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The Geomagnetic Field During a Reversal

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Abstract

By modifying the IGRF it is possible to learn what may happen to the geomagnetic field during a geomagnetic reversal. If the entire IGRF reverses then the declination and inclination only reverse when the field strength is zero. If only the dipole component of the IGRF reverses a large geomagnetic field remains when the dipole component is zero and he direction of the field at the end of the reversal is not exactly reversed from the directions at the beginning of the reversal.

1. Introduction

A reversal of the geomagnetic field is usually identified by an abrupt reversal of direction of magnetization in samples from a stratigraphic sequence. The change occurs so rapidly in geologic time that it is impossible to follow details of the magnetization changes during this short interval. Furthermore such observations are usually confined to one geographic location and so give only a Virtual Geomagnetic Pole (VGP) but little detailed information about the Earth as a whole. There have been several models proposed for the field during a reversal. Seven of these models are briefly described by McElhinny and McFadden (2000). Most assume that only the geomagnetic dipole reverses rather than the entire geomagnetic field, but some assume a geographic rotation of the geomagnetic field to the opposite direction. They do not attempt to describe the detailed behavior of the geomagnetic field vector with time over the entire Earth although two preferred paths of the pole have been suggested (for example *Clement and Kent*, 1984; *Gubbins and Coe*, 1993).

The International Geomagnetic Reference Field or IGRF describes the present internal geomagnetic field by a spherical harmonic series. Individual terms of this series describe the dipole field, both axial and offset/inclined, as well as higher order harmonics of the internal field. Here we assume the dipole component of the IGRF goes through a reversal through a systematic reduction in the spherical harmonic coefficients appropriate to the inclined and offset dipole and follow the behavior of the geomagnetic field components and the field intensity. We will examine how these parameters change over the entire Earth for some discrete stages of the process and then how they change continuously at a few representative places.

For convenience we chose to work with the 1995 version of the IGRF with degree and order 10 (*Barton, et al.*, 1996). Other, more recent versions of the IGRF (i.e. *Olsen, et al.*, 2000) would make no noticeable difference in the principal illustrated here. Between past reversals of the field one has no assurance that the geomagnetic field is like the recent models of the IGRF although it probably had a strong dipole component. Thus our use of the 1995 IGRF is meant to show how the field might have changed and to illustrate that the behavior of the field over time at one place may give little information on how it changes over the entire Earth. Furthermore we show that directional components of the field may not be the best indicator of the full reversal process.

2. Reversal of Entire IGRF

First we examine the simple case when all of the IGRF coefficients reverse. We considered five spherical harmonic models: (a) the IGRF (b) the IGRF with all harmonic coefficients reduced by one half, (c) the IGRF with all components reduced to zero – trivial case, (d) the IGRF components reduced by one half and assigned a negative sign, and (e) the IGRF with all components assigned a negative sign. These models will give a graphic description of the time steps through which the geomagnetic field goes during a reversal. For each of these four (non trivial) cases global maps were made for field strength, declination, and inclination (although those maps are not shown here due to lack of space).

2.1 Global changes in Declination and Inclination, Total IGRF Reversal

Because all components of the field are reduced proportionally there is no change in declination or inclination until the time of zero field strength is reached. Then, because the sign of the field components are all reversed there is an abrupt reversal in sign of the declination and inclination.

2.2 Global changes in Geomagnetic Field Strength, Total IGRF Reversal

The field strength is reduced linearly, at every point on Earth until a zero value is reached, after which it increases linearly. Contours lines of field strength are the same during the reversal, except when the field is zero. although the values on the contour lines change. as they were before the zero value.

It is clear that the reversal of the field may begin long before the reversal in declination and inclination and may continue long after. In order to identify a reversal one must observe the change in field *strength*, or rock magnetization, as well as the change in direction. The time of the change in direction is only a trivial part of the time for a reversal. A number of investigators have reported a decrease, then a recovery of magnetization at a reversal (*Tanaka, et al*., 1995).

3. Reversal of Only the Dipole Component of the IGRF

The first eight coefficients of the IGRF, where n has values of 1 and 2, identify the inclined, offset dipole. The secular variation of these components is much greater than those of the non-dipole components We now assume that these coefficients, and only those coefficients, change during a reversal.

Like the models when the entire IGRF reversed, we now use five models when only the dipole reverses. These were with the total IGRF, the IGRF with only dipole terms reduced by one-half, the IGRF with only dipole terms zero, the IGRF with only dipole terms reduced by one-half and negative, and, finally, the IGRF with only dipole terms negative. Again, due to shortage of space we cannot show all the maps of with these five models. However some are shown in Figures 1 and 2.

3.1 Global Changes in Declination and Inclination, Dipole Only Reversal

Before the center of the reversal calculations show that the field components are only slightly different from the case of full field reversal, but the difference is only a very few degrees (depending on the location). Figure 1 shows the declination and inclination after the reversal compared to those parameters before the reversal. Instead of the declination changing by 180 degrees everywhere, it may be as low as 145 degrees in many places. Thus it would be mistake to make he general statement that the declination is always expected to change by 180 during a reversal – unless the entire IGRF reverses.

Similar remarks apply to the inclination (or dip). After a reversal the inclination is not always exactly equal and opposite to is value before the reversal.

As Figure 2 shows when the dipole component is zero the declination is determined by only the non-dipole terms and form scattered directions across the Earth. These declinations are highly sensitive to the non-dipole values used for the spherical harmonic coefficients in the IGRF. Their exact values are not important to illustrate this fact. Inclination directions are similarly scattered.

3.2 Global changes in Geomagnetic Field Strength, Dipole Only Reversal

Shortly after the reversal begins and just before the reversal ends, there is little difference in field strength in these two cases. And contour maps in the two cases would look similar because the dipole terms of the IGRF are so much larger than the non-dipole terms. At the end point of the reversal the field strength is a few thousand nT different from its values at the beginning of the reversal. Assuming that the Earth's field strength is about 60,000 nT, this suggest that the magnetization of the recovered sample will have changed by about 1/60, which exceeds the limit of rock magnetic technology.

When the dipole terms are much reduced the situation is different (as illustrated in Figure 3, discussed alter) and values before and after the minimum field value may be appreciably different. Figure 2 shows the field strength when the dipole is zero. The global field strength is not zero anywhere on Earth and, of course, the contours of field strength do not resemble the contours of field strength of earlier times. In some parts of the Earth the strength may be about 7000 nT and at other places it may be near zero nT.

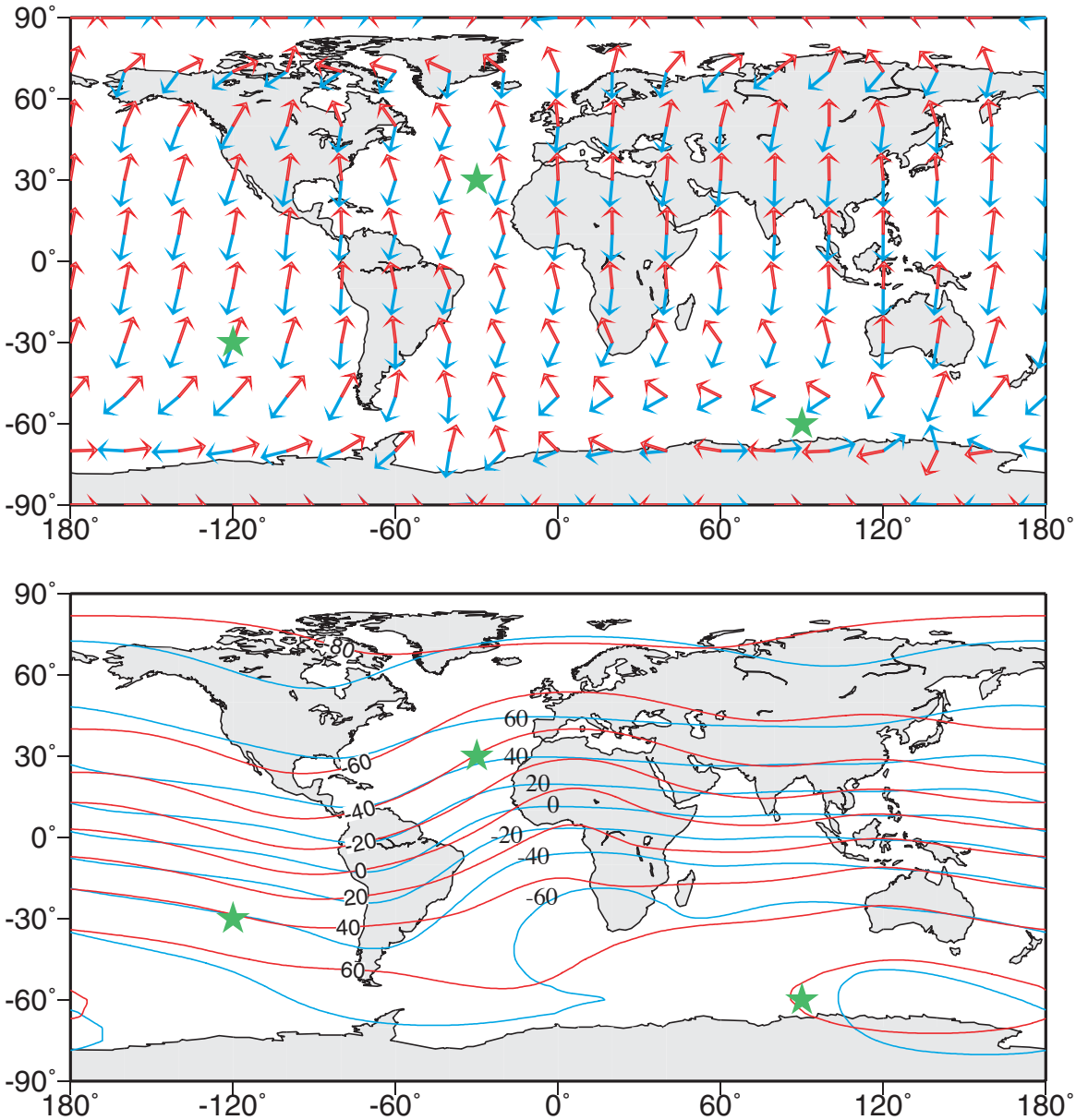

Figure 1. (Upper Panel). Red arrows show the declination according to the 1995 IGRF. Blue arrows show the declination according to the 1995 IGRF with dipole components completely reversed. (Lower Panel) Red contour show the inclination for the 1995 IGRF. Blue contours are inclination for the 1995 IGRF with dipole components completely reversed. Three green stars are locations of three sites discussed in text.

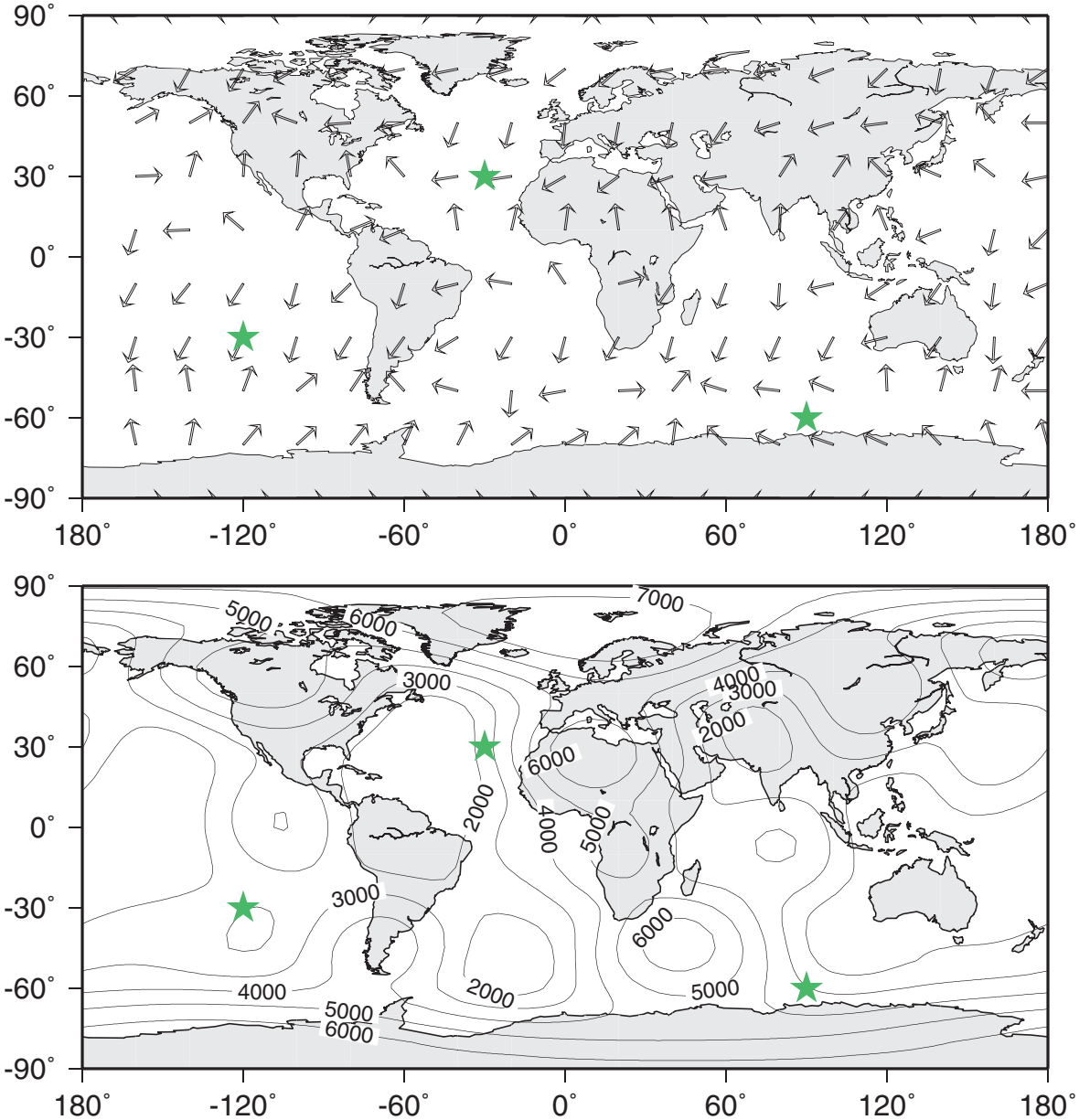

Figure 2. (Upper Panel). Arrows show declination for 1995 IGRF with dipole component zero. (Lower Panel) Field strength, in nT, for 1995 IGRF with dipole component zero. Three stars are locations of three sites discussed in text.

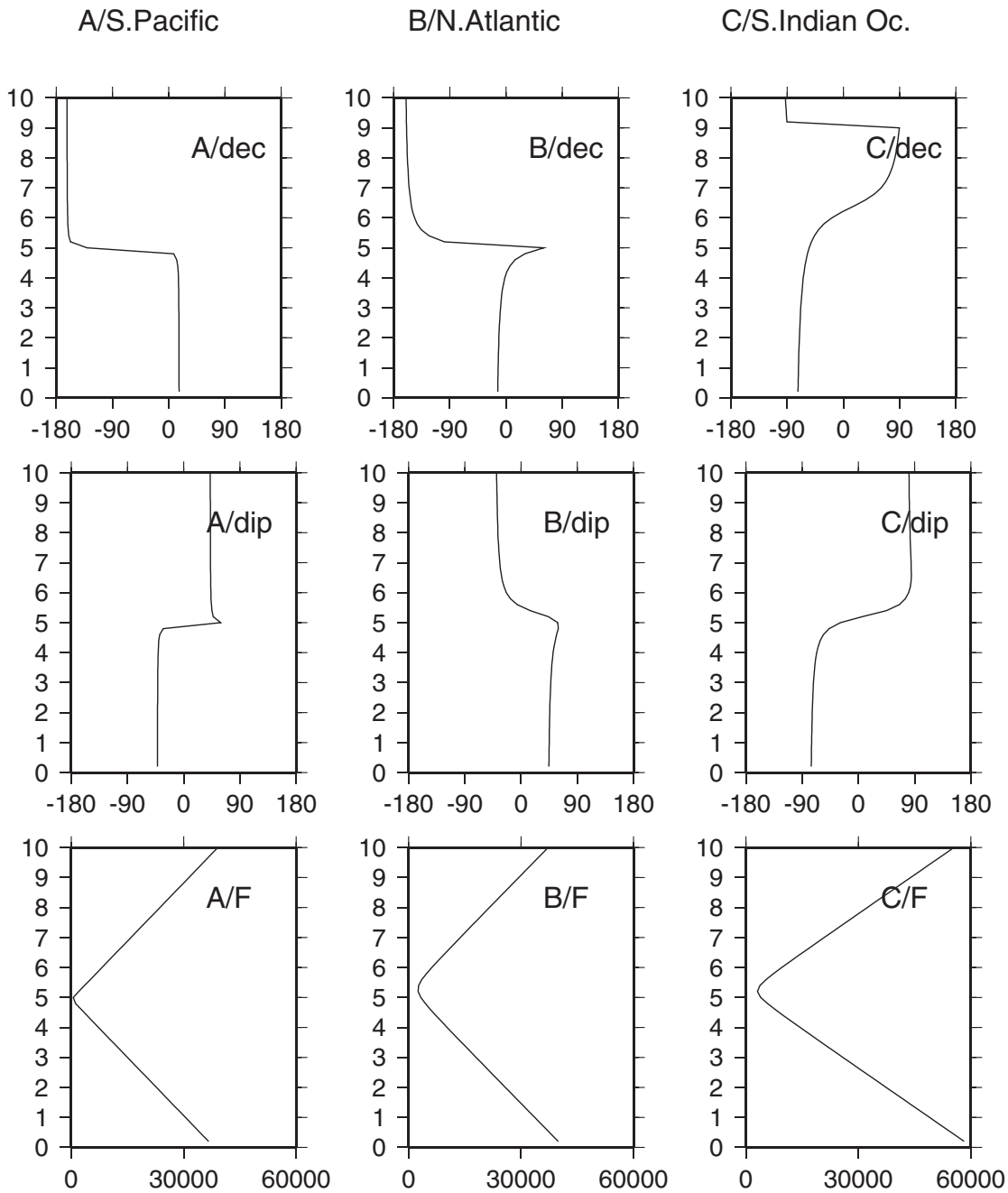

Figure 3. Time history of geomagnetic reversal at three sites when only the dipole reverses. Time of reversal begins with ordinate value 0 and reversal is completed with ordinate value 10. Upper three panels show declination, mid panels show inclination or dip, and bottom panels show field strength in nT. Location of sites A, B, and C are shown by stars in Figures 1 and 2, and identified in the text.

3.3 Changes Through time at Three Sites, Dipole Only Reversal

Since it is impossible to display global maps for many time slices, we present continuous time plots of the geomagnetic parameters for three typical sites. Figure 1 guided the choice of these sites. Site A is in the South Pacific Ocean (30S, 120W), where the declination should be almost completely reversed during a reversal. Site B is in the North Atlantic Ocean (30N, 30W) where the change in direction is somewhat less than opposite, and site C is in the South Indian Ocean (60S, 90E) where the differences should be distinctly different from opposite. The changes in declination, inclination, and field strength for the three sites are shown in Figure 3. In each figure the beginning of the reversal has an ordinate value of zero and the end of the reversal has a value of 10. The axes are plotted in this way to resemble the magnetic profiles resulting from deep-sea cores

For Site A in the South Pacific, the declination changes from 16 degrees before the reversal to –160 after, for a change of 176 degrees. The inclination changes from –42 degrees at the beginning to 42 at the end, showing a reversal with respect to the horizontal plane. The intensity goes from its present value of about 36,639 nT to 48,656 nT at the end of the reversal. At the center of the reversal the intensity drops to 515 nT at this location. Thus directions are reversed and the field goes to near zero.

At Site B in the North Atlantic the declination goes from –13 degrees before to –160 after the reversal. This change is only 147 degrees, and not 180 and the change from the first value to the other is not as sudden as at Site A. The inclination goes from 44 degrees to –39 degrees, which is not exactly a reversal with respect to he horizontal plane. The field strength drops approximately linearly until it approaches the halfway point where it noticeably deviates from linearity and reaches a minimum value of 2,509 nT.

Figure 1 shows Site C to be in place where the declination changes rapidly with position. The declination plot shows the declination starting at –72 degrees, and, after the half way time rising to near 72 degrees for a change of 144 degrees, However, at 90 percent of the way through the reversal the declination drops back to near it original value of –72 degrees, probably due to some inaccuracy in the non-dipole coefficients. The inclination changes from –75 degrees to near 80 degrees at the end, making a good reversal about the horizontal plane. The field intensity reduces to a value of 3,059 nT at the zero dipole point.

4. Conclusions

Can one expect to distinguish a total field reversal from a dipole only reversal from rock or sediment samples? By modifying the IGRF to represent a reversal we show the magnitude of the differences one might expect to find.

1. The reversal of the field takes place over a much longer time than the time for the declination or inclination to reverse. The only way to know the time for a full reversal is to know when the intensity starts to decrease and then to know when it comes back to nearly its original value. In practice one measures the magnetization of the specimen and, if the magnetic susceptibility does not change with time one can compare the field strength before and after a reversal. This change in magnetization is not likely to be more than one part in 60, but the probable error in the measurement probably exceed this amount. If, at the center of the reversal the magnetization was exactly zero that would suggest a complete field reversal, but it is impracticable to get a stratigraphic sample at just this time. A good discussion of the time resolution of samples is given by *Valet* (2003)

2. If only the dipole component of the field reverses then the change in declination and inclination is not as sharp as for a full field reversal. The rapidity of this change may offer a possible clue to see if any higher order terms are not reversing, i.e. only the dipole is reversing. When the dipole component is zero the declination will have diverse directions and the field strength will be up to several thousand nT in different places on Earth. So the minimum magnetization may not be, by itself, a clear indicator of full versus dipole reversal.

3 The non-dipole terms of the geomagnetic field take on considerable importance during a reversal. This suggests that investigators use care in assuming that the VGP represents any actual dipole during a reversal.

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