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On an Interpretation of the Direction of Natural Remanent Magnetization

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1) Introduction

For about twenty years many workers (Blackett et al, 1960; Irving, 1964; McElhinny, 1973) have deduced from measurements of the direction of natural remanent magnetization in rocks that continental land masses have moved relative to each other. Particularly the applications of paleomagnetism to structural problems in geology and geophysics are accepted. They cover a wide field in geophysics and geology. The basic assumptions for these applications are that the remanent magnetization in rocks provides the direction of the geomagnetic field at the time of formation of the rock and that the geomagnetic field has been the field of a geocentric axial dipole.

In the case of the applications of paleomagnetism, many workers mainly direct their attention to deflection in the direction of remanent vector. It is suggested that the deflection in declination of the remanent vector is due to a rotational movement of rocks sampled about one vertical axis. From measured inclination of samples we can estimate an ancient latitude, and then we can trace a drift of land mass of the region sampled from the difference between the present and the ancient latitude, if any. In this case it is assumed that there is no stretching, folding, or distortion of any kind within a given block or land mass. The land masses or rock bodies are generally deformed for long period since the formation. However, some small intrusive rocks can be regarded as a rigid body for tectonic movements from paleomagnetic observations for various granitic masses.

In this paper a possibility of tilting of a block or land mass will be derived from paleomagnetic observations for small intrusive rocks on the basis of some assumptions of paleomagnetism and the principle of minimum rotational movement of rocks.

2) Remanent magnetization in an intrusive rock

In igneous rocks the primary magnetization is acquired when the hot rock cools throughout the Curie temperature of ferromagnetic minerals in the rock. On the other hand, a range of the order of 900° to 600° is generally accepted for the overall solidification of molten granites (Raguin, 1957). This shows that granitic intrusions eventually reaches the Curie temperature of ferromagnetic constituents involved after the rocks solidified.

It is usually considered that granitic intrusions were originally several hundred or thousand meters below the surface. Such deep burial remains hot for long time and is accompanied by regional heating to a few ten or hundred degrees after original cooling. These temperatures may be maintained for long time and they might decay the primary magnetization. This means that there were effects of low temperature viscous magnetization during such burial. Part of the primary magnetization may eventually have decayed during the period of the burial and secondary viscous components may be acquired parallel to the direction of the geomagnetic field throughout the period. There are many examples of such intrusive rocks as most of the primary magnetization have decayed. On the contrary, we can find granitic masses with stable remanent magnetization which imply to be primary by removing secondary components.

Intrusive rocks with the stable remanent magnetization usually have apparent dimension less than about 10 km in diameter. They almost have the same direction of remanent magnetization throughout one rock mass except the extreme marginal part of the body. This is ascertained by collecting samples from many sites within one rock body and by making a comparison between directions of remanent vector for each site. The granitic rock having no significant magnetic disturbances appears to have responded as a rigid body to any tectonic movement. A systematic variation of remanent vector is observed, as a particular case, in intrusive rocks which were formed at the time of a great change of ambient field direction as the field reversal.

If a rock mass has either folded or broken it into blocks which have tilted in different directions, obviously the primary remanent magnetization will also have been similarly tilted. Such examples have not always been found in granitic rocks. However, from paleomagnetic observations of granitic bodies which are not large dimension, most of bodies with remanent directions deviated considerably from the present field direction will be able to note positively that they have moved as a rigid block for any tectonic movement after the intrusion.

A good example is seen in the Ibaragi granitic complex which is circularly differentiated varying in composition from quartz diorite to porphyritic adamellite (Ito and Tokieda, in preparation). This elliptical shape pluton has the apparent dimension of the 5.5 km width and 10 km length, and give biotite whole rock ages ranging from 79 to 83 million years using Rb–Sr method (Ishizaka, 1971). The granitic pluton also has the normal and the reversed magnetization which is extremely deviated from the present geographic poles shown in Fig. 1. The existence of both remanent magnetizations within a rock body is effective to examine any rotational movement or any tilting within the body. This granitic pluton, as far as depending upon only the direction of remanent magnetization, is likely to have moved as one block to some tectonic movements occurred in southwestern Japan since the Cretaceous.

From many measurements of the natural remanent magnetization in granitic intrusions exposed in Japan and U.S.A., it is concluded that granitic rocks with the

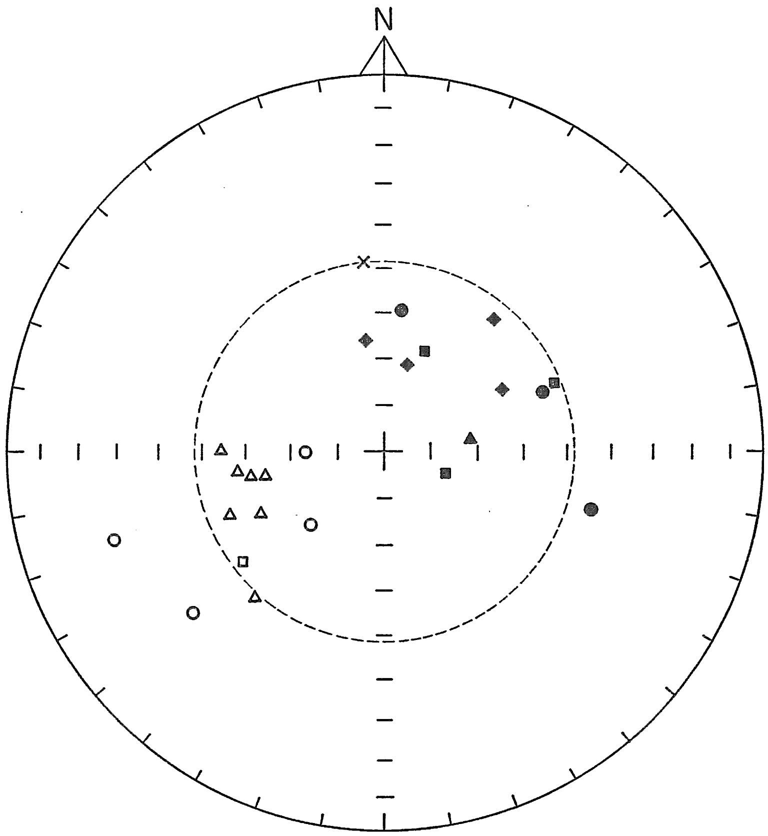

Fig. 1. Mean directions of natural remanent magnetization after demagnetization of 100 oe. Solid symbols represent normal and open symbols represent reversed.

●○: Remanent directions of samples collected from the outermost zone in Ibaragi granitic complex.

▲△: Remanent directions of samples collected from the middle zone.

■□: Remanent directions of samples collected from the innermost zone.

◆ : Remanent directions of samples collected from the Myoken pluton.

× : Present geomagnetic field direction.

stable remanent magnetization after the demagnetization will have moved as a rigid block for any tectonic movements.

3) Paleomagnetic poles since the Cretaceous

Most of the primary magnetization in granitic rocks, which should be stable over geological time, is acquired when liquid magma cools from temperatures above the

Curie point of its ferromagnetic constituents. In this case the important assumptions are that the geomagnetic field has always been the same dipolar field that it is now and that the geomagnetic poles have always coincided approximately with the present geographic poles. If these assumptions are usually accepted for the geomagnetic field since the upper Cretaceous, then a deviation of pole positions at a given time and place relative to the present geographic poles will be to demonstrate that the site itself has moved or that the geomagnetic poles at the time of formation of the rock had themselves shifted.

For the upper Tertiary a paleomagnetic pole is close to the north or south geographic pole and during the lower Tertiary the pole might now lie 20 degrees away from the present geographic poles. Moreover the apparent polar-wander paths from various

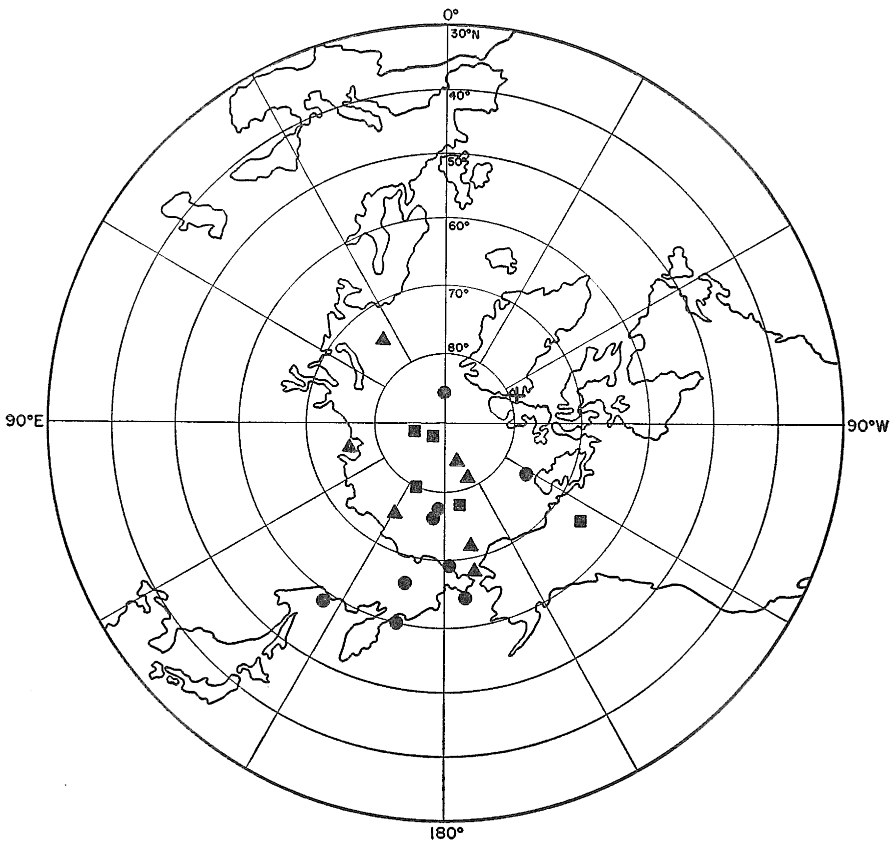

Fig. 2. Paleomagnetic pole positions compiled by McElhinny (1973).
●: Cretaceous poles.
▲: Lower Tertiary poles.
■: Upper Tertiary poles.
+: Geomagnetic pole.

parts of the world appear to fall into 30 degrees of the geographic pole since the Cretaceous (McElhinny, 1973). This shows that paleomagnetic poles from the Cretaceous to recent have been in the range of 30 degrees in latitude from the present geographic pole as shown in Fig. 2. The positions of Cretaceous and Tertiary pole compiled by McElhinny (1973) are likely to lie mainly at a region that is away about 90 degrees in longitude from the dipolar magnetic pole and virtural geomagnetic pole positions calculated from the present field at the magnetic observatories (Doell and Cox, 1961). The fact that Cretaceous group of pole positions departs slightly from the present geographic pole is, of course, explained by a hypothesis of the polar wandering. This means that the inclination obtained from Cretaceous and Tertiary rocks in Japan obviously give more steeper value compared with that of recent rocks. On the other hand, although the dispersion in the present group is expected from the nondipole terms in the geomagnetic field, it is attractive that the scatter of the virtual pole positions calculated is similar to that of paleomagnetic pole positions since the Cretaceous compiled by McElhinny (1973).

Thus it is concluded that the main geomagnetic field since the Cretaceous has always been a axial dipole field and that the poles since the upper Tertiary have approximately coincided with the present geographic poles. The Cretaceous paleomagnetic pole appears to be displaced from the geographic pole. They, however, lie 30 degrees away from the north geographic pole. This divergence of the paleomagnetic pole would be important to make good use of directions of remanent magnetization for structural problems.

4) Analysis of directions of remanent magnetization

As described in the previous sections, the primary remanent magnetization in a rock appears to have been parallel to the ambient field due to a geocentric axial dipole at a given time and place. If the remanent magnetization between sites within the rock have significantly deviated from the geographic or paleomagnetic pole, it is usually concluded that such vectors fixed in the rock have been brought about by movements of the rock after the intrusion. In the case of large intrusive rocks, there may be many changes or modifications that have occurred within the rock after the formation. It is therefore expected that samples collected from a wide area within the large intrusions have mostly random directions of the remanent magnetization or no remanence. Since such large intrusive rocks were originally thousand or more meters below the surface, they might be locally deformed during a process moved to the present position. This means that large intrusions are hard to move as a block as small intrusive rocks.

We will schematically consider on a block with a magnetic vector fixed in its center. If the magnetic vector deviated from the present field direction at a given site, the block should imply to have rotated about an axis that is taken through the center of the block. During the movement of this block vertical displacements and movements along the latitude are unknown, because such movements of the block are not able to contribute the change in direction of magnetic vector fixed. However, a rotation about an axis being in a plane between the vertical axis and an axis in the horizontal plane will part the magnetic vector from the direction of the present field at given site. The axis is successively selected from the vertical to horizontal. In this case the rotations about the vertical axis and the axis in the horizontal plane are the particular case in these movements.

Many workers have so far pointed out that obvious differences between declinations of the present field and measured remanent magnetization are corrected by a rotation about the vertical axis through the site or a pole given at appropriate region and that a discrepancy between inclinations are explained by a drift of the region relative to the geographic or magnetic poles. In order to move the magnetic vector from the present field direction to the observed one, we will be able to prefer a simple procedure corresponding to a tilting on the assumption that the principle of minimum movement is applied. It is to take an axis perpendicular to a plane made by the measured vector and the direction of the present field, and a plane including the axis bisects the plane made by two vectors. A determination of such an axis has some ambiguity in practice because the way of taking the axis is so schematic, so that we would mostly be to prefer an axis close to the earth's surface which is usually the base plane, as shown by $\overline{OA}$ in Fig. 3.

According to the considerations mentioned above, the vertical axis or a bisector which divide the plane made by true north and the direction of remanent vector into two equal parts should be the most reasonable axis in order to restore it to an original position where it might be close to the geographic pole from the measured direction deviated. The way of taking the axis depends positively upon both values of the inclination due to the dipole field and that of the remanent vector. If both inclination angles are small, the rotation about the vertical axis should schematically be possible to explain a deviation of magnetic vector concerned. On the other hand, if both inclination angles are large, the rotation about an axis in the horizontal plane should be possible. However, the most probable axis should be decided considering the other geological or geophysical observations in the field.

In conclusion the author may note that the equal weight as the rotation about a vertical axis will be provided to the rotational movement about an axis in the horizontal plane, that is, demonstrating a tilting of the rock. This suggests that we will be able to deal quantitatively with tilting of intrusive rocks.

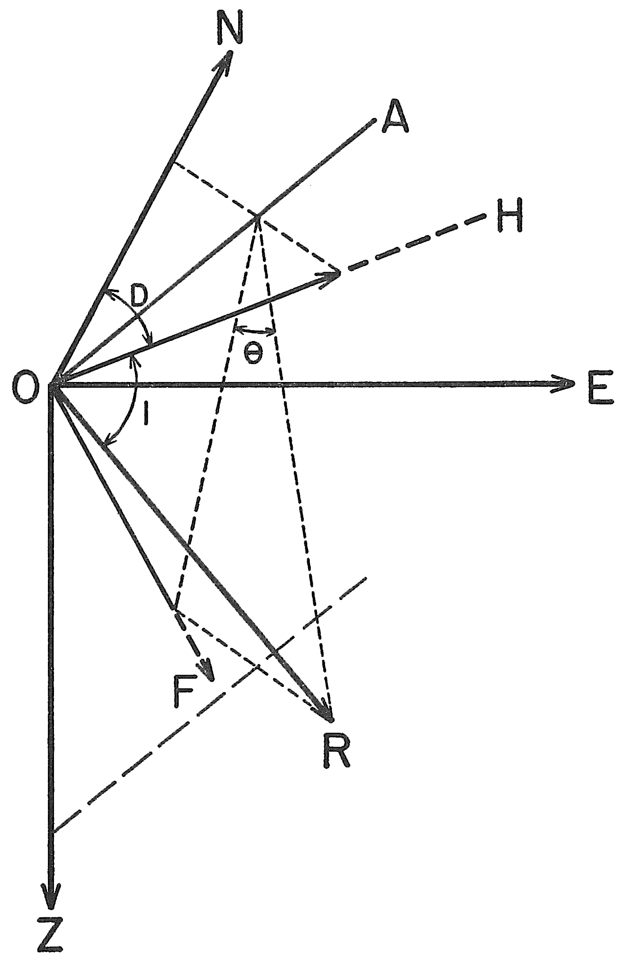

Fig. 3. Schematic rotation about an axis in the horizontal plane.
N: Geographic north.
F: Present field direction due to the dipole field.
R: Remanent magnetic vector
H: Horizontal component of the remanent vector.
D: Measured declination.
I : Measured inclination
θ : Rotation angle.

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