The Complexity of Reversals

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Geomagnetic reversals could be far more complex than even the best, most detailed paleomagnetic record in hand. Sequences of lava flows can give accurate spot readings of the field but yield records that are necessarily shot full of holes, whereas sedimentary recordings smooth temporal variations of the field and may also be subject to hiatuses and delayed, non-uniform lock-in of remanence. Thus, paleomagnetic records are always incomplete and give only lower bounds on how rapidly changing and complex the behavior of the reversing field may have been. Nonetheless, the combined evidence from several high-deposition-rate sedimentary records, multiple lava-flow records of one reversal from the same region, and a reversal record from a dynamically self-consistent numerical geodynamo simulation suggest that at least some reversals are much more complex than typically portrayed, with episodes of oscillatory and very rapid field change.

1. INTRODUCTION

Reversals of the dipole field, surely the most dramatic attribute of the geodynamo, are known only because rocks can record the ancient magnetic field. Reliable paleomagnetic records showing how the field changed during a reversal of polarity, though difficult to obtain, are important for evaluating geodynamo models and the deep-earth parameters prescribed for their operation. For instance, many people working on polarity transitions have suggested that the field direction may move rapidly between points of greater stability, but how rapidly and the locations and significance of stable points remain important questions [*Bogue and Coe*, 1982; *Mankinen et al.*, 1985; *Hoffman*, 1992; *Hoffman*, 2000]. In the same vein, reversal records have been intensely scrutinized for longitudinal confinement and geographical preference of transitional virtual geomagnetic poles (VGPs) because they could carry information about lateral variation of temperature and other properties of the lowermost mantle [e.g., *Clement*, 1991; *Laj et al.*, 1991; *Merrill and McFadden*, 1999, and references therein].

Geologically speaking, reversals occur very quickly and thus involve rates of change in field direction that challenge the capability of natural magnetic recorders. Lava flows are generally considered to offer the most accurate spot readings of the field because, typically, they are almost isotropic in their bulk magnetic properties and become magnetized by a relatively simple mechanism in a time ranging from a few days to a few years. However, the discontinuous and episodic nature of eruption is a major drawback that must always be kept in mind, as well as possible distortion of the local field arising from the magnetization of the lava flows themselves. Sedimentary rocks offer the attractive advantage of quasi-continuous recording, and thus an estimate of duration, but how they get magnetized is more complex, more vari-

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able, and not as well understood as for lavas. How much a particular sedimentary record has smoothed the geomagnetic signal, shallowed the inclination, and suffered from other recording artifacts associated with variable lock-in depth and formation of magnetic minerals during diagenesis is difficult to assess. Thus, although we are not always so cautious, it is entirely justifiable to ask about any reversal record whether it is incomplete or inaccurate or both.

With such questions in mind, we consider selected reversal records and geodynamo simulations, ranging from simpler to more complex, concentrating more on changes in direction than intensity. We propose that, although the complexity of many sedimentary polarity transition records probably owes largely to recording artifacts, there are some complex sedimentary records that may well contain important information about the character of the reversing field. Support for our view may be found, paradoxically, in discrepant directions among multiple records of the same reversal in lava flow sections, and also in some geodynamo simulations.

2. SOME ILLUSTRATIVE POLARITY TRANSITION RECORDS

The conventional view of what happens as the field reverses comes from a collective, 'common-sense' evaluation of transition records. The earliest example is the classic study by van Zijl et al. [1962] of a reversal recorded by the Jurassic Stormberg flood basalts of Lesotho in southern Africa. Rather than a simple progression, they found a sequence of flow-mean directions after blanket AF demagnetization to 22 mT that exhibited significant structure through the transition zone. One feature, however, is clearly the result of episodic volcanism, because the large gap around the midpoint of the reversal is marked by a sandstone interbed. Comparison of AF demagnetization curves of NRM and total TRM produced in the laboratory suggested that the field strength during the transition dropped by a factor of four to five compared to its average value before and after. More recent studies of the same section, while confirming the general conclusions of the earlier study, showed that the demagnetization and paleointensity procedures that had been employed were adequate to obtain accurate directions from only some of the transitional flows and reliable paleointensities from almost none of them [*Prévot et al.*, 2003; *Kosterov et al.*, 1997].

Four years later Ninkovich et al. [1966] presented a contrasting picture with their paleomagnetic study of an azimuthally unoriented deep-sea sediment core from the north Pacific spanning the last three reversals. In this record the inclination progresses smoothly between full polarity states in just a few samples, while the intensity of remanence drops by 80–90% and recovers again over a somewhat greater interval. Based on the average sedimentation rate of around 1 cm/kyr between reversal boundaries, the duration of the transition zones is 1 to 2 kyr and the intensity lows about ten times longer. At the time it was an open question whether these simple sedimentary records or the more complicated lava-flow records discussed above better represent transitional field behavior. Today, however, we ascribe the simplicity of the directional change to smoothing of the geomagnetic signal because of the slow deposition rate.

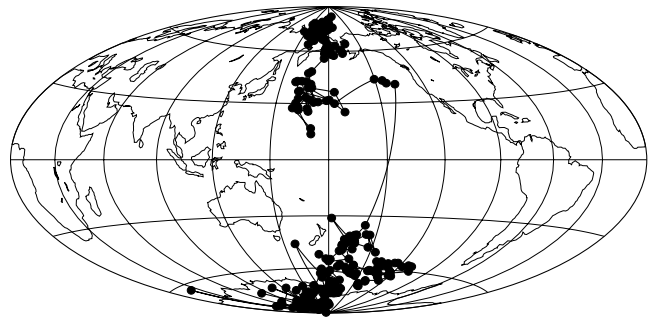

Figure 1. Detailed record of virtual geomagnetic poles (VGPs) spanning the lower Jaramillo reversal from a deep-sea sediment core from the southern Indian Ocean [*Clement and Kent*, 1984].

Clement and Kent [1984] restudied the lower Jaramillo polarity transition in a deep-sea core from the southern Indian Ocean previously investigated by Opdyke et al. [1973]. The sediment carried a particularly strong and well-behaved remanence and was deposited at a higher than average rate (5.9 cm/kyr after downward revision to accord with the more recent estimate for duration of the Jaramillo subchron [*Cande and Kent*, 1995]). Their record (Figure 1) of VGPs, sampled at very close intervals of 0.5 cm through the transition zone, shows more structure than did the previous, lower-deposition-rate record. Most notably, the transition consists of three clusters of VGPs, with a 60° gap in latitude straddling the equator between two of them and considerable east-west VGP movement of 60 to 90° in longitude. Using the average deposition rate, the duration of the directional transition (VGP latitude between 60 S and 60 N) is calculated to be 9.0 kyr, whereas the intensity low (<50% of the full-polarity average) lasted about 14 kyr. Some of the details of this record, however, likely reflect artifacts of common sedimentological processes. For example, the signal has almost certainly been averaged over a longer time interval than the nominal 100 years of deposition spanned by a single sample—perhaps an order of magnitude longer—because post-depositional remanent magnetization (PDRM) is acquired over a non-zero depth range [*deMenocal et al.*, 1990; *Kent and Schneider*, 1995]. Indeed, the amplitude of full-polarity directional variation in this record appears to be significantly lower than is typical for secular variation on the 1000-year timescale observed in

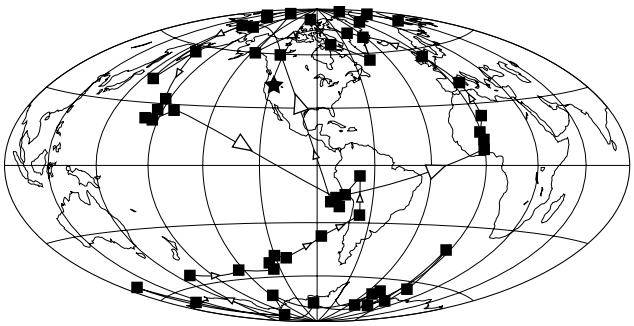

Figure 2. Detailed record of VGPs spanning a Miocene (~16 Ma) reversal from superposed basalt flows at Steens Mountain, Oregon, USA [*Mankinen et al.*, 1985].

archeomagnetic and lake-sediment studies. As a consequence, one can conclude that the absence of VGPs in the latitudinal gap between VGP clusters in Figure 1 marks a depositional hiatus rather than a rapid change in field direction, as suggested in the original paper on sedimentological grounds.

The most studied and still the most detailed volcanic polarity transition record is that found in the middle Miocene Steens Mountain basalt flows. This record consists of two phases (Figure 2): (i) an initial progression of VGPs from reversed-to-normal (R-N) followed by (ii) a rebound to transitional VGPs and then back to stable normal polarity [*Mankinen et al.*, 1985]. The VGP transition path is not confined longitudinally, spanning 90° during the first phase and 180° during the second phase with large swings to the northeast and southeast. Detailed paleointensity determinations by the method of Thellier and Thellier [1959] show that the field strength fell by 80–90% as the direction became intermediate, recovered to almost typical full-polarity values during the temporary normal, then plummeted again during the second phase of the transition until finally regaining strength as normal polarity became established [*Prévot et al.*, 1985]. The VGP revisits the same intermediate cluster near the coast of Peru during both phases of the transition, perhaps for a considerable time: in total, thirteen lava flows and one baked sediment zone record this direction. Moreover, it jumped to this cluster from another cluster of VGPs in the northwest Pacific recorded by sixteen superposed flows. It is particularly interesting that twice during the transition, once as the VGP arrived at the cluster in the northwest Pacific and again as it rejoined the cluster near the coast of Peru, the paleointensity as recorded in three superposed flows decreased progressively by a factor of three without any significant change in field direction. These observations are consistent with the notion that the transitional field may sometimes be dominated by a few flux patches that wax and wane in strength independently [*Hoffman*, 1992; *Gubbins and Coe*, 1993]. In the Steens record the three largest gaps, ranging from 80 to 100°, all occur as the VGP jumps to or away from a cluster (Figure 2). These gaps suggest that the VGP may have moved rapidly as one of the flux patches turned on or off, a notion that is also consistent with the unusual streaking of remanence directions documented in particular individual lava flows emplaced at the beginning of two of the three large gaps [*Coe and Prévot*, 1989; *Coe et al.*, 1995]. Episodic volcanism coupled with selective partial overprinting of the interiors of these particular flows could be an alternative explanation for these observations, but it cannot account for the simultaneous decrease in field intensity and stationary field direction described above with regard to these VGP clusters.

Figure 3 shows a much more complex VGP path than the previous example, along with two simpler ones, for the Matuyama/Brunhes polarity transition [*Valet et al.*, 1989], although all three paths are more longitudinally confined than the Steens Mountain reversal path. The complex record, which features many large oscillatory swings in both inclination and declination during the transition, is from Lake Tecopa in the western U.S. [*Valet et al.*, 1988], whereas the two simple records are from marine cores in the northern [*Clement and Kent*, 1987] and equatorial [*Valet et al.*, 1989] Atlantic Ocean. Could the marine records have completely smoothed rapid field oscillations that the lake sediment record was able to resolve? For this to be true the remanence lock-in window would have had to be much narrower for the Lake Tecopa than for the marine sediments, the more so because the Tecopa transition zone is only 10–12 cm thick, half that of the marine transition zones. Moreover, Valet et al. [1988] noted that secondary components were often quite difficult to remove from Tecopa samples. Thus it seems likely that the directional oscillations reflect unremoved overprints, although some of these swings have a large east-west component that cannot be reconciled with simple normal-polarity overprinting.

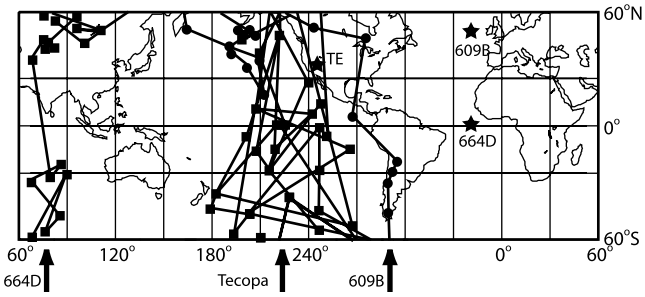

Figure 3. Comparison of three records of VGPs spanning the Matuyama/Brunhes transition from sediments [*Valet et al.*, 1989]. Localities marked by stars—TE: outcrops of ancestral Lake Tecopa sediment [*Valet et al.*, 1988]; 609B: DSDP core from the northeastern Atlantic [*Clement and Kent*, 1987]; 664D: DSDP core from the eastern equatorial Atlantic [*Valet et al.*, 1989].

Van Hoof and colleagues addressed the question of fidelity of sedimentary recording in a series of papers describing their detailed studies of many successive reversals in marls from Sicily [*van Hoof and Langereis*, 1991, 1992; *van Hoof et al.*, 1993a & b]. The deposition rate for these marls is typically 5 cm/kyr and, much like the previous example, these records have VGP paths that are confined to longitudinal bands near the Americas and contain many large oscillations (e.g., Figure 4a). These authors discovered evidence for delayed acquisition of remanence by authigenic magnetite, which they thought probably formed during reduction diagenesis. They noted two components of magnetization in many samples, both carried by magnetite: a lower temperature (LT) and higher temperature (HT) remanence. Because reversal boundaries and other identifiable magnetic features generally occur stratigraphically lower in the HT than in the LT record, the HT component must have formed after the LT component. They invoke a grain-growth, chemical-remanence mechanism to produce both components [*van Hoof et al.*, 1993b], although why the secondary component should have higher unblocking temperatures is not explained. Whatever the mechanism, acquisition of varying amounts of a delayed component of magnetization across a reversal boundary could produce multiple oscillations of remanence direction that might be mistaken for real oscillations of the field during the reversal. Moreover, ordinary sedimentary averaging of the near-transitional or pre- and post-transitional fields can be called upon to explain the longitudinal confinement of the VGP paths [*Langereis et al.*, 1992].

This satisfyingly self-consistent explanation, that the Sicilian-marl reversal paths are rock-magnetic artifacts, is challenged by transition paths of slightly older reversals that strongly resemble the VGP paths of Figure 4a that were obtained from more rapidly deposited marl on Crete that did not reveal such LT and HT components. Furthermore, the extraordinarily similar paths of the same reversals reported by Clement et al. [1998] in Fiji (Figure 4b) offer an even more direct challenge. One of the transition zones spanned 1.8 m of section, much greater than any estimate of remanence lock-in interval, making it unlikely that the longitudinal confinement in that record could be the result of smoothing between pre- and post-transitional directions [*Valet et al.*, 1986, and references therein]. These Fijian VGP paths for the lower and upper Nunivak transitions are recorded by marl that is reported to be more uniform lithologically and deposited at twice the rate (10 cm/kyr) of the Sicilian marl. In two parallel sections 4 km apart the major features of these paths (though not their individual oscillations) are remarkably reproducible. The

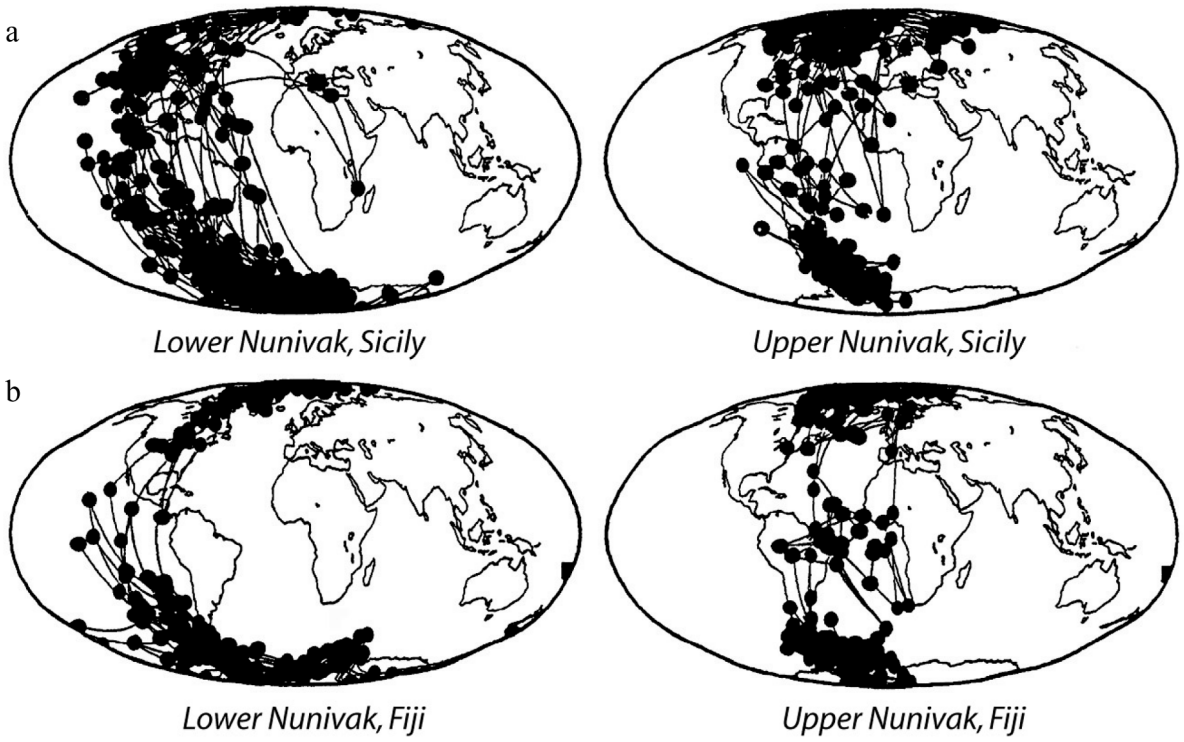

Figure 4. Comparison of four records of VGPs spanning back-to-back reversals from marl outcrop deposits in (a) Sicily [*van Hoof et al.*, 1993a] and (b) Fiji [*Clement et al.*, 1998].

authors attribute the high-frequency oscillations to variations in the timing of remanence acquisition but regard the similarity in longitude of the VGP bands recorded in Fiji and Sicily as evidence for a strong dipolar influence during these reversals. Of course, if the time-averaged, near-transition field were characterized by an equatorial-dipole component at the longitude of the Americas, then sedimentary averaging could account just as well for the coincidence of the VGP bands and also for their longitudinal confinement. Even so, the low-latitude cluster of VGPs in the upper Nunivak records would still imply a strong downward flux patch in that region for a significant period of time during the reversal. In addition, even though both Fiji and Sicily are roughly 90° from their VGP bands through the Americas, one cannot explain the coincidence of their paths with the proposition of Quidelleur and Valet [1994]. This explanation—that spuriously shallow transitional inclinations may be brought about by the inability of the greatly weakened field to maintain alignment of magnetic grains against gravity during deposition—fails because these marls almost certainly carry a post-depositional remanence.

A study by Channell and Lehman [1997] of the last two geomagnetic reversals recorded in high-deposition-rate (12–14 cm/kyr) sediment-drift cores from the North Atlantic offers support for the possible stop-and-go character of reversals, as suggested by the Steens Mountain basalt record presented above (Figure 2), but with many more oscillations. Nine transition records derived, from measurements at 1-cm intervals along U-channels passed through a cryogenic magnetometer and AF demagnetization apparatus, exhibit longitudinally unconfined VGP paths consisting of long tracks and large loops. Figure 5 shows three of them from three separate cores at one locality that record the Matuyama/Brunhes reversal. These paths are striking in that they visit almost the whole globe. Because the magnetometer pick-up coils have a characteristic response width of around 4 cm, these paths should be regarded as smoothed already over four measurements. Although the paths from the three cores are not identical, strong similarities are evident. The tracks oscillate between turning points around South America and in the western and central Pacific. The density of transitional VGPs tends to be greatest near the turning points, especially in the South American and in northeastern Asia/Pacific regions, indicating times of order one thousand years spent during each visit. Some of these 'hang-up' regions are in or not far from two of the flux patches identified by Hoffman [*Hoffman*, 1992] where today's geomagnetic field stripped of its axial dipole component is nearly vertical, whereas others are not. Between these places the VGP density is low, indicating much faster rates of change: along part of one of them four measurements span more than 180°! If the real field behavior during the reversal at this site

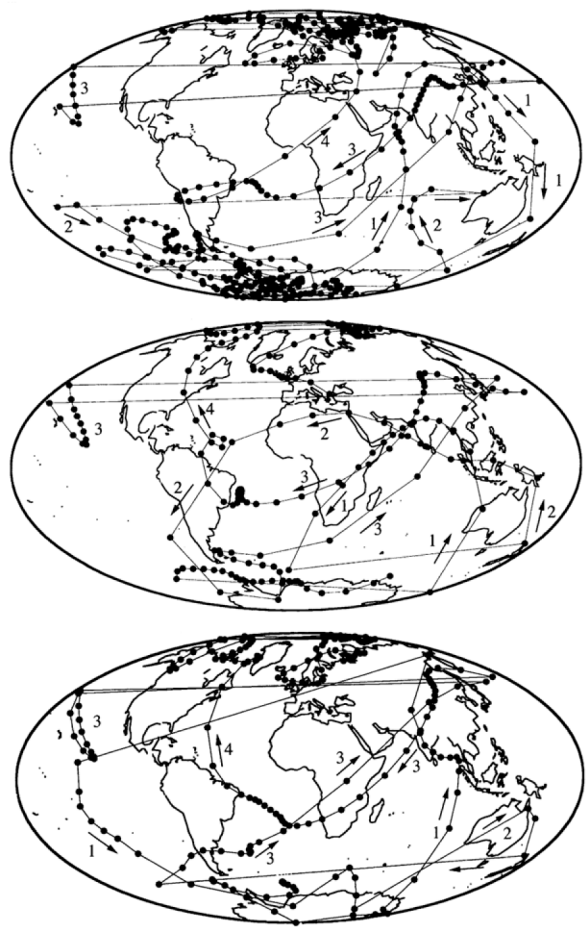

Figure 5. Three high-resolution records of VGPs spanning the Matuyama-Brunhes transition from ODP site 984 drift sediments from the northern Atlantic [*Channell and Lehman*, 1997].

was at least as complex as indicated by Figure 5, then the many much simpler sedimentary Matuyama/Brunhes records from around the globe [see *Jacobs*, 1994, for examples] must be very smoothed, very incomplete (or both), or affected by some other recording artifact.

Figure 6 shows another complex, high-resolution record of a different reversal, the Gauss/Matuyama transition recorded in a core of lacustrine sediment from eastern California [*Glen et al.*, 1999b]. Based on detailed magnetostratigraphy, the average deposition rate was about 22 cm/kyr during late-Gauss and early Matuyama time, almost twice that of the previous example, and the lithololgy is uniform [*Liddicoat*, 1982; *Glen et al.*, 1999a]. The core was sampled continuously at 1-cm spacing through a 2.1 m stratigraphic interval centered on the transition, with two or three 1-cm cubic specimens measured at each level. The quality of thermal demagnetization results are variable, with the lowest quality predictably during the transition when the field

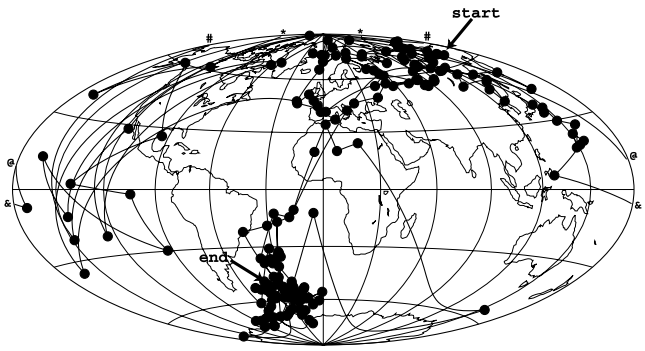

Figure 6. High-resolution record of VGPs spanning the Gauss/Matuyama transition from a long core of sediment from ancestral Searles Lake, eastern California [*Glen et al.*, 1999b].

intensity was weakest, but the broad features of the transition are well-defined even if individual points are sometimes not. From a swath of normal VGPs that extends from the north-polar region to northeastern Siberia, two excursions reach to transitional latitudes in the western Pacific and southern Europe. After a return to normal polarity, the VGPs undergo four large oscillations of 90 to 130° southwestward into the eastern equatorial Pacific and back to normal again. Three of these oscillations contain only one or two transitional VGPs each, but the first oscillation comprises seven. Following another spell near the pole, the VGPs march southeastward across Eurasia into the west-equatorial Pacific and eventually reach reversed polarity via a complex route. A final excursion from reversed polarity to the equatorial Atlantic and back ends the directional transition, which all together took an estimated 5300 years. Note that there are several VGP clusters: one comprising southern Europe and northern Africa, which is visited early, mid, and late in the transition; another in the Atlantic just south of the equator consisting of mid- and late-transitional VGPs; and a third, broad cluster comprising the far-reaching oscillatory VGPs in the east equatorial Pacific.

The large swings of direction accomplished in only a few centimeters of core in the last two, highest-resolution transition records raise some difficult questions. Do they signal an otherwise undetectable dramatic drop in deposition rate, or did the field actually change so rapidly? Could sediment even resolve changes as rapid as a literal interpretation of these records would demand? Is the complexity of reversals indicated by these transition records real, or just the product of faulty magnetic recording? If the oscillations in Figure 6 were caused by patchy remagnetization accompanying diagenesis down the core, then why is there no record higher in the transition zone of a later standstill of the field in the southern Pacific Ocean that could produce the remagnetization?

3. THE CASE FOR COMPLEXITY

Even though there are common features among the transition paths illustrated in Figures 4, 5 and 6 that argue for some degree of true geomagnetic content in these high-resolution sedimentary records, independent sources of evidence are needed to help answer the questions posed above. One completely different body of information we can turn to for insight comes from numerical geodynamo simulations. Glatzmaier and Roberts' [1996] geodynamo model is a dynamically self-consistent simulation and the first to exhibit spontaneous reversals. It solves the equations for the time-dependent thermal, compositional, velocity and magnetic fields in the spherical geometry appropriate for the core. 'Simulation time' (henceforth referred to simply as 'time' when discussing simulations) is scaled to give the appropriate free decay time for electrical currents in the earth's core. Spatial resolution is limited by the necessity of using a time step sufficiently long that the simulations span enough time for reversals to occur, requiring the representation of small-scale eddies by eddy diffusion, as is done in models of the oceans and atmosphere. How the simulations will change as greater computational power enables greater resolution and physical parameters closer to those of the earth is an interesting question. Quite possibly the behavior at larger scales will remain similar, whereas at smaller scales more rapid and complex field variations may emerge.

A suite of eight simulations, each with a different pattern of heat flux prescribed at the core-mantle boundary (CMB) but identical in all other regards including total heat flux out of the core, exhibited different styles of reversals [*Glatzmaier et al.*, 1999]. The six simulations with CMB heat flux that varied symmetrically about the rotation axis yielded fourteen full reversals, eleven of them with relatively simple transition paths and durations (3 to 10 kyr) typically estimated for actual reversals on earth [see *Coe et al.*, 2000 for examples]. Two of the exceptions were for an unstable case in which the dynamo 'died' (intensity dropped more than 95% and never recovered) as it first reversed, and the third was for the case in which the CMB heat flux varied monotonically with latitude from pole to pole. The two simulations with CMB heat flux that varied with longitude reversed three times, two of them with complex VGP paths and directional durations around 15 to 30 kyr. The most relevant of these for the earth is the second reversal of the tomographic simulation, so named because the heat-flux at the CMB was patterned after the large-scale variation of seismic velocity from tomographic studies of the lowermost mantle. The rationale for this case is that relatively more heat can conduct into overlying mantle that is cooler than average, i.e. where seismic velocity is presumed to be higher than average.

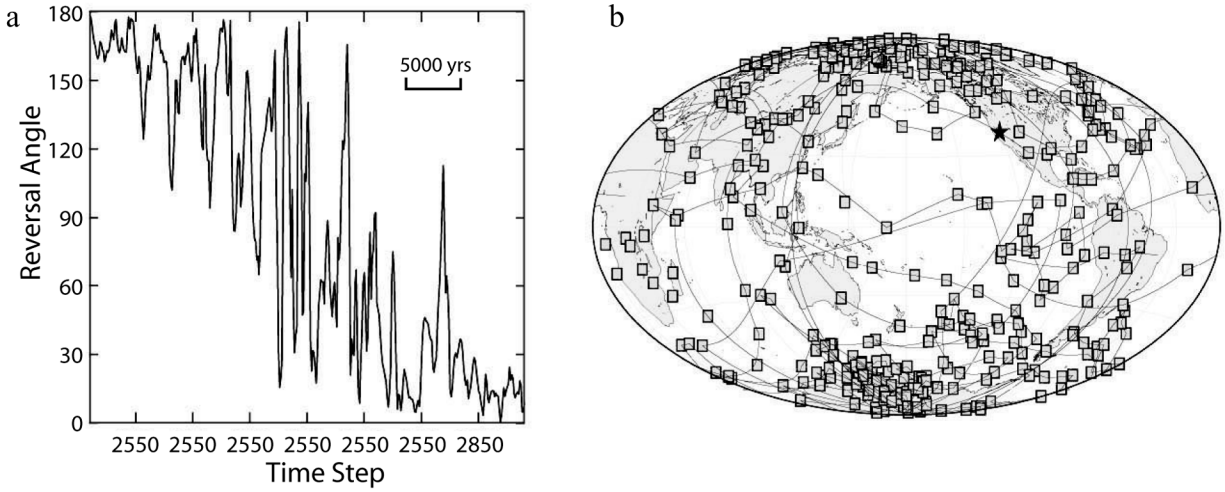

Figure 7. Record of a reversal from the tomographic geodynamo simulation of Glatzmaier et al. [1999] at 40°N, 240°E. (a) Angle between the simulated field and the centered axial dipole field direction versus simulation time step (95 yr). (b) corresponding VGP path spanning the reversal (star shows observation site). Redrawn from Coe et al. [2000].

Figure 7a shows the temporal behavior of the field direction during the complex reversal of the tomographic simulation at a site in the northern hemisphere [*Coe et al.*, 2000]. The record exhibits many oscillations that grow in amplitude and frequency to a maximum at the midpoint of the transition and then decrease as stable normal polarity is achieved. Measured from the first to the last large oscillation, the transition took 26 kyr. The definition of duration is debatable: one could consider the last oscillation to be a post-transitional excursion because it occurs about 4 kyr after the previous one. The VGP path (Figure 7b) is characterized by many long tracks, with VGPs closely spaced in some places and with gaps elsewhere of 90 to almost 180° between successive points (sampling interval 95 years). The density of VGPs is distinctly greater than average in a longitudinal band over the Americas, reminiscent of (but less confined than) the VGP bands first reported by Laj et al. (1991) and exhibited in the paleomagnetic records of Figure 4. A second, more diffuse band is discernible over eastern Asia, and a much lower density of VGPs occurs in the central Pacific and Atlantic regions. Notice as well the similarity between the simulation record and the Matuyama-Brunhes record discussed above. By sprinkling a number of hiatuses into (i.e., removing a number of VGP sequences from) the tomographic VGP path of Figure 7b, we could obtain a record quite similar in character to that of Figure 5. At the same time, it is important to recognize that the tomographic simulation departs very significantly from some time-averaged properties of the earth's field [*Coe et al.*, 2000], so the similarity to a real record must be taken as only suggestive.

The simulation also provides some insight into the degree to which records of the same reversal may vary from place to place over globe. Plate 1 shows the variation of VGP latitude as a function of time through the reversal around seven circles of latitude between 80°N to 80°S. Transitional VGPs first appear in the southern hemisphere around latitude 65°S, but not till about 4 kyr later does the VGP cross the equator. Focusing on these zero crossings for clarity, which are shown by the dashed lines, we see that the field instability spread quickly throughout the southern hemisphere, but much more slowly in the northern hemisphere. There is a tendency for the zero crossings to propagate westward at mid-southern latitudes, whereas at mid-northern latitudes they propagate eastward around the middle of the record and westward later on. Records of the reversal vary greatly with position on the globe. For instance, at 65°S/270°E the VGP crosses the equator 39 times during the transition, whereas at 65°N/180°E it crosses only 9 times. At a given moment the field direction may appear to be fully normal at one place on the globe, reversed at another, and transitional at another—even for points around one circle of latitude. Duration of the transition depends on the definition. Defined as the first and last equatorial crossing of VGPs, it varies greatly between extremes of about 3 kyr at 80°N to 30 kyr for western longitudes at 65°S.

Thus, geodynamo simulations make the case for complex reversals plausible. Can we find more direct evidence for complexity? To do so we return to reversal transitions recorded by lava flows because, even though a gap of unknown length exists at each flow boundary, the stable direction of each flow usually gives a reliable estimate of the true field direction at the time the flow cooled. We return to the 990-meter Steens Mountain section of flow-on-flow basalt that has yielded a detailed record of a Miocene rever-

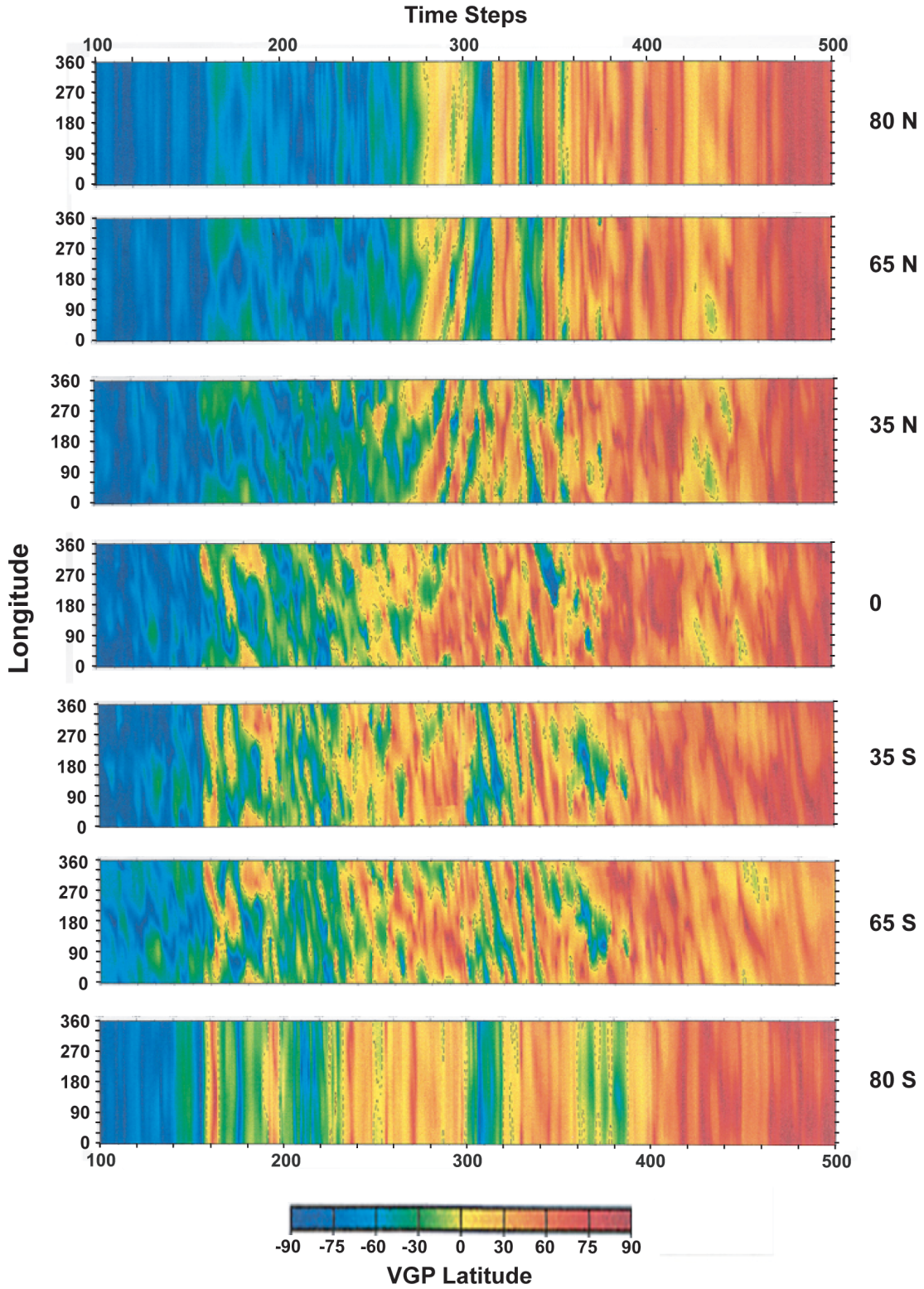

Plate 1. Space-time variation of VGP latitude through the reversal from the same geodynamo simulation as in Figure 7. Time steps along the abscissa are 95 yr (38 kyr total). See text for discussion.

sal with 26 distinct directional groups documenting the transition (Figure 4). Despite its detailed character, we now know that the actual behavior of the reversing field was more complex—perhaps much more complex—than this record shows. A recent study [*Camps et al.*, 1999] of a parallel section only 1.7 km from the original section uncovered a second unsuccessful swing of the field direction to normal polarity that is not represented in the original record (Figure 8). The new swing is definitely not the result of unrecognized sills or fault-repeated section. Rather, it is recorded by three flows that must pinch out before reaching the original section. Note that the rest of the new record matches the original directional path well, even though it is clear that there are additional instances of flows at one section that don't reach the other. It is interesting that the uppermost new direction (flow B33 in Figure 8) represents a swing back toward the cluster of west and down directions. Instead of jumping directly from the B33 to the B32 direction as shown in Figure 8, the transitional field may have completed the oscillation back to the cluster. Indeed, any number of more complicated scenarios are possible.

Other sections from the surrounding region containing the same reversal recorded by the Steens Basalt have been summarized by Mankinen et al. [1987]. The Steens Basalt is now recognized as the initial outpouring of the Yellowstone hot spot flood basalts [*Hooper et al.*, 2002], which explains how a pulse of flows that recorded the reversal can be widely distributed. Some of these records contain features quite different from the record at Steens (Figure 9). In an early record from Poker Jim Ridge, 80 km to the west, the field makes a large excursion during reversed polarity that is not seen at Steens, visits the same two cluster spots as at Steens and then moves directly to normal polarity, missing much of the rest of the Steens record [*Goldstein et al.*, 1969]. In two records from the Santa Rosa Range 120 km to the southeast, the reversal ends along the track by which the Steens reversal passes to stable normal polarity, but exhibits VGPs in western Australia, southern Siberia, the western Indian Ocean and the central Atlantic that are not found at Steens [*Larson et al.*, 1971; *Roberts and Fuller*, 1990].

There are other instances of volcanic reversal records that also suggest that reversals can be too complex and too rapidly

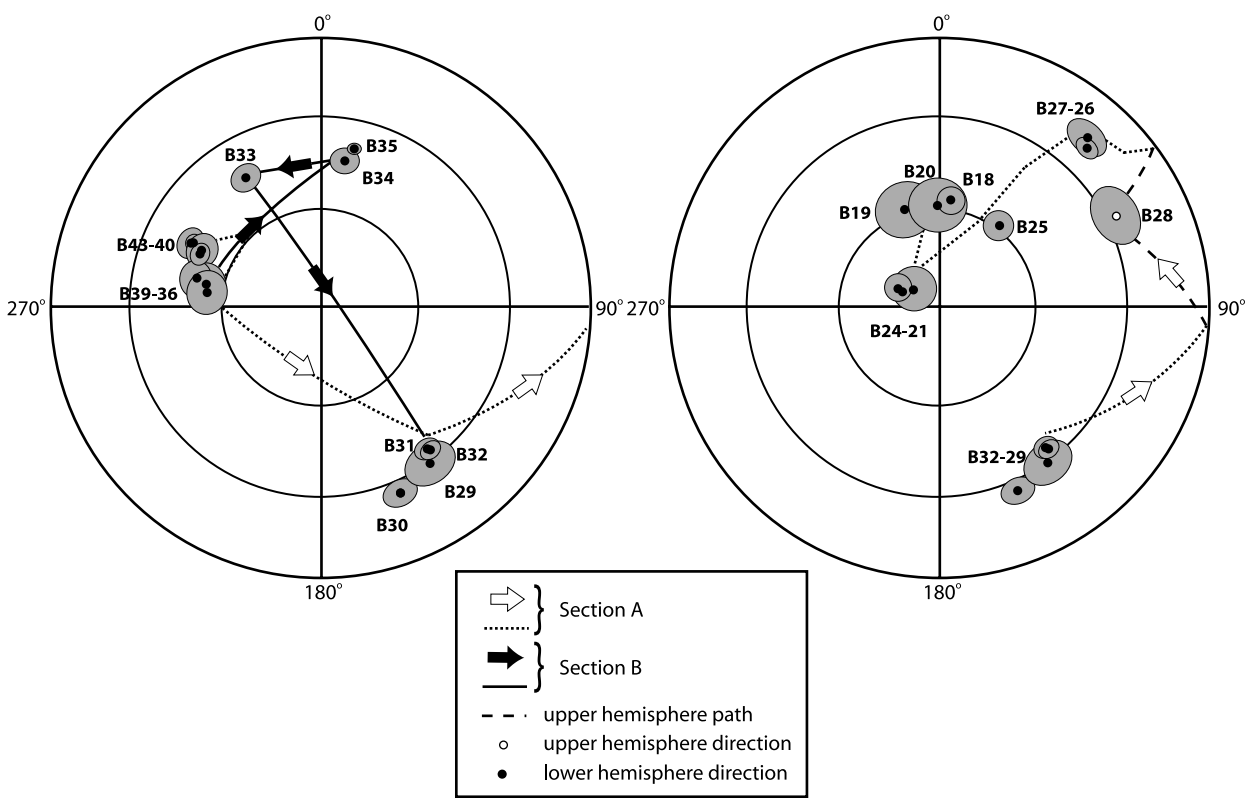

Figure 8. Flow-mean directions and confidence limits from lava flows spanning last half of the Steens Mountain reversal at a new Steens B section [*Camps et al.*, 1999], 1.7 km from original Steens A section. Dotted and dashed line shows progression of directions at Steens A from Mankinen et al. [1985]. They follow the flow means for Steens B quite well, except for the swings from flow B36 to flows B35/B34 and then back to B33 (see text). Modified from Camps [1999].

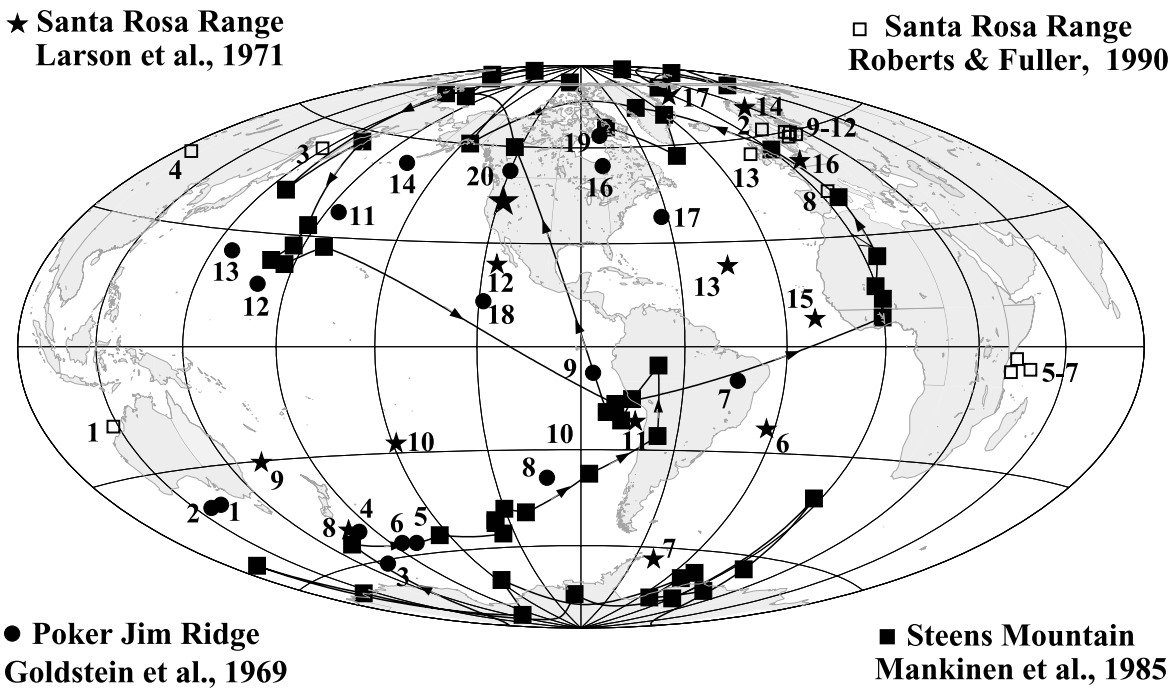

Figure 9. Reversal records showing VGPs of the polarity transition at Steens Mountain and from Steens-equivalent lava flows at Poker Jim Ridge and the Santa Rosa Range. These latter records include some VGPs not found in the Steens Mountain record (see text).

changing to be resolved by even thick sequences of rapidly emplaced flows. One example is the recently published study by Riisager et al. [2003] of the C27n–C26r transition recorded at ~61 Ma by West Greenland flood basalt. The stratigraphy and paleomagnetic directions in two thick sections, KI and NQ, comprising 35 and 45 sampled lava flows indicate that the former overlaps the first half of the latter. Even though the sections are only separated by 16 km and the lava production rate there is estimated to have been an order of magnitude greater than over the current Iceland hot spot, a large swing of the VGP path to Central America and rebound back to normal polarity recorded in the KI section is absent at NQ. Several common directions appear to tie the two sections together, but most of the flows in one section are not matched by flows in the other section. This result is in accord with helicopter photogrammetry of superb sea-cliff exposures, by which individual flows can be frequently observed to pinch out within 2 km. The necessary conclusion is that the records comprise independent paleomagnetic time series at irregular intervals, some of which are too great to track the course of the reversing field adequately.

4. CONCLUSIONS

Geologically speaking, reversals take so little time to happen that they challenge the ability of the best paleomagnetic recorders to resolve the behavior of the transitional field. There are many mechanisms that are capable of degrading paleomagnetic records in sediments. Doubtless many sedimentary reversal records are severely compromised by smoothing, by patchy remagnetization, and perhaps also by breakdown of recording fidelity in weak transitional fields. Even though many sedimentary records presumably do retain some information about the reversing field, it is difficult to know how to separate fact from artifact. Thus it is all too easy to dismiss sedimentary records that are unusually simple or extremely complicated as completely obscured by recording problems. Some recent detailed studies in high-deposition-rate sediments, however, collectively suggest that at least some reversals may be truly complex, with swings and oscillations of field direction that are so rapid that even these exceptional records may smooth or even miss many of them.

This hypothesis requires independent support, because sedimentary recording problems are always a possibility. Numerical geodynamo simulations, though still in their near-infancy in terms of the spatial resolution of fluid motions that can be computed for long-enough simulation times that spontaneous reversals occur, provide such support: namely, examples of complex (as well as simple) polarity transitions with tracks, standstills and oscillations like those envisaged above. It is interesting and perhaps significant that complex paths did not occur in simulations with highly symmetrical patterns of CMB

heat flux (i.e., symmetrical about both the rotation axis and equator).

Independent evidence directly supporting the occurrence of complex reversals comes from transition-zone records in lava flows. No single record is as complex as we propose some reversals may be, but lack of agreement between multiple records through the same reversal implies that the underlying transitional field behavior was much more complicated than indicated by any one record. This inference is based on the assumption that lava flows, unlike sediments, almost always yield reasonably reliable estimates of the instantaneous field direction. When sampling and laboratory demagnetization are carried out correctly, we hold that this is the case.

In summary, sedimentary and volcanic paleomagnetic records are complementary, but both are always incomplete and give only lower bounds on how rapidly changing and complex the behavior of the reversing field may have been. Geodynamo simulations provide a theoretical approach to the question, but limitations in computer power have prevented them from operating near the parameter regime appropriate for the core, with concomitant loss of spatial and temporal resolution. Nonetheless, the combined evidence from all three approaches appears sufficient to conclude that at least some reversals are much more complex than typically portrayed, with episodes of oscillatory and very rapid field change.

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