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REPORT No. 92

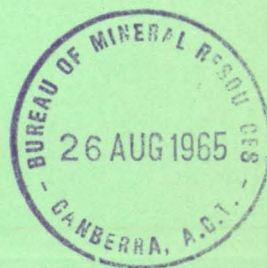
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# Errors and Limitations of the Magnetic Compass

BY

W. D. PARKINSON



*Issued under the Authority of the Hon. David Fairbairn  
Minister for National Development*

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BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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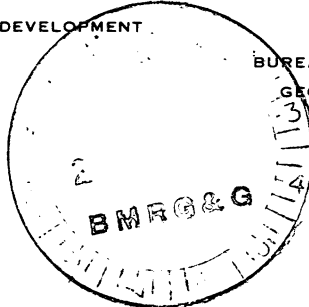
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Forwarded herewith are 5 advance copies of each of the following publications.

REPORT NO. 92 - "Errors and Limitations of the  
Magnetic Compass" - by W. D. Parkinson.

The general release of the above will be made a week from the date of this minute.

*J. M. Rayner*  
J. M. RAYNER )  
Director

*Per KML*

### FOREWORD

Although the magnetic compass is extensively used for determining approximate directions, comparatively few users are familiar with the geophysical phenomena which control its performance. These phenomena often impose limitations on the accuracy obtainable from even a high-quality compass.

This publication is intended to give a simple explanation of some facts about the Earth's magnetic field, particularly those which influence the compass. It includes an example of the isogonic maps published every five years by the Bureau of Mineral Resources, Geology and Geophysics.

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## 1. INTRODUCTION

A compass needle free to turn around a vertical axis comes to rest approximately in a north-south direction. This fact has been known for thousands of years, and was probably the earliest knowledge in the subject that we now call electromagnetism.

Its operation is so simple that the magnetic compass is still a very common way of determining direction, in spite of the numerous errors to which it is subject. This publication is intended to describe the geophysical phenomena which make a compass work and which are responsible for many of its limitations.

### Declination

It is well known that a perfect compass needle does not point exactly towards true north, but "declines" to the east or west by a certain angle called the "declination". The direction to which the compass needle points is called "magnetic north". If magnetic north is east of true north, the declination is said to be easterly or positive; if magnetic north is west of true north the declination is said to be westerly or negative.

The expression "variation of the compass" or "magnetic variation" is sometimes used as a synonym for declination. This is unfortunate, because "variation" implies a change with either time or position.

Values of the declination are shown by maps called "isogonic maps". These contain lines joining places with equal declination, called "isogonic lines". They refer to a particular point of time or epoch, such as 1960.5 (meaning the middle of 1960), or 1965.0 (the beginning of 1965).

### Magnetic Fields

A compass needle is simply a small permanent magnet. If it is near other magnets or electric currents, it experiences a torque which tries to align it in a certain direction. The region in which a compass needle experiences such a torque is said to contain a magnetic field. The other magnets or electric currents are called "sources" of the field. The direction into which the needle is oriented is said to be the direction of the field at the position of the needle. The torque experienced by the needle when it is at right angles to the direction of the field is a measure of the strength or intensity of the field.

## 2. THE EARTH'S MAGNETIC FIELD

The Earth itself has a magnetic field associated with it. This provides the forces that orient a compass needle. To appreciate the limitations of the instrument it is necessary to know something of the field and how it varies in both time and space.

It is convenient to divide the Earth's field into three parts, each of which has a separate source. They are:

- (a) The main field
- (b) The local field
- (c) The external field.

## The Main Field

As its name implies, this constitutes the major part of the field. Its source is almost certainly a system of electric currents in the Earth's liquid core, at least 1800 miles below the surface.

The main field is rather like the field due to a short, very strong magnet at the centre of the Earth, pointing in a direction 11 degrees from the axis of rotation. The field due to this hypothetical magnet is called the "dipole field". It constitutes about 90 percent of the main field. (Notice that the main field is not at all like the field of a long magnet extending through the Earth from the Arctic to the Antarctic. The double meaning of the word "pole" sometimes causes this confusion).

If the dipole field were the only field, the declination would vary in a systematic and predictable way over the Earth. For instance it would be zero along the meridians 111° E and 69° W.

The fact that the axis of the dipole field is only 11 degrees away from the axis of rotation is the reason that magnetic north is generally close to true north, except at high latitudes. Recent research indicates that this is not an accident, but that the current systems that give rise to the main field are closely connected with the rotation of the Earth.

Because its sources are so far below ground, the main field cannot change greatly in a short distance.

## Secular Variation

The main field changes slowly with time as the current system in the liquid core moves. Because of the size of the system and the conductivity of the material between the core and the surface, these changes must be slow. They amount generally to about 0.1 percent per year. In Australia the secular variation of declination at the present time (1964) ranges from about five minutes of arc per year in Tasmania to zero near the north-west coast.

The secular variation does not change rapidly with position. Over distances of 100 miles or so the difference in secular variation is generally quite small.

## The Local Field

This is due to magnetic material in the Earth's crust. At a place where the local field reaches about 0.1 percent of the main field there is said to be a "local magnetic anomaly".

The Earth's crust contains several different magnetic minerals; by far the most important is magnetite, which has the chemical composition  $\text{Fe}_3\text{O}_4$ . Other minerals with only slightly different chemical composition, often including some titanium, also form important sources of magnetism.

At temperatures in excess of 600°C these minerals lose their magnetism. Therefore the sources of the local field are all above the level at which the temperature reaches 600°C, which is at a depth of about 20 miles.



Magnetite and its near relatives are common constituents of igneous rocks, especially basic igneous rocks. On the other hand they are usually absent from sedimentary rocks. The local field is therefore generally much stronger where igneous rocks are at or near the surface. Over deep sedimentary basins the local field is usually only a small fraction of one percent of the main field, and amounts to only a few minutes in declination. Over regions where igneous rocks are at or near the surface, anomalies in declination often reach tens of minutes, occasionally as much as one or two degrees.

In some places magnetite has been concentrated to form an ore. The orebodies are, however, small compared with the Earth as a whole. Near them the local field can be almost as great as the main field, and the declination can reach values of up to 90 degrees or more.

Therefore the regional geology is often a guide to the likely magnitude of the local field. However, it must be remembered that geological maps usually show only the formations that exist at the surface; a region of thin sedimentary rocks overlying a magnetic basement rock will still be subject to quite a large local field.

Because the sources of the local field are near or even at the surface, it can vary greatly within a small distance. Sometimes there are appreciable differences at points only a few feet apart.

Unlike the main field and the external field, the local field does not change with time. There may be a considerable difference between the magnetic fields at places close together, but, although the total field may change at both places, the difference will remain constant. The only exception to this is where volcanic activity changes the temperature of magnetic material in the crust.

The local field is the most important source of error both in the preparation of isogonic maps and in determining directions with a compass.

### The External Field

It has already been explained that secular variation arises from slow movements of the current system in the Earth's core. In addition to secular variation there are more rapid variations with time, which originate in the "external field". This field originates from electric currents flowing in the upper atmosphere and in the space around the Earth (the "magnetosphere"). Of the many time variations due to the external field, only two are of importance here: the diurnal variation and magnetic storms.

Every day the magnetic field undergoes a regular variation. The declination (in the southern hemisphere) moves to the west of its mean value in the morning, returns to the mean at noon, swings to the east in the afternoon, and returns to the mean value in the evening. During the night it usually remains close to the mean value. The amount by which the declination changes in this type of variation depends on latitude. In southern Australia it swings by about five minutes each side of the mean. This swing decreases towards the north until, in tropical latitudes, the external field has almost no effect on the declination. In the northern hemisphere the sign of the diurnal variation of declination is reversed. The observations that are used to compile isogonic maps are corrected for this type of variation. It is of importance only in the case of very accurate magnetic measurements.

Superimposed on the diurnal variations there are more or less sporadic variations. These are usually of small amplitude, but occasionally they become much larger. The phenomenon is then called a "magnetic storm". During a magnetic storm the declination may move in either direction, sometimes as rapidly as a minute of arc per minute. Departures of as much as half a degree from the mean value, however, are very rare in temperate latitudes.

There is no complete explanation of magnetic storms. They are connected with activity on the sun and unusual electrical conditions in the upper atmosphere.

### 3. ISOgonic MAPS

Because the declination varies over the surface of the Earth in a rather irregular manner, the user of a compass must have information about the declination at the place where he is using the compass. This information is contained in isogonic maps. Because of the secular variation, it is necessary to issue a new map every few years. In most countries some government agency is responsible for preparing and issuing isogonic maps. In Australia the Bureau of Mineral Resources, Geology and Geophysics issues an isogonic map every five years. It is published about two years before the date to which it refers. The change in declination over five years is not great - at most, half a degree - and a map showing contours of secular variation of declination (an "isoporonic map") is supplied with the isogonic map. By applying the change indicated by the isoporonic map, correct declinations can be obtained at any other time within the five-year interval.

Plate 1 contains the isogonic map of Australia for the epoch 1965.0. The extremes of declination in Australia are  $13.5^{\circ}$  E in the south-east of Tasmania and  $4.5^{\circ}$  W in the south-west of Western Australia. The line along which the declination is zero runs from near Esperance to Learmonth.

The left-hand inset extends the map to Cocos Islands in the Indian Ocean.

The upper right-hand inset indicates the rate of secular variation. For instance the rate of secular variation at Sydney is  $+2.5$  minutes of arc per year. Using this and the main map we would expect the declination in Sydney to be  $11^{\circ}15'$  E in 1955,  $11^{\circ}40'$  E in 1965, and  $12^{\circ}05'$  in 1975.

The lower right-hand inset shows the locations in Australia and New Guinea at which the magnetic field has been measured.

#### Errors in Isogonic Maps

Approximately it may be said that an isogonic map tries to indicate the main field. The influence of the local and external fields causes errors.

The isogonic map of Australia was based on observations at points shown in Plate 1. It will be seen that the distribution of observations in the central part of the continent is not as uniform as in the parts east of  $140^{\circ}$  E or west of  $120^{\circ}$  E. Values must be interpolated across areas where observations have never been made.

At each observation point the declination has been measured accurately at some time. To use these measurements in compiling an isogonic map the effects of the external and local fields, and secular variation, must be removed.

There is no practical way of eliminating the effects of the local field. If the points at which the measurements have been made are 50 miles apart, and declination values are averaged over groups of about nine stations (three by three) the effects of the local field are uncorrelated at neighbouring stations and so will tend to average out. Moreover, as the main field does not change much over the area covered by nine stations the smoothing process employed when drawing the isogonic lines will tend to eliminate the local field and leave the main field. However, these methods of eliminating the local field are not entirely reliable, statistically, for accidental similarities of local field at adjacent observation points can cause errors in the isogonic map.

The effect of the external field is generally small. The systematic time variation, represented by diurnal variation, can be allowed for. The effects of magnetic storms are not so easily eliminated, but the records from a magnetic observatory, even a distant one, will indicate whether the measurements are affected by a magnetic storm or not. Sometimes it is necessary to discount measurements made during a magnetic storm.

Another source of errors in the isogonic maps is the uncertainty of secular variation. Measurements cannot be made at the same time at all stations. Often they stretch over many years. Therefore an estimate of the secular variation over the entire continent must be made in order to bring the measurements to a common date. Although the pattern of secular variation is not well known all over Australia, the errors from this source are probably much smaller than those due to the local field.

It is likely that the isogonic map of Australia represents the true main field within 20 minutes of arc all over the continent.

#### 4. ERRORS IN COMPASS READINGS

##### Geophysical Errors

If a compass is used to determine true directions, the declination at the time and place of observation must be known. In general this is not known, but the main field can be considered to be known from an isogonic map. The difference between the main field and the actual field constitutes what may be called the "geophysical error" in compass reading.

For all but the most accurate compass readings the effect of the external field is nearly always negligible. Intense magnetic storms are very rare. A departure by more than half a degree from the mean value occurs for a total of only about two hours in an average year in Australia.

The effect of the local field is likely to be the most important source of errors. The magnitude of the error to be expected depends largely on the regional geology. An estimate of the probability of errors of a certain size can be made from the difference between actual observations and the smoothed values given by isogonic maps. Over that part of Australia where sedimentary rocks predominate it can be taken as a rough guide that errors of more than 10 minutes will occur at 10 percent of locations. Over that part of the continent where igneous rocks predominate, errors of more than 10 minutes can be expected at about 33 percent of locations. Large errors in declination can be expected in mineralised areas, such as mining districts.

### Artificial Fields

Artificial fields are a possible source of errors in compass readings. Magnetic materials or direct-current electrical circuits give rise to magnetic fields that can influence magnetic measurements.

The magnetic effect of a direct-current circuit depends on the current and the area of the loop as seen from the point of observation. If the active and return wires are close together, the magnetic effect will be less than if they are separated. Electric trains and trams are the most potent source of disturbances of this type, particularly when they run over long distances and when an appreciable fraction of the return current flows through the ground. The magnetic effect can sometimes be detected some miles away.

Away from electric railways, the commonest source of artificial fields is iron or steel. As a rough guide, errors due to artificial fields will be less than 0.1 degrees at distances of more than 20 yards from a wire fence or motor car and 65 yards from a non-electric railway.

### Instrumental Errors

Instrumental errors in a compass are of three types:

- (a) Errors due to mounting of the needle.
- (b) Errors due to alignment of the magnetic axis.
- (c) Errors due to magnetic material in the body of the instrument.

A compass needle must be mounted so that it can turn in a horizontal plane. This is done either by balancing the needle on a pivot or by suspending it by a fibre. Sometimes the weight on the pivot is decreased by floating the needle (and attached card) in a liquid.

The magnetic field is horizontal only at the magnetic equator, so that generally there is a vertical field tending to make the south end of the magnet dip (in the southern hemisphere). The centre of gravity of the moving system must be adjusted so that the needle remains in a horizontal plane. This adjustment must be changed with changing magnetic latitude.

Static friction is a common source of error in the pivot type of compass. This makes the needle come to rest out of its position of magnetic equilibrium. Its effect can be partly eliminated by averaging a large number of readings, making the needle swing from left to right and from right to left an equal number of times.

In more accurate instruments the needle is supported by a fibre; such instruments are usually called "declinometers". Friction is negligible in this case, but the fibre itself may introduce torsion. This makes the needle come to rest with the magnetic torque not zero, but equal to the mechanical torque due to the torsion in the fibre. This error can be eliminated by replacing the compass needle by a non-magnetic weight of equal mass and adjusting the fibre until there is no torsion in the reading position. The error in a good declinometer is a small fraction of one minute.

Types of compass differ mainly in the way the equilibrium position of the needle is read. In the simplest type the needle moves over a scale fixed in the instrument. In the case of the surveyor's compass, sight vanes are fixed on the instrument in line with the zero of the scale. In some compasses, such as the prismatic compass and the mariner's compass, the scale is attached to the needle and turns with it, the reading being made against a mark (the "lubber's line") fixed in the body of the instrument.

Some compasses, designed to be attached to a theodolite, have no scale of their own. The end of the needle, or a mark on it, is lined up against a mark fixed on the theodolite, and the reading is made on the theodolite circle.

The magnet system of a declinometer is viewed through a small telescope. It is furnished either with a mirror or a scale and collimating lens so that the scale reading depends only on the direction of the magnet. If it has a mirror, the eyepiece itself has a scale, and the observer sees two images of the scale.

In any type of compass or declinometer the geometrical axis of the needle system is determined by marks on the needle, the zero of the scale, or the normal to the mirror. This does not necessarily coincide with the magnetic axis of the needle and, of course, it is the magnetic axis which lies in the magnetic north direction at equilibrium. In some compasses the needle can be inverted (i.e. turned about its major axis) and a reading made with the same marks (or mirror). The mean of "erect" and "inverted" readings is free of this kind of error. If the needle cannot be inverted, the angle between the magnetic and optical axes must be known and applied as a correction to all readings. It can be determined by calibrating the compass in a place where the declination is known.

Commercial brass and copper are usually magnetic to some degree, and their use in the fixed parts of a compass will cause errors. Unfortunately this is not always appreciated by manufacturers. Errors due to magnetic material are particularly objectionable because they change in magnitude with the location in which the compass is used. A compass containing magnetic material may give consistent calibrations if it is always calibrated at the same place, but the error may be different when it is used in a different place.

If the magnetism is permanent (as opposed to induced magnetism) the error will be inversely proportional to the horizontal intensity of the magnetic field. In this case it will vary with latitude. It would be about twice as great in Tasmania as in New Guinea. Induced magnetism will cause errors that are more erratic, but generally they will not vary much more than those due to permanent magnetism.

Some cheap compasses have a true north direction engraved on them to allow for the declination. These marks should be treated with suspicion because they usually apply to the place where the compass was made rather than to where it is being used.

## 5. THE MAGNETIC FIELD IN HIGH LATITUDES

A word should be said about the special difficulties of using a compass in high latitudes. Many of the approximations that hold in temperate latitudes become invalid in polar regions.

Firstly, the fact that the compass points roughly north-south is no longer true at distances less than say 20 degrees from the pole; this follows from the fact that the magnetic axis is inclined at 11 degrees to the axis of rotation. There are large areas near each pole where the declination is more than 90 degrees.

Secondly, all isogonic lines pass through both the geographic pole and another point about 1500 miles away known as the "magnetic pole". This would be so, even if only the main field existed. For this reason the isogonic lines are crowded together in polar regions, and therefore it is no longer valid to consider the declination of the main field as changing only slowly with position. For instance, the declination varies by less than 15 degrees between Perth and Sydney. Along the coast of Antarctica near Terre Adelie, however, it varies by 120 degrees in less than 300 miles.

These two facts would not matter so much if there were accurate isogonic maps of polar regions, but there are not. A number of measurements of declination have been made in Antarctica, and more are being made each year, but there are not yet sufficient to allow a reliable map to be drawn.

Thirdly, the direction of the magnetic field in polar regions is almost vertical. This means that the horizontal intensity of the field, which supplies the torque to turn a compass needle, is very weak. For this reason, errors due to magnetic material near the compass (including that causing the local field) are increased. For instance a compass that has an error of 10 minutes (due to permanent magnetism) in Sydney, will have an error of 13 minutes at Mawson and of 28 minutes at Wilkes.

Another consequence of the comparatively weak horizontal intensity in polar regions is that time variations due to the external field can disturb the declination much more than in temperate latitudes. Furthermore the electric currents causing the external field are concentrated near the polar regions, especially near a circular zone running just south of Macquarie Island and north of Mawson, called the "auroral zone". At Mawson the declination departs by more than half a degree from its average value for about 5.5 percent of the time, or 470 hours per year, compared with only two hours per year near Melbourne.

