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Very rapid geomagnetic field change recorded by the partial remagnetization of a lava flow

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[1] A new paleomagnetic result from a lava flow with a distinctive, two-part remanence reinforces the controversial hypothesis that geomagnetic change during a polarity reversal can be much faster than normal. The 3.9-m-thick lava ("Flow 20") is exposed in the Sheep Creek Range (north central Nevada) and was erupted during a reverse-to-normal (R-N) geomagnetic polarity switch at 15.6 Ma. Flow 20 began to acquire a primary thermoremanence while the field was pointing east and down but was soon buried, reheated, and partially-remagnetized in a north-down direction by the 8.2-m-thick flow that succeeded it. A simple conductive cooling calculation shows that the observed remagnetization could not have occurred unless Flow 20 was still warm (about 150°C near its base) when buried and that the 53° change from east-down to north-down field occurred at an average rate of approximately 1°/week, several orders of magnitude faster than typical of secular variation. **Citation:** Bogue, S. W., and J. M. G. Glen (2010), Very rapid geomagnetic field change recorded by the partial remagnetization of a lava flow, *Geophys. Res. Lett.*, *37*, L21308, doi:10.1029/2010GL044286.

1. Introduction

[2] According to the controversial "rapid transitional field change" (RTFC) hypothesis, brief intervals of magnetic directional change at rates thousands of times faster than typical of secular variation may punctuate geomagnetic polarity reversals. The sole evidence for such behavior comes from a 4-m-thick 16.7 m.y. old [*Jarboe et al.*, 2010] lava flow, part of the Steens Mountain reverse-to-normal (R-N) polarity transition zone [*Mankinen et al.*, 1985; *Prevot et al.*, 1985] in SE Oregon (USA). The top and base of the lava flow (A41-2), its most quickly cooled parts, are magnetized in a different direction than its interior. This pattern could arise if the ancient field direction changed at approximately 6°/day over the interval these different parts of the flow cooled and acquired their thermoremanence [*Camps et al.*, 1995, 1999; *Coe et al.*, 1995]. The RTFC hypothesis has been criticized [*Merrill and McFadden*, 1999] largely because it is difficult to reconcile with some estimates of: (1) the rate of flow in the Earth's liquid outer core [*Bogue and Merrill*, 1992] where the geomagnetic field is generated; and (2) of lower mantle electrical conductivity [*Shankland et al.*, 1993], which limits the frequency of electromagnetic signals observable at Earth's surface. It has also been difficult to defend because of the lack of confirmatory paleomagnetic observations. We report here new paleomagnetic evidence of rapid transitional field variation from a lava flow erupted during a polarity reversal that occurred 1 m.y. after the Steens Mountain event. Within a year of its eruption, well before it had time to fully cool, the flow was capped, baked, and partially thermally remagnetized by a second lava flow as the geomagnetic field underwent 53° of directional change. Because it involves a cooling and remanence acquisition history very different from the Steens example, this new evidence greatly strengthens the observational basis for the RFTC hypothesis.

2. Paleomagnetic Results

[3] The paleomagnetic data described below are from a 150-m-thick section of basaltic and basaltic andesite lava flows that are well exposed in the SE and SW facing fronts of the Sheep Creek Range in north central Nevada (40.73N, 243.15E). A single radiometric age (whole rock ^{39}Ar-^{40}Ar) of 15.58 Ma ± 0.10 Ma [*John et al.*, 2000] from a flow low in the section suggests that the lava flows are 1 m.y. younger than those exposed at Steens Mountain, about 250 km to the northwest in Oregon. Almost all paleomagnetic sites exhibited a simple remanence comprising a primary thermoremanent magnetization (TRM) very consistent in orientation for all samples from the site, plus a secondary component that was effectively removed by either stepwise alternating-field (AF) or thermal demagnetization.

[4] The Sheep Creek lava flows acquired their remanence while the geomagnetic field was evolving from a transitional to normal polarity state, presumably during the completion of a reverse-to-normal (R-N) polarity switch. Expressed as virtual geomagnetic poles (VGPs), the sequence of lava flow magnetization directions shows the north geomagnetic pole tracing a complex, looping path from a starting point near the Arabian Peninsula to positions at high northern latitude, in the eastern equatorial Pacific, in India, at high southern latitudes, and in equatorial South America. The records ends with the VGP transiting from equatorial South America directly to positions typical of stable normal polarity at high northern latitude.

[5] One lava flow from the section, referred to here as Flow 20, attracted our attention because it exhibited a magnetization more complex than those of almost all other flows at the locality. Flow 20 is the middle of three lavas (Flows 19 through 21) that occur near the top of the section and record the final movement of the field toward its normal polarity orientation (Figure 1). Detailed stepwise thermal demagnetization experiments on samples from a vertical profile through Flow 20 reveal that the top meter of Flow 20 is completely magnetized in the Flow 21 direction (Figure 2a), presumably as a result of thermal remagnetization by that flow. Deeper in Flow 20, a second, higher unblocking tem-

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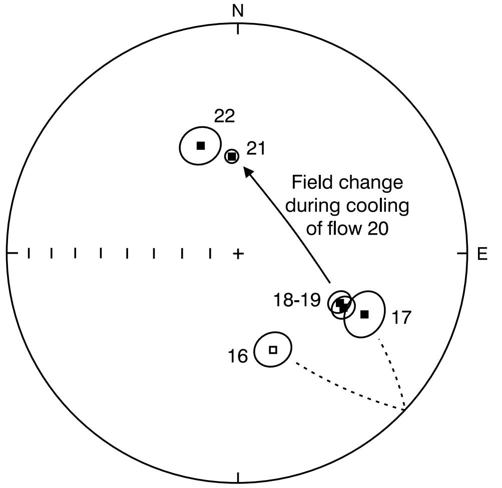

Figure 1. Equal-area plot showing site-mean remanence directions (and 95% confidence limits) from flows near the top of the Sheep Creek transition zone. Open (closed) symbols correspond to upward (downward) pointing directions. Flow 20 is bracketed by Flow 19 (below, with E-down paleomagnetic direction) and Flow 21 (above, with N-down direction).

perature (T_{ub}) remanence component identical in direction to that of the underlying flow (Flow 19) becomes increasingly prominent (Figure 2a). This higher T_{ub} E-down component is oriented about 50° away from the N-down component, and is clearly transitional in direction. Flow 20 apparently erupted and began to acquire its original thermoremanence while the field was pointing in the same E-down direction as Flow 19. Later, it was buried and baked by Flow 21, producing a partial thermal remanent magnetization (PTRM) in the N-down direction that is discernible throughout the entire thickness of the flow.

[6] Baking and partial thermal remagnetization of flow tops is commonly observed in stacks of lava flows, but the effect is typically insignificant in the lower parts of flows. To better understand the unusually deep baking of Flow 20, we resolved the remanence measured at each step in the thermal demagnetization experiments into two components, one oriented N-down (D = 357, I = 64) and one oriented E-down (D = 107, I = 62), so that the change in each component could be tracked. These two reference directions represent averages of the components resolved by thermal demagnetization and are close to the mean directions of Flows 19 and 21. Figure 2c shows T_{ub} distributions for the two components derived from

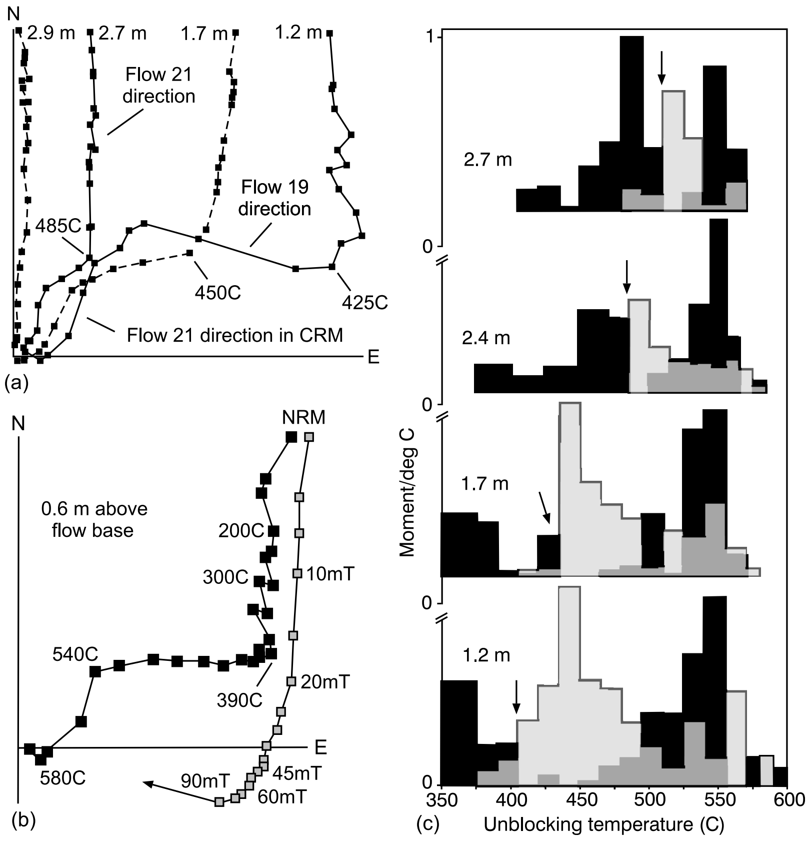

Figure 2. Stepwise demagnetization of samples from a vertical profile through Flow 20. (a) Vector endpoint diagrams (horizontal component only) for thermal demagnetization on samples 1.2 m, 1.7 m, 2.7 m, and 2.9 m above flow base. Labels identify remanence components in the E-down direction of Flow 19 and N-down direction of Flow 21. Above 175°, heating steps range from 25°C to 10°C. Highest temperature steps are all 585°C. Plots are scaled so that north components of NRMs are equal. (b) Vector endpoint diagrams like those in Figure 2a for AF and thermal demagnetization of companion specimens from 0.6 m above flow base. (c) T_{ub} distributions for the N-down (black) and E-down (light gray) components of samples from 1.2 m,1.7 m, 2.4 m, and 2.7 m above base of Flow 20 (overlapping T_{ub} ranges shown in dark grey.) Height of bars is proportional to rate (per °C) of moment loss, with maximum rate at each level normalized to 1. Bars extend from lower to upper T_{ub} of remanence component unblocked. Arrows indicate picks for baking temperature derived from these plots.

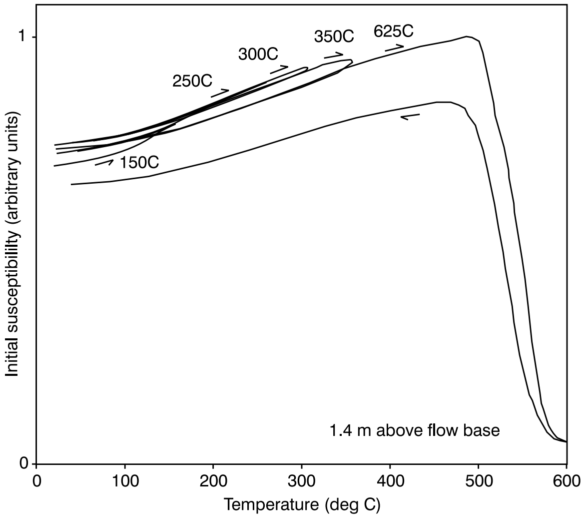

Figure 3. Initial susceptibility versus temperature (in argon) for sample 1.4 m above base of Flow 20. Sample was cycled to target temperatures of 150°C, 250°C, 300°C and 350°C before final heating to 625C. Arrows identify heating and cooling segments of curves. Curve for heating cycle to 250°C obscured by lower temperature portion of the 350°C curve. No progressive increase of Curie temperature during the heating cycles (diagnostic of low-temperature oxidized titanomagnetite) is displayed by the sample.

their stepwise thermal demagnetization. Through much of the Flow 20's thickness, a well-defined T_{ub} separates the N-down overprint (at low T_{ub} values) from the E-down component (at higher T_{ub} values). We use the T_{ub} to estimate the temperature to which Flow 20 was heated (and partially thermally remagnetized) by heat conducting downward from Flow 21. To account for the difference between natural and laboratory cooling times (i.e., approximately 1 year versus 1 hour) we assume that remagnetization occurred at a temperature 50°C lower than that indicated by the laboratory T_{ub} [*Dodson and McClelland-Brown*, 1980]. The inferred baking temperature increases with height in the flow (Figures 2a and 2c). The roughly linear trend, extrapolated downward, implies that the heating increased the temperature at the flow base to between 300°C and 350°C.

[7] In addition to the PTRM produced by the reheating, there is an additional N-down component with a T_{ub} near 550°C, above the T_{ub} range of almost all the E-down remanence (Figure 2). Stepwise alternating-field (AF) demagnetizations of companion specimens (e.g., Figure 2b) show that both N-down components have lower coercivity than the E-down component, and that the ratio of E-down to N-down remanence in a sample is not substantially changed by the laboratory heatings. The lack of such alteration is understandable given that the predominant magnetic mineral in the rock is low-titanium titanomagnetite with Curie temperature near 550°C (Figure 3). We conclude that the high T_{ub} N-down component is part of the natural remanent magnetization of the Flow 20, very likely a chemical remanent magnetization (CRM) associated with deuteric oxidation [*Grommé et al.*, 1969] during the final cooling of Flow 20.

3. Numerical Simulation of Flow 20 Reheating

[8] As described above, the baking of Flow 20 by Flow 21 was unusually intense, raising the temperature of rock at the flow base to between 300°C and 350°C. Could Flow 21 (8.2 m thick) have provided enough heat to do this? We investigated this possibility using a simple one-dimensional cooling model to estimate the temporal evolution of temperature (Figure 4) at all levels in a fully cooled, 3.9 m thick lava flow (i.e., Flow 20) that is capped and conductively heated by a 8.2 m thick lava flow emplaced at 1100°C (i.e., Flow 21). The model (coded in Python 2.6) treats each lava flow as a stack of 10 cm thick infinite slabs. Flow 21 and Flow 20 comprise 82 and 39 slabs, respectively, with another 361 slabs below Flow 20 to accommodate heat conducted downward from it. With the thermal diffusivity κ of the rock

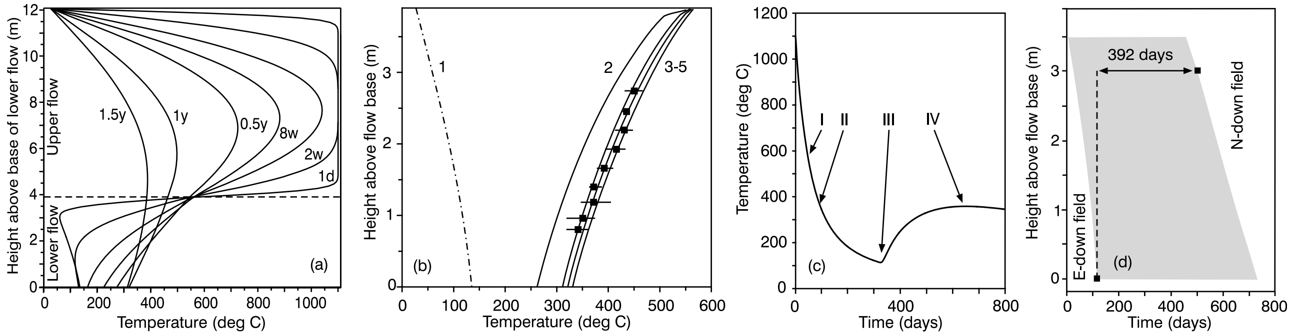

Figure 4. Results from conductive cooling model. (a) Time evolution of temperature profile in 3.9 m thick flow cooled to 150°C then capped by 8.2 m thick flow at 1100°C. (b) Inferred maximum baking temperatures in 3.9 m thick flow baked by 8.2 m flow. Curve with dash-dot pattern (1) shows temperature profile immediately before emplacement of upper flow. Solid curves show maximum baking temperatures if lower flow is fully cooled (2) or conductively cooled to maximum temperature of (3) 125°C, (4) 150°C, and (5) 200°C before upper flow is emplaced. Squares show maximum baking temperatures (corrected for cooling rate) inferred from the paleomagnetic data from Flow 20. Error bars show range of sample estimates. (c) Time evolution of temperature 1 m above the base of 3.9 m flow baked by 8.2 m flow. Remanence acquisition in E-down direction occurs between times I and II and all or part of the interval between II and III. Between III and IV, remanence previously acquired between II and III is unblocked. Remanence acquisition resumes (in N-down direction) starting at IV. Change in field direction occurred between II and IV. (d) Overall constraint on duration of rapid field change. Shaded area corresponds to the interval between times II and IV in Figure 4c.

set at 0.5×10^{-6} m^2/sec, a value typical for basalt [*Hon et al.*, 1994], each iteration of the model corresponds to an interval of 183 seconds.

[9] The model predicts that the maximum reheating temperature through most of the lower flow follows a gently curved trend with average slope near 50°C/m, very similar to that derived from the paleomagnetic data (Figure 4b). The maximum reheating temperature reached at the model flow base, assuming perfect thermal contact between the flows, is 261°C. To explain the significantly higher partial remagnetization temperature inferred for the Flow 20 base, we hypothesize that the cooling of Flow 20 was not complete when Flow 21 was emplaced. Figure 4b shows model cases in which Flow 20 cools from 1100°C to 125°C, 150°C, and 175°C (maximum temperature in Flow 20 or below) and then is capped by Flow 21. The paleomagnetic data from Flow 20 (with cooling rate correction) best match the model case in which the lower flow cooled to 150°C before burial. In this scenario, heat conducting downward from Flow 21 interrupts the cooling of Flow 20, increasing the temperature near the base of Flow 20 by nearly 200°C before its cooling (and remanence acquisition) resumes.

[10] Between the eruption and final cooling of Flow 20, the geomagnetic field direction changed by 53°. The conductive cooling model provides an estimate for the time available for this change to occur, with the result depending (linearly) on the thermal diffusivity κ one assumes for the two flows. Figure 4c shows, as an example, the evolution of temperature 1 m above the base of Flow 20 assuming $\kappa = 0.5 \mathrm{x} 10^{-6}$ m^2/s. At this level, Flow 20 was cooling from 580°C (point I) to 115°C (point III) and acquiring remanence for about 9 months before heat from Flow 21 caused the temperature to start to increase. When the temperature peaked near 360°C about 10 months later (point IV) , the remanence originally acquired between 360°C–115°C (between points II and III) was unblocked, leaving only the part E-down remanence component acquired between I and II. Once cooling resumed, remanence in the lower T_{ub} interval grew in the new N-down direction of the ancient field. At this level in the flow, the paleomagnetic observations constrain the field change to have occurred within 18 months. The remanence acquisition history from low in the flow combined with that from the 3 m level (the highest level where the E-down component is clearly present) tightens the constraint to just over a year (Figure 4d), implying a minimum field change rate of approximately 1°/week. Although lower than that recorded at Steens Mountain, the rate of field change we infer is 2 to 3 orders of magnitude greater than that typical of secular variation.

4. Discussion

[11] Our estimate of the rate of geomagnetic field change from Flow 20 depends critically on our interpretation of the lower T_{ub} of the E-down component (or the upper T_{ub} of the thermal overprint) as a "thermometer" recording the magnitude of baking by Flow 21. An alternative possibility is that this temperature represents the maximum T_{ub} of a CRM produced at some point during the cooling of Flow 20 after the field was pointing in the N-down direction. We consider this explanation unlikely because thermally-induced magnetochemical alteration in titanomagnetites typically produces a secondary remanence in high T_{ub} grains (essentially magnetite) via oxidation and disproportionation of titanomagnetite. Indeed, we interpret the other N-down component in the flow (with T_{ub} near 550°C at all levels in the flow) as being a CRM formed in that way. A CRM with T_{ub} decreasing linearly with depth is certainly unlike one resulting from thermally-induced magnetochemical alteration in the flow interior (but not the flow top or base) as proposed by *Merrill and McFadden* [1999] to explain the unusual, inhomogeneous magnetization of flow A41-2 at Steens Mountain. Furthermore, Flow 20 shows no evidence of having undergone significant low-temperature oxidation (see Figure 3), distinguishing it from some other transition-zone lava flows with complex remagnetizations apparently related to mild baking by overlying flows [*Valet et al.*, 1998].

[12] The paleomagnetic evidence from Flow 20 significantly strengthens the case for RTFC. It not only represents a second observation of the phenomenon, but one involving a polarity reversal and lava flow cooling history that are distinct from those of the Steens Mountain record. The new evidence also revives questions raised by the Steens Mountain result regarding the character of flow in the outer core and the electrical conductivity of the lower mantle. A recent analysis of short-period secular variation of the modern geomagnetic field [*Olsen and Mandea*, 2008] shows evidence of spatially-localized variations of outer core flow occurring on the timescale of months. This observation suggests that standard estimates of lower mantle conductivity are too high or that the conductivity is laterally-variable. In this regard, it is curious that both paleomagnetic records of RTFC come from mid-Miocene rocks of the western North America. This coincidence may be a hint that localized conditions of the deep Earth—flow associated with a particular topography on the core-mantle boundary, a low-conductivity "window" in the lower mantle, or both—may strongly limit when and where RFTC is observable at earth's surface.

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