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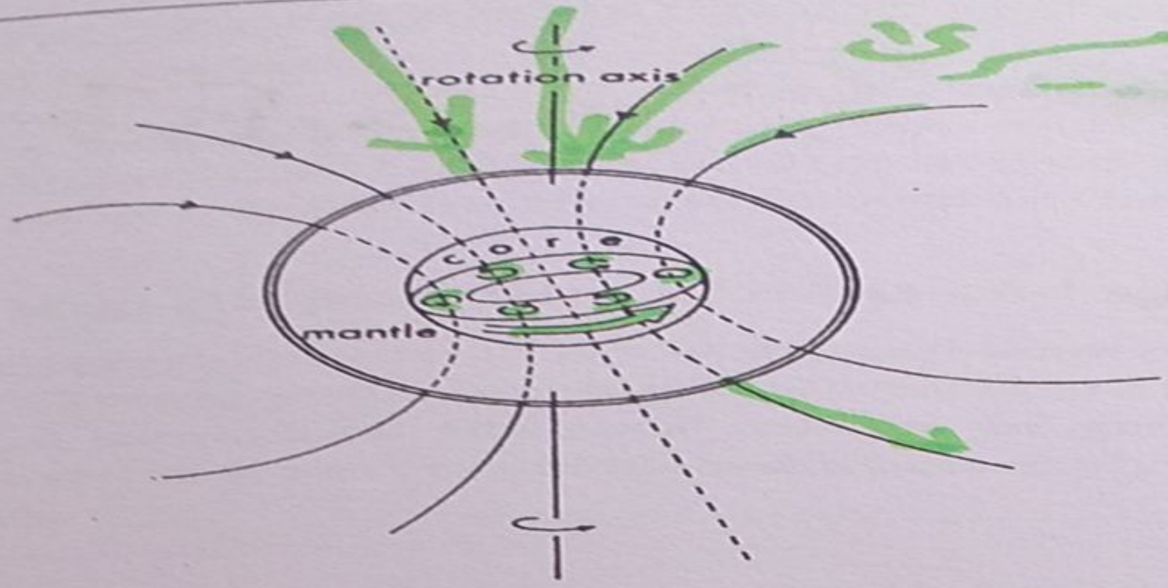

Fig. 3.3 The earth's magnetic field is probably associated with an intense current loop (shown by the broad arrow) circulating in the core. The way in which this current is generated by a self-sustaining dynamo action in the liquid core is not known in detail.

The field, F, is maximum ($2cM/r^3$) when P is along the dipole axis ($\theta = 0$ or $180°$); it is minimum (cM/r^3) when P lies in the central plane perpendicular to the dipole axis ($\theta = \pm 90°$).

If we consider P to be at the surface of the earth and the vertical dipole at its center, then B_r and B_θ represent the vertical and horizontal components of the earth's dipole field, M being the dipole moment of the earth and r its radius. The total intensity of the earth's field (also called the geomagnetic field), F, and its inclination, I, as a function of site latitude, λ, are then given by Eqs.(3.10a) and (3.10b), respectively. It is convenient to mention here that the magnetic dipole that best fits the earth's present field, F (measured worldwide at various observatories), is found to have a moment of approximately 8×10^{22} A m^2, with an axis inclined at about 11.5° from the geographical axis. The origin of the earth's main field (dipole field) is believed to be in the outer core, where the material is fluid (Fig. 3.3).

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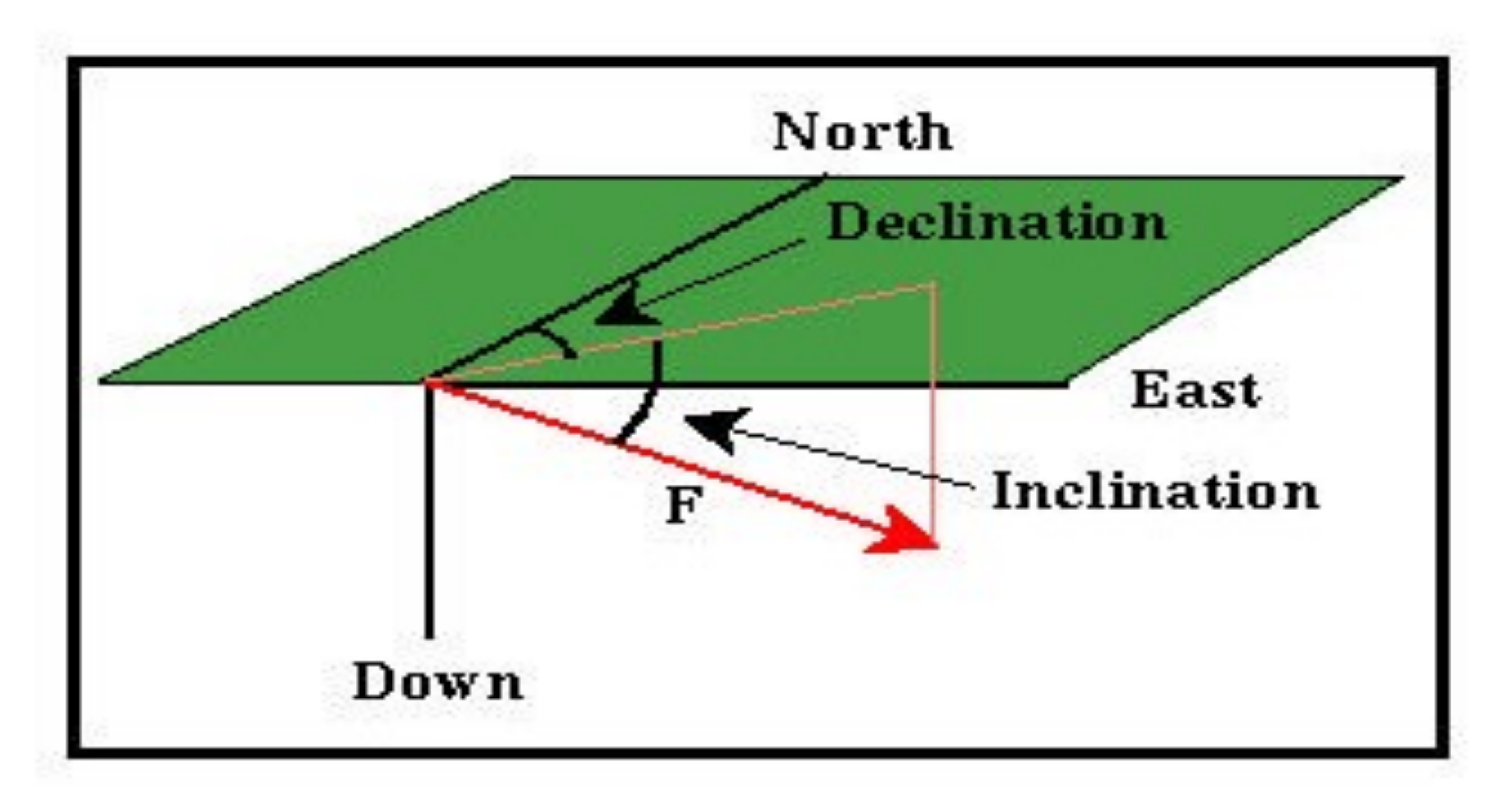
...) is believed to be in the outer core, where the material is fluid (Fig. 3.3).

The earth's magnetic field requires the specification of three 'elements' for a complete statement of its magnitude and direction at any point. A common combination comprises the vertical component, *Z*, the horizontal component, *H*, and the declination, *D*, which is the angle between the direction of the horizontal component (i.e., the magnetic north) and the true or geographical north. An alternative set of elements is the total-field intensity, *F*, its inclination, *I*, with respect to the horizontal, and the declination, *D*. Occasionally the field components are directly referred to geographical coordinates, north component (*X*), east component (*Y*), and vertical component downwards (*Z*). The interrelationships between the geomagnetic elements can be derived from the diagram shown in Fig. 3.4, and are:

Magnetic Field Nomenclature



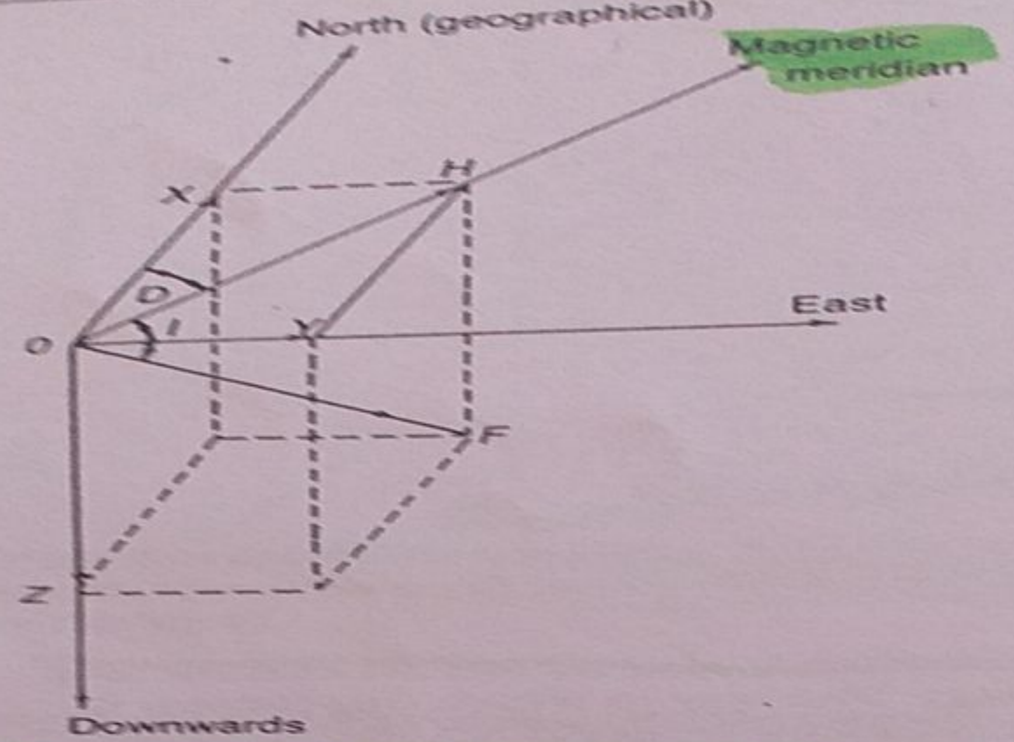


Fig. 3.4 Main elements of the geomagnetic field. *D* and *I* are the declination and inclination, respectively, of the total-field vector **F**.

$$F=\sqrt{X^2+Y^2+Z^2}=\sqrt{H^2+Z^2};\ \tan I=Z/H$$
$$X=H\cos D;\ Y=H\sin D;\ Z=F\sin I. \qquad (3.11)$$

The data from magnetic observatories, compiled on a world map, show intensity variations in the total field, *F*, from roughly 25,000 nT at the geomagnetic equator to more than 60,000 nT at the poles. The geomagnetic equator (where the inclination, *I*, of the field is zero) deviates considerably from the geographical equator and so do the geomagnetic poles (where $I=\pm 90°$) from the geographical poles. The observatory data also show secular (long-term) variations in the magnitude as well as the direction of the field. In addition, there are short-period changes (diurnal varia-

Geomagnetic Equator - The location around the surface of the Earth where the Earth's magnetic field has an inclination of zero (the magnetic field vector *F* is horizontal). This location *does not* .correspond to the Earth's rotational equator

Geomagnetic Poles - The locations on the surface of the Earth where the Earth's magnetic field has an inclination of either plus or minus 90 degrees (the magnetic field vector *F* is vertical). These locations *do not* correspond to the Earth's .north and south poles

Declination - The angle between north and the horizontal projection of *F*. This value is measured positive through east and .varies from 0 to 360 degrees

Inclination - The angle between the surface of the earth and *F*. Positive inclinations indicate *F* is pointed downward, negative inclinations indicate *F* is pointed upward. Inclination varies from -90 .to 90 degrees the geomagnetic poles (where $I = \pm 90°$) from the geographical poles. The observatory data also show secular (long-term) variations in the magnitude as well as the direction of the field. In addition, there are short-period changes (diurnal variations) in the intensity of the earth's field, which are of considerable practical significance in magnetic surveying (Section 3.4.2).

The advent of satellites dedicated to measuring the total field (**F**) or its vector components (H, Z), has remarkably augmented the global coverage and improved the data for analysis of the earth's field. A widely accepted standard to provide reliable spatial distribution of the geomagnetic field is called the 'International Geomagnetic Reference Field' (IGRF) and is revised every five years. The IGRF standard includes time-variable terms which attempt to predict the secular changes in the main field of the earth from previous fluctuations and takes into account the latitude and longitude of the position on the earth's surface, as well as its height relative to sea-level. Maps of the total intensity, F, declination, D, and inclination, I, of the magnetic field over the earth's surface (IGRF 1990.0) are shown in Fig. 3.5.

The Earth's Magnetic Field

Ninety percent of the Earth's magnetic field looks like a magnetic field that would be generated from a dipolar magnetic source located at the center of the Earth and aligned with the Earth's rotational axis. This first order description of the Earth's magnetic field was first given by Sir William Gilbert in 1600. The strength of the magnetic field at the poles is about 60,000 nT. If this dipolar description of the field were complete, then the magnetic equator would correspond to the Earth's equator and the magnetic poles would correspond to the geographic poles. Alas, as we've come to expect from magnetism, such a simple description is not sufficient for analysis of the of the
.Earth's magnetic field
.
The remaining 10% of the magnetic field can not be explained in terms of simple dipolar sources. Complex models of the Earth's magnetic field have been developed and are available. Shown below is a sample of one of these models generated by the USGS. The plot shows a map of declinations for model of the magnetic

If the Earth's field were simply dipolar with the axis of the dipole oriented along the Earth's rotational axis, all declinations would be 0 degrees (the field would always point toward the north). As can be seen, the observed declinations are quite .complex

As observed on the surface of the earth, the magnetic field can be broken into three .separate components

Main Field - This is the largest component of the magnetic field and is believed to be caused by electrical currents in the Earth's fluid outer core. For .exploration work, this field acts as the inducing magnetic field

External Magnetic Field - This is a relatively small portion of the observed magnetic field that is generated from magnetic sources external to the earth. This field is believed to be produced by interactions of the Earth's ionosphere with the solar wind. Hence, temporal variations associated with the .external magnetic field are correlated to solar activity

Crustal Field - This is the portion of the magnetic field associated with the magnetism of crustal rocks. This portion of the field contains both magnetism caused by induction from the Earth's main magnetic field .and from remanent magnetization

As in the case of gravity, the magnetic field anomaly is simply the observed minus the predicted value at the observation site. If F_{obs} is the measured total field (corrected for temporal variations) and F_R is the reference field (given by the IGRF tables) at the site, the geomagnetic anomaly in the total field (ΔT) is given by $\Delta T = F_{obs} - F_R$. Observations of the ΔT anomaly field (or its vertical or horizontal component) over the area of survey reflect subsurface variations in the magnetization of rock formations.

3.3 Magnetic properties of rocks and soils

Magnetic characteristics of rocks depend largely on the content of magnetic minerals (such as magnetite, maghemite) which are normally in the form of fine grains dispersed throughout the rock matrix. In general, both induced and remanent magnetization are to be considered when studying the bulk magnetization of rocks and soils.

3.3.1 Induced magnetization and susceptibility

When a magnetizable body is subjected to an external magnetizing field, H, it acquires a magnetization that is lost when the applied field is removed. Such a magnetization is said to be induced by the applied field. For most rock bodies, the induced magnetization, J_i, is parallel and proportional to the applied field, H. This proportionality is valid for small field strengths and is expressed by the simple relationship

$$J_i = \kappa H \tag{3.12}$$

The factor κ is called the *magnetic susceptibility* and is a characteristic constant for a tionship

$$J_i = \kappa H \tag{3.12}$$

The factor κ is called the *magnetic susceptibility* and is a characteristic constant for a magnetizable material. In SI units, κ is dimensionless, since J and H are both measured in the same units (A/m). In the e.m.u.c.g.s. system, the magnitude of κ (volume susceptibility) is $1/4\pi$ of that expressed in the SI units.

×4π

The induced magnetization in a rock body of susceptibility, κ, due to the earth's field, F (in tesla), can be obtained from Eq.(3.12) simply by replacing H by F/μ_0 (see Eq.(3.4)); thus

$$J_i = \kappa(F/\mu_0) \tag{3.13}$$

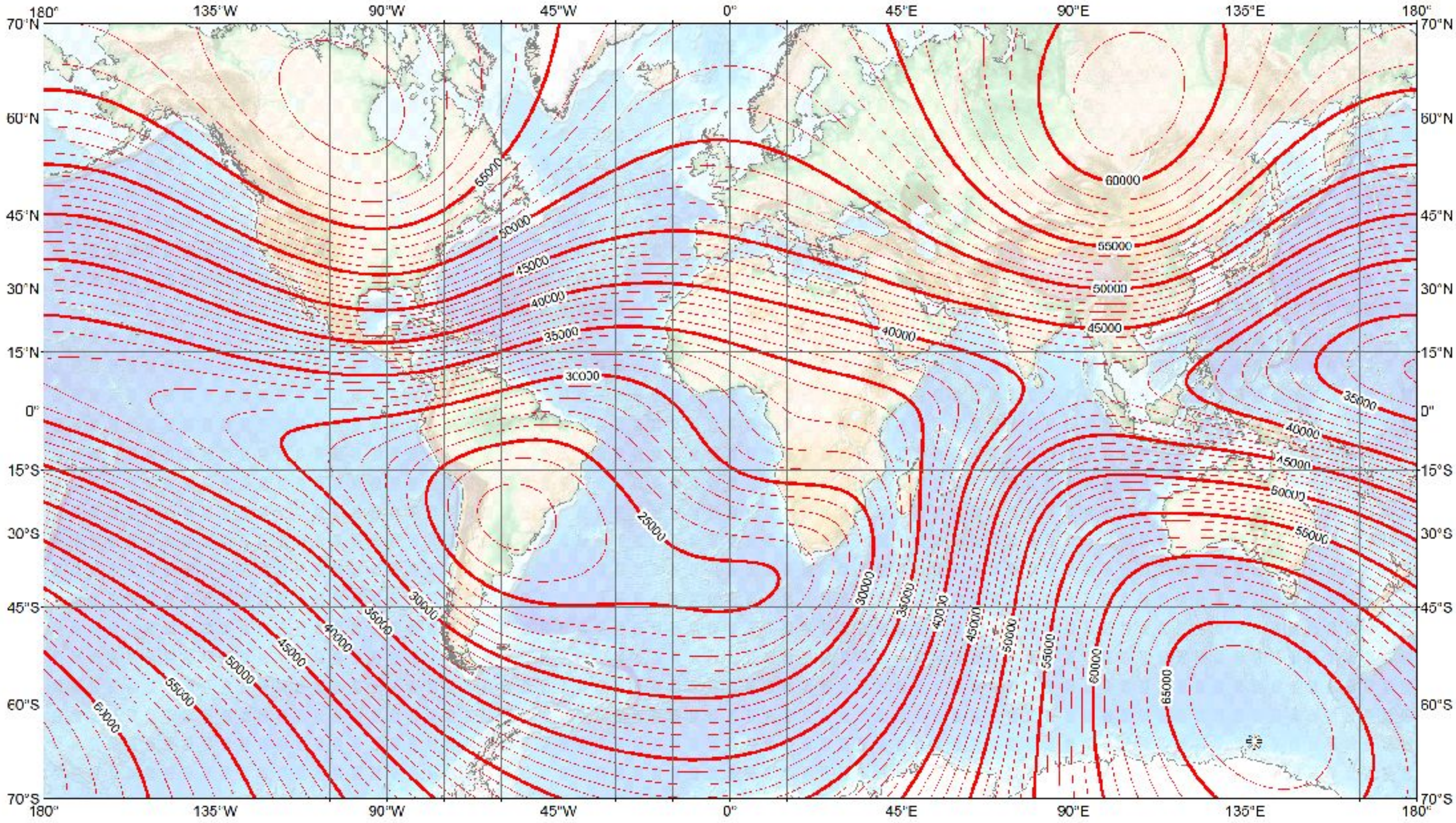
The symbol F is used throughout this chapter to denote the earth's field in the sense of flux density (i.e., B-field).

The magnetic susceptibility of rocks is primarily dependent on the volume percent content of magnetite which is a ferrimagnetic mineral of relatively high susceptibility. Magnetite is a common accessory mineral in igneous and metamorphic rocks and occurs in trace amounts in sediments and sedimentary rocks. The susceptibilities of rocks show an extremely wide range. Igneous and metamorphic rocks generally show higher susceptibility values than sedimentary rocks, but the range of

Material	*(Susceptibility x 10^3 (SI
Air	0~
Quartz	0.01-
Rock Salt	0.01-
Calcite	0.01 - 0.001-
Sphalerite	0.4
Pyrite	5 - 0.05
Hematite	35 - 0.5
Illmenite	3500 - 300
Magnetite	19,200 - 1200
Limestones	3 - 0
Sandstones	20 - 0
Shales	15 - 0.01
Schist	3 - 0.3

Unlike density, notice the large range of susceptibilities not only between varying rocks and minerals but also within rocks of the same type. It is not uncommon to see variations in susceptibility of several
orders of magnitude for different igneous rock samples. In addition, like density, there is considerable
overlap in the measured susceptibilities. Hence, a knowledge of susceptibility alone will not be sufficient to determine rock type, and, alternately, a knowledge of rock type is often not sufficient to .estimate the expected susceptibility
This wide range in susceptibilities implies that spatial variations in the observed magnetic field may be readily related to geologic structure. Because variations within any given rock type are also large, however, it will be difficult to construct corrections to our observed magnetic field on assumedsusceptibilities as was done in constructing some of the fundamental gravitational .(corrections (Bouguer slab correction and Topographic corrections
d

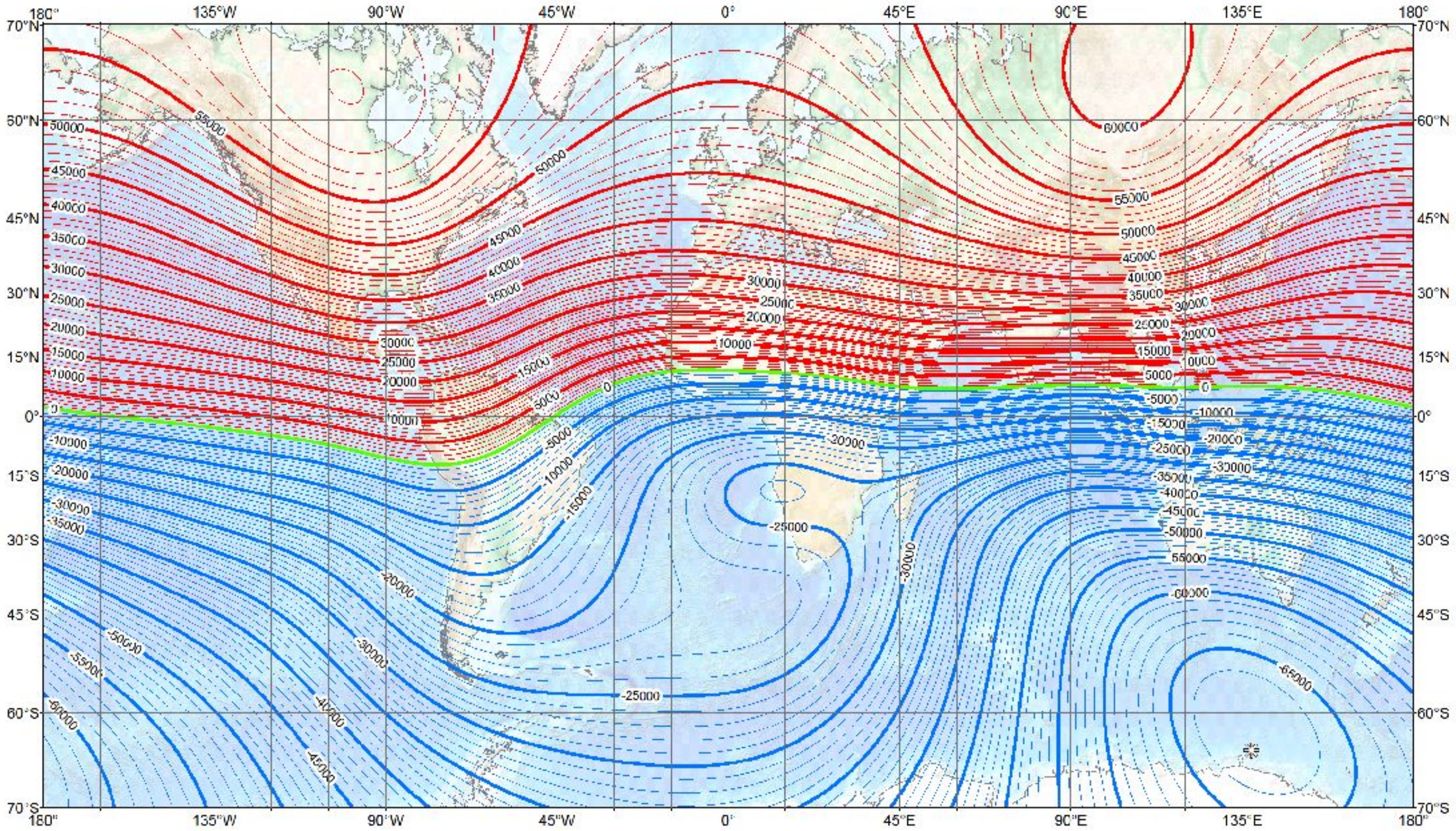
Main Field Total Intensity (F)



Main Field Total Intensity (F)
Contour interval: 1000 nT.
Mercator Projection.

Map developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM/
Map reviewed by NGA/BGS

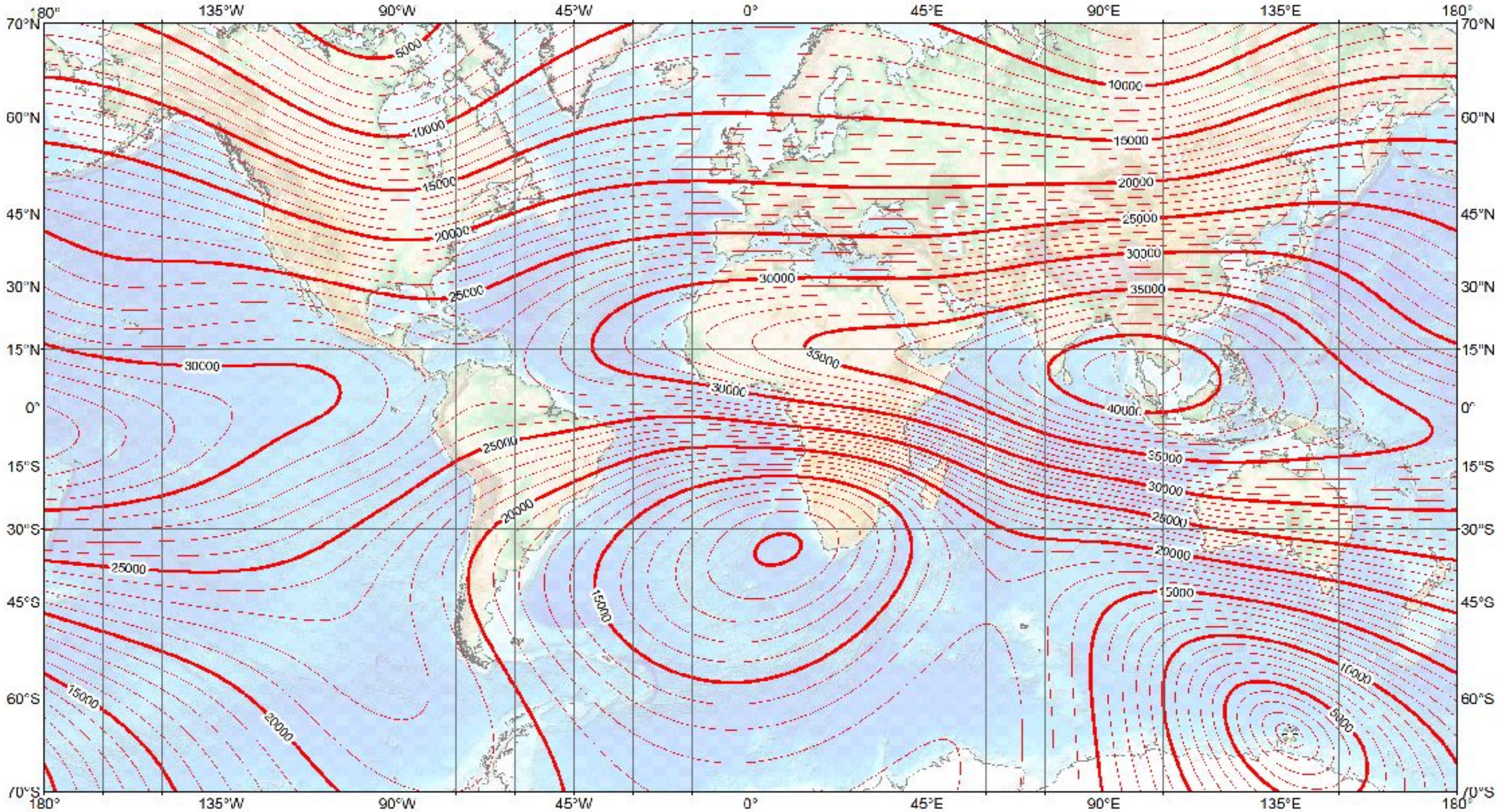
US/UK World Magnetic Model -- Epoch 2010.0
Main Field Down Component (Z)



Main field down component (Z)
Contour interval: 1000 nT, red contours positive (down); blue negative (up); green zero line.
Mercator Projection.
: Position of dip poles

Map developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM/
Map reviewed by NGA/BGS
Published January 2010

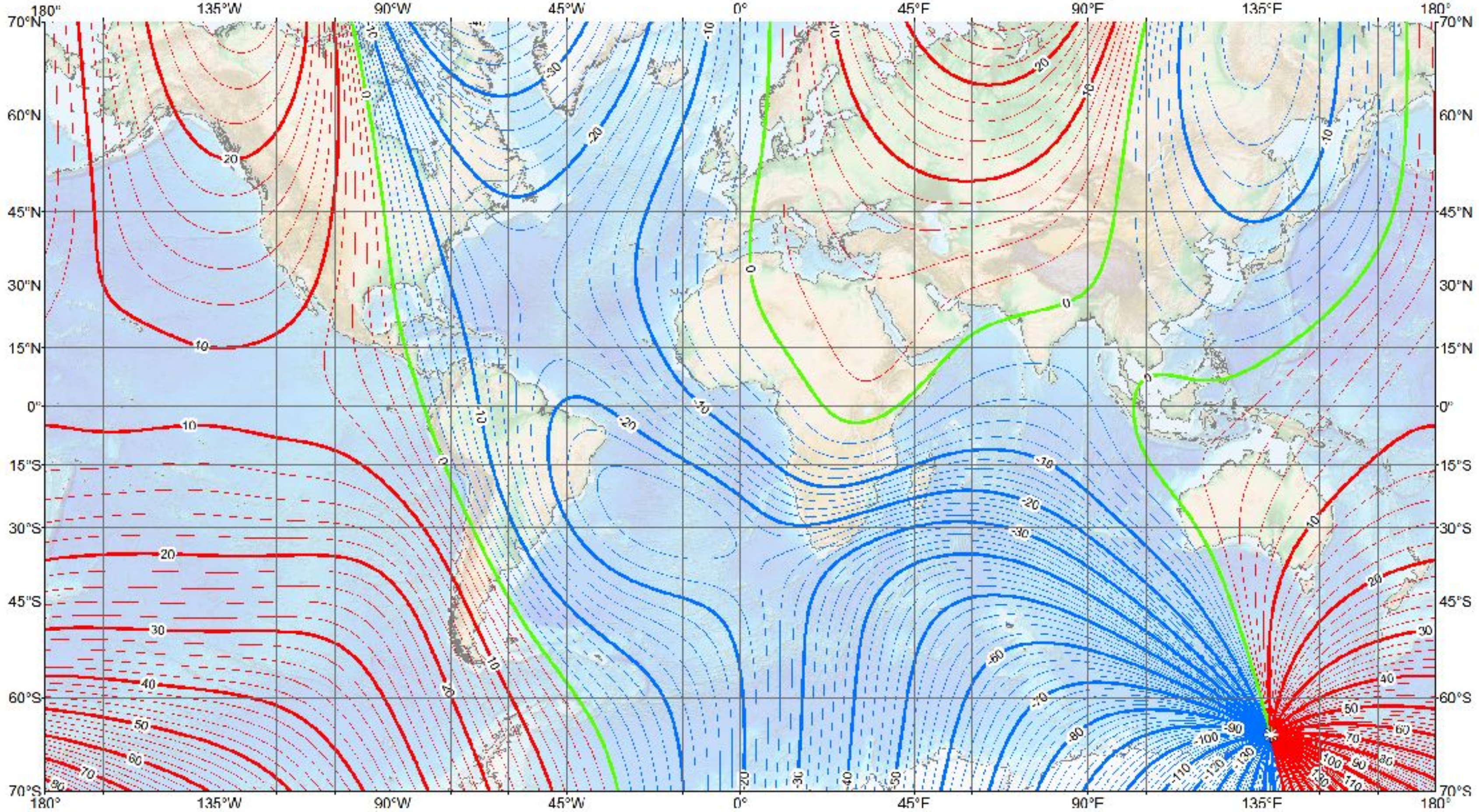
US/UK World Magnetic Model -- Epoch 2010.0
Main Field Horizontal Intensity (H)



Main field horizontal intensity (H)
Contour interval: 1000 nT.
Mercator Projection
: Position of dip poles

Map developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM/
Map reviewed by NGA/BGS
Published January 2010

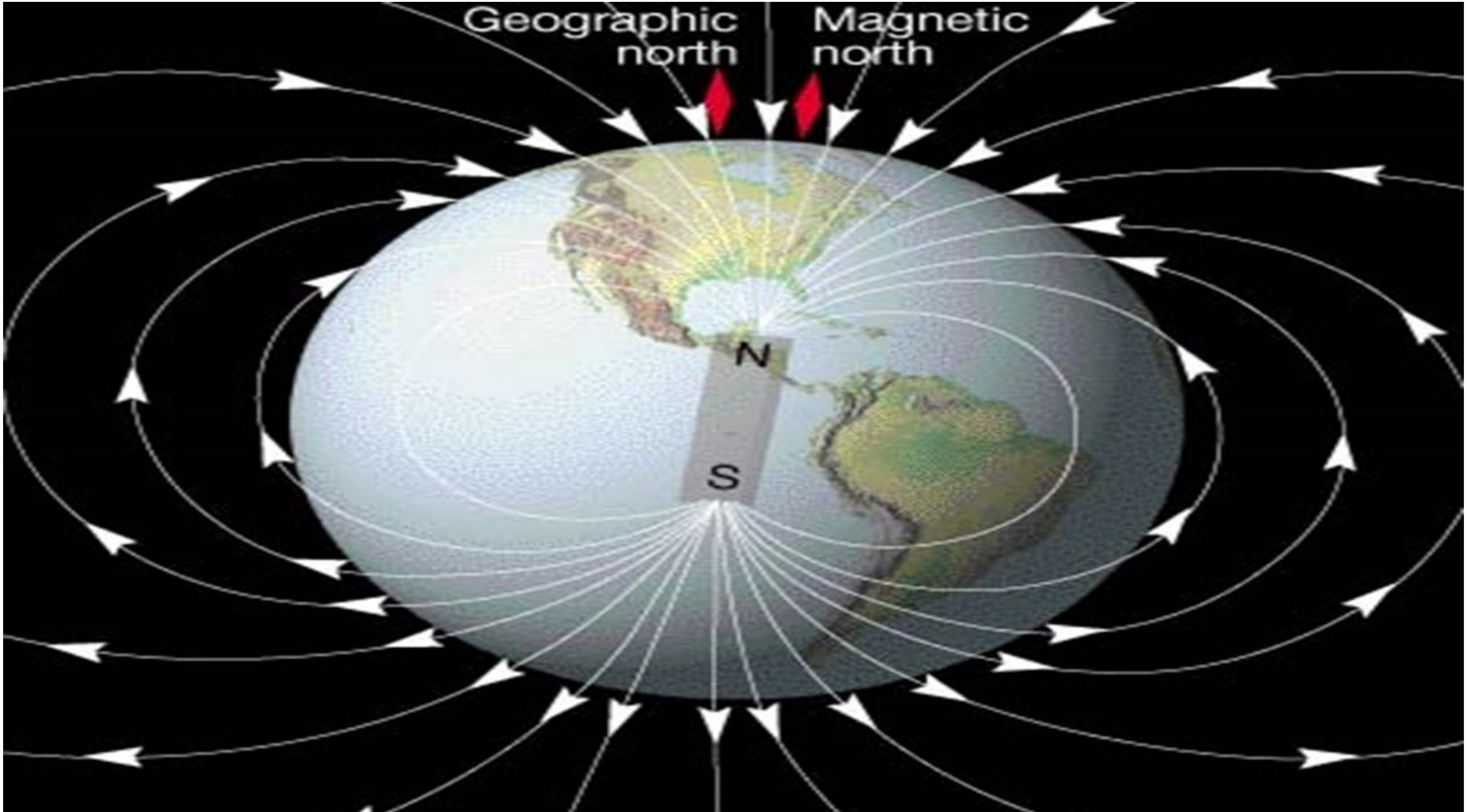
US/UK World Magnetic Model -- Epoch 2010.0
Main Field Declination (D)



Main field declination (D)
Contour interval: 2 degrees, red contours positive (east); blue negative (west); green (agonic) zero line.
Mercator Projection.
✲ : Position of dip poles

Map developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM/
Map reviewed by NGA/BGS
Published January 2010

reconstruction of continental motion using Geocentric Axial Dipole (GAD) hypothesis



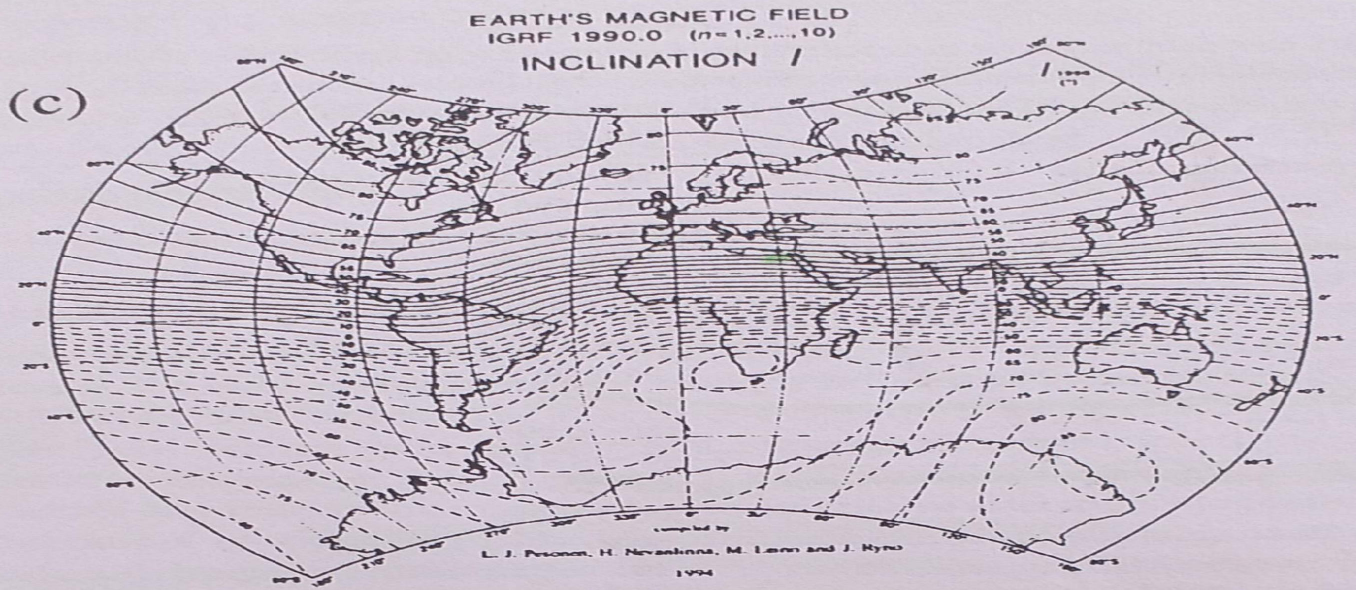


Fig. 3.5 (*cont.*)

variation is so great that it is not possible to identify rock types from the knowledge of the susceptibility and vice versa. It is, therefore advisable to directly determine the susceptibility of rocks within the area of interest. The values listed in Table 3.1 give a rough idea of the susceptibility of common rocks and minerals.

Susceptibility can be measured either in the field on rocks *in situ* using a handy instrument called the 'kappameter', or in the laboratory on small samples. For accurate measurement of low susceptibilities, commercial instruments are available that measure the effect of a sample on a balanced inductance bridge.

3.3.2 Remanent magnetization

Most rocks have a **remanent** (permanent) magnetization, J_r, in addition to J_i induced by the earth's field. J_r may originate in different ways and at different times in the history of the rock. One principal type of J_r, especially found in igneous rocks, is **thermoremanent magnetization (TRM)** acquired by magnetic grains during cooling from the Curie temperature (about 580°C for magnetite grains) to normal atmospheric temperature in the presence of an external field (such as that of the earth). In general, J_r is not related to the earth's present field but is governed instead by the field that existed when the rock was formed. The intensity of J_r and its direction in a rock formation are measured on an oriented drill core in the laboratory using a spinner or astatic magnetometer.

(The International Geomagnetic Reference Field (IGRF

The IGRF is a global model of the geomagnetic field. It allows spot values of the geomagnetic field vector to be calculated anywhere from the Earth's core out into space. The IGRF is generally revised every five years by a group of modellers associated with the International Association of Geomagnetism and Aeronomy (IAGA).

The IGRF program prompts for a number of input parameters. It requires the latitude and longitude of the position where you want geomagnetic field values. These must be supplied in either degrees and minutes (two integers) or decimal degrees. For negative latitudes and longitudes it is necessary to only supply the figure for degrees as negative, (except for zero degrees). The date must also be given in decimal years. The 12th Generation IGRF will accept dates in the range 1900 to 2025.

The program asks whether you are supplying geodetic or geocentric latitude and longitude. The 'usual' values defining positions on the Earth's surface are geodetic coordinates. If you specify geodetic coordinates then the height in kilometres above the WGS84 spheroid is also required. If you only know the height above mean sea level that should be used as the difference in total intensity is very small (mostly less than 1 nT with maxima less than 3 nT). If you specify geocentric coordinates then the geocentric distance in kilometres is required.

The program then calculates the geomagnetic field values, and their rates of change (secular variation) according to the options ticked, at the position and time specified and displays these on the screen.

BGS Global Geomagnetic Mod -'

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Susan Macmillan

What is it?

The BGS Global Geomagnetic Model (BGGM) is a mathematical model of the Earth's magnetic field in its undisturbed state. It is revised every year to allow for the inclusion of new data collected since last revision and any development of the modelling methodology. With annual revisions it is also possible to minimise errors arising from predicting the field at some date after the time span of input data. The BGGM includes long to medium wavelength crustal field but does not include the short wavelengths of the crustal field, or the rapidly varying external field.

What is it for?

The BGGM is widely used in the oil industry for directional drilling with Measurement-While-Drilling (MWD) magnetic survey tools. These tools measure the direction of the well-bore relative to the direction of the local geomagnetic field and are used to navigate wells towards precisely known underground targets. The local geomagnetic field is determined using the BGGM and the MWD data can then be used to give the drilling location in a geographic reference frame. An enhancement of this is to determine the local crustal field using either local absolute observations of the geomagnetic vector or transformation of local total intensity data collected during an aeromagnetic or marine survey. A further enhancement is to take account of the rapidly varying external field using nearby observatory data. These enhancements are referred to as In-Field Referencing (IFR)/IFR1 and Interpolation In-Field Referencing (IIFR)/IFR2 respectively.