | 17 | 299.6 | 49.0 | 157.2 | 40.8 |
| 29 | 5 | 338.8 | 57.8 | 144.1 | 73.4 |
| 30 | 1 | 352.5 | 81.1 | 237.0 | 59.8 |
| 31 | 7 | 143.4 | 36.1 | 277.7 | -18.9 |
| 32 | 1 | 140.7 | 29.6 | 282.2 | -21.3 |
| 33 | 2 | 134.9 | 35.7 | 285.1 | -15.1 |
| 34 | 1 | 122.5 | 40.9 | 292.4 | -5.4 |
| 35 | 2 | 134.1 | 12.4 | 293.9 | -25.8 |
| 36 | 1 | 155.4 | 10.3 | 272.8 | -37.2 |
| 37 | 1 | 175.7 | -3.6 | 248.0 | -49.0 |
| 38 | 1 | 181.0 | -0.6 | 239.9 | -47.7 |
| 39 | 10 | 184.5 | -8.1 | 234.3 | -51.2 |
| 40 | 1 | 184.7 | -11.8 | 233.8 | -52.1 |
| 41 | 1 | 183.8 | -16.2 | 234.9 | -55.5 |
| 42 | 1 | 199.2 | -21.7 | 205.9 | -54.8 |
| 43 | 7 | 220.4 | -47.2 | 161.8 | -54.5 |
| 44 | 1 | 143.8 | -69.2 | 7.0 | -64.0 |
| 45 | 3 | 112.2 | -62.4 | 357.3 | -42.0 |
| 46 | 9 | 161.2 | -65.9 | 0.6 | -75.7 |
| 47 | 2 | 174.3 | -49.5 | 263.7 | -76.9 |
| 48 | 2 | 212.8 | -69.7 | 113.4 | -65.8 |
| 49 | 9 | 233.9 | -74.6 | 102.1 | -53.4 |
| 50 | 5 | 189.8 | -59.2 | 163.1 | -82.3 |
| 51 | 1 | 190.3 | -44.3 | 212.6 | -70.5 |
| 52 | 5 | 148.7 | -61.8 | 342.8 | -67.1 |
| 53 | 1 | 157.4 | -68.5 | 10.1 | -71.9 |
| 54 | 1 | 161.8 | -61.8 | 339.6 | -76.6 |
| 55 | 3 | 151.8 | -61.0 | 339.2 | -69.2 |

DG is the directional group calculated from *Mankinen et al.*'s [1985] recommendations, assuming that consecutive lava flows whose α_{95} confidence angles overlap and whose average directions do not exhibit a regular trend with time represent a single field reading; N is the number of flows; Dec. and Inc. are the declination and inclination, respectively; PLONG and PLAT are longitude and latitude of corresponding VGP position, respectively. Boldface indicates the new DG determinations obtained by combining the directions from section A, B, and F

^a The two new directional groups are located either between DG21 and DG22 (hypothesis 1) or between DG23 and DG24 (hypothesis 2).

tion before recovering to a stable normal polarity. This so-called "rebound effect" was assumed to be due to an instability of the dipole field during the final stage of the transition. Now there are two successive rebounds, as illustrated in terms of VGPs in Figure 6a under the preferred hypothesis that the flows recording the new directions were erupted between the flows that record the last pre gap and the first post gap directions in Steens A.

Because we saw no evidence of an unusually long temporal break between these flows, we suspect that the flip from transitional to normal to transitional direction occurred rather quickly, though not at the astonishingly fast rate that must be accepted [Coe *et al.*, 1995; Camps *et al.*, 1995b] if change of such magnitude occurred during cooling of an individual flow. The same can be said for the third directional gap. The status of the first directional gap [Coe and Prévot, 1989] remains unchanged, with an intervening flow containing streaked directions that are distributed as a function of vertical position between pre gap and post gap directional groups of lavas in a manner that could be explained at least qualitatively by extremely rapid field change during cooling. The results and preferred interpretation reported in this paper for the second directional gap incline us toward a similar interpretation for this case, but we cannot be finally happy with an explanation of variable thermochemical remagnetization induced by heating from above, reaching a maximum near the center of the flow, unless we can finally detect the rock magnetic properties that would have allowed such an unexpected variability to occur. Further investigation of samples from the critical flows at sections Steens A and D, including examination under the transmission electron microscope, is planned.

5. Conclusion

The Steens Mountain transition record, which has come to be somewhat of a benchmark in paleomagnetic reversal studies, is augmented in this study by three Steens B flows and one Steens F flow that record two new intermediate directional groups at the level of the second directional gap. It is further strengthened by 22 consecutive overlying lava flows that overlap and correspond extremely well with the earlier directional record of Mankinen *et al.* [1985] at Steens A. The new directions make the record more complex, with two rebounds from normal polarity instead of one. The preferred position for the new directions is within the second directional gap as defined at Steens A. This choice makes the hypothesis of rapid field change during cooling of an individual flow in the gap more ad hoc, and therefore we now regard it as less likely. The more likely hypothesis, however, of thermochemical remagnetization of a flow that originally recorded the pre gap direction, induced by heating from the overlying flow, still suffers from our inability to detect the variable rock magnetic properties

as a function of vertical position in the flow that could be responsible for its unusual pattern of variable remanence directions.

Acknowledgments. We greatly appreciated the help given by Daniel Brito and Jonathan Aurnou during our 1996 field trip. The comments of R.D. Elmore, R. Merrill, and an anonymous reviewer helped improve this paper. This work was supported by NSF grant EAR-9526553, by CNRS-INSU programme interieur Terre (contribution 190) and the NATO international Scientific Exchange program (grant CRG 940215).

References

- Bogue, S.W., and R.S. Coe, Successive palaeomagnetic reversal records from Kauai, *Nature*, **295**, 399-401, 1982.
- Bruto, D., P. Cardin, H.C. Nataf, and P. Olson, Experiments on Joule heating and the dissipation of energy in the Earth's core, *Geophys. J. Int.*, **127**, 339-347, 1996.
- Camps, P., M. Prévot, and R.S. Coe, L'hypothèse des impulsions géomagnétiques pendant un renversement du champ: Confrontation des données paléomagnétiques avec un modèle de refroidissement des laves, *C. R. Acad. Sci. Paris*, **320**, 801-807, 1995a.
- Camps, P., M. Prévot, and R.S. Coe, Revisiting the initial sites of geomagnetic field impulses during the Steens Mountain polarity reversal, *Geophys. J. Int.*, **123**, 484-506, 1995b.
- Christensen U., P. Olson, and G.A. Glatzmaier, A dynamo model interpretation of geomagnetic field structures, *Geophys. Res. Lett.*, **25**, 1565-1568, 1998.
- Coe, R.S., and M. Prévot, Evidence suggesting extremely rapid field variation during a geomagnetic reversal, *Earth Planet. Sci. Lett.*, **92**, 292-298, 1989.
- Coe, R.S., M. Prévot, and P. Camps, New evidence concerning impulsive field change during a geomagnetic reversal, *Nature*, **374**, 687-692, 1995.
- Glatzmaier, G.A., and P.H. Roberts, A three-dimensional self-consistent computer simulation of a geomagnetic field reversal, *Nature*, **377**, 203-208, 1995.
- Hoffman, K.A., Dipolar reversal states of the geomagnetic field and core-mantle dynamics, *Nature*, **359**, 789-794, 1992.
- Kirschvink, J.L., The least-squares line and plane and the analysis of palaeomagnetic data, *Geophys. J. R. Astron. Soc.*, **62**, 699-718, 1980.
- Kristjansson, L., Some statistical properties of palaeomagnetic directions in Icelandic lava flows, *Geophys. J. R. Astron. Soc.*, **80**, 57-71, 1985.
- Kuang, W., and J. Bloxham, An Earth-like numerical dynamo model, *Nature*, **389**, 371-374, 1997.
- Langereis, C.G., A.A.M. van Hoof, and P. Rochette, Longitudinal confinement of geomagnetic reversal paths as a possible sedimentary artefact, *Nature*, **358**, 226-230, 1992.
- Love, J.J., Paleomagnetic volcanic data and geometric regularity of reversals and excursions, *J. Geophys. Res.*, **103**, 12435-12452, 1998.
- Mankinen, E.A., M. Prévot, C.S. Grommé, and R.S. Coe, The Steens Mountain (Oregon) geomagnetic polarity transition, 1, Directional history, duration of episodes, and rock magnetism, *J. Geophys. Res.*, **90**, 10393-10416, 1985.
- Merrill, R.T., Principle of least astonishment, *Nature*, **374**, 674-675, 1995.
- Prévot, M., E.A. Mankinen, S. Grommé, and R.S. Coe, How the geomagnetic field vector reverses polarity, *Nature*, **316**, 230-234, 1985.

- Quidelleur, X., J.P. Valet, M. LeGoff, and X. Bourdoin, Field dependence on magnetization of laboratory-redeposited deep-sea sediments: First results, *Earth Planet. Sci. Lett.*, 133, 311-325, 1995.
- Rochette, P., Rationale of geomagnetic reversals versus remanence recording processes in rocks: A critical review, *Earth Planet. Sci. Lett.*, 98, 33-39, 1990.
- Valet, J.P., T. Kidane, V. Soler, J. Brassart, V. Courtillot, and L. Meynadier, Remagnetization in lava flows recording pretransitional directions, *J. Geophys. Res.*, 103, 9753-9775, 1998.
- Wakkins, N.D., Non-dipole behavior during an upper Miocene geomagnetic polarity transition in Oregon, *Geophys. J. R. Astron. Soc.*, 17, 121-149, 1969.
-
- P. Camps and M. Prévot, Lab. de Géophysique et Tectonique, ISTEEM Université Montpellier 2, Case 060, 34095 Montpellier Cedex 5, France. (camps@dstu.univ-montp2.fr; prevot@dstu.univ-montp2.fr)
- R.S. Coe, Earth Science Dept., University of California Santa Cruz, Santa Cruz, CA 95064. (rcoe@earthsci.ucsc.edu)
- (Received November 3, 1998; revised April 28, 1999; accepted May 6, 1999.)